NOVA REPORT 2008-2009

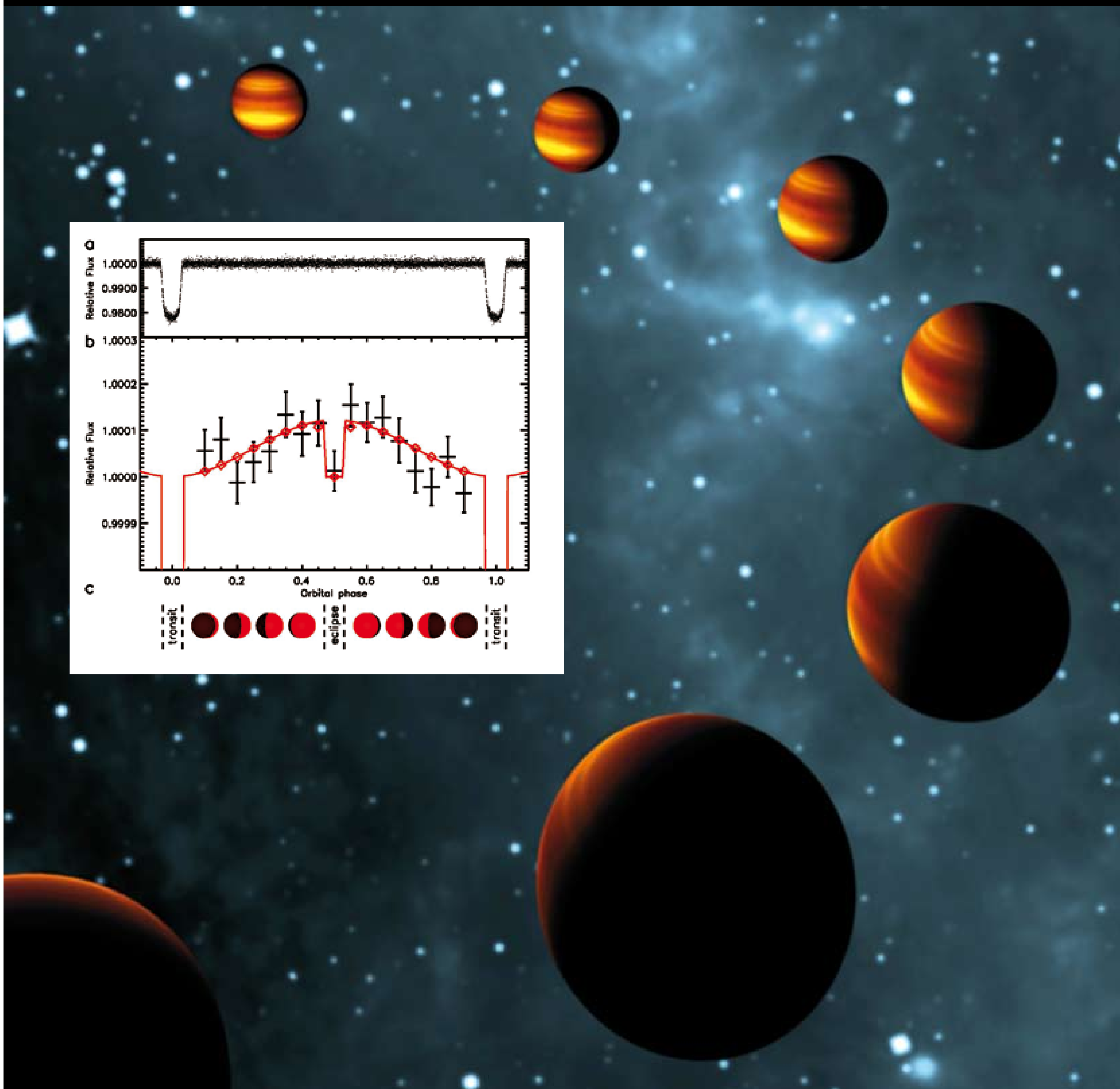

Illustration on the front cover

In the background an artist's impression of the changing phases of exoplanet CoRoT-1b is shown. The panel shows the phase folded lightcurve of this planet as observed with the CoRoT satellite. In sequence, the planet first transits the star, after which the dayside rotates into view, the planet gets eclipsed by the star, and finally the nightside rotates into view and the planet transits the star again. The nightside hemisphere is consistent with being entirely black, just as seen for the interior planets in our own solar system. The dayside flux is most likely thermal emission (from: Snellen, de Mooij & Albrecht, 2009, Nature 459, 543).

Illustrations on the back cover

Counter clockwise starting at upper left.

1. The Sloan Great Wall. Top and face-on view of the SDSS DR7 volume within R<300 h-1Mpc. The Sloan Great Wall is the region roughly located in between the grey lines at Y=155-230 h-1Mpc. The location of well known supercluster are indicated, along with prominent underdense regions like the Bahcall-Soneira Rift and the Boötes and Virgo Supervoid. The outline of supervoids that lie in front are shown as dashed circles (from: Platen & van de Weygaert MNRAS, submitted).

2. Spectral scan of the Orion molecular cloud around 1 THz obtained with the Herschel-HIFI instrument built under leadership of SRON, showing strong lines of water and other simple and complex molecules (credit: ESA, HEXOS and the HIFI consortium). Dutch astronomers are using similarly high quality HIFI spectra to investigate the physical and chemical structure of star-forming regions in our own and nearby galaxies.

3. Hα image of the field of SAX J1712.6-3739. The bright and large bow shock shaped nebula is most likely associated with the X-ray binary. The position of the bright X-ray source is indicated with a white circle. The inset gives a rough guide to the main features (from: Wiersema et al. 2009, MNRAS 397, L6).

4. The Polarimetric Imaging sub-system ZIMPOL overview of the optical bench.

NOVA Report

2008 - 2009

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NOVA is a federation of the astronomical institutes at the universities of Amsterdam, Groningen, Leiden, Nijmegen and Utrecht, legally represented by Utrecht University.

Table of contents

1. Introduction

Throughout the ages, mankind has been fascinated by the night sky. Questions concerning the nature and evolution of the Universe appeal to a deep human desire to understand our origins and place in the Universe. Much remains to be understood. Only in the last few years has it become clear that the Universe consists for 96% of dark energy and dark matter which leave no directly observable trace; everything we see with the most powerful telescopes comprises the remaining 4%. Galaxies can now be studied at the edge of the Universe from which the radiation takes 13 billion years to reach Earth. Much closer to home an amazing variety of planets circling nearby stars has been found, none of which resemble our own Solar System. The tip of the dusty veils surrounding the birth of galaxies, stars and planets, and perhaps even life itself, is finally being lifted. New interdisciplinary topics such as astroparticle physics, computational astrophysics, astrochemistry and astrobiology are emerging worldwide. Astrophysicists study phenomena involving enormous scales of length and mass (the entire Universe), huge densities (e.g., neutron stars), enormous gravitational fields (black holes), ultra-high vacua (interstellar and circumstellar media), and immense energies and intense fluxes of particles and radiation (gamma ray bursts and supernovae, accreting neutron stars and black holes). The desire and curiosity to understand this fascinating Universe is shared between astronomers and the general public, and astronomy presents a unique opportunity to enhance appreciation for the natural sciences to the younger generation.

The NOVA program: *The life-cycle of stars and galaxies*
In 1998, NOVA, together with five other national research schools, received significant funding for a ten year program covering 1999-2008 through the Incentive Bonus Scheme for National Research Combinations funded by the Ministry of OCW, following a highly competitive selection process among all disciplines. In 2007, this funding was renewed for an additional 5 years for the period 2009-2013. This grant enabled NOVA to set up its collaborative research and instrumentation program. The purpose of the incentive bonus scheme was 'to identify and foster national focuses of excellence in scientific research at research schools. They must compare favorably with leading institutes in other countries working in related fields at the outset (1999), and have the potential to develop further into world-class research centers.' A major program review will occur in 2010 which could result in continuation of funding beyond 2013 if excellent quality in comparison with the best foreign institutes in their field of research can be demonstrated.

The central theme of the research carried out within NOVA is 'The Life-Cycle of Stars and Galaxies: from high-redshift to the present' (see Chapter 3). Stars form in galaxies from interstellar material, and at the end of their lives return chemically enriched material to the interstellar medium from which new generations of stars and planets are born. The most massive and luminous stars evolve fastest, and leave neutron stars and black holes. This life cycle causes evolution in the stellar population of a galaxy as a whole which can now be observed all the way back to epochs when the Universe was less than 5% of its present age. Essential for the success of this research program is access to state-of-the-art observational facilities. A key component of the NOVA program is therefore to build and develop new astronomical instruments and to carry out technical R&D for the next generation instruments (see Chapter 5).

In the reporting period the NOVA program involved ~285 fte scientific staff members spread over the five universities participating in NOVA. This number includes ~60 fte senior staff members in permanent and tenure-track positions, 50 fte postdoctoral fellows, 140 fte PhD students, and ~35 fte staff working on instrumentation projects. NOVA funds about 19% of these positions, as well as an active workshop and visitor program (see Chapter 7), and outreach efforts through the NOVA Information Center (see Chapter 8).

The period 2008-2009 saw once again a large variety of new astrophysical results which are summarized in Chapter 3. A total of 57 PhD degrees in astronomy were awarded at the five NOVA institutions (Chapter 4) with cum laudes for Ormel (RuG, 2008), Barnabe (RuG, 2009), Hu (RU, 2009), Öberg (UL, 2009), and Snik (UU, 2009).

Many NOVA researchers received awards and honors, including

- Martinus van Marum prize from the Royal Holland Society of Sciences and Humanities for the best dissertation in sciences by Labbé (2008).
- Alexander von Humboldt professorship to Langer (2008)
- Foreign honorary member of the US National Academy of Arts and Sciences to van Dishoeck (2008)
- Election to the Royal Dutch Academy of Sciences (KNAW) for Waters (2008) and Franx (2009)
- Election to the Young Academy of the KNAW for Groot (2009)
- AAS Brouwer award to de Zeeuw (2009)
- Royal knighthood to Kuijpers (2009) for his efforts to promote astronomy in the Netherlands in general and at the Radboud University in particular (Ridder in de Orde van de Nederlandse Leeuw).
- Christiaan Huygens award for best dissertation in space sciences to Kriek (2009)

In the new European Research Council (ERC) grant system 4 out of the first 12 advanced ERC grants in astronomy have gone to astronomers at the NOVA institutes: Falcke (2008), Franx (2008), Aerts (2008; Leuven, also RU), Tielens (2009) and Wijers (2009). Furthermore ERC starting grants were received by Wijnands (2008), Helmi (2009) and Baryshev (2009).

NWO awarded research innovation grants to the following persons: VICI grant for Portegies Zwart (2008), VIDI grants for Hoekstra (2008), Nelemans (2008), Haverkorn (2009) and Watts (2009), and VENI grants for Gurkan (2008), Hessels (2008), Russell (2008), Johansen (2009), Leenaarts (2009) and Patruno (2009).

The NOVA instrumentation program (Chapter 5) saw the completion and delivery of the flight hardware of the spectrometer main optics for JWST-MIRI, the near-IR spectrometer for X-Shooter, and ~20 ALMA Band-9 receiver cartridges in 2008-2009.

In November 2008 the Ministry of OCW and NWO granted NOVA and its consortium partners (ASTRON, SRON, TNO, technical universities and Dutch industry) in total M€ 18.8 for participation in the design and construction of instrumentation for the E-ELT. The grant was obtained in a competitive process for funding of Dutch contributions to the large-scale research infrastructures on the European Strategy Forum on Research Infrastructures (ESFRI) list.

2. Mission statement and research program

NOVA is a federation of the astronomical institutes of the universities of Amsterdam, Groningen, Leiden, Nijmegen and Utrecht, officially recognized by the Royal Dutch Academy of Sciences in 1992. When NOVA was established as an inter-university collaboration, it was agreed that its legal representation ('penvoerderschap') should rotate between the participating universities. Accordingly, Leiden University (UL) and the University of Amsterdam (UvA) were penvoerder in the first and second five year period, respectively. Since September 1, 2007, NOVA is legally represented by Utrecht University (UU) for a term of five years.

2.1 NOVA's mission and objective(s)

NOVA's mission is to carry out front-line astronomical research in the Netherlands and to train young astronomers at the highest international levels.

NOVA's objectives for the next decade are 1) to continue scientific innovation in the three main lines of NOVA's coherent research program while maintaining its high quality; 2) to further strengthen NOVA's instrumentation program by having a leading role in designing and realizing cutting-edge instrumentation for Europe's Extremely Large Telescope; 3) to keep attracting very talented PhD students and educating them to levels where they compete successfully for the best positions in science and elsewhere; 4) to share enthusiastically our increased understanding of the Universe with the general public; and 5) to secure continued, long-term access to direct government funding for NOVA beyond 2013 to make all of this possible.

2.2 The NOVA program: The life-cycle of stars and galaxies

The research program carried out by NOVA is called '*The lifecycle of stars and galaxies: from high-redshift to the present*'. It is organized along the following three interconnected collaborative thematic programs (also called networks) which together study the questions raised in the introduction:

- Network 1: Formation and evolution of galaxies: from high redshift to the present
- Network 2: Formation of stars and planetary systems
- Network 3: The astrophysics of black holes, neutron stars and white dwarfs

Each network is led by 6-10 key researchers with strong scientific records. The list of NOVA Key Researchers is given in Chapter 9. The networks have regular (one to two times per year) face-to-face meetings with scientific presentations, mostly by PhD students.

Network 1: Formation and evolution of galaxies: from high redshift to the present

Galaxies contain billions of stars, as well as interstellar gas and dust, and are embedded in dark halos of unknown constitution. Astronomers are able to look back in time, by observing galaxies at ever greater distances. Because light travels at finite velocity, distant objects are seen at a time when the Universe was young. The expansion of the Universe causes light to be redshifted, so that the most distant galaxies are those with the highest redshift. How did galaxies form? What processes have occurred between high redshift and the present? Do evolved galaxies contain relics which are clues to their formation? What are the influences of the environment, of nuclear activity, and of the original large-scale distribution of dark matter? What is the role of massive black holes in galactic nuclei?

Network 2: Formation of stars and planetary systems

New stars continue to be born deep inside molecular clouds in galaxies. The birth process leads to a circumstellar disk of gas and dust from which planets and comets may subsequently form. What are the physical processes that lead to these new solar systems, and how do they evolve? How is the chemical composition of the gas and dust involving the major biogenic elements modified during the collapse from the cold, tenuous interstellar medium to the dense protoplanetary material? What is the nature of exo-planets orbiting other stars? Massive stars are important in driving the chemical evolution and energetics of the interstellar medium in galaxies. Do massive stars form in a similar way as solar type stars, and are they capable of forming planetary systems? How important are chemical composition, rotation and mass loss for the evolution of massive stars?

Network 3: The astrophysics of black holes, neutron stars and white dwarfs
At the end of its life, a massive star explodes and ejects its outer layers. The stellar core collapses to form a neutron star or a black hole. These are the densest objects that exist, and the ones with the strongest gravitational fields. What are the properties of matter at the extreme density in the interior of a neutron star? What are the observational signatures of black holes? Can we observationally verify the extraordinary predictions of General Relativity for the properties of curved space-time near these objects? How do particles and radiation behave near these compact objects? What happens when two compact objects orbiting each other eventually merge? Is this the origin of the most powerful explosions we know, the enigmatic gamma-ray bursts?

The aim of the *NOVA instrumentation program* is to develop, construct and exploit new instrumentation and high-level software for world-class observatories, with a focus on instrumentation for the European Southern Observatory (ESO), and to increase technical expertise at the universities. The program is carried out in collaboration with the NWO institutes ASTRON and SRON, and institutions abroad. Current projects include instrumentation for the ESO Very Large Telescope, the ESO-VLT Interferometer (VLTI), the VLT Survey Telescope (VST), the European Extremely Large Telescope (E-ELT), the Atacama Large Millimeter/submillimeter Array (ALMA), the Atacama Pathfinder Experiment (APEX), the James Webb Space Telescope (JWST), the LOw Frequency ARray (LOFAR) and the Sackler Laboratory for Astrophysics (Chapter 5).

As part of its graduate education program, NOVA organizes an annual 5-day NOVA fall school in Dwingeloo with the aim to broaden the astrophysical background of starting PhD students and improve their presentation skills. Monitoring of the actual graduate research is carried out on behalf of NOVA by the so-called ‘Graduate Student Review Committee’ at each of the NOVA institutes which meets annually with each of the graduate students to discuss progress, problems and future career prospects.

The entire program enables NOVA researchers to obtain a rich harvest of results from unique ground-based and space-based facilities, and will allow NOVA to maintain and strengthen its status as a premier international center for research and education in astronomy.

3. Progress reports from the research networks

3.1. Formation and evolution of galaxies: from high redshift to the present

3.1.1. Large-scale structure of the Universe

Weak gravitational lensing can be used to study the mass distribution around galaxies, as well as on larger scales. With this in mind the Kilo-Degree Survey (KiDS) project was conceived, a large collaboration of 9 institutes in Europe (PI Kuijken) which will map 1500 square degrees of sky in good seeing conditions from Paranal with OmegaCAM on the VST. Unfortunately the telescope construction has been long delayed, with start of operations in 2010 considered likely at the time of writing. During 2008/2009 preparations for KiDS continued in algorithm development for multi-color photometry and for weak lensing measurement. Members of the KiDS team are also involved in the analysis of the Canada-France-Hawaii Telescope Legacy Survey (CFHTLS), currently the most powerful data set for weak lensing measurements. It comprises 170 square degrees of sky imaged in five bands. The CFHTLS analysis allows identifying and addressing all systematic effects that plague the measurements. The KiDS survey is expected to yield substantial new insight into the relation of luminous and dark matter, and place tight constraints on cosmological parameters.

Schrabback (PD), Hoekstra, Kuijken, Hildebrandt and Semboloni completed a comprehensive analysis of the large-scale mass distribution in the HST map of the COSMOS field, together with collaborators in the EU-funded DUEL network. A key development is the inclusion of accurate photometric redshifts for large numbers of galaxies, allowing a measurement of the evolution of the growth of large-scale structure and a 3-D tomographic lensing analysis. For the first time, it is shown that the weak shear of distant galaxies scales with redshift as expected in the standard lambda-CDM model (Fig. 3.1). This establishes the combination of weak lensing and photometric redshifts as a cosmological probe. The results of this 1.6-square degree survey confirm the accelerated expansion of the universe, and demonstrate the potential of all-sky space-based weak lensing + photometric redshift surveys for precise measurements of the properties of the dark energy.

Together with Velander (PhD), van Uitert (PhD), Hildebrandt, Hoekstra, Kuijken, Schrabback and Semboloni also worked on the analysis of the CFHT Legacy Survey. To reach the main goal of determining competitive constraints on the properties of dark energy, various systematic signals need to be identified and corrected for. Photometric redshifts have been derived for the whole survey and recent efforts have focussed on the correction for PSF-related biases. In addition to the determination of cosmological parameters, the results will also be used to study the properties of dark halos around galaxies and the mass distribution of clusters of galaxies.

Using the 4 square-degree CFHTLS-deep survey, Hildebrandt and collaborators (including members of the Leiden lensing group led by Kuijken and

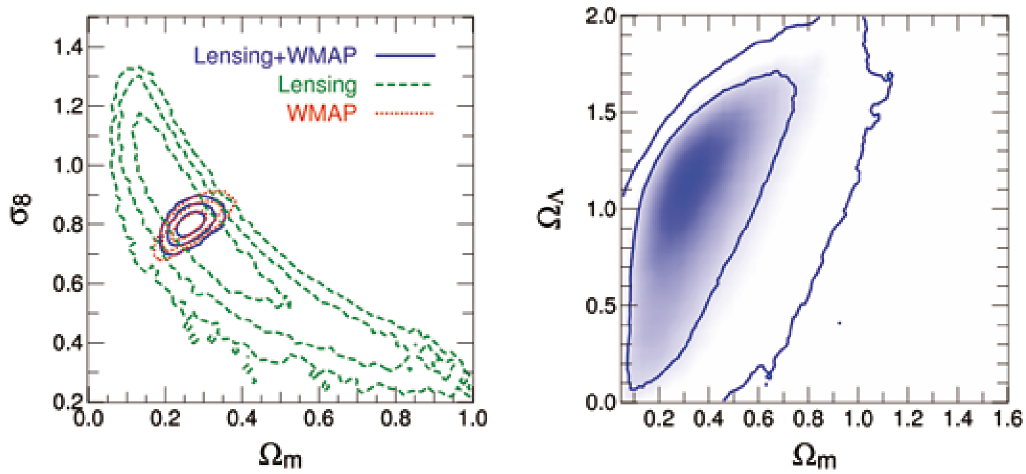


Figure 3.1: Left: Constraints on the matter density Ω_m and amplitude of matter fluctuations σ_8 for a standard, spatially flat Λ-CDM cosmology. The COSMOS lensing constraints are nearly orthogonal and hence complementary to WMAP5 results from the cosmic microwave background. Right: Constraints on the density of matter Ω_m and vacuum energy Ω_Λ for a Λ-CDM cosmology with curvature from COSMOS. From these constraints we compute a 96% probability for cosmic acceleration, providing further support for the presence of dark (or vacuum) energy (from: Schrabback et al. submitted to A&A).

Hoekstra) compiled a large sample of high redshift Lyman-break galaxies. They convincingly demonstrated that these sources are correlated with foreground galaxies, due to the magnifying action of gravitational lensing. Though the effect is statistically less powerful than weak shear measurements, it can be applied to distant unresolved galaxies and therefore provides a complementary way of measuring the matter distribution from gravitational lensing, particularly for sources at high redshift. The study also serves as an excellent confirmation of photometric redshifts, which are a crucial component of any future projects to probe the cosmological model using gravitational lensing.

Together with Zhao (Leiden & St. Andrews UK), Hoekstra and collaborators used numerical simulations to study the matter distribution for a class of alternative theories of gravity, with a particular focus on how current and future lensing studies may constrain such models.

With collaborators, van de Weygaert also studied the large scale evolution of a supercluster that freezes shortly after the present cosmological epoch, in contrast to their vigorously continuing internal development in splendid isolation. The study follows the external and the internal evolution of the supercluster island universes, as they gradually detach themselves from the cosmic background, by means of 512^3 dark matter particle simulations. The spatial distribution and mass function of the supercluster remains the same after the present epoch. Meanwhile, the internal evolution of these objects proceeds vigorously. Nearly all evolve towards an almost perfect spherical, uniform, and virialized, object at an expansion factor a=100.

Schaap (PhD) and van de Weygaert summarized the Delaunay Tessellation Field Estimator (DTFE) in a series of papers on the details of the method and tests of their ability to measure anisotropy, substructure and void structure, as well as in a major review. Platen (PhD) has shown the superior performance of DTFE with respect to the reconstruction of the cosmic density field from SDSS resembling datasets compared to higher order Natural Neighbor Interpolation and that of a local natural neighbor version of Kriging interpolation.

On the basis of the DTFE density field reconstruction of the SDSS galaxy distribution out to a distance of 300 h^{-1} Mpc (z<0.01), Platen and van de Weygaert have identified clusters, supercluster complexes and great walls, supervoids and their spatial connection in the local Universe (see figure on back cover of this report). The identity of the supercluster and supervoid complexes is defined on the basis of the corresponding (Abell) cluster distribution in the same region. The detailed and intricate structure of the Coma Great Wall and the Sloan Great Wall is investigated, along with the bridging features in between them. The intricate substructure of the Boötes Supervoid is nicely outlined by the DTFE maps.

Following the recent 3rd final release of the complete 6dF survey, van de Weygaert, Pan (PhD, Drexel Univ), Platen and Vogeley (Drexel Univ) have been trying to identify voids in the survey's interior volume. To this end they have applied the Watershed voidfinder of Platen et al., as well as the VoidFinder of Hoyle & Vogeley. In total, some ~1000 voids in the SDSS catalog were detected and ~200 in the 6dF volume.

The one-point probability density function of the DTFE reconstructed density field based on the SDSS DR7 catalogue was studied by Platen and van de Weygaert on scales ranging from the (present-day) nonlinear (R_f=1h^{-1} Mpc) to the weakly nonlinear density regime (R_f = 20h^{-1} Mpc). The DTFE method is found to unbiased on scales larger than the mean separation between the points. The DTFE density field based evaluation outperforms the conventional Counts in Cells approach, which is fundamentally limited by shot-noise and discreteness effects. The one-point probability density function (pdf) for the dark matter and mock galaxy distribution in the Millennium simulation, and the pdf for the observed galaxy distribution in the SDSS DR7 are reasonably well approximated by the lognormal distribution on intermediate and large scales. The Millennium simulation is used to study the relation between the dark matter density field and the galaxy distribution: Low density regions are often strongly affected by biasing. The SpineWeb procedure analyzes the topological structure of the landscape, defined by its singularities – minima, maxima and saddle points – and their mutual connections. Based on the watershed segmentation of the cosmic density field, the SpineWeb method invokes the local adjacency properties of the boundaries between the watershed basins to trace the critical points in the density field and the separatrices defined by them and classify the separatrices into walls and the spine.

3.1.2. The intergalactic medium

Werner (PhD), Kaastra, Vink et al. detected the first hot gas in a filament connecting a pair of clusters. Due to the favorable orientation of the filament, viewed almost edge-on, it was possible to trace the hot X-ray emitting gas at an overdensity of 150. The

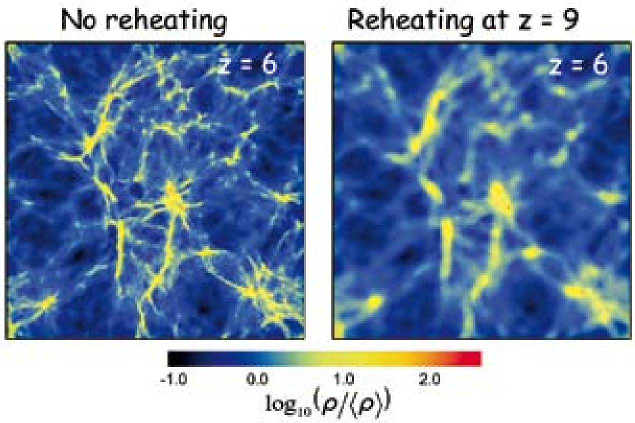


Figure 3.2: The effect of photo-heating on the gas density distribution of the intergalactic medium at redshift z=6. The figure shows the gas density contrast in a slice of comoving 3.125 Mpc/h on a side through a hydrodynamical simulation at redshift z = 6. The simulation on the left did not include reionization, while for the one shown on the right the ionizing background radiation was turned on at z = 9. The reheating associated with reionization strongly suppresses the clumpiness of the intergalactic medium. The associated reduction of the recombination rate strongly reduces the star formation rate required to keep the universe ionized (from: Pawlik, Schaye, & van Scherpenzeel 2009, MNRAS, 394, 1812).

properties of the gas in the filament are consistent with results of simulations of the densest and hottest parts of the warm-hot intergalactic medium (IGM).

Aguirre (UCSC), Dow-Hygelund (UCSC), Schaye, and Theuns (Durham) have studied the abundance of oxygen in the IGM by analysing O VI, C IV, Si IV, and H I pixel optical depths derived from a set of high-quality VLT and Keck spectra of 17 quasars at redshifts $2.1<z<3.6$. Comparing ratios of oxygen and carbon optical depths to those in realistic, synthetic spectra drawn from a hydrodynamical simulation and comparing to existing constraints on [Si/C], they were able to place strong constraints on the ultraviolet background model using weak priors on allowed values of [Si/O]: for example, a quasar-only background yields [Si/O]~1.4, which is highly inconsistent with the [Si/O]~0 expected from nucleosynthetic yields and with observations of metal-poor stars. Assuming a fiducial quasar+galaxy UV field consistent with these constraints yielded the primary result that [O/C]=0.66±0.06±0.2. Subdividing the sample revealed no evidence for evolution, but low and high H I optical depth samples were inconsistent, suggesting either density dependence of [O/C] or, more likely, prevalence of collisionally ionized gas at high density.

Radiative cooling is central to a wide range of astrophysical problems. Despite its importance, cooling rates are generally computed using very restrictive assumptions. Wiersma (PhD), Schaye, and Smith (Colorado) investigated the effects of photoionization of heavy elements by the meta-galactic ionizing background and of variations in relative abundances on the cooling rates of optically thin gas in ionization equilibrium. They found that photoionization by the background radiation strongly reduces the net cooling rates for gas densities and temperatures typical of the shock-heated intergalactic medium and proto-galaxies. They concluded that photoionization by the ionizing background and heavy elements both need to be taken into account in order for the cooling rates to be correct to an order of magnitude. Moreover, if the rates need to be known to better than a factor of a few, then departures of the relative abundances from solar need to be taken into account.

The critical star formation rate density required to keep the intergalactic hydrogen ionised depends crucially on the average rate of recombinations in the intergalactic medium (IGM), which is proportional to the so-called clumping factor. Pawlik (PhD), Schaye, and van Scherpenzeel performed a suite of cosmological simulations to calculate the clumping factor of the IGM at redshifts $z \geq 6$ (Fig. 3.2). They found that photoionization heating by the ultraviolet background strongly reduces the clumping factor because the increased pressure support smoothes out small-scale density fluctuations, making it easier to keep the universe ionized. Using conservative assumptions, they found that if the IGM was reheated at $z \geq 9$, the observed population of star-forming galaxies at $z \sim 6$ may be sufficient to keep the IGM ionized, provided that the fraction of ionizing photons that escape the star-forming regions to ionize the IGM is larger than ~0.2.

3.1.3. Clusters of galaxies

Hoekstra, Bildfell (PhD, Victoria), Babul (Victoria) and Mahdavi (San Francisco State) studied a sample of 50 massive clusters of galaxies, using multiwavelength observations. The aim of the project is to calibrate the masses of these clusters using weak gravitational lensing and compare these to observations at various wavelengths. This will allow them to assess the effectiveness of the various baryonic tracers for cosmological studies of cluster number densities. Furthermore, the study of the relations and their residuals provide direct constraints on models of cluster formation.

Hoekstra, Graham (PhD, Victoria), Sand (Harvard) and collaborators obtained multi-epoch observations of a sample of 60 nearby clusters of galaxies with the aim to constrain the rate of type Ia supernovae in galaxy clusters. The excellent image quality of the CFHT also allows for a unique study of the tidal truncation of the dark matter halos of cluster galaxies, which forms the thesis of Remco van der Burg (PhD).

Jaffe, Oonk (PhD) and Hatch explored the distribution, energetics and kinematics of the warm (300-2000 K) gas phases at the centers of cool core clusters. These studies are based on VLT infrared IFU spectroscopy and HST imaging, and are critical both to the understanding of the nature of the intracluster medium (ICM) in these clusters and to the physics of AGN feedback at low and high redshifts. The measurements confirmed that the heating of the ICM cannot be explained by photoionization or shock models, and remains a mystery. Also the spatial and kinematic distribution of the molecular clouds is not consistent with the virial theorem and requires another mechanism for pressure support. The team is a member of a Herschel Key Project on Cool Core clusters. Science demonstration data from Herschel were received in late 2009 and are being processed.

Kaastra was the organizer of an international review team and editor of the book on the current observational and theoretical status of the non-virialized X-ray emission components in clusters of galaxies. The subject is important for the study of large-scale hierarchical structure formation and the 'missing baryon' problem. The topics of the team include thermal emission and absorption from the warm-hot intergalactic medium, non-thermal X-ray emission in clusters of galaxies, physical processes and chemical enrichment of this medium and clusters of galaxies, and the relationship between all these processes.

Werner (PhD), Kaastra et al. studied the radial distribution and two-dimensional maps of the X-ray emitting gas in the Hydra-A cluster of galaxies. Thanks to the sensitivity of XMM-Newton, it was possible to demonstrate the presence of multi-temperature gas. This significantly affects the derived metal abundances. From the metal abundances, the ratio between different supernova types contributing to the chemical enrichment could be estimated. The maps show the lift-up of cool gas due to the presence of energetic outflows from the central massive galaxy. At the low mass-end, Werner, Kaastra et al. detected resonance scattering in the some key spectral lines in a few groups of galaxies. The presence of this scattering indicates that turbulence is dynamically not important in these systems.

Diffuse radio emission in clusters, radio "relics" and "halos", trace regions with shocks and turbulence created by cluster merger events. Van Weeren (PhD), Röttgering, Bruggen (Bremen) and Cohen (NRL) have carried out low-frequency radio observations with the Giant Meterwave Radio Telescope (GMRT) at 610 MHz of diffuse ultra-steep spectrum sources. These sources are thought to trace (i) old long-lived shock fronts, or (ii) less energetic cluster merger events. These observations were used to construct the first sample of diffuse ultra-steep spectrum sources allowing them to show that smaller relics have steeper spectra. Larger relics are mostly located in the outskirts of clusters while smaller relics are located closer to the cluster center. A likely explanation is related to larger shock waves occurring mainly in lower-density regions and having larger Mach numbers.

The same team also took deep GMRT observations at 610 MHz of MACS J0717.5+3745, an X-ray luminous and complex merging cluster located at z=0.55 (Fig. 3.3). They discovered a giant radio halo with a size of about 1.2 Mpc at a location that roughly coin-

Figure 3.3: GMRT radio (green), Chandra X-ray (blue/magenta) and HST (whitish/red) observations of the merging cluster MACS J0717.5+3745 (z = 0.5). The main central radio emitting region is located at the interface between merging clusters. The temperature of the X-ray gas in this interface region is relatively high, indicating that shocks in the X-ray gas accelerate the radio emitting particles (based on: van Weeren et al. 2009, A&A, 505, 991 and Ma et al. 2009, ApJ, 693, L56).

cides with regions of the ICM that have a significant enhancement in temperature as shown by Chandra. This provides strong evidence that the relic may be the result of a merger-related shock wave, where particles are accelerated via the diffuse shock acceleration mechanism.

The cluster of galaxies Abell 2255 has been the subject of a detailed multi-frequency radio continuum study using the WSRT by Pizzo and de Bruyn. Several new diffuse radio structures, akin to relics or LSS-formation related shocked plasma, were discovered in the peripheral regions of the cluster at distances of several Mpc from the cluster centre. The polarized emission of the filamentary structures projected towards the centre of the cluster, previously attributed to a radio halo, was analyzed using rotation measure (RM) synthesis and also involved Bernardi and Brentjens. Based on their RM of the polarized sources it is concluded that they are located on the front side of the cluster.

Verheijen and Deshev have worked on the determination of the atomic gas content of galaxies in and around two galaxy clusters at intermediate redshifts. The ultra-deep WSRT observations have been completed and reduced, and a first analysis reveals some 150 detections of atomic gas in individual galaxies. The deep optical imaging of the two WSRT fields with the INT allow for the optical identification of HI detected galaxies of low optical surface brightness, and the characterization of the populations of blue galaxies in the cores of the clusters, responsible for the Butcher-Oemler effect, as well as in the surrounding field.

Van de Weygaert, Araya and Jones investigated the cluster Faber-Jackson (FJ), Kormendy and Fundamental Plane (FP) relations between the mass, radius and velocity dispersion of cluster size halos in cosmological N-body simulations. The simulations span a wide range of cosmological parameters, representing open, flat and closed Universes. The one outstanding effect is the influence of Ω_m on the thickness of the Fundamental Plane.

3.1.4. Protoclusters of galaxies

Miley, Röttgering and collaborators continue to use high-redshift radio galaxies (HzRGs) as probes of the early Universe. Luminous HzRGs are among the most massive galaxies at z>2 and the likely progenitors of cDs and Brightest Cluster Galaxies. The topic was recently reviewed by Miley & De Breuck.

Miley and collaborators found that HzRGs are usually surrounded by overdense galaxy structures, having the properties expected for the ancestors of rich local clusters ("protoclusters"). The HzRGs and surrounding protoclusters have several distinct constituents that often interact with one another and are laboratories that are rich in diagnostics for studying the formation and evolution of galaxies and clusters. Present studies focus on (i) population and kinematic study of radio-selected protoclusters from 4>z>2, (ii) studies of merging, AGN feedback and galaxy downsizing in the massive cD progenitor hosts and (iii) preparation for a search for z>6 HzRGs with LOFAR (potential probes of the epoch of reionization).

Ly-α is a powerful tracer for investigating the young star-bursting population. Using the VLT, Venemans (NOVA PhD) and collaborators showed that there are Ly-α overdensities around 6 HzRGs. Velocity dispersions of the protoclusters are in the range ~300 - 1000 km/s, centered within a few hundred km/s of the mean velocity of the radio galaxies. Typical star formation rates are a few $M_\odot$ per year, derived from UV continuum and Ly-alpha luminosities. Taking the measured galaxy overdensities of ~5 - 15 and the typical measured sizes of the protocluster structures of ~2 to 5 Mpc, the resulting protocluster masses are a few times 10^{14} $M_\odot$, i.e. comparable with the masses of local rich clusters. Miley and collaborators have been allocated an ESO large project with the tunable OSIRIS camera on the GTC to make a Ly-alpha-based kinematic study of 19 HzRGs with 3.5>z>2.

The observation of the star-forming protocluster members are being complemented by studies of the evolved protocluster populations. Combining ACS and NICMOS/HST observations, Zirm and colleagues showed that there is an emergent red sequence in the MRC 1138-262 protocluster at z=2.2. Kurk and collaborators had previously shown that for this protocluster there is spatial segregation between the populations, with the "older" red galaxies more spatially concentrated towards the centre than Ly-α excess galaxies. This spatial segregation is related to the well-known morphology-density relation, in which early-type (redder) galaxies are found in denser regions of the Universe. Other highlights of these studies are the population studies of Maschietto (PhD) and collaborators and Kuiper (PhD) on the protocluster MRC0316-257 at z=3.1 and of Overzier (PhD) and colleagues on the protoclusters at z>4.

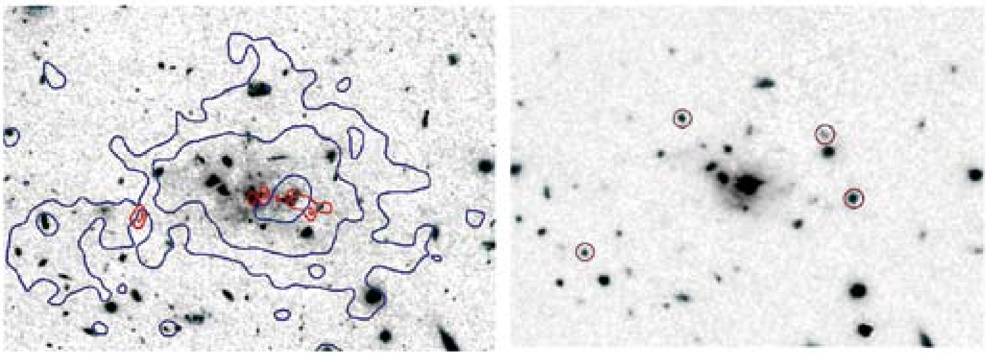


Figure 3.4: Left panel: Deep HST/ACS image of the Spiderweb Galaxy at the center of the MRC 1138-262 protocluster at z = 2.2, with VLT Ly-α contours (blue) delineating the gaseous nebula and the VLA 8 GHz radio contours (red) superimposed on the composite ACS image. The gaseous nebula is extended by ~200 kpc and comparable in size with the largest cD galaxies in the local Universe. Right panel: A H-band HST/NICMOS image at ~ 5000 Å rest-frame. Red circles indicate red galaxies with little UV continuum. Note differences between the ACS image (young population) and the NICMOS image (old population). Spectral comparisons and IFU spectroscopy are being used to disentangle the history of star formation and structure assembly (from: Miley et al. 2006, ApJ. Lett. 650, L29 (left), Hatch et al. 2008, MNRAS, 383, 931 and Hatch et al. 2009, MNRAS, 395, 114).

Miley and collaborators are also making an intensive study of the HzRGs at the centres of protoclusters and their relation to the protocluster as a whole. They showed that HzRGs have many of the properties expected from progenitor cD galaxies - clumpy optical morphologies, spectra indicative of extreme star formation and large stellar masses. The best studied example is the spectacular Spiderweb Galaxy at z=2.2, with a mass of ~10^{12} $M_{\odot}$, among the largest known. The galaxy is surrounded by a giant 200 kpc Ly-alpha halo and embedded in dense hot ionized gas with an ordered magnetic field (Fig. 3.4). It is associated with a 3 Mpc-sized structure of galaxies, of derived mass > 2×10^{14} $M_{\odot}$, a presumed antecedent of a local rich cluster. Indeed, tens of satellite galaxies (“flies”) presumably are merging into the “Spiderweb Galaxy” 11 Gyr ago. The morphological complexity and clumpiness agrees qualitatively with predictions of hierarchical galaxy formation models.

The Spiderweb galaxy and other similar HzRGs are unique laboratories for studying several ingredients of current massive galaxy formation models. These include:

1) Merging. The clumpy morphologies provide the most convincing observational evidence that hierarchical merging is important in the early Universe.
2) Downsizing. The concept that more massive galaxies undergo star formation earlier than least massive ones was introduced in models to explain the observed color statistics. For the Spiderweb, comparison of the UV luminosity (young stars) with the IR luminosity (old stars) implies that most of the mass had already assembled by z ~ 2.2, consistent with downsizing scenarios. Intriguingly, Hatch and colleagues showed that downsizing may also be occurring within the Spiderweb itself.
3) AGN Feedback. To produce downsizing, current models often invoke a process called “AGN feedback” in which star formation is quenched preferentially in more massive galaxies by an AGN-driven wind. However, the physical basis of this hypothesis needs justification. There is a multitude of ways in which AGN can interact with their host galaxies, and AGN-produced radio jets can actually also induce star formation. There is evidence that gas is both (i) driven outwards by jets and AGN winds and (ii) accreted inwards onto the nuclear massive black holes. A plausible scenario hypothesizes that (i) merging fuels the supermassive black hole that produces the radio source and (ii) pressure from the radio source expels sufficient gas from the galaxies to quench star formation.

Hatch and collaborators also showed that about 40% of the UV light from the Spiderweb is in a diffuse intergalactic component and that this is probably produced by intergalactic star formation, with ~60 $M_{\odot}$ per year. This discovery poses several questions. How ubiquitous is the extended light and what role does it play in massive galaxy evolution? Are extended stars produced by gas that has been stripped from the satellite galaxies?

3.1.5. Faint submillimeter galaxies

Part of the research of Van der Werf and co-workers concentrates on IR and submm-selected galaxies in the distant universe. In collaboration with Knudsen (former PhD, now MPIA) and Kneib (Marseille), the SCUBA 850 micron survey of gravitationally lensed submillimeter galaxies (SMGs) was completed. This survey significantly increases the number of known intrinsically faint SMGs, with 10 new sources with intrinsic (lensing-corrected) 850 micron fluxes below 2 mJy (the JCMT confusion limit), doubling the number of such sources known. These results significantly affect the source counts of faint SMGs. Based on these number counts, at a source plane flux limit of 0.1 mJy, essentially all of the 850 micron background emission will be resolved. The dominant contribution (>50%) to the integrated background arises from sources with 850 micron fluxes between 0.4 and 2.5 mJy, while the bright sources (>6 mJy) contribute only 10%.

The same group also studied the CO properties of intrinsically faint SMGs, gravitationally lensed by the massive cluster A2218. Using the IRAM-PdBI, CO(2-1) and (4-3) were detected in two SMGs at redshifts z=1.034 and z=3.187. The results were used to estimate molecular gas masses and star formation efficiencies, with results consistent with the local L(FIR)-L(CO) relation. One of the objects has the lowest far-IR luminosity of all SMGs with a known redshift and is one of the few high-redshift LIRGs whose properties can be estimated prior to ALMA.

In collaboration with Rigby (Carnegie) and Egami and Rieke (Steward), Van der Werf studied the mid-IR spectra of strongly lensed SMGs using Spitzer IRS. A key object is again the triple-lensed SMG behind the massive cluster A2218, which was detected with very high S/N ratio. All objects show the well-known PAH features characteristic of vigorous star formation. However, the ratio of PAH flux with respect to total IR luminosity is found to have evolved modestly towards lower values from z=2 to z=0. Since the high aromatic-to-continuum flux ratios in these galaxies rule out a dominant contribution by an AGN, this finding implies systematic evolution in the structure (in particular the size of the emitting region) and/or metallicity of infrared sources with redshift. It also has implications for the estimates of star-forming rates inferred from 24 micron measurements, in the sense that at z~2, a given observed frame 24 micron luminosity corresponds to lower bolometric luminosity than would be inferred from low-redshift templates of similar luminosity at the corresponding rest wavelength.

Van der Werf also participated in a new large-area submillimeter survey that was carried out with the LABOCA 870 micron bolometer camera at APEX, by a team led by Smail (Durham), Weiss (MPIfR) and Walter (MPIA). The LABOCA ECDFS Submillimetre Survey (LESS) covers the full 30' × 30' field size of the Extended Chandra Deep Field South and is thus the largest deep submillimeter survey undertaken to date. In total 126 SMGs were detected above 3.7 σ. The field is sufficiently large that it can be shown that the slope of the source counts is not uniform across the field. Instead, it steepens in regions with low SMG density, indicating a paucity of in particular luminous galaxies in these regions. This survey also allows an investigation of the clustering of SMGs by means of a two-point correlation function, providing evidence for strong clustering on angular scales smaller than 1' with a significance of 3.4 σ. A characteristic angular clustering scale of 14" ± 7" and a spatial correlation length of 13 ± 6 h^{-1} Mpc are derived. Another result is the discovery of the most distant SMG known today with a spectroscopic redshift (z=4.76).

3.1.6. Dynamics of infrared-selected galaxies at z~2

Van der Werf and Van Starkenburg (NOVA PhD) continued their study of the dynamical properties of a sample of IR-selected z~2 galaxies, using H-alpha velocity fields obtained with SINFONI at the VLT. A highlight is the observation that strongly star-forming disk galaxies at high redshift have very high gas velocity dispersions. This leads to a strongly increased Jeans length, which provides a natural explanation for the fact that these galaxies are dominated by a small number of huge (several kpc size) star-forming regions. One galaxy from the sample has an exceptionally large gas-to-stellar mass ratio of 2.5, underlining its nature as a galaxy that is still in formation.

3.1.7. Gravitational lensing: galaxy structure and CDM substructure

The formation of galaxies, in particular that of early-type galaxies as end products of this process, is still a major open problem in cosmology. It is made especially difficult to study because dark matter dominates much of galaxy formation, whereas only baryons can be observed directly. To address this problem, Koopmans, Vegetti (PhD), Antunano-Vaquero (PhD), Spiniello (PhD), Czoske (U. Vienna), Barnabe (former PhD, now Stanford/KIPAC), with long-time collaborators Treu (UCSB) and Bolton (Utah), have nearly completed a major survey started in 2003 to search for new galaxy-scale gravitational lenses: the Sloan Lens ACS (SLACS) Survey (PI: Koopmans). By combining spectroscopy from the SDSS and imaging follow-up with HST (Fig. 3.5), they discovered nearly 100 new lens systems, half of the currently total known population and the largest strong lens survey thus far conducted.

Major results that came out of follow-up studies of these systems, in combination with stellar dynamics and stellar population studies using data from a VLT-VIMOS large program and Keck-LRIS spectroscopy, include (i) massive early-type galaxies have a remarkably homologous and isothermal structure; (ii) weak lensing studies (with Gavazzi, IAP) have extended this result to much larger radii, well into their dark matter halos; (iii) the tilt in the Fundamental Plane can be almost fully explained by an increase of dark-matter in the inner regions of the most massive early-type galaxies, something that can only be easily shown because of the accu-

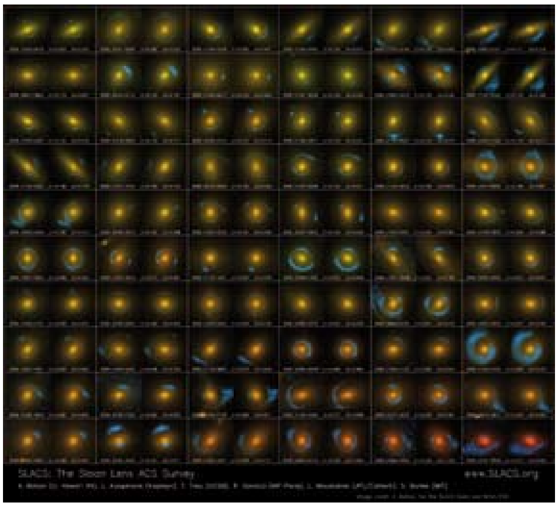


Figure 3.5: This mosaic is based on Hubble Space Telescope F814W images. The colors of the foreground elliptical galaxies have been assigned based upon the g-r colors measured by the SDSS, and the lensed background-galaxy features have been enhanced in blue. The cutout regions centered on each lens are 6 arcseconds to a side. The brightness levels for each lens have been rescaled so as to make all galaxies appear to be of roughly equal brightness in the mosaic. The left panel in each cell shows the Hubble data, while the right panel shows a mathematical model used to describe the foreground and background galaxies, including the lensing effect that distorts the image of the latter. The foreground and background redshifts in each system are given as z1 and z2 respectively (from: Bolton et al. 2008, ApJ, 682, 964).

rate mass measurement afforded by gravitational lensing.

The sample is currently being studied for indications for the presence dark-matter mass substructure (with Vegetti). In parallel, comparisons with numerical simulation (with Vaquero) from the OWLS collaboration (with Schaye) have commenced. With Spiniello, Czoske and Trager also a new project was started to use VLT-X-shooter to probe the stellar populations of the most massive lens galaxies in the universe at look-back times exceeding five billions years and combine lensing, dynamical and stellar-population studies of early-type galaxies to break the existing degeneracies in their modelling.

Hoekstra, van Uitert (PhD) and collaborators have analyzed the imaging data from the second generation Red-sequence Cluster Survey (RCS2) to study the dark matter halos of galaxies. Thanks to the large increase in survey area (almost a factor of 20 compared to RCS1), these data have yielded the most accurate measurement of the galaxy-galaxy lensing signal to date and will provide unique tests of the cold dark matter paradigm by placing constraints on the shapes and sizes of dark matter halos.

The PN.S team (including Kuijken, Douglas, Arnaboldi, Capaccioli, Coccato, Freeman, Gerhard, Merrifield, Napolitano, Noordermeer, Romanowsky) is carrying out a study of elliptical galaxy halos. The PN.S is a purpose-built narrow-band, two-arm slitless counter-dispersing spectrograph that finds, and measures velocities for, planetary nebulae in external galaxies from a single observation. The ongoing survey typically yields 100-200 planetary nebulae per galaxy, mostly beyond two effective radii from the center where their motions are dominated by the dark matter halo potential. A dozen galaxies now have good datasets. Interestingly, a significant number of galaxies exhibit a sharply declining velocity dispersion profile. The goal of this project is to make a detailed study of the outer stellar kinematics of ellipticals, for comparison to early-type galaxy formation models.

Duffy (PhD, Manchester), Schaye, Kay (Manchester) and Dalla Vecchia used a combination of three large N-body simulations to investigate the dependence of dark matter halo concentrations on halo mass and redshift in the Wilkinson Microwave Anisotropy Probe year 5 (WMAP5) cosmology. They found that the median relation between concentration and mass is adequately described by a power law for halo masses in the range 10^{11}-10^{15} $M_\odot/h$ and redshifts z<2, regardless of whether the halo density profiles are fitted using Navarro, Frenk & White or Einasto profiles. Interestingly, the predicted concentrations were much lower than inferred from X-ray observations of groups and clusters.

3.1.8. Galaxy evolution

Brinchmann, in collaboration with Pettini (Cambridge) and Charlot (Paris), carried out a comparative study of the ionization properties in high- and low-redshift galaxies. The low-redshift study focused on the SDSS and was a study looking at relative changes in ionization properties as a function of position in diagnostic diagrams. This was contrasted with high redshift observations and it was found that their ionization conditions are similar to the most intensely star-forming galaxies at low redshift. This implies that when using the low-redshift universe for calibration relations to apply at high redshift, great care must be taken to compare samples with similar physical conditions because the average low-redshift galaxy is not similar to the high-redshift galaxies normally observed.

Brinchmann participated in two efforts to determine metallicities in galaxies at redshifts between 0.5 and 1.3 from the Vimos Very Deep Survey. The effort led by Lamareille (Toulouse) focused on the evolution of the mass-metallicity relation with redshift using the same methods as has been used for the SDSS. The main result here was to find a modest evolution in the relation out to z~0.7 and possibly some evidence for a change in shape. The second effort, led by Pérez-Montero (Toulouse), focused on calibrating a new metallicity indicator for use at redshifts out to z~1.3. This was used to extend the study of the mass-metallicity relation to higher redshift, and an evolution relative to the present-day universe was found but no statistically significant evolution between z~0.7 and 1.

Van Dokkum (Yale), Franx and collaborators studied massive galaxies at z=2.3 with little star formation. Using deep near-infrared spectroscopy, Kriek (former PhD, now Princeton) et al. found that ~45% of massive galaxies at z~2.3 have evolved stellar populations and little or no ongoing star formation. Van Dokkum et al determined the sizes of these quiescent galaxies using deep, high-resolution images obtained with HST/NIC2 and laser guide star (LGS)-assisted Keck/adaptive optics (AO). Considering that their median stellar mass is $1.7 \times 10^{11}\ M_{\odot}$, the galaxies are remarkably small, with a median effective radius of only 0.9 kpc. Galaxies of similar mass in the nearby universe have sizes of ~5 kpc and average stellar densities that are 2 orders of magnitude lower than the z~2.3 galaxies. These results extend earlier work at z~1.5 and confirm previous studies at z>2 that lacked spectroscopic redshifts and imaging of sufficient resolution to resolve the galaxies. These findings demonstrate that fully assembled early-type galaxies make up at most ~10% of the population of K-selected quiescent galaxies at z~2.3, effectively ruling out simple monolithic models for their formation. The galaxies must evolve significantly after z~2.3, through dry mergers or other processes, consistent with predictions from hierarchical models.

Kriek, Franx, and collaborators also obtained high resolution imaging of the starforming z=2.3 galaxies with previously obtained rest-frame optical spectroscopy. The study shows that the star forming galaxies are large, whereas the quiescent galaxies are small. It is clear that the equivalent of the Hubble Sequence is present at that redshift.

Muzzin (Yale), Franx and collaborators analyzed the properties of the very compact massive galaxies at z=2.3. It was found that the stellar masses derived for these galaxies are consistently high, when different model assumptions were used. Hence it is very hard to explain their small sizes by postulating that their masses are overestimated by a large factor.

Van der Wel (former PhD, now Heidelberg), Franx, and collaborators analyzed the size evolution of galaxies, at fixed velocity dispersion. Using measured dispersions and sizes, they found significant evolution to z=1, consistent with the trend observed out to z=2 (and beyond) based on masses derived from stellar population fits.

Kriek, Franx and collaborators obtained a very deep spectrum of a compact, massive galaxy at z=2.1. The spectrum shows clear absorption lines, indicating a 2 Gyr old galaxy. The galaxy must have formed at significantly higher redshift. In addition, the galaxy has weak liner-like emission lines, indicating the presence of an AGN. Van Dokkum (Yale), Kriek and Franx measured the velocity dispersion of this galaxy. It was found to have a dispersion of 510 ± 100 km/s. Whereas the error on this measurement is unusually large, the measurement shows clearly that the galaxy is truly massive, and lies far off from the local mass-size or velocity dispersion -size relation.

Franx and collaborators published an analysis of galaxies in the CDF-South. They found a tight relation to z=3 between color and size at a given mass, with red galaxies being small, and blue galaxies being large. They showed that the relation is driven by stellar surface density or inferred velocity dispersion: galaxies with high surface density are red and have low specific star formation rates, and galaxies with low surface density are blue and have high specific star formation rates. Stellar mass by itself is not a good predictor of the star formation history of galaxies. In general, galaxies at a given surface density have higher specific star formation rates at higher redshift. Specifically, galaxies with a surface density of $(1\text{-}3) \times 10^{9}\ M_{\odot}/\mathrm{kpc}^{2}$ are "red and dead" at low redshift, approximately 50% are forming stars at z=1, and almost all are forming stars by z=2. The sizes of galaxies at a given mass evolve like $1/(1+z)^{0.59\pm0.10}$. Hence galaxies undergo significant upsizing in their history. The size evolution is fastest for the highest mass and quiescent galaxies. The persistence of the structural relations from z=0 to z=2.5, and the upsizing of galaxies imply that a relation analogous to the Hubble sequence exists out to z=2.5, and possibly beyond. The star-forming galaxies at z≥1.5 are quite different from star-forming galaxies at z=0, as they have likely very high gas fractions, and star formation timescales comparable to the orbital time.

Damen (PhD), Franx and collaborators found that the increase in specific star formation for massive galaxies to a redshift of 3 is as rapid as $(1+z)^5$. The increase is similar for all masses, but galaxies with higher masses have lower average specific star formation rates. The current models for galaxy formation cannot reproduce the high specific star formation rates observed at high redshift.

Williams, Quadri, Franx, and collaborators studied galaxies out to z=2. They found, using the Ultra Deep Near-IR Survey that galaxies with little star formation can be identified in a red sequence out to redshift of 2. The red sequence can be identified when combining the Near-IR photometry with optical and 3-5 micron photometry from the Spitzer Space Telescope. In the rest-frame U-V, V-J color-color diagram, the star forming galaxies lie in a different area from the 'quiescent galaxies'. This new diagnostic is confirmed by using the mid-IR emission at 24 micron, which shows strong emission for the galaxies classified as star forming, and no emission for the quiescent galaxies.

Kriek, Franx and collaborators studied the red sequence at a redshift of 2.3. The sample is drawn from their near-infrared spectroscopic survey for massive galaxies. The color distribution shows a statistically significant red sequence, which hosts ~60% of the stellar mass at the high-mass end. The red-sequence galaxies have little or no ongoing star formation, as inferred from both emission-line diagnostics and stellar continuum shapes. Their strong Balmer breaks and location in the rest-frame U-B, B-V plane indicate that they are in a post-starburst phase, with typical ages of ~0.5-1.0 Gyr.

Holden (UCSC), Franx and collaborators showed that early-type galaxies in clusters at high redshift have the same ellipticity distribution as early-type galaxies in clusters at low redshift. This suggests strongly that the average bulge-to-disk ratio is rather similar, and does not evolve. It also indicates that the previous efforts in trying to distinguish ellipticals and S0s are not effective.

Brammer (Yale), Franx, and collaborators used a new, medium band Near-IR survey to derive very accurate photometric redshifts and rest-frame colors of field galaxies to a redshift of 2. The survey shows a distinct red sequence for the galaxies without star formation. These galaxies can be selected based on their spectral energy distributions, or based on the absence of mid-IR emission as measured by the Spitzer Space Telescope.

Marchesini (Yale), Franx, and collaborators studied the evolution of the stellar mass function from z=3.5 to low redshift. They specifically studied the uncertainties due to random and systematic effects, including the effect of metallicity, extinction law, stellar population synthesis model, and initial mass function. They show that these uncertainties dominate all other uncertainties.

Bouwens (UCSC), Franx, and collaborators analyzed very high redshift galaxies in deep HST imaging data. In total, they found eight z~7.3 dropouts in their search fields, but no z~9 J-dropout candidates. A careful consideration of a wide variety of different contaminants suggests an overall contamination level of just ~12% for their z-dropout selection. After performing detailed simulations to accurately estimate the selection volumes, they derive constraints on the UV luminosity function at z~7 and z~9. For a faint-end slope α = -1.74, their most likely values at z~7 are M^*_{UV}=-19.8±0.4 mag and $1.1^{+1.7}_{-0.7}$ x10^{-3} Mpc^{-3}, respectively. Their search results for z~9 J-dropouts set a 1 sigma lower limit on M^*_{UV}=-19.6 mag. This lower limit on M^*_{UV} is 1.4 mag fainter than their best-fit value at z~4, suggesting that the UV luminosity function has undergone substantial evolution over this time period. No evolution is ruled out at 99% confidence from z~7 to z~6 and at 80% confidence from z~9 to z~7.

Bouwens (UCSC), Franx, and collaborators also analyzed the intrinsic properties of high redshift galaxies. It was found that high redshift galaxies become bluer at higher redshift (from z=3 to z=7), and at lower intrinsic magnitude. The highest redshift galaxies are extremely blue, and hard to model.

Astronomical research using the Astro-WISE system in the Netherlands was carried out by Valentijn, McFarland, Belikov, Verdoes Kleijn, Peletier, den Brok, Sikkema, Buddelmeijer, Nelemans and Spooren. In Groningen it focused on the area of galaxy evolution as a function of environment: in the Coma cluster using the HST/ACS Coma Legacy Survey by PhD Den Brok en collaborators; in nearby superclusters and field using a WFI survey by PhD Sikkema and of large volumes of the nearby universe using UKIDSS/SDSS catalogs (PhD Buddelmeijer).

3.1.9. Low-redshift galaxies

Brinchmann, in collaboration with Kunth (Paris) and Durret (Paris), carried out a search for galaxies with Wolf-Rayet features in the spectra using SDSS data (Fig. 3.6). The search was performed using a combination of automatic classification tools and manual inspection and resulted in the currently largest sample of Wolf-Rayet galaxies (570 secure objects). This led to a comprehensive characterization of the physical properties of these galaxies. For the first time it was possible to show an increase in nitrogen abundance consistent with rapid enrichment of the ISM by Wolf-Rayet winds.

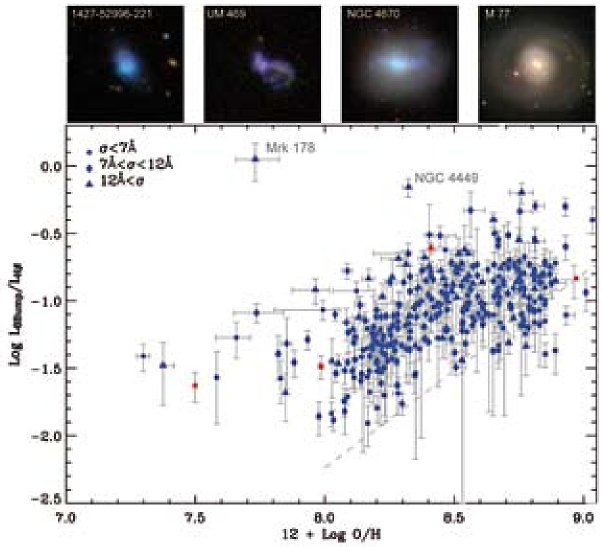


Figure 3.6: This figure shows the ratio of the luminosity due to optical Wolf-Rayet emission lines to that of the H-beta Balmer line in a sample of galaxies from the SDSS. The x-axis shows the oxygen abundance of ionized gas in the galaxies, while the ratio on the y-axis is approximately proportional to the relative abundance of Wolf-Rayet and O-stars. Since the abundance of Wolf-Rayet stars is connected to the strength of stellar winds and stellar winds decrease towards lower metallicity, the ratio declines as well. But note that at very low metallicity the ratio appears to level off and reach a plateau, indicating the presence of an additional channel for formation of Wolf-Rayet stars, either binary evolution or significant rotation in massive stars. The different symbols indicate different line-widths in the Wolf-Rayet stars and the red symbols indicate the location of the galaxies whose images are shown above the plot. The dashed line indicates the approximate detection limit of the survey (from: Brinchmann, Kunth & Durret 2008, A&A, 485, 657).

They were also able to show that models for the formation of Wolf-Rayet stars must be updated to include either rotation or binary evolution or possibly both, to explain the observed high abundance of Wolf-Rayet stars at low metallicity.

Brinchmann participated in an effort to study the effect of lopsidedness on the properties of galaxies in the SDSS. The effort was led by Reichard (Johns Hopkins) and used the m=1 azimuthal Fourier mode in the outer parts of galaxies to define lopsidedness. They showed that lopsidedness in galaxies correlate with residuals in the mass-metallicity relation and that powerful AGN tend to be hosted by lopsided galaxies but that this is an incidental correlation. The physical correlation appears to be that the delivery of cold gas to the central regions of galaxies, triggering star formation and black hole growth, is aided by the process that produce lopsidedness.

3.1.10. Spiral galaxies

Verheijen, Martinsson (PhD) and co-workers have strengthened their involvement in the Disk-Mass Survey, which aims to use integral field spectroscopy to determine the stellar velocity ellipsoid for spiral galaxies. The observed stellar velocity dispersion in most galaxies follows the near-infrared luminosity profiles in detail. The corresponding stellar mass-to-light ratios indicate sub-maximal disks, even for galaxies with a high central surface brightness. Radio synthesis imaging of the atomic gas in all galaxies has been completed using the WSRT and GMRT. The extracted rotation curves will supplement the optical rotation curves in the faint outer regions of the disk. Westfall (NSF/NWO postdoc) has started his work on deriving the stellar velocity dispersion ellipsoids using the PPak and SparsePak data.

Van der Hulst, Boomsma, Sancisi, Oosterloo and Fraternali completed a study of the gas kinematics in the spiral galaxy NGC6946. Very sensitive H I observations reveal the presence of widespread high-velocity H I (up to about 100 km/s) and find 121 H I holes, most of which are located in the inner regions where the gas density and the star formation rate are higher. The overall kinematics of the high-velocity gas is characterized by a slower rotation as compared with the regular disk rotation and is presumed to be extraplanar gas. Stellar feedback (Galactic Fountain) is probably at the origin of most

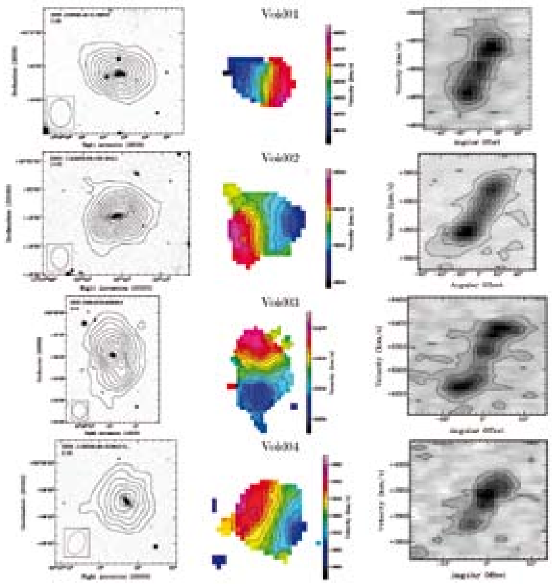


Figure 3.7: Radio maps of 4 targeted void galaxies. Contours in the total intensity maps (left) are at 5x10^{19} cm-2 plus increments of 10^{20} cm^{-2}. Confidence level (σ) of the lowest contour is given in the top left corner of each image. Lines in the velocity field images (center) indicate increments of 8 km/s. Position-Velocity diagrams (right) are along the kinematic major axis, contours are at increments of -1.5, 1.5 + increments of 3σ. Void03 is the polar ring galaxy, located in a tenuous wall between two large voids (from: Stanonik et al. AJ, in press).

of the high-velocity gas and of the H I holes. Very faint extensions and velocity anomalies in the outer H I disk point at the possibility of recent accretion of minor companion galaxies.

Van de Weygaert, Jones and Aragon-Calvo (Johns Hopkins) have identified galaxies in SDSS that carry the most significant fossil alignment in the cosmic Web using the Multi-scale Morphology Filter. Subsequently, they restrict the analysis to the edge-on galaxies, whose perfectly known orientation guarantees a clean signal. Following a local and individual statistical analysis based on three feature measures, they have found a significant signal of alignment. From their sample, they pointed to fourteen galaxies that have an uncommon perpendicular orientation with respect to the filaments in which they are embedded.

Van de Weygaert, van der Hulst and collaborators also are carrying out an extensive multi-wavelength campaign to study the morphology, star formation rates, gas content, mass distributions and environment of a set of 60 carefully selected void galaxies: The Void Galaxy Survey. Among the first fully analyzed sample of 15 H I observed void galaxies, the most outstanding specimen is a polar disk galaxy. Amongst the most lonely galaxies in the universe, it has a massive, star-poor H I disk that is perpendicular to the disk of the central void galaxy. The galaxy is located within a tenuous wall in between two large roundish voids (Fig. 3.7). The undisrupted appearance of the original stellar disk renders a merger origin unlikely and suggests slow accretion of cold gas, at the crossing point of the outflow from the two voids.

3.1.11. Galaxy surveys (data releases) and catalogues

Brinchmann, mainly in collaboration with Tremonti (Wisconsin), carried out a re-analysis of all SDSS DR7 spectra and derived physical parameters for all galaxies in the SDSS DR7, about 1 million. This dataset has been provided on-line at http://www.mpa-garching.mpg.de/SDSS/DR7 and is a reference dataset for galaxy properties in the SDSS.

Wuyts (former PhD, now CfA), Franx, and collaborators published multi-wavelength photometry of the Chandra-Deep-Field South. The catalogue spans the U band through 24 micron imaging.

Kriek, Franx and collaborators published their spectroscopic catalogue of galaxies at z~2.3 observed in the rest-frame near-ir with GNIRS on the Gemini-South telescope.

As PI of the Herschel Comprehensive ULIRG Emission Survey (HerCULES) Open Time Key Program, Van der Werf obtained first results in December 2009. This program aims at a full census of the neutral gas cooling radiation from an unbiased sample of 26 (ultra)luminous infrared galaxies ((U)LIRGs), including the fine structure lines of oxygen and carbon as well as the entire accessible CO ladder with the SPIRE FTS. The first results show a spectrum of the ULIRG Mrk231 with nine CO lines, two [CI] lines, an [NII] line as well as six H_2O lines detected. This is the first result in a project that will provide a fundamental local benchmark for future high-z studies with ALMA, and break new ground in the characterization of the warm and dense interstellar medium in nearby (U)LIRGs.

3.1.12. The SAURON survey

De Zeeuw, van den Bosch (former PhD, now Texas) and Weijmans (PhD) are members or associates of the SAURON team that built a panoramic integral-field spectrograph for the WHT, in a collaboration which involves groups in Lyon (Bacon) and Oxford (Davies). SAURON was used to measure the kinematics and line strength distributions for a representative sample of 72 nearby early-type galaxies (ellipticals, lenticulars, and Sa bulges, in clusters and in the field). The entire survey was completed in 2003, and since then several follow-up projects were carried out on specific targets. In parallel with the data taking, the team developed a number of tools that are key to analyze all the resulting maps, and has been publishing the main results in a long series of papers.

The main achievement for 2008 and 2009 is based on combination of the SAURON maps with Spitzer images of PAH emission, UV images from GALEX, as well as X-ray, H I and CO maps. This revealed that 15% of the early-type objects show signs of star formation in the past 2 Gyr, demonstrating the importance of continued minor gas-rich mergers (fi). The slowly rotating objects often contain a kinematically decoupled core; comparison with triaxial dynamical models shows that in many cases these are not distinct components but are caused by the presence of extended counter-rotating disks (van den Bosch). The net rotation observed is nearly zero over the bulk of the object, but is not exactly cancelled in the central region, leading to what appears to be a rapidly rotating separate core.

Weijmans used SAURON in an innovative way to measure the stellar kinematics and absorption line strengths out to four half-light radii in a small number of objects. The observed kinematics indicate the presence of dark matter. Line-strength gradients also continue to these distances.

3.1.13. The epoch of reionization: neutral hydrogen in the first billion years

De Bruyn, Zaroubi, Brentjens and Koopmans lead the LOFAR Epoch of Reionization Key Science Project, ramping up rapidly for the major observational phase of the project in 2010-2012. The aim of this project is to detect, for the first time, the redshifted 21-cm line emission of hydrogen from the era when the first stars, quasars and galaxies formed (i.e. the first billions years after the big bang). The aim is to unveil processes that have laid the foundation for all structures that we observe in the present-days Universe, including late and early-type galaxies.

Koopmans received a NWO-M grant for a powerful Graphics Processor Unit (GPU) cluster that will be used to analyze the few peta-byte data set that is expected to be collected by the team in the next several years. This cluster of 160 TFlop will be the most powerful machine in the Netherlands for these type of calculations. The software and algorithm have (partly) been developed by Laproboulos, in collaboration with other team members (e.g. Yatawatta and Pandey). In addition, team members have been developing theoretical (Zaroubi, Thomas, Jelic) models of the expected EoR signal, analysis tools (Yatawatta, Pandey) and conducted the deepest WSRT observation ever at frequencies corresponding to redshifted HI emission from the EoR (de Bruyn, Bernardi).

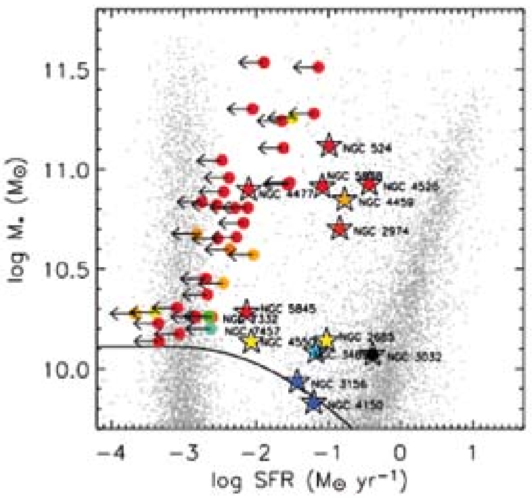


Figure 3.8: Relation between stellar mass and star formation rate. The SAURON galaxies are colored by their stellar population age such that young stellar populations are blue while older populations are red. Systems with clear evidence for star formation from Spitzer images are indicated by stars. The grey dots represent the results from the Millennium simulation, and the solid line is the selection limit for the SAURON galaxies. There is evidence for star formation in about 15% of the SAURON objects, with central star formation occurring in intermediate-mass fast rotators, and wide-spread star formation occurring in low-mass fast rotators (from: Shapiro et al. 2010, MNRAS, in press).

3.1.14. Star formation and feedback in galaxies

When averaged over large scales, star formation in galaxies is observed to follow the empirical Kennicutt-Schmidt (KS) law for surface densities above a constant threshold. While the observed law involves surface densities, theoretical models and simulations generally work with volume density laws (i.e. Schmidt laws). Schaye and Dalla Vecchia derived analytic relations between star formation laws expressed in terms of surface densities, volume densities, and pressures. Their analytic relations enabled them to implement observed surface density laws into simulations. Because the parameters of their prescription for star formation are observables, they were not free to tune them to match the observations. They tested their theoretical framework using high-resolution simulations of isolated disc galaxies and were able to reproduce the star formation threshold and both the slope and the normalization of arbitrary input KS laws. Their prescription therefore enables simulations of galaxies to bypass our current inability to simulate the formation of stars. On the other hand, the fact that they could reproduce arbitrary input thresholds and KS laws, rather than just the particular ones picked out by nature, indicates that simulations that lack the physics and/or resolution to simulate the multiphase interstellar medium can only provide limited insight into the origin of the observed star formation laws.

Feedback from star formation is thought to play a key role in the formation and evolution of galaxies, but its implementation in cosmological simulations is currently hampered by a lack of numerical resolution. Dalla Vecchia and Schaye presented and tested a subgrid recipe to model feedback from massive stars in cosmological smoothed particle hydrodynamics simulations (Fig. 3.9). The energy was distributed in kinetic form among the gas particles surrounding recently formed stars. They studied the impact of the feedback using a suite of high-resolution simulations of isolated disc galaxies. They focused on the effect of pressure forces on wind particles within the disc, which they turned off temporarily in some of their runs to mimic a recipe that has been widely used in the literature. They found that this popular recipe gives dramatically different results because (ram) pressure forces on expanding super-bubbles

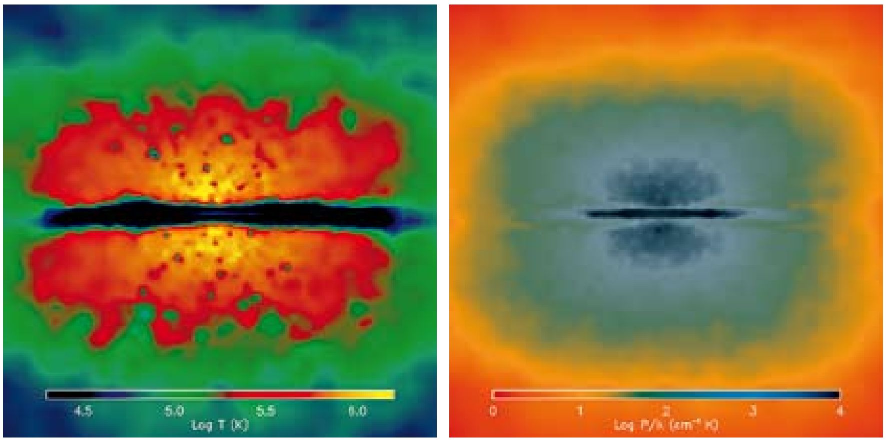


Figure 3.9: Edge-on projections of the gas temperature (left) and pressure (right) for a model disc galaxy in a 10^{12} $M_\odot$ halo. The image shows a snapshot of the simulation 250 Myr after winds driven by supernovae were turned on. The image is 45 kpc/h on a side. The color coding is logarithmic in pressure. Energy from supernovae drives a bi-conical outflow perpendicular to the disk. By the time shown, thermal instabilities in the hot wind fluid are starting to result in the formation of dense clouds. Many of these clouds are in fact falling in rather than flowing out (from: Dalla Vecchia & Schaye, 2008, MNRAS, 387, 1431).

determine both the structure of the disc and the development of large-scale outflows. Pressure forces exerted by expanding super-bubbles puff up the disc, giving dwarf galaxies an irregular morphology and creating galactic fountains in massive galaxies. Hydrodynamic drag within the disc results in a strong increase in the effective mass loading of the wind for the dwarf galaxy, but quenches much of the outflow in the case of the high-mass galaxy.

Photo-heating associated with reionization and kinetic feedback from core-collapse supernovae have previously been shown to suppress the high-redshift cosmic star formation rate. Pawlik (PhD) and Schaye investigated the interplay between these processes using a set of cosmological simulations. They showed that photo-heating and supernova feedback mutually amplify each other's ability to suppress the star formation rate.

Wiersma (PhD), Schaye, Theuns (Durham), Dalla Vecchia, and Tornatore (Trieste) presented an implementation of stellar evolution and chemical feedback for smoothed particle hydrodynamics simulations. They considered the timed release of individual elements by both massive (Type II supernovae and stellar winds) and intermediate-mass stars (Type Ia supernovae and asymptotic giant branch stars). A comparison of nucleosynthetic yields taken from the literature indicated that relative abundance ratios may only be reliable at the factor of 2 level, even for a fixed initial mass function. Abundances relative to iron are even more uncertain because the rate of Type Ia supernovae is not well known. Wiersma et al. contrasted two reasonable definitions of the metallicity of a resolution element and found that while they agree for high metallicities, there are large differences at low metallicities, which they argued is indicative of the lack of metal mixing caused by the fact that metals are stuck to particles. Using several large simulations, they investigated the evolution of the distribution of heavy elements, which they found to be in reasonably good agreement with available observational constraints. By z = 0 most of the metals are locked up in stars. The gaseous metals are distributed over a very wide range of gas densities and temperatures. The shock-heated warm-hot intergalactic medium has a relatively high metallicity of 0.1 solar that evolves only weakly, and is therefore an important reservoir of metals. Any census aiming to account for most of the metal mass will have to take a wide variety of objects and structures into account.

3.1.15. The interstellar medium of nearby galaxies

Israel presented studies of the molecular gas in five nearby and active galaxy centers (NGC1068, NGC2146, NGC3079, NGC4826, and NGC7469), and in five nearby starburst galaxy centers (NGC278, NGC660, NGC3628, NGC4631, and NGC4666). In all galaxies but NGC278 and NGC4631, bright CO concentrations occur in the center, which require modeling with at least two distinct gas components. The physical conditions differ from galaxy to galaxy. In the starburst galaxies, in NGC2146 and in NGC3079, high kinetic gas temperatures of ~125 K are found, and very high densities of 30,000 cm^{-3} or more occur in NGC2146, NGC3079, and NGC7469, but not in the starburst galaxies. In these, the warm component is relatively tenuous and mixed with cooler (~20 K) and moderately dense gas. The molecular gas is always contained within a radius of 0.6-1.5 kpc and has a mass of 100-250 million solar masses, i.e. no more than a few per cent of the dynamical mass. The merger galaxy NGC4826 (the 'Evil Eye' galaxy) is exceptional with all gas sharply constrained to radii of 300 parsec or less and with a total mass of only 30×10^6 $M_\odot$. In all galaxies, there is less H_2 than the CO intensity suggests, by an order of magnitude.

As part of the JCMT Nearby Galaxies Legacy Survey (NGLS), a team also including Van der Werf, Vlahakis and Israel published a CO (3-2) study of four spiral galaxies in the Virgo cluster ((NGC4254, NGC4321, NGC4569, and NGC4579). The first three have total molecular gas masses of about one billion solar masses and gas depletion times of about 1.5 Gyr. NGC4254 has a smaller gas depletion time (i.e. larger star formation rate) than the others, perhaps because it is on its first passage through the Virgo Cluster. The interaction of NGC4569 with the intracluster medium is directly affecting the dense star-forming portion of the interstellar medium. NGC4579 has weak CO (3-2) emission although it is bright in the mid-infrared. Much of the central luminosity in this galaxy may be due to the presence of a central AGN.

In the very nearby SABcd galaxy NGC2403, the dust surface density is a function of the total hydrogen gas surface density and galactocentric radius. The gas-to-dust ratio ranges from ~100 in the nucleus to ~400 at 5.5 kpc radius, and it closely follows the oxygen abundance, implying that metallicity is primarily determining its slope. The CO (3-2) radial profile has an exponential scale length identical to that of the (stellar continuum-subtracted) 8 micron PAH emission, but on sub-kpc scales, CO and PAH surface brightness's are uncorrelated.

To understand the impact of low metallicities on giant molecular cloud (GMC) structure, Israel, as part of a large international team working on Spitzer, compared far-infrared continuum and mm line emission in the star-forming complex N83 in the Small Magellanic Cloud Wing; dust emission probes the total gas column independent of molecular line emission and traces shielding from photodissociating radiation. They resolved the relative structures of H_2, dust, and CO within this GMC cloud complex, one of the first times such a measurement has been made in a low-metallicity galaxy. The results indicate that, in contrast to self-shielding H_2, the CO is photodissociated in the outer parts of low-metallicity GMCs. This is strong evidence that dust-shielding and self-shielding are the primary factors determining the distribution of CO emission in dense hydrogen environments. The CO-to-H_2 conversion factor averaged over the whole cloud is very high, 20 to 55 times the local Galactic value. This factor also varies across the complex, with the lowest values near the CO peaks, in lines-of-sight with high extinction.

In a different study, the Spitzer team, including Israel, determined the dust properties of the Tail region of the Small Magellanic Cloud. In the Tail, the overall gas-to-dust ratio is about 1200. This value is higher than expected (500-800) from the known Tail metallicity, which suggests dust grain destruction. Two star clusters in the Tail were resolved into multiple sources. Their local gas-to-dust ratios of about 440 and 250 respectively suggest that in these regions dust formation occurs, that they contain significant amounts of ionized gas, or both. The results support the notion that the SMC Tail is a tidal tail of gas, dust, and young stars, recently stripped from the SMC.

3.1.16. Active galactic nuclei

Jaffe, Röttgering and Raban (PhD) collaborated with Meisenheimer (MPIA) and Burtscher (PhD, MPIA) and Tristram (MPIfRA) in the observation, analysis and interpretation of the so-called "obscuring tori" in more than a dozen Seyfert galaxies (Fig 3.10), radio galaxies, and quasars with the MIDI VLTI interferometer. The results are reforming the paradigm of these structures, demonstrating misalignments, and clumpiness and "non-unification", i.e. that individual galaxies of the same type show significantly different structures.

Israel, Raban (PhD) and collaborators used archival WMAP data to determine, for the first time, the high-frequency (cm and mm wavelength) radio continuum spectrum of the radio galaxy Cen A (NGC5128). The radio spectrum steepens at 5 GHz, with spectral index changing from -0.70 to -0.82. The steepening is more pronounced for the south-

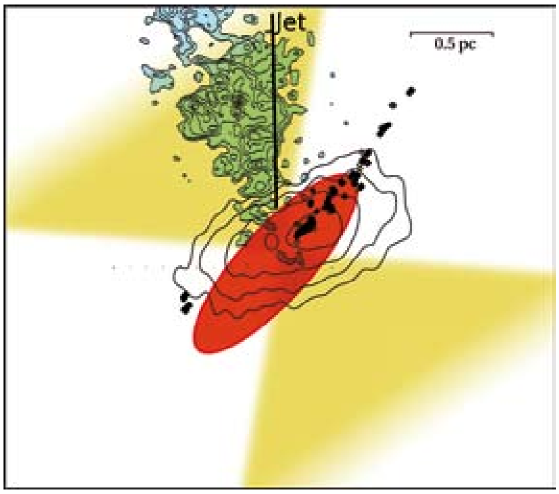


Figure 3.10: The figure shows the geometric relations between the dust disk of NGC1068 as seen by MIDI, the water masers as seen by VLBA, the radio jet position, and the ionization cone. The disk is misaligned with respect to the radio jet and the ionization cone is asymmetric with respect to the disk, implying an irregular or clumpy structure at its base (from: Raban et al, 2009, MNRAS, 394, 1325).

ern than for the northern lobe, and reflects significant relativistic electron energy losses.

Israel, Raban (PhD) and co-workers also monitored the millimeter wave emission from the active nucleus of Cen A between 3.5 mm and 0.85 mm wavelength from 1989 to 2005. Over this period, the core of Cen A was variable by about 30%, well-correlated with X-ray variability in the 20-2000 keV window, but not so well with that in the 2-10 keV window. The quiescent core radio spectral index of -0.3 steepens when the core brightens. The variability is primarily associated with the (VLBI) inner nuclear jets, which are optically thick below 45-80 GHz.

As part of a team led by Espada (CfA), Israel used the Smithsonian Millimeter Array (SMA) in Hawaii to obtain high resolution CO(2-1) maps of the center of NGC5128. The molecular gas is distributed perpendicular to the radio/X-ray jet, and follows the dust continuum, ionized gas, and H_2 line emission. Adopting a warped disk model, the team confirmed the existence of an emission gap at radii of 200-800 pc.

Tasse (PhD), Röttgering and Best (Edinburgh) identified the optical and IR counterpart of the point-like X-ray sources in the XMM-LSS field, and selected a subsample of Type-2 AGNs. The fraction of galaxies that are X-ray AGN is a strong function of the host galaxy stellar mass and the shape of that relation is in good agreement with the fraction of galaxies that are emission line AGN, while it significantly differs from the same relation for the radio selected AGN. The AGN in the sample show a strong infrared excess, at wavelengths as short as 3.5 micron, suggesting the presence of hot dust, while they are preferentially found in underdense environment, where galaxy mergers and interaction are likely to occur. This all suggests that the X-ray selection probes a population of AGN that have actively accreting black holes (quasar mode), due to a galaxy merging event. This is in contrast to the conclusion they had reached for the sample of radio loud objects in the XMM-LSS field. For these objects they argued that the radio loudness in the most massive galaxies had their AGN activity triggered by the cooling of the hot gas observed in their atmosphere.

de Vries (PhD), together with Snellen, Schilizzi and Röttgering, studied very young radio galaxies which shed new light on why certain galaxies become active and how the central activity influences the surrounding galaxy. They showed that the expansion velocities of young radio sources depend on their radio luminosity. Furthermore their analyses indicate that the mortality rate of radio-loud AGN is high during the earliest phase of their evolution.

Low redshift QSOs are investigated by Barthel and collaborators, targeting the symbiosis of accretion driven energy production and host galaxy star formation. Radio and optical imaging is combined with molecular gas spectroscopy: an extensive census of molecular gas in nearby QSO hosts with the IRAM 30m has been carried out. Analysis of the radio and far-infared properties indicates that the host galaxies of QSOs cannot be quiescent galaxies, but must be in the process of forming stars.

Star-formation and nuclear activity in more distant galaxies is investigated by Barthel together with Garrett (JIVE, Dwingeloo) and Chi (PhD). The faint radio source population of the HDF-N and its flanking fields are targeted using ultra-sensitive VLBI: an intriguing population of obscured high redshift radio-weak AGN is found.

Barthel and collaborators also studied the far-IR properties of AGN. First results of the Herschel Space Telescope using Barthel's Mission Scientist time are anxiously awaited. Mid-IR imaging of powerful AGN at 0.4" resolution using VLT-VISIR guaranteed time by Van der Wolk (PhD) reveals important facts dealing with AGN obscuration, hence AGN unification. In particular, thick dusty tori are absent at low accretion rates or low efficiencies.

The compact scintillating radio quasar J1819+3845 (z=0.54) suddenly stopped varying sometime in 2007. This made an end to 8 years of WSRT multi-frequency radio monitoring by de Bruyn and collaborators. The implication is that the highly turbulent and extremely anisotropic plasma screen, estimated to be only 1-2 pc from the Sun, has moved on and must have very sharp edges with density structure on a scale of only 1 AU. The nature of this screen is still a mystery.

Booth and Schaye presented a method that self-consistently tracks the growth of supermassive black holes (BHs) and the feedback from active galactic nuclei (AGN) in cosmological, hydrodynamical simulations. Because cosmological simulations at present lack both the resolution and the physics to model the multiphase interstellar medium, they tend to strongly underestimate the Bondi-Hoyle accretion rate. To allow low-mass BHs to grow, it is therefore necessary to increase the predicted Bondi-Hoyle rates in star-forming gas by large factors. Booth and Schaye found that the freedom introduced by the need to increase the predicted accretion rates by hand, is the most significant source of uncertainty in the model. Their simulations demonstrate that supermassive BHs are able to regulate their growth by releasing a fixed amount of energy for a given halo mass, independent of the assumed efficiency of AGN feedback, which sets the normalization of the BH scaling relations. They further showed that, regardless of whether BH seeds are initially placed above or below the BH scaling relations, they grow on to the same scaling relations. Finally, they demonstrated that AGN feedback efficiently suppresses star formation in high-mass galaxies.

3.1.17. Resolved and unresolved stellar populations

Tolstoy and collaborators continued their studies of resolved stellar populations of nearby dwarf galaxies, in particular using VLT stellar spectroscopy of individual stars in nearby dwarf spheroidal galaxies, following up on the DART program. The DART project involves Helmi, Starkenburg (PhD), de Boer (PhD), Lemasle and a group of international collaborators. One recent result is a detailed theoretical analysis of the Ca II triplet metallicity indicator and its application to the DART dwarf galaxy metallicity distribution functions.

Tolstoy and co-workers also continued the analysis of Color-Magnitude diagrams. Using HST data, an inventory was made of the short period variable star observations of Cetus and Tucana dwarf galaxies with Bernard (PhD IAC). In addition a detailed determination of the star formation history of the Tucana dwarf spheroidal galaxy was made. Color-Magnitude diagram analysis is also ongoing by de Boer for the nearby Sculptor and Fornax dSph from CTIO-MOSAIC wide field imaging. Tolstoy and Fiorentino (PD), together with Saha (NOAO) and Cole (Tasmania) look for RR Lyr variable stars in Leo A using the Gemini-North. This study uses an HST data set as a basis for searching for RR Lyr candidates which need to be verified with better time resolution available at Gemini-N with GMOS. This study will allow a detailed insight into properties of ancient stellar population in Leo A.

Tolstoy used FORS multi-object spectroscopy of stars in dwarf galaxies in the local group to compare the stellar kinematics with gas kinematics, and also gas abundances (from HII regions) with stellar abundances of individual stars for a range of ages, wherever possible within the same galaxies. Work was published on the Tucana dwarf spheroidal and WLM dwarf irregular.

Tolstoy, together with Starkenburg, Helmi and Hill (Nice) and Francois (Paris-Meudon) has performed a spectroscopic follow up study of the metal poor stars in dwarf galaxies using VLT-X-shooter. First GTO data of a candidate extremely metal poor star in the Sculptor dSph have been obtained.

Tolstoy and Mapelli (Zurich), Ripamonti (Insurbia), Irwin (Cambridge) and Battaglia (ESO) studied blue stragglers in dwarf spheroidal galaxies using wide field images. The aim of these studies is to determine if the presence of small numbers of blue stars above the oldest main sequence turnoffs are bona fide blue stragglers or represent very low levels of star formation. From comparison with globular clusters the spatial distribution of these stars was determined to be more similar to blue stragglers than to a younger population in the Sculptor dwarf spheroidal, but not in the Fornax dwarf spheroidal.

Tolstoy, in collaboration with Tosi (Bologna) and Hill (Paris/Nice) published an Annual Reviews article on star formation histories, abundances and kinematics of dwarf galaxies in the Local Group. This is an overview of the current state of our understanding of Local Group dwarf galaxies from imaging, low and high resolution spectroscopic studies of individual stars using ground based 8m telescopes and HST. The review synthesizes all the most recent results and puts dwarf galaxies together into a single class of objects.

Tolstoy, Fiorentino (PD), Deep (PD), Battaglia, and Valenti (both ESO) developed techniques and methods to observe resolved stellar populations in the infrared with Adaptive Optics and orientate these studies to the future planning for a E-ELT. This involves careful test studies of nearby, resolved stars in a bulge globular cluster (NGC6441) and the LMC using the ESO multi-conjugate adaptive optics demonstrator (MAD). In addition, in collaboration with Bologna, the best way to carry out PSF fitting photometry on AO data sets was investigated. This work is part of the phase A study for MICADO (led by MPE), and for the MCAO module for the ELT, MAORY (led by Bologna).

Trager and collaborators continued their observational work on the stellar populations of early-type galaxies. They found that the stellar populations of galaxies in the Coma Cluster are much younger than expected (5 Gyr instead of nearly as old as the Universe) and show little sign of "downsizing", the tendency for small galaxies to have more recent star formation – and thus be younger – than big galaxies. Trager and Somerville (StScI) pursued this further using hierarchical galaxy formation models, showing that these observations can be explained within this paradigm. However, it is clear that better data are needed to test the models. With Arrigoni (PhD), this modeling has been extended to include detailed galactic chemical evolution and it has been shown that the metallicities, abundance ratios, and supernova rates of local early-type galaxies can be explained only if a slightly flat IMF and a bimodal distribution of type Ia supernovae delay times are assumed.

Trager and co-workers also explored the combination of stellar population tracers (absorption lines and colors) with gas tracers (neutral hydrogen) of early-type galaxy formation and evolution. For example, Serra (PhD) found that neutral-gas-poor early-type galaxies often have younger stellar populations in their cores than their envelopes, a situation which is not true for neutral-gas-rich galaxies. Furthermore, that study also showed that the presence of HI in an early-type galaxy implies the presence of ionized gas with the same kinematics as the HI – which is almost always in a different orbital plane than the stars, reflecting an external origin.

Donovan (Columbia), in collaboration with Trager, van der Hulst and others, combined neutral gas, stellar population analysis, and GALEX UV imaging to probe the formation of an early-type galaxy with a FUV-bright star-formation ring. Together with Peletier and collaborators, these studies are being pushed into the near-infrared: With Marmol-Queralto (Madrid) and others it was demonstrated that intermediate-aged AGB stars can be seen in the NIR spectra of nearby early-type galaxies. Stellar population modeling is crucial to these efforts, and the first results of a long-term effort to provide self-consistent stellar population models with a wide range of possible elemental mixtures were reported in collaboration with Lee (Washington).

Trager and co-workers are also studying the resolved stellar populations of the nearest elliptical galaxy, M32. In collaboration with Sarajedini (Florida) and Fiorentino (PD), the detection of bona fide RR Lyrae in this galaxy have been demonstrated, proving that it does indeed contain an ancient stellar population, a fact that was unclear from previous studies of its integrated light. This result will be crucial to understanding the spectrum of M32 and by extension, the spectra of other early-type galaxies in the local Universe.

3.1.18. Star clusters

Chies-Santos (PhD), Larsen and collaborators studied the age- and metallicity distributions of globular clusters (GCs) around 14 nearby early-type galaxies using optical/near-IR imaging. This is the largest sample of GC systems that have been investigated in this way to date. The data suggest that the GCs in early-type galaxies are generally as old as those in the Milky Way, in contrast to conclusions reached by some previous studies. It was also found that bimodal optical GC color distributions may be at least partly an artifact due to non-linear color-metallicity relations.

In a study of field stars and star clusters in nearby spiral galaxies, Larsen and Silva-Villa (PhD) constrained the formation efficiency of star clusters relative to the total star formation. It was found that only 1-2% of stars in the galaxy NGC4395 form in bound star clusters. This ratio may however depend on the star formation rate of the parent galaxy.

Larsen, Origlia (INAF/Bologna) and collaborators continued a long-term project to carry out an abundance analysis of extragalactic star clusters using integrated spectroscopy. Keck/NIRSPEC spectra of the young super-star cluster NGC1569-B revealed a sub-solar overall metallicity and also constrained the properties of red supergiants in the cluster. The properties (log g, T_{eff}) were consistent with independent estimates based on resolved stellar photometry from HST imaging. Additional data for this project have been obtained with X-Shooter on the VLT as part of the Dutch Guaranteed Time.

Larsen studied the mass function of young star clusters and found that it is well described by a Schechter-like function with a cut-off mass of about 200,000 $M_\odot$ in normal spiral galaxies. This is lower compared to starburst galaxies and old GC populations, where the limit is at least several million $M_\odot$. Larsen was also involved in a project to use the Hubble Legacy Archive to study young star cluster populations in 500 galaxies.

Anders, Lamers and collaborators studied the effects of star cluster dissolution in a tidal field. Based on N-body simulations, they showed that standard spectro-photometric models fall short of the new, more realistic models. When the standard models are used to analyze dissolving star clusters, their ages and masses can be wrong by a factor of a few.

In addition, Anders, Portegies Zwart and Baumgardt (Bonn) studied the reliability of N-body studies. Even though there are only 2 major N-body codes available, which are used in a multitude of studies (the family of NBODY codes, and the STARLAB suite), there had not yet been a detailed study to check whether these codes give comparable results.

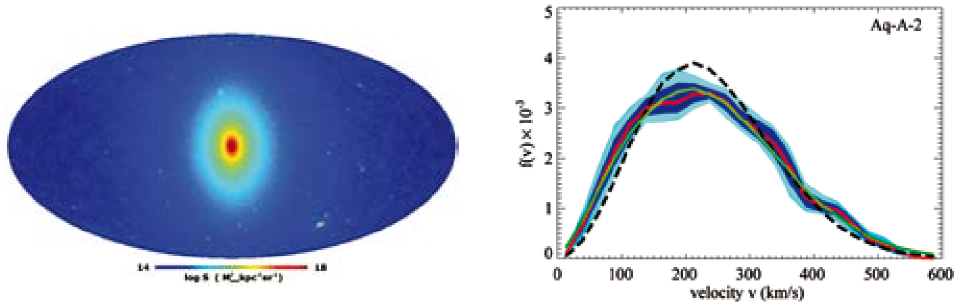


Figure 3.11: Left: This all-sky map shows the surface brightness from dark matter annihilation at the position of the Sun, calculated directly from the Aquarius Project (from: Springel et al. 2008, Nature, 456, 73). Right: Velocity distribution predicted by the Aquarius Project for dark matter particles in the Solar neighborhood. The features in the velocity distribution reflect the detailed assembly history of the dark matter halo (from: Vogelsberger et al. 2009, MNRAS, 395, 797).

Small differences were found, which for the majority of applications is below the tolerance. However, when high-precision simulations are needed, these systematic differences do need to be taken into account.

3.1.19. The Milky Way

Using the largest ever particle simulation of a Milky Way sized dark matter halo from the Aquarius project by Springel et al., Helmi and collaborators have reported that the dominant and probably most easily detectable gamma-ray signal will be produced by diffuse dark matter towards the center of the Milky Way (Fig. 11 left). In the same context, Vogelsberger (MPA), Helmi and collaborators from the Aquarius project made predictions for the dark matter phase-space structure near the Sun. One of the most interesting results is the discovery that the local velocity distribution of dark matter is predicted to be very smooth, but to differ systematically from a (multivariate) Gaussian distribution due to broad features that reflect the detailed assembly history of a halo (Fig. 11 right). This implies that once direct DM detection has become routine, features in the detector signal can be used to study the dark matter assembly history of the Milky Way. A new field, “dark matter astronomy”, will then emerge.

De Lucia (MPA) and Helmi have studied the Milky Way formation and evolution by coupling high-resolution N-body simulations to semi-analytic methods to study the evolution of the baryonic components within dark matter haloes. They find that the physical properties of the model Milky Way are in quite good agreement with observational measurements for our Galaxy, and in particular are able to explain the dual nature of the Galactic stellar halo as a result of a mass-metallicity relation imprinted in the building blocks of this component. Li (PD) applied this model to the dwarf galaxies surrounding the Milky Way, and was able to explain the surprising finding that all these galaxies appear to have the same mass in the central regions, while spanning more than 5 orders of magnitude in luminosity. Furthermore, these models are able to reproduce the luminosity function of the satellites of the Milky Way, as well as many of the scaling relations that these objects follow.

Li and Helmi discovered that satellites in cosmological simulations are often accreted in groups, a finding that has a wide range of implications. For example, it explains the ghostly streams proposed by Lynden-Bell & Lynden-Bell, the peculiar disk-like distribution of the Milky Way satellites and provides a natural interpretation of the disturbed morphologies of the Magellanic Clouds (Fig. 12).

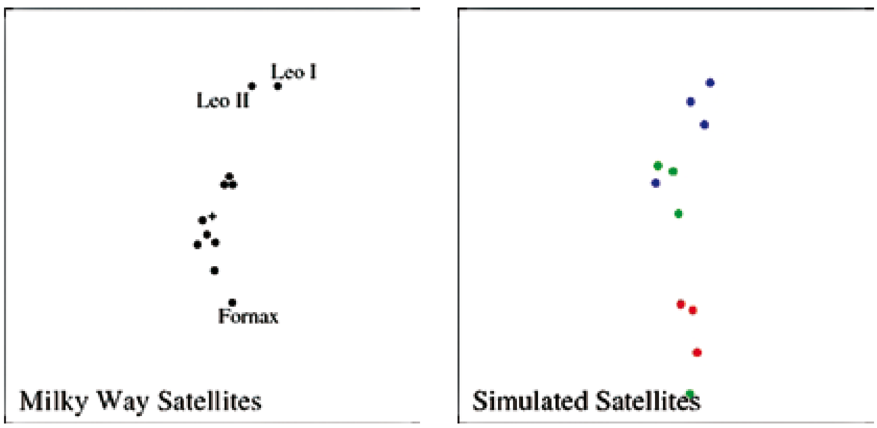


Figure 3.12: The satellite galaxies of the Milky Way have a peculiar spatial distribution, as they appear to be on a plane (left panel). This puzzle can be explained if most of these satellites originated in a few groups that were accreted by the Milky Way (right panel), as shown by the analysis of cold-dark matter simulations (from: Li & Helmi, 2008, MNRAS, 385, 1365).

As part of the DART survey, Battaglia (former PhD, now ESO), Helmi and Tolstoy have modeled the dark matter content of the Sculptor (Scl) dwarf spheroidal galaxy. The accurate velocities and large area coverage of Scl have allowed the measurement of intrinsic rotation in a dwarf spheroidal galaxy for the first time.

Starkenburg (PhD), Helmi and collaborators from the Spaghetti survey have developed a method to quantify the amount of substructure present in this survey, and found that at least 10% of the outer Galactic halo must have been accreted. However, comparison to numerical simulations shows that their results are also consistent with a halo entirely built up from disrupted satellites, provided that the dominating features are relatively broad due to early merging or relatively heavy progenitor satellites. In the local stellar halo, Morrison (CWRU), Helmi and collaborators find, by examining the distribution of stellar orbital angular momenta, a new component which has an axial ratio c/a ~ 0.2, a similar flattening to the thick disk. It has a small prograde rotation but is supported by velocity anisotropy, and contains more intermediate-metallicity stars. This component may have formed quite late, during or after the assembly of the disk.

In the current era of large surveys of the Milky Way, and in particular in view of the Gaia mission, a critical question is how to retrieve and characterize the satellite debris associated to past merger events our Galaxy has experienced. Gomez (PhD) and Helmi have established that the space of orbital frequencies may be the most suitable. In frequency space individual streams can be easily identified, and their separation provides a direct measurement of the time of accretion, even for systems that have evolved strongly in time (Fig.3.13).

Villalobos & Helmi carried out simulations of the formation of thick discs via the accretion of satellites onto a pre-existing thin disk, to establish the detailed characteristics of the thick discs obtained in this way. They found, for example, that some structural properties are sensitive to the inclination of the merger, while others depend on the mass ratio. Their thick discs typically show boxy isophotes at very low surface brightness levels (>6mag below their peak value). Near the Sun, the accreted stars are expected to rotate more slowly and to have broad velocity distributions, while the z-component of the angular momentum of thick-disc stars may be used to discriminate between stars from the pre-existing disc and those from the satellite, particularly at large radii.

Several other models (Fig. 3.14) have been proposed for the formation of thick disks. Sales (PD) et al. compared the orbital properties of stars in four such models and discovered that the distribution of orbital eccentricities is predicted to be different for each case, and therefore that the characterization of this distribution for nearby thick-disc stars may help elucidate the dominant formation mechanism of the Galactic thick disc.

The Radial Velocity Experiment (RAVE, PI: Steinmetz at AIP, Germany; NL-PI: Helmi) has produced its second data release in 2008 (see http://www.rave-

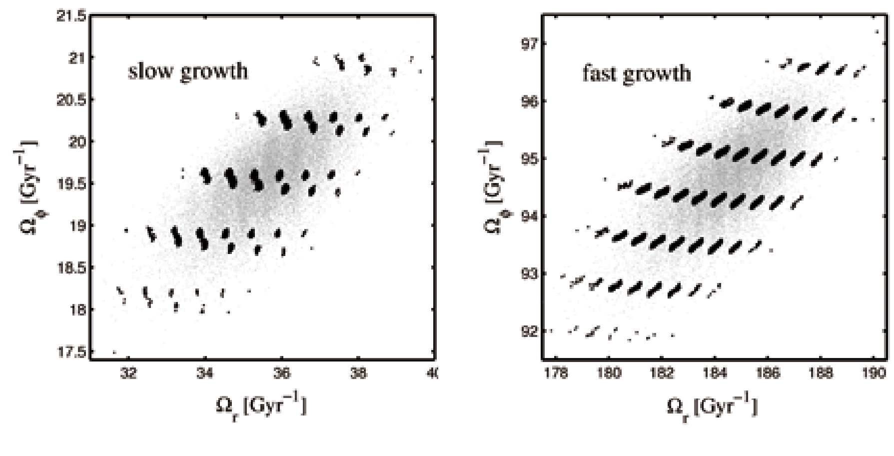


Figure 3.13: The space of orbital frequencies is very well suited to identify debris from past merger events the Galaxy has experienced. In this space, streams define a regular lattice whose characteristic separation depends on the time of the merger. The identification of these features in observational surveys such as Gaia would allow the reconstruction of the assembly history of the Galaxy, independently of how fast (right) or how slowly (left) the Galactic potential varied (from: Gomez & Helmi, 2010, MNRAS, 401, 2285).

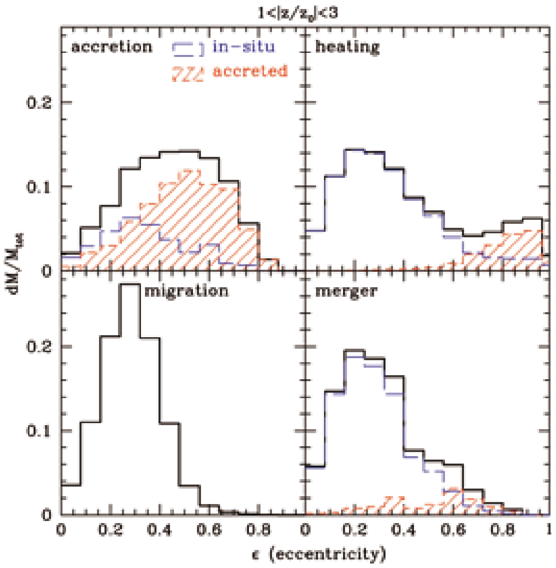


Figure 3.14: The distribution of orbital eccentricities in four different mo6dels of the formation of thick disks. A prominent peak at low eccentricity is expected for the heating, migration and gas-rich merging scenarios, while the eccentricity distribution is broader and shifted towards higher values for the accretion model. These differences can be traced back to whether the bulk of the stars in each case is formed in situ or is accreted, and is robust to the peculiarities of each model (from: Sales et al. 2009, MNRAS, 399, L64).

survey.org). The current release doubles the sample of published radial velocities, now containing 51,829 radial velocities for 49,327 individual stars. For the first time, values of stellar parameters from 22,407 spectra of 21,121 individual stars are also made publicly available. These were derived by a penalized chi-square method using an extensive grid of synthetic spectra calculated from the latest version of Kurucz stellar atmosphere models. From comparison with external data sets, conservative estimates of errors of the stellar parameters for a spectrum with an average S/N ratio of ~40 are 400 K in temperature, 0.5 dex in gravity, and 0.2 dex in metallicity. The data release includes also proper motions from Starnet2, Tycho-2, and UCAC2 catalogs and photometric measurements from Tycho-2 USNO-B, DENIS, and 2MASS. The internal releases now contain more than 300,000 stars.

Soto (PhD), Kuijken and Rich (UCLA) constructed a model of the stellar kinematics in the Milky Way bulge/bar. It is based on new measurements of proper motions and radial velocities from HST and the VLT, respectively. The VLT observations use an IFU to take spectra of very crowded star fields in the bulge, from which stellar spectra are then extracted using the precise position information that is measured on the HST images. HST images separated by 3-5 yr allow accurate proper motions (equivalent to 30 km/s accuracy at the distance of the bulge) to be measured. A separate analysis of a data set of K giants revealed a significant vertex deviation, a clear signature of bar-like kinematics, in the metal-rich stars, and was published. Leiden MSc students Zeballos and Astramaadja used their research projects to make proper motion measurements from HST data for three new fields, at galactic longitudes between 5 and 10 degrees.

3.1.20. The Galactic center

Madigan (PhD), Levin, and Hopman discovered a secular instability of eccentric stellar discs in Galactic nuclei, which are embedded in a spherical stellar cusp. They have investigated this instability in the context of young stars in the vicinity of supermassive black hole SgrA*, and have shown that it is consistent with the eccentricity distribution of the stars in the clockwise stellar disc. They have also shown that the instability may help explain the population of the eccentric B-stars near the black hole.

Madigan (PhD), Gurkan, Hopman, and Levin have developed a model to study long-term resonant relaxation in Galactic Nuclei. They have applied this model to study the distribution of stars in the Galactic Center (in particular, to the distribution of the B-stars), and have calculated the rate of tidal stellar disruptions in other galactic nuclei. They have shown that the resonant relaxation naturally leads to angular momenta distribution which is secularly unstable.

Levin, together with colleagues at MPA and elsewhere, has found that the clockwise disc in the Galactic Center has a strong warp at the outer edge, and that the initial mass functions of the stars in the disc are very top-heavy.

3.1.21. Computational techniques

Pawlik & Schaye developed TRAPHIC, a novel radiative transfer scheme for smoothed particle hydrodynamics (SPH) simulations. TRAPHIC is designed for use in simulations exhibiting a wide dynamic range in physical length-scales and containing a large number of light sources. It is adaptive both in space and in angle and can be employed for application on distributed memory machines. The commonly encountered computationally expensive scaling with the number of light sources in the simulation is avoided by introducing a source merging procedure. The (time-dependent) radiative transfer equation is solved by tracing individual photon packets in an explicitly photon-conserving manner directly on the unstructured grid traced out by the set of SPH particles. To accomplish directed transport of radiation despite the irregular spatial distribution of the SPH particles, photons are guided inside cones. They presented and tested a parallel numerical implementation of TRAPHIC in the SPH code GADGET-2, specified for the transport of monochromatic hydrogen-ionizing radiation. The results of the tests are in excellent agreement with both analytic solutions and results obtained with other state-of-the-art radiative transfer codes.

3.2. Formation and evolution of stars and planetary systems

3.2.1. The galactic interstellar medium

All stars and planets, throughout the history of the universe, are made from interstellar matter (ISM) consisting of enormous gas and dust clouds. The gas comprises atomic hydrogen and helium as well as molecules like carbon-monoxide, water, methane (and many more). The dust consists of small silicate particles (sand) and carbonaceous material (soot). This interstellar gas and dust forms part of the life and death cycle of stars and is enriched with fresh material when stars explode as (super)novas, both in our own galaxy and in external galaxies. Interstellar matter also serves as the fuel for supermassive black holes in the centers of active galaxies.

3.2.1.1. Photon-dominated regions

Pérez-Beaupuits (NOVA PhD), Spaans, Hogerheijde and Güsten (Bonn) have studied the heating and cooling balance of interstellar clouds close to young and hot stars (photon-dominated regions – PDRs), in an effort to quantify how stars form in the presence of existing star formation (so-called feedback). The Omega Nebula, M17SW, in our Milky Way is a case in point of radiation feedback. M17SW is a giant molecular cloud at a distance of 2.2 kpc illuminated by the M17 OB association about 1 pc to the east. Several studies of molecular emission indicate that the gas is highly clumped. APEX-CHAMP+ array observations of CO 6-5 and 7-6 lines reveal warm gas at about 100 K across the cloud, indicating that the dense clumps can survive the strong radiation field and are potential sites for future high-mass star formation (Fig. 3.15).

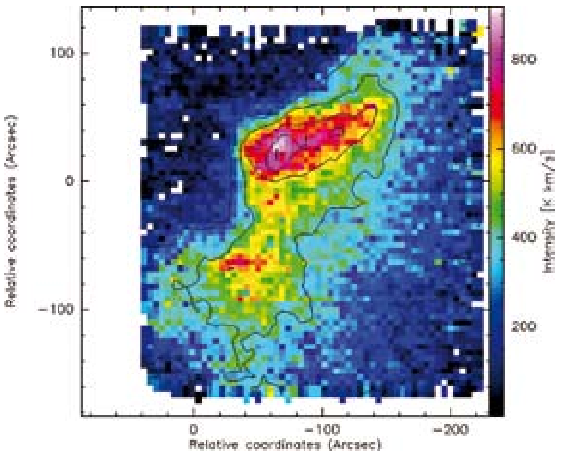


Figure 3.15: Color map of the Omega nebula in ^{12}CO J=7-6, contour lines correspond to ^{12}CO J=6-5 emission. The gas is clumped with a temperature of at least 100 K, promoting high-mass star formation (from: Pérez-Beaupuits et al. 2009, A&A, 503, 459).

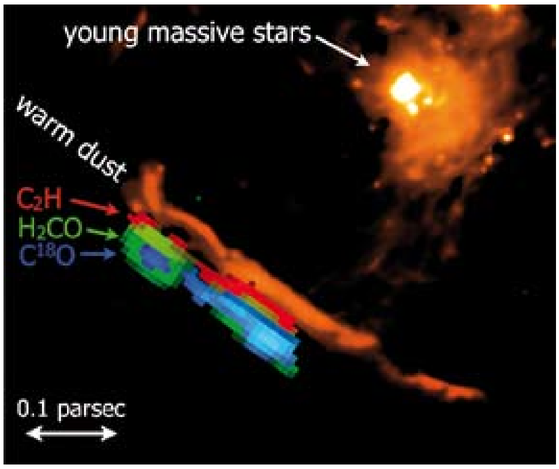


Figure 3.16: Chemical layering in the Orion Bar, as observed in legacy data from the James Clerk Maxwell Telescope. UV photons emitted by young massive stars impinge on the molecular cloud and give rise to a layered structure (from: van der Wiel et al. 2009, A&A, 498, 161).

3.2.1.2. JCMT Spectral Legacy survey of the Orion Bar

The Spectral Legacy Survey, a ground-based spectral imaging survey (330-373 GHz) of star-forming environments, uses the 16-pixel HARP array at the JCMT. One of the regions studied in this survey is the Orion Bar, a molecular cloud illuminated by intense UV radiation from young massive stars. Like many other PDRs, the Orion Bar is known to have layers: a hot region of ionized atoms on the side of the cloud facing the UV radiation, and colder layers of various molecular species deeper into the cloud. Van der Wiel (PhD), Van der Tak, Ossenkopf, Spaans and collaborators have used recent JCMT data to map the chemical stratification pattern of the Orion Bar (Fig. 3.16) C_2H, a radical molecule produced by the dissociation of PAH molecules, is seen closest behind the layer of warm dust, followed by grain evaporation products formaldehyde and SO. Differences between modeled and observed structures indicate the need for models that include grain surface chemistry.

3.2.1.3. Dust coagulation and fragmentation in molecular clouds

The cores in molecular clouds are the densest and coldest regions of the ISM. In these regions ISM-dust grains have the potential to coagulate. Ormel (NOVA PhD), Paszun (PhD), Dominik, and Tielens investigated the collisional evolution of the dust population by combining two models: a binary model that simulates the collision between two aggregates and a coagulation model that computes the dust size distribution with time. In the first, results from a parameter study quantify the outcome of the collision - sticking, fragmentation (shattering, breakage, and erosion) - and the effects on the internal structure of the particles in tabular format. These tables are then used as input for the dust evolution model, which is applied to a homogeneous and static cloud of temperature 10 K and gas densities between 10^3 and 10^7 cm^{-3}. The coagulation is followed locally on timescales of 10^7 yr. The growth can be divided into two stages: a growth dominated phase and a fragmentation dominated phase. Initially, the mass distribution is relatively narrow and shifts to larger sizes with time. At a certain point, dependent on the material properties of the grains as well as on the gas density, collision velocities will become sufficiently energetic to fragment particles, halting the growth and replenishing particles of lower mass. Eventually, a steady state is reached, where the mass distribution is characterized by a mass spectrum of approximately equal amount of mass per logarithmic size bin.

The amount of growth that is achieved depends on the cloud's lifetime. If clouds exist on free-fall timescales the effects of coagulation on the dust size distribution are very minor. On the other hand, if clouds have long-term support mechanisms, the impact of coagulation is important, resulting in a significant decrease of the opacity on timescales longer than the initial collision timescale between big grains.

3.2.1.4. Proto-galaxies and cooling by fine-structure lines

Aykutalp (PhD) and Spaans have studied the cooling by atomic fine-structure lines and molecular rotational transitions for metal-poor proto-galaxies at high redshift. For metallicities above 10^{-3} they find a multi-phase ISM that allows the second generation of stars to be formed efficiently. The impact of radiation, chemical and mechanical feedback is vital in this. The first type, when it takes the form of UV photons, forbids molecular gas to survive in significant amounts. Subsequently, adaptive mesh refinement simulations indicate that collapsing high redshift clouds are less prone to fragmentation in the presence of ongoing low-metallicity star formation and a population III mode of star formation persists (partly) to a redshift of 5. This result is very relevant for upcoming observational studies of the early universe.

3.2.2. Protostars and early disk evolution

Stars are continuously formed and removed from the stellar population. How this happens is one of the fundamental issues in contemporary astrophysics. Molecules and dust are used to trace both the physical evolution of these systems as well as the chemical inventory of simple and complex species available for planet formation.

3.2.2.1. Molecular tracers of pre-stellar cores

The initial conditions for star formation are characterized by temperatures < 10 K and densities > 10^5 cm^{-3}. Van der Tak, Müller (Cologne), Gauss (Mainz) and Harding (Austin) have completed a study of the hyperfine structure of the J=1-0 transitions of DCO^+, DNC, and $HN^{13}C$. These molecules are highly abundant during the early phases of star formation, when molecular D/H ratios are strongly enhanced due to freeze-out on grain surfaces. Van der Tak et al. use IRAM 30m observations with very high spectral resolution (13 m/s) of the L 1512 cloud, which has extremely narrow lines, to derive accurate hyperfine structure parameters for these lines. The results compare very well with quantum-chemical calculations. With this information in hand, astronomers now have the 1-0 lines of DCO^+ and DNC as excellent new tools to study the gas motions at the earliest phases of star formation. The results are also of interest from a molecular physics point of view, as they indicate a significant non-rigidity of DNC, in particular along the bending coordinate.

H_3^+ and its isotopologues play a key role in the exotic chemistry caused by the freeze-out of molecules. Caselli (Leeds) et al., with participation by Van der Tak, have made the first survey of H_2D^+ 372 GHz emission toward nearby pre-stellar and protostellar cores using the CSO telescope. The H_2D^+ emission is found to peak near the end of the pre-stellar phase, when the cores are very dense and centrally concentrated. As soon as a protostar ignites, it warms up its surroundings and reduces the H_2D^+ abundance. Follow-up work is in progress at the JCMT.

3.2.2.2. Cloud collapse and disk formation

Brinch and Hogerheijde, together with van Weeren (MSc) and Richling (Paris), finished two theoretical studies on the evolution of molecular-line emission originating from protostellar cores during their collapse and subsequent formation of a disk. The first study shows that observations of millimeter-wavelength emission lines of a variety of species (CO, HCO^+, HCN, ^{13}CO, $H^{13}CO^+$, ...) and on a range of spatial scales (from 20", 3000 AU, attainable with single-dish telescopes down to a few arcsec, 300 AU, obtained with interferometers) can uniquely characterize the dynamics of the material, as it transitions from infall-dominated to rotation-dominated: a protostellar growth chart (Fig. 3.17). The second study shows that chemical processes such as freeze-out of CO onto dust grains does not seriously

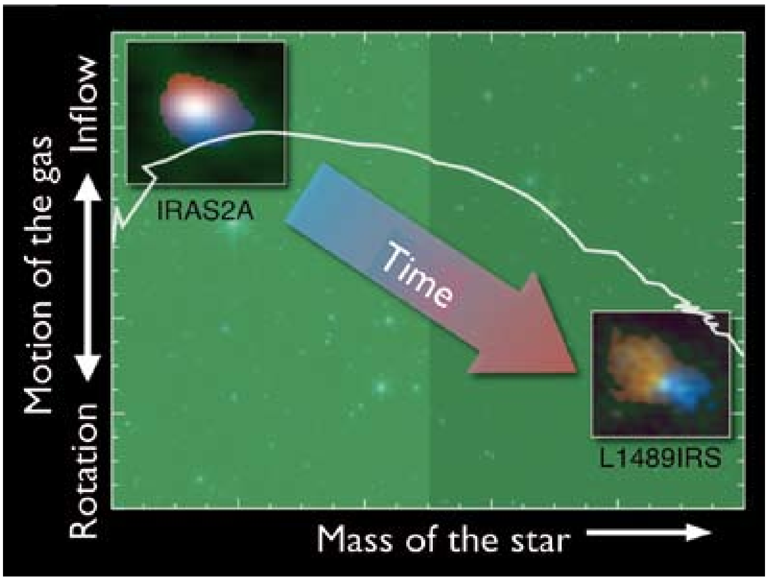


Figure 3.17: Protostellar growth chart illustrating how the velocity of material during the embedded phase of star formation transitions from infall-dominated to rotation dominated (based on: Brinch et al. 2009, A&A, 502, 199).

limit the applicability of these growth charts. This modeling involved a novel method to follow the time dependent nature of the chemistry in the evolving core, and in a separate study van Weeren, Brinch and Hogerheijde show how this method can be applied also to model the full gas-phase chemistry.

Brinch, Hogerheijde, and Jörgensen (MPIfR Bonn) subsequently contrasted this theoretical study with two observational studies of the objects L1489 IRS and NGC 1333 IRAS 2A. They show that these objects form two extreme examples of disk formation, with the latter dominated by infall and with only a very small degree of rotation, while the former is almost fully (but not completely!) characterized by Keplerian rotation.

3.2.2.3. Probing disks in the embedded phase

In a complementary study, Jörgensen (Bonn), van Dishoeck, Visser (PhD), Lommen (NOVA PhD) and collaborators used the SMA to characterize young disks in the embedded stage of star formation. Following an initial paper by Lommen et al. for two sources, a large sample of 20 sources was surveyed. The interferometer data allow the disk and envelope emission to be disentangled. The envelope mass is found to sharply decrease from the Class 0 to the Class I stage, but the disk mass shows no evolution between these stages. In addition, four Class I sources exhibit signs of Keplerian disk rotation in HCO^+ 3-2 data. The inferred stellar masses indicate that the stars contain 70-98% of the total mass in the star-disk-envelope system, confirming that most of the material has already accreted onto the central star at this stage. Comparison with evolutionary models shows that theory tends to overestimate disk relative to stellar masses. Thus, material accreted from the large scale envelope has to be processed more rapidly onto the central star by some mechanism.

3.2.2.4. Ice survey of low-mass protostellar envelopes

Öberg (PhD), Bottinelli, Boogert (IPAC), Pontoppidan (Caltech), van Dishoeck, Lahuis and the 'Cores to Disks' (c2d) IRS team finalized their Spitzer and ground-based 3-38 μm spectral survey of a sample of 41 low luminosity young stellar objects (YSOs) down to proto-brown dwarfs. The third major paper in the series focused on CH_4, an important building block for making large carbonaceous molecules. Solid CH_4 abundances have previously been determined mostly toward high-mass star-forming regions. The inferred solid CH_4/H_2O abundance ratio from the weak 7.7 μm feature is 4.7% ± 1.6%. These abundances are consistent with models where CH_4 is formed through sequential hydrogenation of atomic C on grain surfaces. The equal or higher abundances toward low-mass YSOs compared with high-mass objects and the correlation studies with other species support this formation pathway, but not the two competing theories: formation from CH_3OH and formation in gas phase with subsequent freeze-out.

The fourth paper addressed the solid NH_3 and CH_3OH abundances, both of which are thought to be key ingredients for making prebiotic molecules in ices. Identification of these molecules is complicated by the fact that their main features at 9.0 and 9.7μm are blended with the strong silicate absorption band (Fig. 3.18), so different methods were developed to extract the weak features. The resulting NH_3 abundances range between 2 and 15%, whereas those for CH_3OH show a broader range from <1% to nearly 30% with respect to H_2O ice. Comparison with a systematic set of laboratory experiments by Bouwman (PhD), Beckwith (student) and Linnartz shows that NH_3, like CH_4, is formed largely by hydrogenation of atomic N on grains, whereas the CH_3OH data are consistent with significant formation through

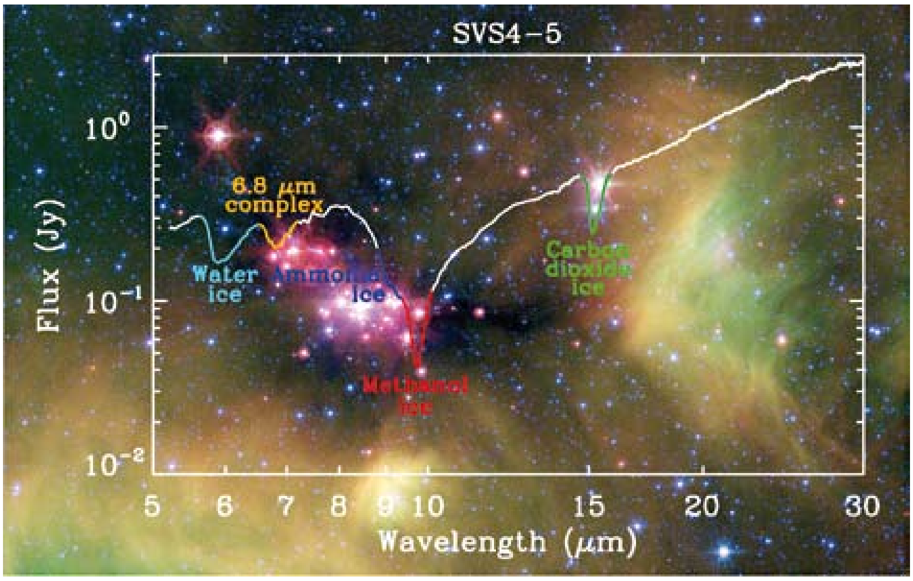


Figure 3.18: Spitzer infrared spectrum toward the deeply embedded solar mass protostar Serpens SVS 4-9, showing CH_3OH and NH_3 ice absorptions at 9.7 and 9.0 µm superposed on the silicate feature. The background image is the Spitzer c2d 3.6, 8.0 and 24 micron color image of the Serpens core (from: Bottinelli et al. 2010, ApJ, in press).

hydrogenation of CO in a nearly pure CO ice environment. Quantitative simulations of the latter process have been carried out by Cuppen and collaborators using the latest Leiden laboratory data.

3.2.2.5. Modeling water emission from low-mass protostellar envelopes

Water vapor plays a key role in the chemistry and energy balance of star-forming regions. Van Kempen (PhD), van Dishoeck, Hogerheijde, Doty (Denison) and Jörgensen (Bonn) simulated the emission of rotational water lines from low-mass YSO envelopes in preparation for Herschel data. A large number of parameters that influence the water emission have been explored: luminosity, density, density slope, and water abundances. The results show that lines can be categorized in: (I) optically thick lines, including ground-state lines, mostly sensitive to the cold outer envelope; (II) highly excited (E_u > 200-250 K) optically thin lines sensitive to the water abundance in the hot inner part; and (III) lines which vary from optically thick to thin depending on the abundances. A correct treatment of the dust in the water excitation and line formation is essential. Observations of $H_2{}^{18}O$ lines, although weak, provide the strongest constraints on abundances.

3.2.2.6. Origin and evolution of complex organic molecules in space

Organic compounds are ubiquitous in space: they are found in diffuse clouds, in the envelopes of evolved stars, in dense star-forming regions, in protoplanetary disks, in comets, on the surfaces of minor planets, and in meteorites and interplanetary dust particles. Van Dishoeck wrote three review articles on this topic, including an Annual Reviews paper with Herbst (Ohio State). The observational evidence for the types of organics found in different regions was summarized and similarities and differences in various regions have been discussed in the context of the processes that can modify them (UV irradiation, shocks, chemistry). There is now strong evidence that the rich variety of volatile complex molecules seen in the millimeter spectra of young stellar objects is primarily formed in the ice mantles on interstellar grains. This chemistry appears ubiquitous throughout the Milky Way, with remarkably similar abundances on large scales.

Öberg, Bottinelli and van Dishoeck developed an indirect method for testing this hypothesis through two molecules – CH_3OH and HNCO - that can be observed both in the gas and in the ice. A tentative correlation between the ice and gas abundances was found with a measured gas to ice ratio of 10^{-4}. This value agrees well with predictions for the photodesorption mechanism measured in the laboratory by Öberg and collaborators. This provides a 'proof of concept' that non-thermal desorption products in cold clouds can serve as a signature of the (complex) ice composition.

3.2.2.7. Small scale organic chemistry: the protobinary IRAS 16293 -2422

To test the complex organic chemistry on smaller scales, Bisschop (NOVA PhD), Jörgensen (Bonn), Bottinelli, and van Dishoeck investigated the chemical relations in the low-mass protobinary YSO IRAS 16293-2422 using the SubMillimeter Array (SMA) at 5'' (800x500 AU) resolution (Fig. 3.19).

Nitrogen-bearing molecules show compact emission primarily from source A, whereas oxygen-bearing molecules have comparable strength on both sources or are seen exclusively from source B. Their relative abundances are very similar to those found in high-mass YSOs illustrating that the chemistry appears to be independent of luminosity

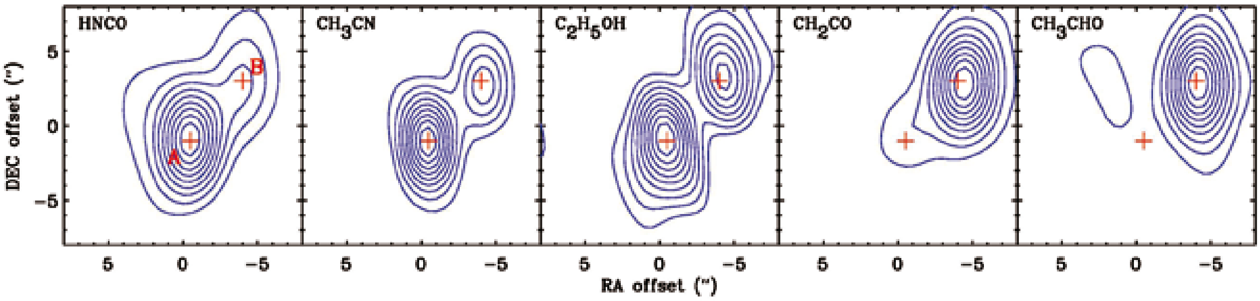


Figure 3.19: Interferometric line images of the low-mass protobinary object IRAS 16293-2422 obtained with the SubMillimeter Array. Different distributions of the oxygen and nitrogen-bearing complex organic molecules are seen, even though the two sources are separated by only 800 AU (from: Bisschop et al. 2008, A&A, 488, 959).

and cloud mass. The bigger abundance differences seen between the two binary components may be linked to different local initial ice abundances, especially that of OCN$^-$ ice. The data illustrate the importance of interferometric over single dish data to test chemical models.

3.2.2.8. Chemical evolution from cloud to disk

Visser (PhD), van Dishoeck, Doty (Denison) and Dullemond (MPIA Heidelberg) developed a semi-analytical two-dimensional (2D) model to describe how material changes physically and chemically as it is transported from a collapsing cloud to a protoplanetary disk. So far, only 1D models have been used but they cannot properly describe the incorporation of material into disks. The model computes infall trajectories from any point in the cloud and tracks the radial and vertical motion of material in the viscously evolving disk. It includes a full time-dependent radiative transfer treatment of the dust temperature, which controls much of the chemistry. As a first application, the freeze-out and evaporation of CO and H_2O ice has been studied, as well as the potential for forming complex organic molecules in ices (Fig. 3.20). Interestingly, weakly bound ices like CO evaporate and re-adsorb multiple times during the infall and disk formation phases, whereas H_2O ice remains solid almost everywhere. Thus, a fraction of the ices in comets are indeed expected to be pristine molecular cloud material. Material that ends up in the planet- and comet-forming zones of the disk (~5-30 AU from the star) is predicted to spend enough time in a warm zone during the collapse to form first-generation complex organic species on the grains.

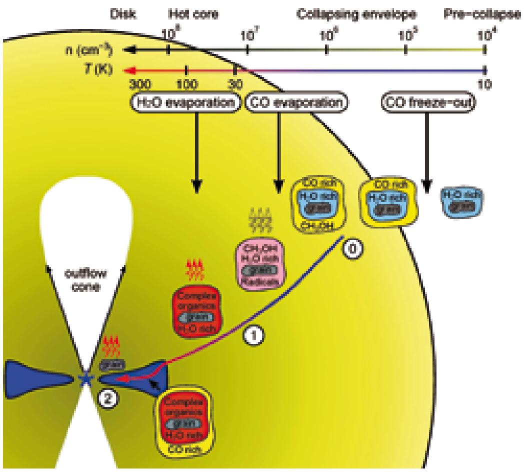


Figure 3.20: Cartoon representation of the evolution of material from the prestellar core stage through the collapsing envelope (size ~0.05 pc) into a protoplanetary disk. The formation of zeroth- and first-generation organic molecules in the ices is indicated with 0 and 1, and second-generation molecules in the hot-core region with 2. Once material enters the disk, it will rapidly move to the cold midplane where additional freeze-out and grain surface chemistry occur. All ices evaporate inside the (species-dependent) sublimation radius (`snow line') (from: Herbst and van Dishoeck 2009, ARA&A, 47, 427, based on: Visser et al. 2009, A&A, 495, 881).

3.2.2.9. Sunbathing around low-mass protostars: CHAMP+ high-J CO observations

Van Kempen (PhD), van Dishoeck, Hogerheijde, Kristensen, Guesten (Bonn) and collaborators used the new CHAMP+ camera on APEX to image CO J=6-5, 7-6 lines, as well as lines from isotopologues and [C I] 809 GHz, in a sample of about 10 low-mass protostellar sources on scales of several arcmin to probe the origin of warm gas in their surroundings (Fig 3.21). Such studies have only become possible due to the development of heterodyne arrays at high frequency combined with an excellent site. Surprisingly strong quiescent extended narrow high-J ^{12}CO 6-5 and 7-6 lines are seen toward all protostars, suggesting that heating by UV photons along the outflow cavity dominates the emission, a mechanism proposed by Spaans et al. a decade ago. At the source position itself, passive heating of the collapsing inner envelope by the protostellar luminosity also contributes. The UV photons are generally not energetic enough to dissociate CO since the [C I] 2-1 emission, also probed by these data, is weak except at the bow shock at the tip of the outflow. Shock-heated warm gas characterized by broad CO line profiles is seen only toward the more massive Class 0 outflows.

The power of large scale mapping with heterodyne arrays is also demonstrated through JCMT HARP-B and IRAM 30m EMIR maps by Kristensen, van Dishoeck and collaborators of species like CH_3OH, CN and CS which are tracers of grain chemistry, UV radiation and density, respectively.

In collaboration with Bruderer, Benz (both ETH) and Doty (Denison), multidimensional chemical models have been developed which can tackle the physical and chemical structure of irradiated outflow walls. The initial application has been to high-mass YSOs, but such models are now being constructed for low-mass YSOs together with Visser.

3.2.2.10. **Lack of PAH emission toward low-mass embedded YSOs**

Polycyclic aromatic hydrocarbons (PAHs) have been detected toward molecular clouds and a few T Tauri stars with disks, but not yet toward embedded YSOs. Geers (PhD), van Dishoeck, Pontoppidan (Caltech), Lahuis and co-workers used sensitive VLT-ISAAC and Spitzer-IRS spectra to search for the 3.3, 7.7 and 11.3 μm bands of PAHs in a sample of 53 embedded YSOs. No detections were found. Using radiative transfer codes from Dullemond (MPIA Heidelberg) combined with a PAH excitation module from Visser, the sensitivity of the PAH emission to PAH abundance, stellar radiation field, inclination and the extinction by the surrounding envelope has been studied. Assuming typical stellar and envelope parameters, the absence of PAH emission is best explained by the absence of emitting carriers, implying a PAH abundance at least an order of magnitude lower than in molecular clouds but similar to that found in disks. Thus, most PAHs likely enter the protoplanetary disks frozen out in icy layers on dust grains and/or in coagulated form.

3.2.2.11. **Characterizing the nature of embedded YSOs**

Crapsi, van Dishoeck, Hogerheijde, Pontoppidan (Caltech) and Dullemond (MPIA Heidelberg) used 3D axisymmetric radiative transfer calculations of YSOs including envelope, disk and outflow cavity to show the effects of different geometries on the main indicators of YSO evolutionary stages, such as silicate emission, ice absorption, spectral slope and bolometric temperature. All of these indicators misclassify edge-on systems for inclinations larger than ~65°. The simplest and most reliable classification scheme consists of comparing submillimeter fluxes obtained with a single dish and an interferometer, but such data will not be available for large samples until the ALMA era.

Van Kempen, van Dishoeck and collaborators subsequently developed an alternative method to characterize the truly embedded population in Ophiuchus. They used the extent and strength of a high density tracer, HCO^+ J=4-3 observed with JCMT HARP-B, combined with two column density tracers, $C^{18}O$ 3-2 and SCUBA dust continuum. Of the 40 candidate sources, only 17 turned out to be bona-fide embedded YSOs. Accurate classification is essential to determine reliable lifetimes of the various evolutionary phases.

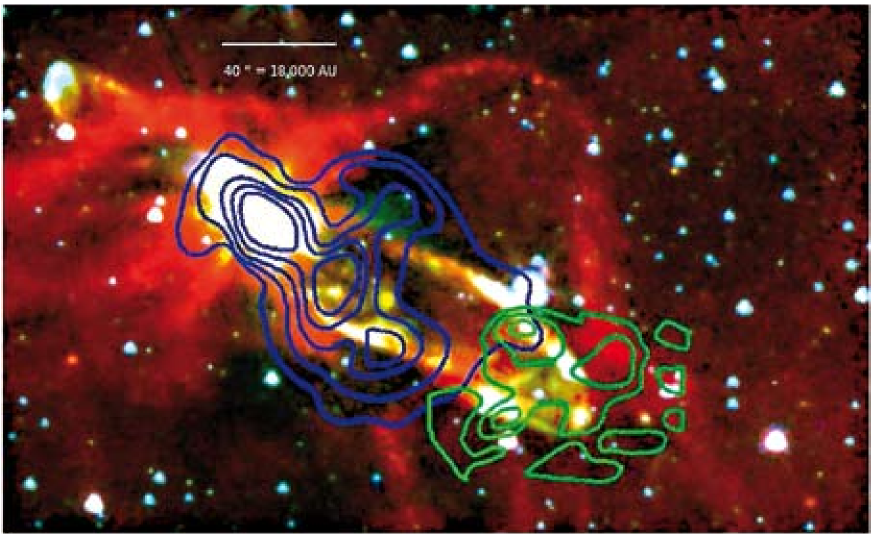


Figure 3.21: Spitzer three color (3.6 (blue), 4.5 (green) and 8 μm (red)) image of the low-mass protostar HH 46 with the contours of integrated CO J=6-5 emission (blue/dark) observed with APEX-CHAMP+ overlaid. The [C I] 2-1 emission (green/light) is detected weakly on source but peaks further down at the tip of the outflow where the UV photons produced in the fast bow shock are hard enough to dissociate CO. Analysis of the line profiles shows that the emission consists both of accelerated swept-up gas along the outflow as well as quiescent, photon-heated gas surrounding the outflow cavity walls (from: van Kempen et al. 2009, A&A, 503, 601).

3.2.2.12. **The Spitzer c2d legacy: statistics**

The Spitzer c2d legacy team, led by Evans and including van Dishoeck, van Kempen and Merin, performed a statistical analysis of the more than 1000 YSOs found in the five star-forming clouds mapped by c2d. Current star-formation efficiencies are found to range from 3% to 6%, overall from 15% to 30%. The star-formation surface density is more than an order of magnitude larger than would be predicted from the Kennicutt relation used in extragalactic studies, reflecting the fact that those relations apply to larger scales where more diffuse matter is included in the gas surface density. The derived lifetime for the embedded Class I phase is 0.44 Myr, considerably longer than some estimates. Similarly, the lifetime for the Class 0 SED class, 0.1 Myr, with the notable exception of the Ophiuchus cloud, is longer than early estimates. The great majority (90%) of young stars lie within loose clusters with at least 35 members and a stellar density of 1 $M_\odot$ pc^{-3}. The data confirm and aggravate the 'luminosity problem' for protostars. At a given T_{bol}, the values for L_{bol} are less than predicted by standard infall models and scatter over several orders of magnitude. These results strongly suggest that accretion is time variable, with prolonged periods of very low accretion.

3.2.2.13. **First results from the Herschel WISH key program**

Water is a key molecule for probing the physics and chemistry of star-forming regions because of its large abundance variations between warm and cold regions. Thus, water acts like a 'switch' that turns on whenever energy is deposited in molecular clouds, highlighting key episodes of stellar birth such as gravitational collapse, outflow injection, and stellar heating of envelopes and disks. Water is also of chemical importance as one of the main oxygen reservoirs. The 'Water in Star Forming Regions' (WISH) guaranteed time key program on Herschel, led by van Dishoeck and involving Dominik, Hogerheijde and van der Tak, will use HIFI and PACS to follow the water 'trail' through the various stages of star formation from prestellar cores to disks, and from the lowest to the highest mass young stellar objects. The first PACS data, obtained in late 2009 and presented in Fig. 3.22, reveal strong water and [O I] emission associated with deeply embedded YSOs, probing these energetic processes.

3.2.3. Structure of protoplanetary disks around pre-main sequence stars

3.2.3.1. **Shape of protoplanetary disks**

The spectral energy distributions of circumstellar disks around Herbig Ae/Be stars have been classified into two major groups, group I (flaring) and group II (self-shadowed). Meijer (PhD), Dominik, de Koter, and Waters, in collaboration with Dullemond and van Boekel from Heidelberg, executed an extensive parameter study of self-consistent models of protoplanetary disks around Herbig AeBe stars. The

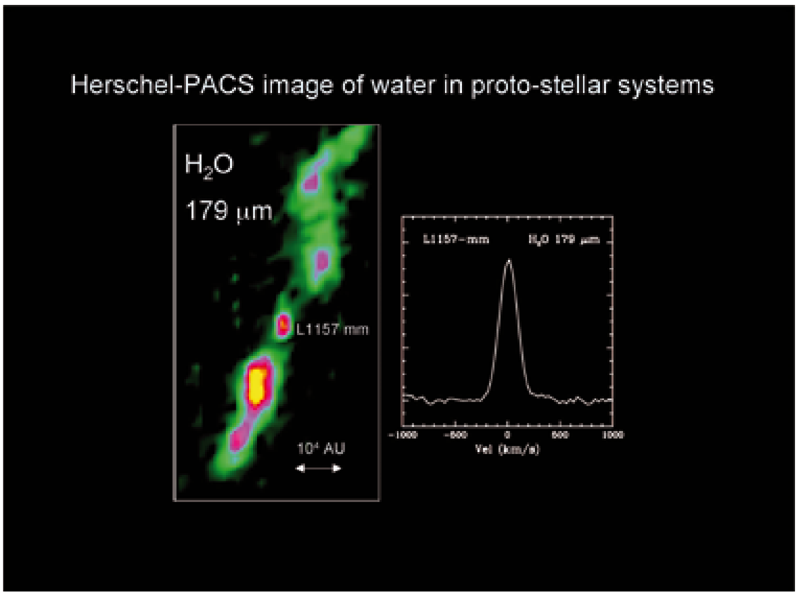


Figure 3.22: Herschel-PACS first results image of the 179 micron line of water toward the low-mass protostar L 1157, lighting up the 'hot spots' in the bipolar outflow where the shock dumps energy into the cloud (from: Nisini et al. 2010, A&A, submitted).

models are computed using a 2D radiative transfer code with self-consistent vertical structure. In the parameter study, stellar and disk properties were varied in order to assess the influence on the overall appearance of the spectral energy distribution, focusing on near and mid-IR regions only, addressing the classification of Herbig Ae/Be stars into two groups, with a flaring (group I) or self-shadowed (group II) SED. The parameter of overriding importance to the SED is the total mass in grains smaller than 25 μm. All other parameters studied have only minor influences, and will alter the SED type only in a minor way. It is found that, from a modeling point of view, there is no natural dichotomy between group I and II. The transition is a continuous function of the small dust mass.

Acke (Leuven) and colleagues (including Waters, Ochsendorf and Min) used spectra taken with the Spitzer Space Telescope of Herbig Ae/Be stars as a probe of the geometry of the proto-planetary disks that surround these stars. They discovered a correlation between the magnitude of the infrared excess at a wavelength of 7 μm and the slope of the continuum measured between 13.5 and 30 μm. This correlation can be understood in terms of a simple physical picture involving a so-called puffed-up inner disk, which casts a shadow over the outer disk. Stars with large inner rim heights cast a larger shadow and hence most of the outer disk is cold, causing the IR emission to be dominated by the inner rim. This results in a 'blue' infrared continuum between 13.5 and 30 μm. Stars with small inner rim height have a small shadow and more of the outer disk can receive direct stellar radiation. This results in a 'red' infrared continuum. The amount of flaring of the disk is governed by the abundance of small grains in the disk.

3.2.3.2. Radiative transfer in very optically thick disks

The high density regions of proto-planetary disks around young stars can be extremely opague at optical and IR wavelengths. This greatly complicates the computation of self-consistent disk models, which rely on an accurate temperature structure in order to compute the vertical disk stratification. Min, Dominik, de Koter, Hovenier and Dullemond (Heidelberg) present two efficient implementations of the diffusion approximation to be exploited in Monte Carlo simulations of radiative transfer in dusty media of massive circumstellar disks. First, an energy diffusion approximation is used to improve the accuracy of the temperature structure in highly obscured regions of the disk. Second, a modified random walk approximation is employed to ensure that photons that end up in the high-density regions can quickly escape to the lower density regions, while the energy deposition by these photons in the disk is still computed accurately. A new radiative transfer code, MCMax, is presented in which both these diffusion approximations are implemented.

3.2.3.3. The inner rim in protoplanetary disks

The inner boundary of protoplanetary discs is structured by the dramatic opacity changes at the transition from the dust-containing to a dust-free zone. Kama, Min, and Dominik explore the variety and limits of inner rim structures in passively heated dusty discs. Detailed sublimation physics were implemented in a fast Monte Carlo radiative transfer code. It was shown that the inner rim in dusty discs is not an infinitely sharp wall but a diffuse region which may be narrow or wide. Furthermore, high surface densities and large silicate grains as well as iron and corundum grains decrease the rim radius, from a 2.2 AU radius for small silicates around a 47 $L_\odot$ Herbig Ae star typically to 0.4 AU and as close as 0.2 AU. A passive disc with grain growth and a diverse dust composition must thus have a small inner rim radius.

3.2.3.4. Cold disks: Spitzer c2d census of disks with large inner dust holes

Understanding how disks evolve and dissipate is essential to studies of planet formation. Merín, van Dishoeck, Brown (MPE) and collaborators used the Spitzer c2d survey to identify a set of disks that are clearly in transition of losing their material. The initial c2d IRS spectral survey revealed four so-called 'cold' disks, i.e., disks which clearly lack mid-infrared emission due to lack of small warm dust. Their SEDs require large (20-40 AU) dust holes, which have been directly confirmed with submillimeter imaging using the SMA by Brown et al.

Subsequently, the c2d imaging survey was used to identify 35 additional candidates for which IRS spectra were obtained in a follow-up Spitzer program. Of these, 15 turn out to be cold disks, whereas a large fraction of the remaining 20 are disks in which the grains have grown and settled to the mid-plane. These statistics give a frequency of cold disks of 4-8% of the YSO population, indicating that transitional disks represent a short-lived phase in disk evolution. Hole sizes are generally smaller than for previously discovered cold disks (a few AU) and reflect a distribution more consistent with exoplanet radii. Reliable criteria for identifying disks with inner holes from Spitzer photometry have been determined, which can be applied to larger samples.

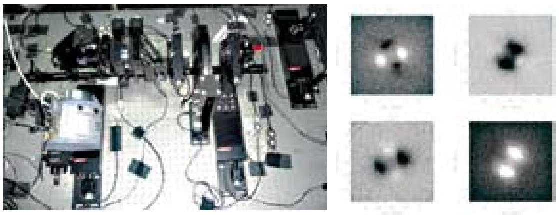


Figure 3.23: Left: ExPo on the optical bench in the WHT Nasmyth focus observing station. The light from the telescope is sent onto this optical bench from the right side in this picture. Most parts are off-the-shelf with custom-made adapters for the optics. The entire instrument is controlled from a single PC that also acquires and stores the data. Right: the protoplanetary disk around the young star AB Aur as seen in linearly polarized light. The four pictures correspond to different directions of the linear polarization (0, 45, 90, and 135 degrees). The 'butterfly' pattern is expected for a face-on circumstellar disk where the linear polarization shows a radial orientation (from: Keller private comm.)

3.2.3.5. Polarization images of protoplanetary disk

Keller, together with Jeffers (PD), Rodenhuis (PhD) and Canovas (PhD) finished developing the first version of ExPo, the Extreme Polarimeter, and had the first observing runs at the 4.2-m WHT (Fig. 3.23). ExPo is designed to image the scattering polarization signal of circumstellar material. The first observing run has been extremely successful by detecting known proto-planetary disks to a much larger distance from the central star than what has been done by others at visible wavelengths and by detecting protoplanetary disks around stars that have not been seen before. The data reduction approach related to speckle interferometry is now working on observations from the WHT, the innermost parts of circumstellar disks can be detected much closer in than any other technique operating at visible wavelengths.

3.2.4. Dust in protoplanetary disks around pre-main sequence stars

3.2.4.1. Shape of emission features

The shape of dust emission features contains information about the typical size of the dust particles residing in protoplanetary disks. A flattened 10 μm silicate feature is often interpreted as proof that grain growth has taken place, while a point feature is taken as evidence for the pristine nature of the dust. Dominik and Dullemond (Heidelberg) investigated what the effect of dust sedimentation is on the shape of the observed 10 μm amorphous silicate dust resonance and how this may affect the interpretation of the observations. Using a combination of modeling tools, the sedimentation of a dust grain size distribution in an axisymmetric 2-D model of a turbulent disk was modeled. Subsequently, a radiative transfer program was used to compute the resulting spectra. It was found that the sedimentation can turn a flat feature into a pointy one, but only to a limited degree and for a very limited set of particle size distributions. If the distribution is too strongly dominated by small grains, then the feature is pointy even before sedimentation. If the distribution is too strongly dominated by big grains, the sedimentation will not be enough to cause the feature to be pointy. Only a bimodal size distribution, i.e. a very small grain population and a bigger grain population, does transform from a flat to a pointy feature upon dust sedimentation. However, if sedimentation is the sole reason for the variety of silicate feature strengths observed in protoplanetary disks, disks with weak mid- to far-infrared excess are expected to have stronger 10 μm silicate features than disks with a strong excess.

3.2.4.2. Crystalline silicates in disks

As part of the c2d legacy program, Olofsson, Augereau (Grenoble), van Dishoeck and the c2d team analyzed Spitzer-IRS spectra of ~100 T Tauri stars to quantify their crystallinity fraction. More than 3/4 of the objects show at least one crystalline silicate feature that can be essentially attributed to Mg-rich silicates. The Fe-rich crystalline silicates are largely absent in the c2d sources. The strength and detection frequency of the crystalline features seen at long wavelengths (probing <10 AU) correlate with each other, but not with those at 10 μm (probing <1 AU). This leads to a crystallinity paradox: the crystalline silicate features are detected 3 times more frequently in the colder outer disk (~55% vs. ~15%) than in the much warmer inner disk regions where they are supposedly crystallized. Thus, an efficient outward radial transport mechanism in disks around T Tauri stars is needed.

3.2.4.3. Theoretical spectra of disks with crystalline grains

Meijer (PhD), Waters, de Koter, Min, Dominik and collaborators studied theoretical spectra at mid-infrared (5-40 μm) wavelengths of protoplanetary disks surrounding intermediate-mass pre-main-sequence stars. Observations show a wide range of spectral shapes and a rich variety in strength and shape of dust resonances. These strong variations in spectral shape reflect differences in the nature and spatial distribution of dust particles in the disk. The aim is to establish what disk properties influence the mid-IR spectra of planet-forming disks. It is found that the 33.5 μm emission of the crystalline silicate forsterite is a good probe of the spatial structure of the disk up to 50 AU. The disk is found to be spatially flaring at large distances, only if the feature is relatively strong. Also, only models with a substantial abundance (>5%) of crystalline silicates at a large distance from the star (>20-50 AU) show detectable emission in the 33.5 μm forsterite band.

3.2.4.4. Pebbles in disks

Grains in disks around young stars are thought to grow from interstellar submicron sizes to planetesimals, up to km in size, over the course of several Myr. The largest grains that can be detected have sizes of pebbles, and can be best observed at centimeter wavelengths. However, other emission mechanisms can contribute, most notably free-free emission from stellar winds and chromospheric activity. Lommen (PhD), Wright (ADFA), Maddison (Swinburne) and collaborators used ATCA to determine the mechanisms of cm emission for several T Tauri stars through monitoring over several years. Some disks have confirmed grain growth up to at least millimeter sizes, whereas one source shows variable emission at the longest wavelengths indicative of non-thermal emission. In collaboration with van Dishoeck and Langevelde, a larger sample has subsequently been surveyed with ATCA and SMA to search for correlations between the submillimeter spectral slope, characteristic of grain growth across the disk midplane, and the 10 µm feature, indicative of growth in the surface layers in the inner disk.

3.2.4.5. Disk properties of an unbiased sample in Serpens

The Spitzer c2d survey has revealed a new population of YSOs in a previously unexplored region of the Serpens molecular cloud. Compared with other low-mass star-forming clouds, Serpens has a much higher star formation rate per unit volume. Thus, it is an excellent laboratory to test disk properties

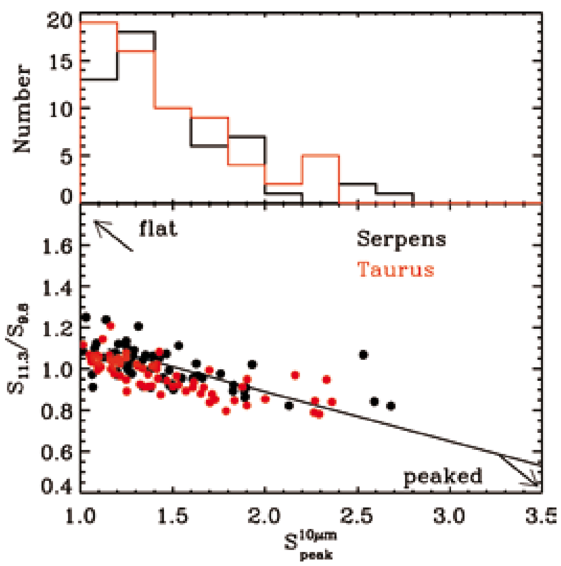


***Figure 3.24*: Bottom: Shape vs. strength of the 10 µm silicate feature for disks in Serpens (black) and Taurus (red). Each sample contains about 100 sources. Top: distribution of the 10 µm peak strength for the two clouds. The similar distributions show that environment (clustered vs. isolated) does not play a role (from: Oliveira et al. 2010, ApJ, in press).**

in a clustered environment. Oliveira (PhD), Pontoppidan (Caltech), van Dishoeck, Merín (ESOC) and collaborators have carried out a flux-limited IRS spectroscopic survey of some 100 disks down to the young brown dwarf limit. In addition, complementary optical spectroscopy, millimeter emission and X-ray surveys have been done. The majority of the disks show silicate emission, 8% have 30/13 µm flux ratios consistent with cold disks with inner holes and <4% of the disks show PAH emission. Comparison with models indicates that dust grains in the surface layers have sizes of at least a few µm. No significant difference is found in the distribution of silicate feature shapes and strengths between sources in clusters and in the field in Serpens, nor with other well-studied large samples of disks such as the c2d survey across 5 clouds and that of Taurus (Fig. 3.24). The remarkably similar distributions in samples with different median ages imply that the dust population in the disk surface results from an equilibrium between dust growth and destructive collisional processes that is maintained over a few million years, irrespective of environment.

3.2.4.6. IR excess around stars: debris disks or heated ISM?

As disks evolve and turn into mature planetary systems, cold small dust grains in disk or ring-like structures very similar to our own Kuiper belt can be observed. However, in many cases, the only evidence is the thermal emission from the dust and its interpretation remains ambiguous since one cannot distinguish between large micron-sized dust grains in a Kuiper belt structure and very small sub-micron sized grains farther away from the star. Kamp, Martinez-Galarza and G. Rieke (Arizona) investigated the latter scenario when the star generates a shock wave and warms up the small interstellar grains as it travels through the interstellar medium. A nice example observed with Spitzer is shown in Fig. 3.25 together with the proposed model and SED. This scenario of a disk-cloud interaction, where only the metal-poor interstellar gas is accreted, is sometimes invoked to explain the peculiar surface abundance of λ Bootis stars. In a follow-up project, Spijkman (MSc) and Kamp analyzed Spitzer IRS spectra probing the environment of a sample of λ Bootis stars to search for convincing spectral features of interstellar origin. This included a search for PAH features, which would be a clear indication. No PAHs have been detected so far, thus putting constraints on the column densities of any interstellar material and the geometry of both the cloud itself and the cavity that the star creates inside the cloud.

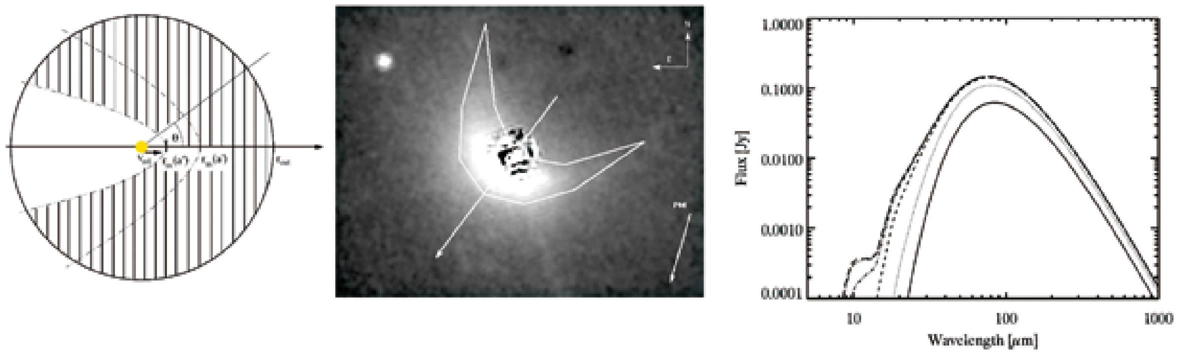


Figure 3.25: **Left panel: Sketch of the interaction between a star and the surrounding diffuse interstellar medium. Middle panel: Spitzer 24 μm image of the dust emission around the star δ Vel. The location of the bow shock and the direction of the modeled relative velocity are indicated by the white contours and arrow. Right panel: dependence of the dust SED on the relative velocity between star and cloud (0.9, 1.5, 4, 10, 35 and 100 km/s going from solid to long-dashed lines) (Left and right from:Martínez-Galarza et al., 2009, ApJ, 694, 165. Middle from: Gáspár et al., 2008, ApJ, 672, 974).**

3.2.5. Gas in disks

3.2.5.1. Warm gas and PAHs in disks

While the small dust particles in protoplanetary disks provide valuable information about the grain processing and early phases of planet formation, the bulk of the mass in the disk is in the form of (molecular) gas. This gas slowly dissipates as the disk evolves and planets form. The gas in the disk can be used to study the kinematics as well as the physical and chemical conditions in the disk. Van der Plas (PhD) and co-workers use the [OI] line at 630 nm to study the atomic gas in the upper disk layers of several intermediate mass Herbig Ae/Be stars. The double-peaked line profiles are indicative of a rotating gaseous disk geometry and the line strength and shape are used to distinguish between flaring and self-shadowed disk geometries.

Carmona (Heidelberg), van den Ancker (ESO), Waters and others searched for emission from H_2 in a sample of Herbig Ae/Be stars and were able to set strict limits on the amount of warm H_2 gas in these disks. Boersma (PhD), Bouwman (Heidelberg), Tielens, Waters and others investigated the nature of PAHs in different environments. Substantial modifications of the PAH composition in disks as compared to PAHs in the interstellar medium are found. Interestingly, these changes in PAH properties may already take place in the parent molecular cloud, i.e. before these large molecules enter the disk.

Boersma (PhD) and collaborators (including Verhoeff (PhD) and Waters) studied the nature of the PAH emission from a small sample of four Herbig Ae/Be stars in more detail, using both ground-based mid-IR spectra and images, and data taken with ISO and Spitzer. Contributions from PAHs typical for reflection nebulae dominate for the luminous Herbig Be stars, whereas those more typical for PAHs in disks dominate the Herbig Ae stars emission spectra. In one case, TY CrA, the characteristics of both types of PAHs can be found. These observations can be interpreted in terms of the luminosity of the source. The more luminous Herbig Be stars are capable of exciting PAHs in the wider environment, and these PAHs have characteristics of those in reflection nebulae. PAHs in the immediate circumstellar environment of Herbig Be stars do not contribute strongly. Less luminous Herbig Ae stars are dominated by PAHs in the (flaring) disks that surround these stars. Boersma (PhD), Spaans, Cox (Vilspa) and Tielens (Leiden) have also constructed synthetic PAH spectra, through quantum-chemical calculations, to determine the degree of ionization in disks and the ISM and to asses the strength of the interstellar radiation field.

In collaboration with Allamandola and Bauschlicher (NASA Ames) and Peeters (Ottawa), Boersma and Tielens have studied the emission characteristics of large PAH molecules at far infrared wavelengths. This analysis is based upon the NASA Ames data base of infrared spectra of PAHs. The results show that the so-called drum head modes of PAHs are very characteristic for the size of the molecule but less so for the molecular structure. Observations with Herschel-PACS can therefore provide key information on the population large PAH molecules in space.

3.2.5.2. Mind the gap: spectro-astrometric imaging of gas in protoplanetary disk gaps

Pontoppidan, Blake (both Caltech), van Dishoeck, Brown (MPE) and collaborators presented the first velocity-resolved spectro-astrometric imaging of the 4.7 μm ro-vibrational lines of CO gas in protoplanetary disks, obtained using VLT-CRIRES at a resolving power of 10^5, as part of a large VLT program led by van Dishoeck. The method has been applied to three disks with known dust gaps out to 45 AU and achieves an unprecedented spatial resolution of 0.1-0.5 AU, comparable to or better than mid-infrared interferometry (Fig 3.26). Keplerian disk models fitted to the position-velocity curves provide geometrical parameters, including position angles and inclinations with accuracies as good as 1-2°. The detection of molecular gas well inside the dust gaps in all three disks supports the scenario in which the dust gap is caused by partial clearing by a <1-10 M_{Jup} planetary body and rules out other clearing mechanisms such as photo evaporation.

3.2.5.3. Imaging CO infrared emission in disks around Herbig Ae stars

Van der Plas and co-workers used the same instrument, VLT-CRIRES, to determine the spatial distribution of hot CO in disks surrounding Herbig Ae/Be stars. In two objects, HD100546 and HD97048, spatially and spectrally resolved CO ro-vibrational emission from the fundamental vibrational band and its hot bands near 5 μm was used to measure the excitation temperature and column density. Both stars show a lack of CO emission from the inner 5 to 10 AU. This is remarkable because other gas tracers such as the forbidden [OI] line at 630 nm discussed above show that gas is present in the innermost disk regions of both stars. The lack of CO emission could be due to the details of the gas and dust temperatures in these regions, or due to the destruction of CO in the inner disks of these stars.

3.2.5.4. Water and organic molecules in the terrestrial planet-forming zones of disks

Salyk, Pontoppidan and Blake (all Caltech), in collaboration with Lahuis, van Dishoeck and Evans (Texas) detected numerous emission lines from hot water in the 10-20 μm range of Spitzer-IRS spectra of two protoplanetary disks around T Tauri stars. Follow-up 3-5 μm Keck-NIRSPEC data confirm the presence of abundant hot water and spectrally resolve the lines. Lines from OH, CO and ^{13}CO are also detected. Line shapes and LTE models suggest that the emission from all three molecules originates between ~0.5 and 5 AU, and thus provides a new window for understanding the chemical environment during terrestrial planet formation. The high columns of H_2O and OH suggest physical transport of volatile ices either vertically or radially in the disk. Follow-up Spitzer and VLT-CRIRES programs have found signatures of water and organic molecules (HCN, C_2H_2) in many more disks, indicating that these species are common in the inner zones of disks.

3.2.5.5. PAHs in shocks and hot ionized gas

In collaboration with Jones (Paris), Micelotta (PhD) and Tielens have studied the processing of large PAHs in interstellar shocks and in the hot gas associated with supernova remnants. This analysis is based upon a detailed model for the physical interaction of energetic electrons and ions with large molecules. The results show that PAH molecules will be destroyed on a timescale of approximately 100 million years in the interstellar medium. The widespread association of PAH emission with hot, X-ray emitting gas reveals the importance of entrainment of neutral material by the fast stellar winds and explosions. PAHs act thus as colorful dyes with which this process can be followed.

3.2.5.6. Imaging molecular gas and dust in the outer disks

Panić (PhD), together with Hogerheijde, Wilner (CfA), Qi (CfA) and other colleagues analyzed sin-

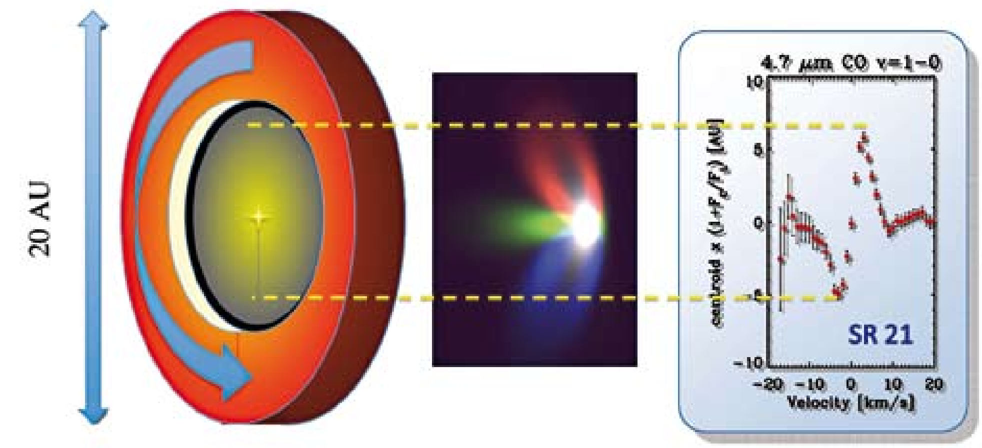


Figure 3.26: Illustration of the spectro-astrometry technique. Left: sketch of a protoplanetary disk with gas in Keplerian rotation seen at non-zero inclination. Middle: velocity pattern of the rotating gas, with the blue- (bottom) and red- (top) shifted emission offset from the central star. Right: observed spectro-astrometry pattern for the source SR 21 with VLT-CRIRES, in which the location of the peak emission in each velocity bin is recorded. For high signal/noise data, this location can be determined much more accurately than the spatial resolution given by the slit and AO system. For SR 21, an accuracy better than 1 milliarcsec is reached (Based on: Pontoppidan et al. 2008, ApJ, 684, 132; ESO press release September 2008).

gle-dish and millimeter-interferometric observations of molecular gas in the planet-forming disks around a number of low- and intermediate mass young stars. This sample includes objects studies in detail, such as HD169142, IM Lup, and HD100546; as well as two sets of T Tauri and Herbig Ae stars studied statistically. Panić et al. find that the gas-content of the warmer (>20 K) disks around the more luminous Herbig Ae stars is well described by models that start from the broadband Spectral Energy Distribution (SED), which essentially probes the location of the dust. In general these disks are smaller than 200 AU, although exceptions exist. The cooler disks around the less-luminous T Tauri stars show a much larger variety in their gas content than expected from their SEDs alone: freeze out and gas loss are likely to blame. For IM Lup, Panić et al. find that the gas disk extends to 900 AU while the dust disk is mostly confined to 400 AU from the star.

For HD 100546, in a collaboration with Güsten (Bonn) and van Dishoeck, APEX-CHAMP+ has been used to detect the CO 6-5 and 7-6 lines probing higher temperatures. The asymmetric line profiles indicate that the disk may be asymmetrically heated resulting in a 20-40 K temperature difference across the disk surface layers. Surprisingly, no [C I] emission is detected. An even larger asymmetry is seen toward the star DoAr 21, where spatially resolved H_2 S(1) 1-0 line emission using VLT-SINFONI forms an arc at 70--200 AU distance from the star. The most likely explanation for this emission is that unrelated cloud material is illuminated and heated by the strong X-ray emission of this star as it travels through the ρ Ophiuchus cloud.

3.2.5.7. Gas modeling

A new generation of protoplanetary disk models has been developed by Kamp, Woitke and Thi (both Edinburgh) in preparation for Herschel, which combines frequency-dependent two-dimensional dust continuum radiation transfer, kinetic gas-phase and UV photo-chemistry, ice formation, non-LTE heating and cooling of the gas, and a self-consistent treatment of the vertical hydrostatic equilibrium structure. These models (Fig. 3.27) confirm earlier results of a complete de-coupling of gas and dust temperatures in the disk surfaces where most of the line emission originates. The disk inner rim is more vertically extended than in the simpler pure dust radiative transfer models.

The model results of Kamp et al. have been coupled with detailed two-dimensional radiative transfer calculations for the water molecule (involving Hogerheijde), which indicate three main water reservoirs in protoplanetary disks. The inner hot reservoir (0.7-20 AU in disks around Herbig stars) contains most of the mass, but sits close to the midplane where gas and dust temperature couple and thus very little line emission is expected. A cold water belt surrounds the water ice reservoir (20-150 AU) and originates from UV photodesorption of that ice. The typical temperature is 40 K and this region contributes significantly to the low excitation lines that can be observed with HIFI. The final reservoir is a warm layer (1-30 AU) in the disk atmosphere where the water has a temperature of several 100 K and the PACS lines are expected to come entirely from this region.

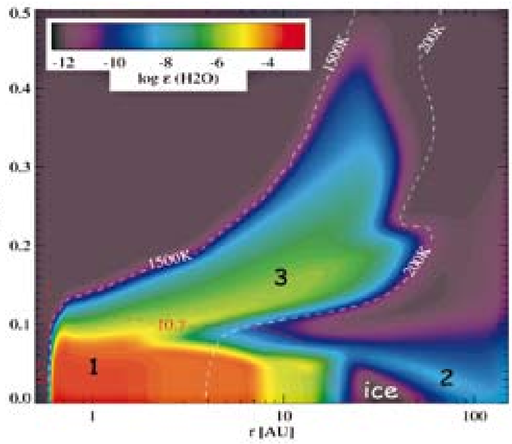


Figure 3.27: Concentration of water molecules in the protoplanetary disk around a Herbig Ae star. Three different regions can be distinguished: (1) A big water reservoir behind the inner rim with large water concentration. (2) A belt of cold water around the icy midplane beyond 20 AU. (3) A layer of hot water at high altitudes where the gas temperature ranges from 200 to 1500 K (from: Woitke et al., 2009, A&A, 501, L5).

Thi, Woitke & Kamp have also studied the deuteration of water in the dense inner regions of the disks. Numerical as well as analytical models predict very high HDO/H_2O ratios for the gas in the inner 3 AU of the disk; the difference in activation energy between deuteration enrichment and the back reactions is the main reason for this. The values found in the Earth oceans are high and it was previously thought that this tracer could discriminate between various origins of water on Earth such as cometary impact or hydrated silicates. The new results show that this HDO/H_2O ratio may in fact not be a unique criterion to distinguish between the various scenarios.

Along the same lines, Kamp, Tilling, Woitke, Thi & Hogerheijde investigated the origin and diagnostic power of the atomic fine structure lines [OI] and

[CII] as well as the submm CO lines from these disk models. While the [CII] line originates from the entire disk surface (in LTE), the [OI] lines originate mostly from the 30-100 AU region (in non-LTE) and from much deeper layers (down to A_V=1). Even though the absolute strength of the lines often depends on many parameters such as UV irradiation and dust grain size distribution, the combination of the [OI] 63/[OI] 145 μm and [OI] 63/[CII] 158 μm line ratios can serve as a potential tracer of gas mass.

In a further step, Aresu (PhD), Kamp, Meijerink and Spaans have expanded these disk models to include X-ray chemistry and heating of the gas. The X-rays are mainly deposited in the disk inner rim. There, the additional ionization and heating leads to an increase in the height of the inner disk rim, thereby casting also a more pronounced UV shadow on the outer disk. The molecule formation is pushed slightly outward and the distribution of mass in the various water reservoirs changes.

3.2.5.8. CO isotope selective photodissociation revisited

Photodissociation by UV light is an important destruction mechanism for CO in many astrophysical environments. Visser, van Dishoeck and Black (Onsala) revisited this process using recent spectroscopic data which allow determination of depth-dependent and isotope-selective photodissociation rates at higher accuracy. It is the first such model to include the rare isotopologues $C^{17}O$ and $^{13}C^{17}O$. The results have been applied to diffuse and translucent clouds, photon-dominated regions, and circumstellar disks. Increasing the excitation temperature reduces the isotopic selectivity by as much as a factor of three, whereas grain growth can enhance it by an order of magnitude. The photodissociation rates of $C^{17}O$ and $C^{18}O$ show almost exactly the same depth dependence so ^{17}O and ^{18}O are equally fractionated with respect to ^{16}O. This supports the recent hypothesis that CO photodissociation in the solar nebula is responsible for the anomalous ^{17}O and ^{18}O abundances in meteorites.

Using the unprecedented quality of VLT-CRIRES data, high precision measurements of $C^{17}O$, $C^{18}O$ and $C^{16}O$ abundances have been made by Smith (UCLA), Pontoppidan (Caltech) and collaborators (including van Dishoeck) of one disk and one protostellar envelope. The derived oxygen abundance ratios for the VV CrA disk show a significant mass-independent deficit of $C^{17}O$ and $C^{18}O$ relative to $C^{16}O$ compared to ISM baseline abundances, consistent with the isotope selective process in the upper layers of the disk. The Reipurth 50 envelope shows no clear differences, as expected.

3.2.5.9. Desorption of molecules in disks

Absorption of UV radiation by water ice can lead to dissociation and desorption of the ice molecules, a process thought to be important in the gas-grain chemistry in clouds and protoplanetary disks. Andersson and van Dishoeck computed photodesorption efficiencies of amorphous water ice using a classical molecular dynamics method and elucidated the mechanisms by which desorption occurs. The probability for H_2O desorption per absorbed UV photon is found to be 0.5-1% in the top three monolayers, then decreases to 0.03% in the next two monolayers, and is negligible deeper into the ice. The main H_2O removal mechanism is through separate desorption of H and OH fragments. The probability of any removal of H_2O per incident photon is estimated to be 4×10^{-4}, within a factor of two of values found by Öberg et al. in laboratory experiments.

This process of photodesorption is important in the interior of protoplanetary disks. Even though the disk midplane regions cannot be readily observed, the formation of molecules and ices there has consequences for the composition of planetesimals and planets that form over timescales of Myr. Chaparro (PhD) and Kamp studied the formation of water and CO ice and the details of desorption processes in the dense and dark midplane regions. The amount of cosmic-ray induced UV photons depends strongly on the local dust grain surface area (dust grain sizes on average larger than in the ISM) and can be up to a factor 15 higher than under typical cloud conditions. The OH abundance is significantly enhanced if the details of the UV photodesorption process and cosmic ray induced photodissociation are taken into account; this leads to the favored formation of CO and O_2 as opposed to H_2O, CH_3 and CH_4.

3.2.6. Young T Tauri stars

3.2.6.1. Captured at millimeter wavelengths: A flare from the classical T Tauri star DQ Tau

Salter, together with Hogerheijde and Blake (Caltech), serendipitously detected a flare of the classical T Tauri star DQ Tau at a wavelength of 3 mm. Over the course of just a few hours, the star brightened by at least a factor 27, followed by a decay over another eight hours (Fig. 3.28). A subsequent literature study revealed that DQ Tau is an eccentric close binary with a 15 day orbit. The flare coincides within the accuracy of the orbital parameters to the periastron passage of the stars, when the respective magnetospheres overlap. Salter et al. hypothesize that the magnetic interaction accelerates electrons to relativistic speeds, thus creating a sudden burst of synchrotron emission. Follow up observations on

December 28 2008 show that the flare likely repeats every periastron passage. During each flare, DQ Tau may easily outshine at 3 mm every other T Tauri in the Taurus star-forming cloud.

3.2.6.2. Characterizing young stars in Serpens

The Spitzer c2d mapping of the Serpens molecular cloud has revealed several hundred young stellar objects, many of which were not known before. Disk evolution studies require knowledge of the properties of the central star. Hence, Oliveira, Merín (Madrid), Pontoppidan (Caltech), van Dishoeck et al. embarked on an optical spectroscopy survey of all young stars found by c2d in Serpens, using the WHT, VLT and other optical telescopes. Spectral types, effective temperatures, extinctions and luminosities are estimated for the sample, and comtaminants (background giants, galaxies) are weeded out. Most stars are young K- and M-type stars with a spread in stellar ages from 1-15 Myr, peaking at 2-6 Myr. Strong Hα emission is detected for half of the sample, indicative of active accretion.

3.2.7. Planet Formation

3.2.7.1. Replenishment of small grains in disks

Turbulent coagulation of dust grains is known to operate on a timescale far shorter than the lifetime of the disk. In the absence of mechanisms that replenish the small dust grain population, protoplanetary disks would rapidly lose their continuum opacity-bearing dust. This is inconsistent with infrared observations of disks around T Tauri stars and Herbig Ae/Be stars, which are usually optically thick at visual wavelengths and show signatures of small (<3 μm) grains. Dominik and Dullemond (Heidelberg) investigated replenishing mechanisms that may form an alternative to the earlier proposed production of small grains by collisional fragmentation or erosion of large dust aggregates. They studied the effect of residual, low-level infall of matter onto the disk surface and found that infall rates as low as 10^{-11} $M_\odot$/yr can, in principle, replenish the small grain population to a level that keeps the disk marginally optically thick. However, such rates are difficult to reconcile with observational and theoretical limits.

3.2.7.2. Material properties for porous aggregates

The formation of planetesimals requires the growth of dust particles through collisions. Micron-sized particles must grow by many orders of magnitude in mass. To understand and model the processes during this growth, both the mechanical properties and the interaction cross sections of aggregates with surrounding gas must be well understood. Paszun and Dominik used recent advances in experimental (laboratory) studies as background for pushing numerical aggregate models to a new level. The experimental results were used in order to calibrate the numerical model of aggregate dynamics. Plastic deformation of surface asperities can be used as a model to match the velocities needed for sticking with experimental results. The modified code can be used to compute both the compression strength (Fig. 3.29) and the velocity of sound in the aggregate at different densities, and shows excellent compliance with the experimental constraints.

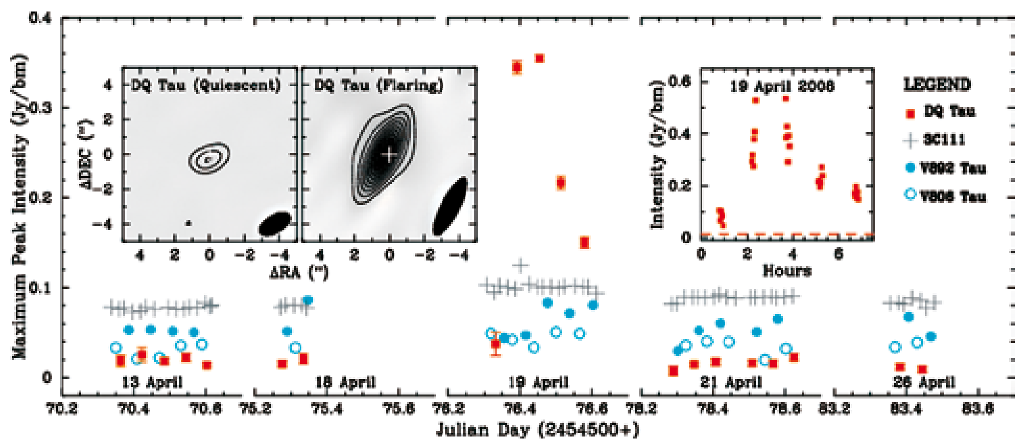


Figure 3.28: The flux of DQ Tau vs time on April 19 2008. For comparison, the fluxes of other sources and calibrators observed at the same time with the same instrument are also shown. DQ Tau brightens by at least a factor 27 over just a few hours. Salter et al. suggest that the overlapping magnetospheres of this eccentric close binary cause the remarkable brightening. Follow-up observations revealed that this flare repeats every 15 days near periastron passage of the system (from: Salter et al. 2008, A&A, 492, L21).

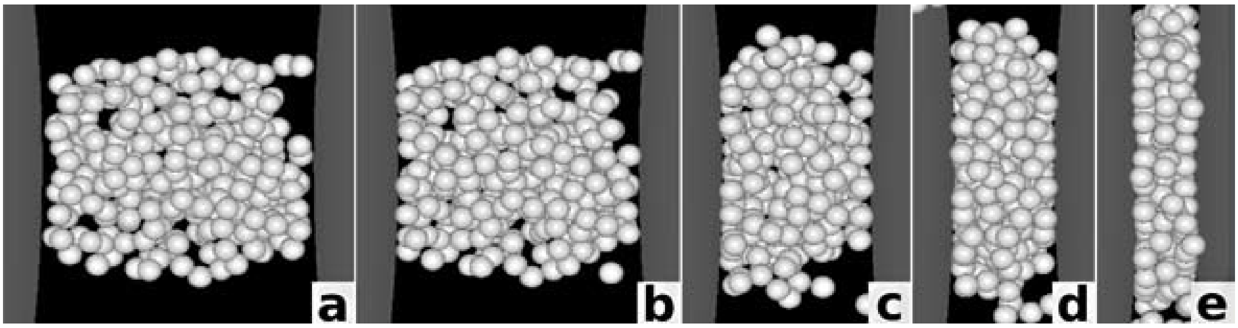


Figure 3.29: A numerical compression experiment used to calibrate the dust aggregation code by Paszun et al to laboratory experiments (from: Paszun & Dominik, 2008, A&A, 484, 859).

3.2.7.3. Collision physics of dust aggregates

The coagulation of dust aggregates occurs in various astrophysical environments. Each one is characterized by different conditions that influence the growth, e.g., relative velocities, composition, and size of the smallest constituents (monomers). Paszun and Dominik executed a large study of the microphysics of collisions of dust aggregates in a four-dimensional parameter space, using a molecular dynamics-like code. The results show the importance of the impact parameter that causes formation of elongated particles, due to tensile forces acting in offset collisions. In head-on impacts, aggregates are compacted at lower energies. A sufficiently high energy causes restructuring to reach maximum compaction. If more energy is provided, pancake-like structures are formed. It is found that the outcome of collisions can be represented in a simple way. A highly pronounced large fragment component coexists with a power-law distribution of small fragments. The structural parameter of these small fragments is described very well by a simple relation, largely independent of the initial compactness, impact energy or impact parameter.

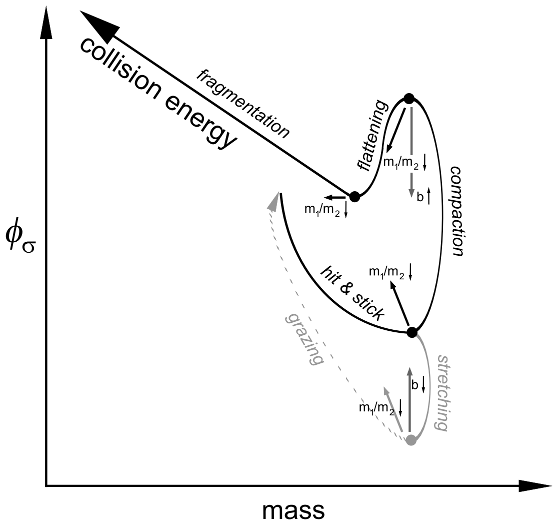


Figure 3.30: Sketch of the motion of particles and mass/filling factor space due to collisions of different energy, starting with the lowest energy and proceeding all the way to catastrophic disruption (from: Paszun & Dominik, 2009, A&A, 507, 1023).

The simulations show that erosion by collisions with high mass-ratio can be significant. The ejected mass can be several orders of magnitude higher than the impactor mass. This contrasts with collisions of equal mass aggregates, where the same impact energy can lead to perfect sticking. The findings can be summarized in the form of a simple collision recipe that can be applied in coagulation calculations. The recipe specifies the outcome of a collision, averaged over the impact parameter. Fig. 3.30 shows a sketch of how mass and compactness change during collisions.

3.2.7.4. Runaway growth

Ormel (Heidelberg) and Spaans have developed a very efficient Monte Carlo method to tackle the problem of runaway growth of dust particles covering many scales (Fig. 3.31). It relies on grouping particles together and zooming in on those particles that undergo the fastest dynamical changes.

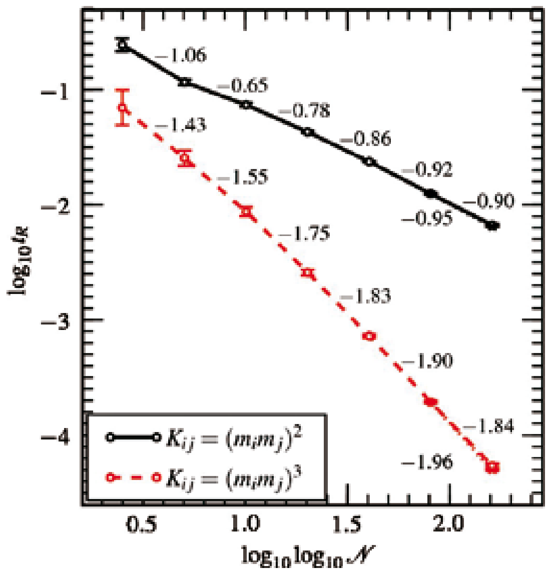


Figure 3.31: The relative time, t_R, for run-away growth to occur decreases with the number of particles inside a system. For two different mass dependencies of the gravitational collisional process (quadratic and cubic) one finds different limiting behaviors. (from: Ormel & Spaans, 2008, ApJ, 684, 1291).

Run-away gravitational growth can be followed over 20 orders of magnitude in mass. It is found that gravitational focusing (important for speeds below the escape velocity) and fragmentation due to collisions together determine the planetesimal mass distribution and facilitate the formation of a run-away/planet-forming mode. This very fast growth mode ends when the resulting large bodies start to gravitationally stir and heat up the smaller bodies around them. This transition, studied with Dullemond (Heidelberg), introduces a phase of 'oligarchy', where a few large bodies dominate the dynamics of a system. Such a transition could help to explain the size properties of the asteroid and Kuiper belts.

3.2.8. Solar system

3.2.8.1. The chemical composition of cometary ices

Hogerheijde, together with de Pater (UC Berkeley), Blake (Caltech), and others completed the analysis of millimeter-wavelength molecular-line interferometric observations of the comet C/2002 T7 (LINEAR). The observations were obtained simultaneously with two instruments, the OVRO array in Owens Valley and the BIMA array in Hat Creek, and subsequently combined. The detected HCN and CH_3OH line emission is well reproduced by a model where both species evaporate off the nucleus. Taking into account uncertainties in the measurement, in the non-equilibrium excitation of the molecules, and of collision rates with water, rigorous error bars on the molecular production rates have been made. In spite of these uncertainties, the respective production rates of HCN (0.1% compared to water) are within the narrow range observed toward other comets while those of CH_3OH (0.7%) are on the low end of the commonly observed range.

3.2.9. Extrasolar planets

3.2.9.1. Transit method

Snellen and collaborators continued their work on the detection and characterization of transiting extrasolar planets. Most of the more than 200 known extrasolar planets have been found using the radial velocity technique. Although their orbits are well known, not much is learned about the planets themselves. This is very different when the orientation of a planet is such that it transits its host star, regularly blocking off a fraction of the star light. For these planets, the mass, radius and average density can be determined, and their atmospheres probed through secondary eclipse photometry and transmission spectroscopy.

Together with Albrecht (PhD), de Mooij (PhD) and Le Poole, the first detection of the atmosphere of the famous transiting exoplanet HD209458b from the ground was presented. Archival Subaru data were reanalyzed to reveal sodium in its transmission spectrum. Furthermore, the planet found by Leiden students was confirmed using the VLT and turned out to have 4.5 Jupiter mass and to be the first discovered around a hot fast rotating main sequence star. De Mooij and Snellen presented the first ground-based K-band detection of the secondary eclipse of an extrasolar planet. Together with Albrecht they published in Nature the optical phase curve of an extrasolar planet using CoRoT data (see front cover).

Albrecht lead a study using the Rossiter-McLaughlin effect which reveals the spin-orbital alignment in two binary star systems, a technique also used for transiting extrasolar planets (Fig. 3.32). Through another publication in Nature, they reveal that in one system, DI Herc, the orbital plane and spin-axis are strongly misaligned, which solves a 20 year old mystery about the slow apsidal motion for this binary star system.

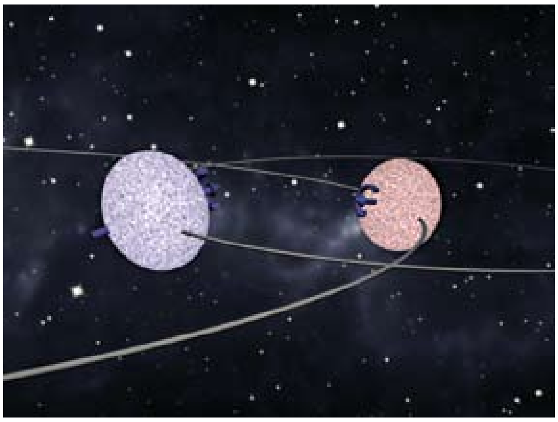


Figure 3.32: Artist impression of the peculiar stellar binary DI Herculis. Its very slow apsidal motion was once considered to be in discrepancy with Einstein's theory. However, Albrecht et al. (2009, Nature, 461, 373) show that it is due to the rotation axes of the two stars being tipped over on their sides with respect to the orbital plane.

3.2.10. Formation and evolution of massive stars

3.2.10.1. Clustered star formation

One of the crucial aspects of star formation is why stars are formed in clusters, even in the outskirts of our Milky Way where ISM conditions like density, pressure, metallicity and cosmic ray flux are expected to decrease as we move out from the Galactic centre. This may result in fewer cloud-cloud collisions,

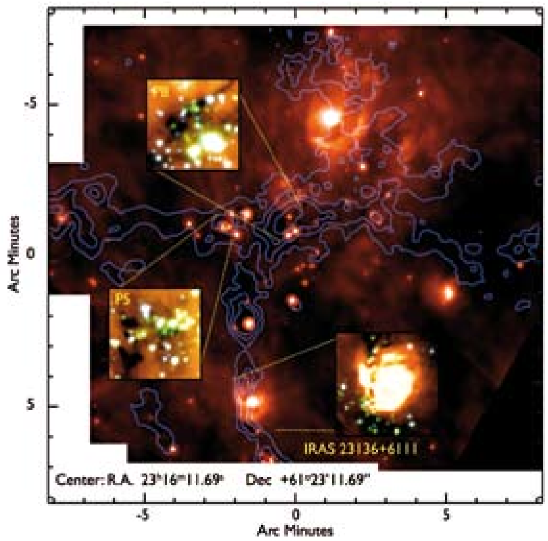


Figure 3.33: Clustered star formation in the dense and massive molecular cloud G111 in the outer Galaxy. Blue contours represent emission from $C^{18}O$, tracing the column density. The red color scaling shows the 24 micron emission as observed with the multi-band imaging photometer onboard Spitzer. Infrared array camera (IRAC) Spitzer images are included as 4-color blow-ups (from: Frieswijk et al. 2008, ApJ, 685, L51).

changes in energy balance and variation in the initial star-forming conditions. Hence, stars may form slower, with lower efficiency and the stellar mass spectrum may deviate from a standard IMF at large Galacto-centric radii.

A key question of high-mass star formation is the link to the formation of stellar clusters. Van der Tak participated in two studies of high-mass star formation which consider different scales of the problem: (1) Mapping of molecular line emission toward the IRAS 18151 region with the IRAM 30m telescope shows significant differences in outflow activity and molecular abundances on 10000 AU scales. Increased outflow activity leads to brighter mid-infrared emission during high-mass protostellar evolution, as material is increasingly asymmetrically distributed. This evolution is accompanied by decreasing N_2H^+ and increasing CS abundances; the abundance ratio of these molecules is proposed as evolutionary tracer. (2) High-resolution imaging of dust continuum and SO_2 and SiO line emission toward the W3 IRS5 region with the IRAM interferometer reveals an extremely high density towards its core, suggesting that protostellar coagulation may play a role. The central five massive protostars drive SiO outflows, while the SO_2 data show signatures of converging flows as predicted by 'gravoturbulent' star formation theories. The data thus strongly indicate that the clustered environment has a major influence on the formation of high-mass stars.

Frieswijk (PhD), Shipman and Spaans have used the Spitzer Space Telescope and ground-based sub-millimeter observatories to investigate these aspects for the dense molecular cloud G111 in the outer Galaxy (Fig. 3.33). Objects like G111, often observed in mid-IR extinction toward the inner Galaxy, are believed to represent the earliest observable stages of clustered star formation. Very few of these young stages are known so far in the quiescent regions of the Galaxy outside the solar circle. Bright point-like sources near the dense molecular cores have been found and identified as very young (massive) stars. These data confirm the presence of early stage clustered star formation in G111 for the first time.

Van der Wiel (PhD), Shipman and Spaans have obtained Spitzer IRAC and MIPS data, which has resulted in the identification of a number of newly born stars associated with a so-called infrared dark cloud. The filamentary dark cloud structure is thought to form dense clumps, collapsing under the force of gravity, thereby continuously forming new stars. Complemented by ground-based near-infrared and sub-millimeter observations, the Spitzer data were used to classify the young stars according to their evolutionary stage and mass. Surprisingly, only young stars with masses less than ~7 solar masses were found in IRDC G048.65.

3.2.10.2. Methanol lasers in high mass star formation regions

Torstensson (PhD) and Van Langevelde studied methanol masers associated with high mass star formation. In collaboration with Vlemmings (Bonn) new results were obtained on the nearest high mass star forming region Cep A, which is taken as the archetypical source in the sample. The methanol masers that straddle the waist of Cep A are interpreted to outline a large scale ring structure perpendicular to the outflow axis of the central source. Remarkably, the velocity field does not show a rotation signature, but seems to be dominated by a radial motion. Similar results were also obtained in EVN studies of a larger sample in a collaboration with the group in Torun, Poland. It could be hypothesized that the ring outlines an accretion shock, where in-falling gas hits the accretion disk. Polarization observations of the same transition indicate that the dynamics of the methanol region are dominated by magnetic fields, which has important implications for high mass star formation.

With van der Tak, the same team also carried out an analysis of JCMT-HARP data with the objective to derive temperatures and column densities of the associated thermal methanol gas. The methanol is clearly associated with the central source in this famous HII region and the derived temperature peaks at the location where the maser is found. Methanol is believed to be a short-lived species in the gas phase, requiring a shock process or ther-

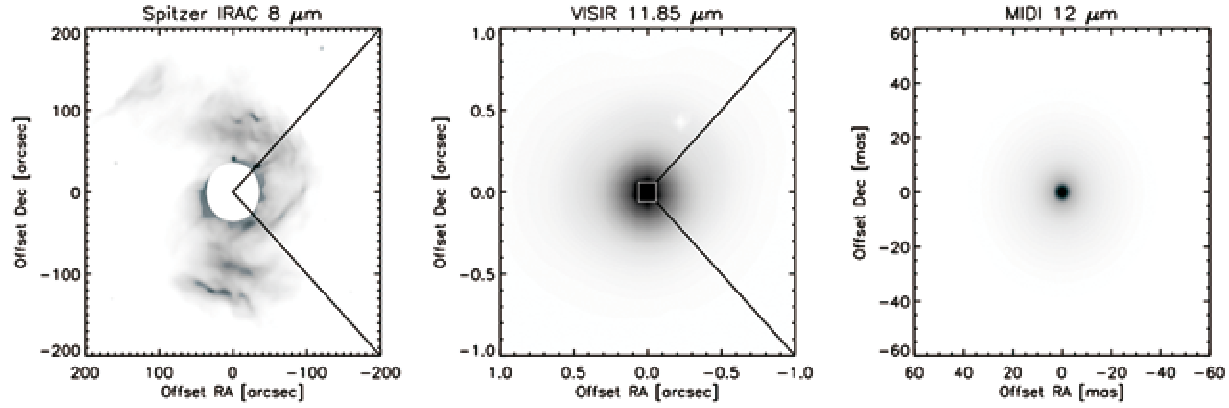


Figure 3.34: Zoom, from left to right, into the center of the nearby young massive B[e] star MWC 297, which is found to be rotating at a velocity that exceeds the critical velocity of the star. Left: Spitzer IRAC image at 8 µm. Clearly visible is a complex, large-scale cloud structure. A numerical circular mask covers the saturated part of the image. Middle: VISIR image at 11.85 µm, zooming-in at the center of the Spitzer image. The image is seeing-limited, but in terms of extension is significantly larger than that of calibrator sources. Right: interferometric image at 12 µm, zooming-in at the center of the VISIR image. The grey scale in the three images is linear (from: Acke et al. 2008, A&A, 485, 209)

mal heating to be released from interstellar grains. The data show a large scale outflow from the central source where also the masers reside, consistent with the masers arising close to the place where the methanol is released.

3.2.10.3. **MWC 297**

Acke, Waters, de Koter and co-workers studied the nature of the nearby young massive B[e] star MWC 297. In particular, the geometrical structure of the circumstellar material that is responsible for the near- to mid-infrared flux excess was probed with VLTI-AMBER and MIDI (Fig. 3.34). The authors argue that the circumstellar matter in the MWC 297 system is organized in a circumstellar disk, seen under moderate inclination. The low inclination of the disk implies that the already high projected rotational velocity of the star corresponds to an actual rotational velocity that exceeds the critical velocity of the star. This result shows that stars can obtain such high rotation rates already at birth.

3.2.10.4. **Hydrogen line ratios in B[e] stars**

The observed line flux ratio Hu-14/Br-α and Hu-14/Pf-γ from different types of objects associated with circumstellar material, such as Be stars, B[e] stars, and Luminous Blue Variable (LBV) stars are known to be well separated in a diagnostic diagram. This diagnostic is thus a tool to constrain the spatial distribution and physical condition of circumstellar material around hot massive stars. Jones (Ontario), de Koter and collaborators investigate this diagnostic tool theoretically, using a non-LTE gaseous disk model. The focus in on Be discs. Good agreement between the empirical and predicted locations of Be stars is found showing that indeed this diagnostic tool can be used to constrain basic properties of the disks of these stars, notably their spatial structure.

3.2.10.5. **Massive binary stars**

Massive stars in clusters and OB associations have a high degree of multiplicity. Yet, the exact binary frequency and whether it is universal or changing with the environment remain poorly constrain. Sana (PhD) and collaborators engaged in detailed multi-epoch spectroscopy of the massive star population of nearby young open clusters, with a focus on NGC 6611 at the core of the Eagle nebula. Using a much more extended data set than previously available, the spectral classification and multiplicity status of the O-type stars in NGC 6611 was revised. Though the minimal binary fraction in the sample is 44% it could be as high as 67% if all the binary candidates are confirmed. With 75% of the O star population in NGC 6611 being part of an O+OB system, this implicitly excludes random pairing from a classical IMF as a process to describe the companion association in massive binaries. The present study provides further quantitative constraints on the formation and early dynamical evolution of massive stars through three diagnostics: binary fraction, period-eccentricity diagram and mass-ratio distribution.

Together with Kouwenhoven (former PhD, now at Kavli Beijing), Goodwin (Sheffield), Kaper, and Portegies Zwart, Brown studied several commonly used modeling methods to pair individual stars into binary systems, so-called pairing functions. These pairing functions are frequently used by observers and computational astronomers, either for their mathematical convenience, or because they roughly describe the expected outcome of the star-forming process. It was found that the observed binary fraction and mass ratio distribution generally depend strongly on the range in primary spectral type used to select a sample. The mass ratio distribution and binary fraction derived from a binarity survey among a mass-limited sample of targets is thus not representative for the population as a whole. It was also concluded that neither theory nor observations indicate that random pairing of binary components from the mass distribution, the simplest pairing function, is realistic. It is more likely that companion stars are formed in a disc around a star or that a pre-binary core fragments into two binary components.

Williams, Gies, Kaper and collaborators performed an optical spectroscopic investigation of the massive binary system [L72] LH 54-425 in the LH 54 OB association in the Large Magellanic Cloud. They revise the ephemeris of [L72] LH 54-425 and find an orbital period of 2.24741 ± 0.00004 days and spectral types of O3 V for the primary and O5 V for the secondary. They obtain a combined solution of the radial velocities and previously published V-band photometry to determine the inclination for two system configurations, $i=52^{\circ}{}^{+2^{\circ}}_{-3^{\circ}}$ for the configuration of the secondary star being more tidally distorted and $i=55\pm1^{\circ}$ for the primary as the more tidally distorted star. They argue that the latter case is more probable, and this solution yields masses and radii of $M_1=47\pm2\ M_\odot$ and $R_1=11.4\pm0.1\ R_\odot$ for the primary, and $M_2=28\pm1\ M_\odot$ and $R_2=8.1\pm0.1\ R_\odot$ for the secondary. Their analysis places LH 54-425 among the most massive stars known. Based on the position of the two stars plotted on a theoretical HR diagram, they determine the age of the system to be 1.5 Myr.

3.2.11. Spectroscopy and modeling of massive stars

The VLT Flames survey is an ESO large program to derive the properties of early-type massive stars in the local universe in order to better understand the role of mass loss, rotation and chemical composition in the evolution of these stars. An overview of the results of the project, in which over 800 high-quality spectra were gathered and analyzed, are given by Evans (Edinburgh), de Koter, Mokiem, and co-workers.

An important focus was on rotation in B-type stars. Together with Hunter (Belfast)and co-workers, de Koter estimated chemical compositions (of C, N, O, Mg, and Si) of 135 early B-type stars in the LMC with projected rotational velocities up to about 300 km/sec. Evolutionary models, including rotational mixing, have been generated attempting to reproduce these observations by adjusting the overshooting and rotational mixing parameters. These models (Fig 3.35) produce reasonable agreement with about 60% of the core hydrogen burning sample. Interestingly, excluding known binaries, a significant population of highly nitrogen-enriched intrinsic slow rotators is found, incompatible in their models. Furthermore, while fast rotators with enrichments in agreement with the models are found, the observation of a population of evolved fast rotators that are relatively unenriched challenges the concept of rotational mixing. Because of these results a picture

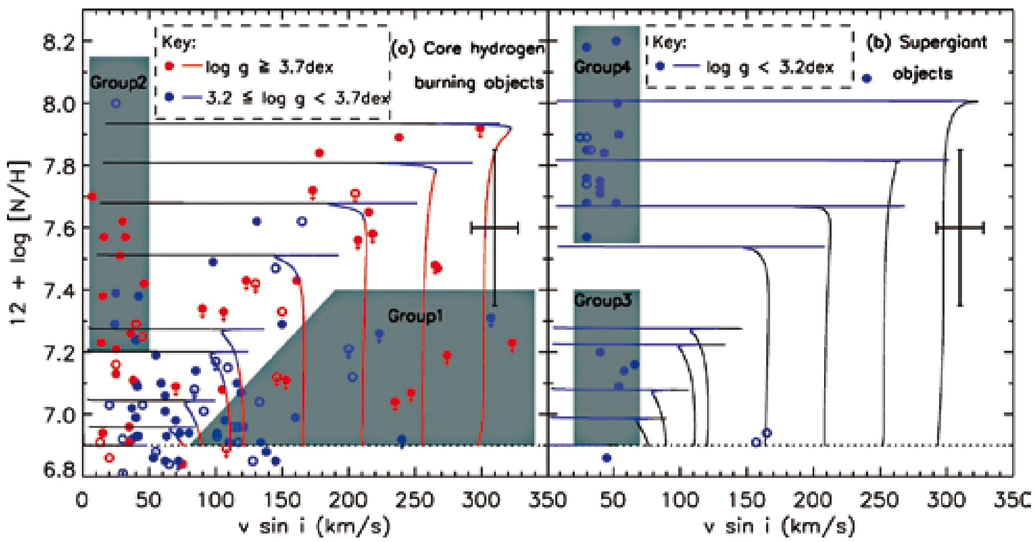


Figure 3.35: **The surface nitrogen abundance of 135 B-type stars in the LMC is plotted against projected rotational velocity. The panel on the left shows main sequence stars; the panel on the right displays post main-sequence stars. The bulk of the core hydrogen burning objects occupy a region at low v sin i and show little or modest nitrogen enrichment. The curves represent predictions of the surface nitrogen enrichment as a function of rotational velocity (assuming random orientation). Surface gravity has been used as an indicator of the evolutionary status and the objects and tracks have been split into red and blue to indicate younger and older stars, respectively. Gray shading in the left panel highlights two groups of stars which remain unexplained by the stellar evolution tracks. In the left panel gray shading highlights the apparent division of the supergiants into two distinct groups. The stars in group 3 are consistent with being in the core hydrogen phase within their uncertainties (from: Hunter et al. 2008, ApJ, 676, L29).**

emerges in which invoking binarity and perhaps fossil magnetic fields is required to understand the surface properties of about 40% of the population of massive main-sequence stars.

Hunter (Belfast), in collaboration with Brott (PhD), Langer, de Koter and others have extended this study to Galactic and SMC metallicities. In the SMC a population of slowly rotating nitrogen-rich stars is found amongst the early B type core-hydrogen burning stars, which is comparable to that found previously in the LMC. High nitrogen abundances in these stars cannot be explained by rotational mixing. In each metallicity regime a population of highly enriched supergiants is observed, which cannot be the immediate descendants of core-hydrogen burning stars. Their abundances are, however, compatible with them having gone through a previous red supergiant phase. Together, these observations paint a complex picture of the nitrogen enrichment in massive main sequence and supergiant stellar atmospheres, where age and binarity have crucial effects. Whether rotational mixing is required to understand these results remains an open question at this time, but could be answered by identifying the true binary fraction in those groups of stars that do not agree with single-star evolutionary models.

Together with Vink and collaborators, de Koter discussed recently reported quasi-sinusoidal modulations in the radio lightcurves of SN 2001ig and SNe 2003bg. They show that both the sinusoidal behavior and the recurrence timescale of these modulations are consistent with the predicted mass-loss behavior of Luminous Blue Variable stars, and propose that LBV stars may be direct supernova progenitors.

3.2.11.1. Formation of intermediate-mass black holes from massive stars

Yungelson, van den Heuvel, Vink, Portegies Zwart and de Koter study the evolution and fate of solar composition super-massive stars in the mass range of 60-1000 $M_\odot$. Though at present it is unclear whether stars initially more massive than about 150-200 $M_\odot$ may actually form, the mechanism of runaway stellar collisions has been proposed to produce super-massive stars. The result of this pilot study is that super-massive stars with initial masses up to 1000 $M_\odot$ end their lives as objects less massive than 150 $M_\odot$ due to excessive mass loss in stellar winds. Such objects are expected to collapse into black holes or explode as pair-instability supernovae. This would imply that if ultraluminous X-ray sources contain black holes of order 1000 $M_\odot$, these are unlikely to be the result of runaway stellar collisions in the cores of young clusters.

3.2.11.2. Sub-surface convection

Cantiello (PhD), Langer, Brott (PhD), de Koter and collaborators studied the occurrence and properties of convection zones in the outer envelopes of hot massive stars. These zones arise due to peaks in the iron opacity. Though only a minor fraction of the envelope mass suffers from this convection, in terms

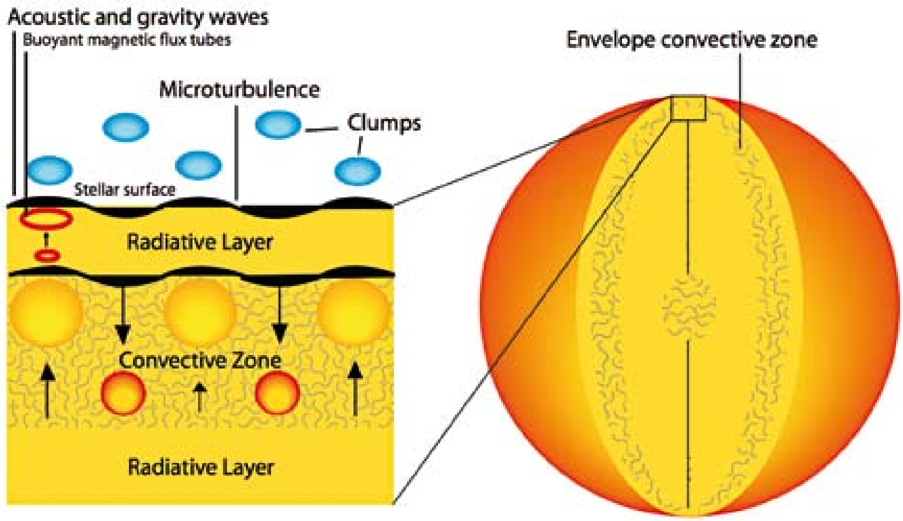


***Figure 3.36*: Schematic representation of the physical processes connected to sub-surface convection in massive stars. Acoustic and gravity waves emitted in the convective zone travel through the radiative layer and reach the surface, inducing density and velocity variations. In this picture microturbulence and clumping at the base of the wind are a consequence of the presence of sub-surface convection. Buoyant magnetic flux tubes produced in the convection zone could rise to the surface (from: Cantiello et al. 2009, A&A, 499, 279).**

of volume a large fraction of the star may be convective (Fig. 3.36). It is found that they are more prominent for lower surface gravity, higher luminosity and higher initial metallicity. Mapping of the strength of the iron convection zone on the HR diagram for Galactic and Magellanic Cloud metallicities reveals that all three trends correlate with the strength of empirical microturbulent velocities in massive star atmospheres. This argues for a physical connection between sub-photospheric convective motions and small scale stochastic velocities in the photosphere of O- and B- type stars. It is suggested that clumping in the inner parts of the winds of these stars could be caused by the same mechanism, and that magnetic fields produced in the iron convection zone could appear at the surface of O- and B-type stars as diagnosed by discrete absorption components in ultraviolet absorption lines.

3.2.11.3. Magnetic fields

Henrichs and Schnerr, in collaboration with Hubrig (ESO), conducted a large survey of magnetic fields of O stars with VLT-FORS1 in polarimetric mode. No new fields were discovered, which showed that strong fields are not very common among these type of hot stars. They also observed five O stars with WSRT to search for non-thermal radio emission, which is considered to be an indirect indicator for the presence of magnetic fields. In three of them such non-thermal emission was indeed detected, which supports further searches for the magnetic fields in O stars, being the progenitors of the strongly magnetized neutron stars. The results of all remaining magnetic measurements of O and B stars observed at the Pic du Midi over the past 8 years have been published with upper limits for all program stars. This work puts strong constraints on the maximum value of the field strengths.

3.2.12. Late stages of stellar evolution

3.2.12.1. Magnetic fields in the outflow of evolved stars

Amiri (PhD) worked with Van Langevelde and Vlemmings (Bonn) on the role of magnetic fields in structuring the outflow of evolved stars that are in transition to become a planetary nebula. MERLIN observations of the OH maser in the water fountain source W43A reveal circular polarization. When interpreted as the Zeeman effect, the measured magnetic field is 100 micro Gauss. This is consistent with the previous estimate of 70 mG extrapolated from water maser polarization observations. Together these measurements seem to confirm that magnetic fields play an important role in shaping the circumstellar material in the transition to planetary nebulae. New observations were made targeting more obscured OH/IR stars in order to determine the role of the magnetic field with increasing mass-loss rate.

3.2.12.2. Geometry of post-AGB stars

Verhoelst (Leuven) and collaborators (including Waters and Verhoeff) measured the spatial and spectral structure of the proto-planetary nebula IRAS16342-3814 using VLT-VISIR. This bi-polar nebula has collimated high velocity jets that are shaping the nebula. The mid-IR images and spectra show that even at these wavelengths the dense equatorial regions are opaque to the radiation of the central star. The nebula can best be described as the result of a roughly spherically symmetric AGB mass loss phase (on the scale that can be probed with the observations) in which the precessing jets are causing the bi-polar appearance.

3.2.12.3. Mineralogy of disks around binary post-AGB stars

Gielen (PhD Leuven), Min, Waters and co-workers have investigated the mineralogy and dust processing in the circumbinary disks of binary post-AGB stars using high-resolution TIMMI2 and Spitzer infrared spectra. They performed a full spectral fitting to the infrared data allowing for the identification of the carriers of the different emission bands. It is found that in all but one stars the dust is oxygen-rich: amorphous and crystalline silicate dust species prevail. The exception to this is EP Lyr, where a mixed chemistry of both oxygen- and carbon-rich species is found. A high degree of dust grain processing is found; the grains are large and highly crystalline. Temperature estimates from our fitting routine show that a significant fraction of grains must be cool, significantly cooler than the glass temperature. This, together with the high degree of crystallinity, shows that radial mixing is very efficient in these disks and/or indicates different thermal conditions at grain formation. This study clearly shows that strong grain processing is not limited to young stellar objects and that the physical processes occurring in the disks around post-AGB stars are very similar to those around YSOs.

In a further step, Gielen and collaborators (including Min, Waters and Dominik) studied the thermal infrared spectrum of two binary-post-AGB stars. Both objects show peculiar spectral bands in spectra taken with Spitzer, in particular prominent emission bands from CO_2 and its isotopologues. This emission comes from the gas in the circum-binary disk which has a oxygen-rich chemistry. The overall spectral shape can be modeled using a passively heated disk surrounding the system, in which settling is taking place. EP Lyr shows emission from

PAHs classified as 'C-type', which is rarely detected. The mixed chemistry of EP Lyr (both silicates and PAHs) suggests an evolutionary link with the J-type carbon stars.

3.2.12.4. **Winds from evolved stars**

The nuclear reactions in stellar interiors turn light elements (H, He) into heavier ones (C, N, O, ...) and these products are returned to the interstellar medium near the end of the stellar lifetime. The strong stellar winds in the AGB phase are the dominant channel for this enrichment of the ambient ISM by stellar reaction products. The chemical composition of these winds is not well know though, particularly the dominant oxygen carrier, because major species cannot be observed from the ground. Polehampton (RAL) and collaborators (including Van der Tak) have analyzed the ISO-LWS spectrum of the late-type supergiant VY CMa and found thousands of H_2O lines arising from up to 3000 K above the ground state. The spectrum also shows lines of CO and other molecules, and comparison to model calculations shows that H_2O is at least 10 times more abundant than CO in the wind, and thus dominates the oxygen budget. Follow-up studies with Herschel are ongoing.

Decin, de Koter and collaborators studied the unusual Mira variable R Hydrae. This star is well known for its declining period between AD 1770 and 1950, which may possibly be attributed to a recent thermal pulse. The molecular lines of the CO molecule bear evidence of a change in mass-loss rate some 220 years ago. While the mass loss before AD 1770 is estimated at about $2 \times 10^{-7}\ M_\odot$ per year, the present day mass-loss rate is a factor of 20 lower. This gives empirical evidence to the thermal-pulse model, which is capable of explaining both the period evolution and the mass-loss history of R Hydrae. The star VY Canis Majoris is in the same evolutionary stage as R Hydrae and also shows a time dependent mass-loss rate. Decin, de Koter, Waters and coworkers showed that the star underwent a phase of high mass loss some 1000 years ago, lasting some 100 years, followed by a period of relatively low mass loss taking some 800 years. The current mass loss of VY CMa is again high. This behavior is also in support of the thermal-pulse model.

3.2.13. The Sun

3.2.13.1. **Convective collapse in the Sun**

Fischer (PhD student) and Keller together with de Wijn, Centeno and Lites (all at High Altitude Observatory, USA) observed the convective collapse, a theoretically predicted process that intensifies existing weak magnetic fields in the solar atmosphere. It was first directly observed in a single event by Nagata et al. using the high resolution Solar Optical Telescope (SOT) of the Hinode satellite. Using the same space telescope, they observed 49 such events and presented a statistical analysis of convective collapse events. Their data sets allowed them to study the implication of convective collapse events on the high photospheric and the chromospheric layers. They found that in all cases, the event was accompanied by a continuum bright point and nearly always by a brightening in the Ca II H images. The magnesium dopplergram exhibits a strong downflow in about three quarters of the events that took place within the field of view of the magnesium dopplergram. They found event durations of about 10 minutes, magnetic element radii of about 0.43 arcsec and 0.35 arcsec, before and after the event, respectively, and field strengths of up to 1.65 kG.

3.2.14. The interstellar medium in external galaxies

3.2.14.1. **Effects of black hole radiation onto the ISM in galaxies**

Many galaxies enjoy highly energetic phenomena like starbursts, accreting black holes and powerful jets and outflows. Interstellar gas in galaxies is both the source for, and recipient of, star-formation and black hole feedback processes. This is crucial to the evolution of galaxies through cosmic time. Thus, this is an area in which the interests of NW2 and NW1 meet.

Loenen (PhD), Baan and Spaans have compared observational data of a large sample (more than 100) of active galaxies, bright in the infra-red, to the results of theoretical modeling of the physics and chemistry of the gas. They found that the different stages of star-formation (from early to late times) can be clearly separated. Loenen, Baan and Spaans also found that ambient gas densities in galactic nuclei are high and ultraviolet radiation fields strong, indicative of recent star formation. A large part of the observed sources is found to be in a state where the ongoing star formation has lowered the average gas density, and the gas temperature has increased by the mechanical energy (turbulence) from strong supernova shock waves. This mechanical heating can even dominate over photon heating.

X-ray dominated regions (XDRs) are regions in the ISM where the hard radiation field of an accreting black hole completely determines the temperature and chemical composition of interstellar gas. As such, XDRs are direct manifestations of the supermassive black hole (SMBH) accretion process. Spaans and Meijerink (former PhD, now at Caltech) have studied how X-ray photons from nearby sources heat through photo-ionization and dissociate the gas by UV emission following collisions of H and H_2 with secondary electrons. Fine-structure lines of O and C^+ as well as molecular emissions of, e.g., CO and H_2O provide cooling. In this light, Spaans and Meijerink have computed the growth of SMBHs in the early universe. Interestingly, rotational line emission of CO, as well as fine-structure emission of [O I] and [C II], is produced at high brightness due to the accretion power of the AGN. This radiating gas orbits around the black hole at distances between 100 and 0.1 parsec (light travel time of 300 years to 4 months). Crucially, these lines are observable with ALMA and allow the rise of SMBHs as the absolute power houses of the universe to be probed and understood.

Pérez-Beaupuits (NOVA PhD), Spaans, Van der Tak, and others have completed a study of the dense molecular gas in the active nucleus of NGC 1068. Comparing JCMT observations of mid-J CN, HCN, HNC and HCO^+ lines to models of collisional and radiative excitation, they show that most line emission originates in the dense warm gas close to the nucleus. Only the HCO^+ 1-0 line is dominated by the more extended, less dense and colder gas in the starburst ring. Previous controversies about the domination of starbursts or AGN to this prototypical galaxy are now resolved: the starburst dominates on larger scales, whereas the AGN influence becomes dominant when approaching the nucleus.

Van der Tak, in collaboration with Aalto (Onsala) and Meijerink (Berkeley), have made the first detection of H_3O^+ line emission outside our Galaxy. Using the JCMT, they observed the 364 GHz line towards the starburst galaxy M82 and the ultraluminous merger Arp 220. Comparison with models of the chemistry of irradiated molecular gas shows that the high ionization in M82 is due to a combination of UV radiation and cosmic rays, as expected for an evolved starburst, whereas in Arp 220, the ionization is likely due to X-rays. The X-rays from a central AGN are unlikely to escape from the highly obscured nucleus, but a distributed source of X-rays from a young starburst seems plausible. Follow-up work is being done with the JCMT and SMA telescopes.

3.2.14.2. H_2 formation on grains in the early universe

Many molecules are formed on dust grains. In particular, the most abundant molecule in the universe, H_2, is formed this way through physi-chemical processes aided by quantum-mechanical tunneling. Cazaux and Spaans have studied the properties of dust grains, like temperature and size, in the early universe. They investigated how H_2 and HD can be formed on the very first cosmic dust grains, when the universe was less than a billion years old, just after the very first stars ended their lives. On these grains, H_2 is formed much faster than in the gas phase, facilitating the efficient formation of lower mass stars like the Sun and thus aides the population III to population II transition. Interestingly, the presence of dust grains allows H_2 and HD formation to impact the chemical balance of high redshift clouds already for a metallicity of only 10^{-5} of solar.

3.2.14.3. Fragmentation and the initial mass function

In the study of star formation it is fundamental to understand the origin of the initial mass function (IMF). In the Milky Way, the IMF appears to have a 'universal' shape. It is as yet unclear whether this also applies to environments with vastly different ambient conditions, like starbursts, dwarf galaxies or the early universe. Properties of candidate stars, forming out of molecular clouds, depend on the conditions of the parent cloud. Feedback effects from mechanical processes (turbulence, outflows, shocks) due to stars and accreting black holes, and initial chemical abundances, affect the thermodynamic properties of gas, which in turn influence the fragmentation process of molecular clouds. It is thus crucial to understand the nature of run-away

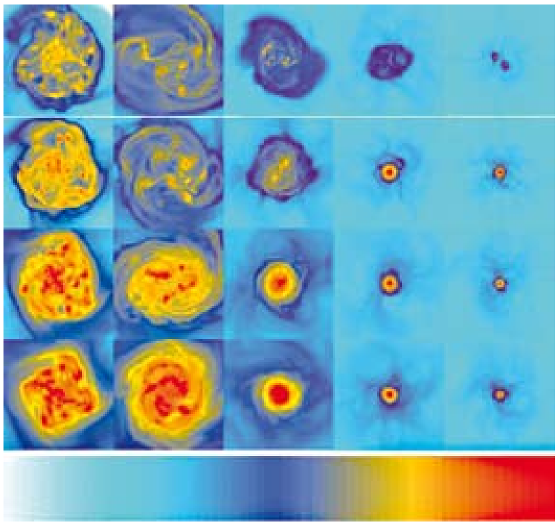


Figure 3.37: Numerical simulations of binary star formation. Time is from left to right, rotation decreases from top to bottom. Simulations with high angular momentum in the parental cloud lead to binaries, while low angular momentum systems allow single stars to be formed (from: Hocuk & Spaans, 2010, A&A, 510, 110).

gravitational collapse in the presence of feedback processes.

Hocuk (PhD) and Spaans have performed hydrodynamical simulations which show that metallicity and rotational moment are crucial to the fragmentation of molecular clouds in starburst and dwarf galaxies (Fig. 3.37). Cosmic rays produced by supernova explosions and gas-grain collisional heating may suppress fragmentation and lead to the formation of very massive stars, ~10 times the mass of the Sun, due to a strong increase in the ambient Jeans mass for gravitational instability. Also, local gas dispersions driven by stellar outflows have a negative impact on the fragmentation level. Indeed, this unambiguously confirms that mechanical feedback influences the evolution of molecular clouds strongly and shapes the (upper end of the) IMF.

3.2.15. Laboratory studies

3.2.15.1. Light Scattering and properties of dust in space

The atmospheres of (exo)planets and moons, as well as many nebulae, contain in general independently scattering particles in random orientation. In model computations such media are often assumed to be (locally) plane-parallel. The radiation coming from a distant source, like the Sun or a star, can be scattered many times by the particles inside the medium before leaving it at the top. The directional distribution of this reflected radiation is usually expressed in terms of the so-called reflection function. Hovenier and Stam developed a variety of relations for the reflection function when the directions of incidence and reflection both tend to horizontal directions. These relations are quite general and may be applied, for example, for interpreting photo-polarimetric observations of regions near the intensity poles of a celestial body surrounded by an atmosphere.

Cosmic particles are defined as all particles located outside the Earth. Two types of cosmic particles can be distinguished, namely liquid and solid particles. Liquid particles may occur, for instance, in the form of clouds, hazes, fog and rain in the atmospheres of (exo)planets and satellites. These particles are (nearly) spherical so that their scattering and absorption properties can easily be computed with Mie theory. Solid particles are also called cosmic dust particles and occur in numerous astronomical objects and environments, such as comets, the interplanetary medium, circumstellar disks and the interstellar medium. These particles are often far from spherical. Hovenier and Min (VENI) wrote an invited review of light scattering by cosmic particles with emphasis on modern experimental and computational methods to determine their scattering properties. Key areas for further research were also pointed out.

Dust from the surface of Mars is regularly swept up by winds and then becomes suspended in the atmosphere, sometimes covering the whole planet. These airborne dust particles scatter and absorb solar radiation and are, therefore, very important for the thermal structure of the thin Martian atmosphere. The material palagonite is believed to be a reasonable analog for the Martian dust particles. Results of measurements of light scattering by randomly oriented palagonite particles at 632.8 nm were reported by Laan, Volten (PD), Stam, Munoz (PD), Hovenier and Roush. From these data a normalized synthetic scattering matrix covering the entire scattering angle range from 0 to 180 degrees was constructed. This matrix can be used, not only for Mars, but also for other dusty media, like circumstellar disks. It also provides the necessary input for computations of multiple scattering.

The detection of the first rocky exoplanets has fueled the quest for signs of habitability. Climate plays a key role in this respect. The detection of clouds on an exoplanet and especially the characterization of their physical properties will provide crucial information on the planet's climate and surface conditions, and hence on its habitability. Karalidi (PhD), Stam and Hovenier numerically simulated flux and polarization signals for Earth-like exoplanets covered with liquid water clouds. Such clouds may indicate the presence of liquid surface water, which is widely considered to be an important factor for the presence of life. First results of this investigation show the advantages of polarimetry, compared to photometry, for the characterization of water clouds on exoplanets.

Hovenier and Munoz (PD) studied the information that can be obtained by analyzing the intensity and polarization of light scattered in the visible part of the spectrum by particles in the atmospheres of (exo)planets, satellites, comets, asteroids and planetary rings, as well as interplanetary dust particles. Both experimental and numerical approaches were investigated. It was shown that the nature of atmospheric particles can now be determined not only for spherical particles, but also for many kinds of non-spherical particles. Good arguments were found to ascribe the linear polarization of comets to a mixture of aggregates and compact particles, instead of aggregates only. Current theories for reflection by particulate surfaces, as on Mars and atmosphere-less planets, satellites and asteroids were shown to be still unsatisfactory, but the expected increase in computer capabilities will probably provide a major improvement in the near future by directly solving Maxwell's equations for such media.

In order to deduce properties of dust in astrophysical environments where dust growth through aggregation is high, knowledge of the way aggregated particles interact with radiation is needed. For this purpose Min et al. have studied the interaction of light with inhomogeneous aggregates consisting of highly irregularly shaped constituents. The initial step taken is to numerically compute the optical properties. In addition, an empirical recipe to compute the optical properties of such aggregates in a fast and accurate manner is derived. Min et al. also computed the spectral structure of the emission efficiency in the 10 micron region for aggregates composed of carbonaceous and silicate materials (Fig. 3.38). It is found that the spectral appearance of the various components of the aggregate is very different and depends on its abundances. Most notably, materials that have a very low abundance appear spectroscopically as if they were in very small grains, while more abundant materials appear spectroscopically to reside in larger grains. The new empirical method incorporates all these effects and is fast enough to be easily implemented in fitting procedures trying to deduce the dust characteristics from astronomical observations.

Figure 3.38**: Model of a chemically inhomogeneous aggregate dust particle for which the optical properties have been calculated (from: Min et al. 2008, A&A, 486, 779).**

3.2.15.2. **Photodissociation and origin of small carbonaceous molecules in PDRs**

Van Dishoeck and van Hemert (Chemistry) have carried out ab initio quantum chemical calculations of the vertical excitation energies, transition dipole moments and oscillator strengths for a number of astrophysically relevant carbonaceous molecules: C_3, C_4, C_2H, l- and c- C_3H, l- and c- C_3H_2, HC_3H, l-C_4H and l- C_5H. The resulting photodissociation rates are large, typically an order of magnitude more rapid than found for other small hydrides. This implies that the small carbonaceous molecules observed in photon-dominated regions most likely result from fragmentation of larger molecules rather than synthesis from smaller species.

3.2.15.3. **Interstellar and circumstellar ice analogues**

It has become clear in recent years that many of the saturated complex organic molecules such as dimethylether (CH_3OCH_3) and ethylene glycol $(CH_2OH)_2$ observed in star-forming regions must be formed in the ices rather than in the gas phase. A major line of research in the Sackler Laboratory for Astrophysics, led by Linnartz and in collaboration with van Dishoeck, is to simulate and quantify these processes in the laboratory and extrapolate the results to interstellar conditions for inclusion astrochemical models.

3.2.15.4. **Atom bombardment of ices**

Tielens and Hagen postulated more than 25 years ago that the dominant molecules formed on the grains are those resulting from hydrogenation and oxidation of the main species to be accreted from the gas, i.e., O, C, N and CO. The resulting species, H_2O, CH_4, NH_3, H_2CO and CH_3OH, are indeed the main molecules observed in the ices with ISO and Spitzer, but their formation routes have never been quantified. Using the new SURFRESIDE (SURFace REactions SImulation Device) set-up, several solid state reaction schemes have been studied in detail by Ioppolo (NOVA PhD), Bisschop (NOVA PhD), Cuppen (VENI), Fuchs (NOVA PD) and Romanzin (NOVA PD). In particular, the formation of H_2CO and CH_3OH through subsequent hydrogenation reactions of CO ice has been confirmed down to 10 K.

In a typical experiment, a pure CO ice is grown under ultra high vacuum (UHV) conditions with monolayer precision at thicknesses of 1 to 100 monolayers by exposing a cold temperature controlled substrate to a steady flow of CO. The ice is subsequently bombarded by H-atoms that originate from a special H_2 thermal cracker source. A sensitive surface analytical technique – RAIRS (reflection absorption infrared spectroscopy) – is used to provide time resolved information about the destruction (i.e. use-up) of the CO precursor ice and the simultaneous formation of the new molecules, H_2CO and CH_3OH, yielding reaction rates and yields. The experimental data are used by Cuppen to derive energy barriers by fitting Monte Carlo simulations to the laboratory results. Finally, the formation of new molecules in the ice is also confirmed by TPD (Temperature Programmed Desorption), a method in which the ice is heated in a controlled way and ice components are detected mass spectrometrically. The combined outcome of experimental and modelling work shows that surface hydrogenation of CO ice can now be safely used to explain the observed abundance of methanol in the interstellar medium.

3.2.15.5. UV-photoprocessing of ices

Another way to form larger species is through UV processing of ice samples on CRYOPAD (CRYogenic Photoproduct Analysis Device). This has been experimentally realized by Öberg (PhD) and Fayolle (NOVA PhD) by irradiating ices with the output of a broadband hydrogen-microwave discharge lamp. This lamp simulates the cosmic-ray induced interstellar radiation field, peaks around 121 nm (Lyα) and covers the 115 to 170 nm (~7.5-10.5 eV) with a variable photon flux covering roughly (1-10)x10^{13} photons per cm^2 per sec at the substrate surface. The resulting ice behavior is monitored using RAIRS to identify (changes in) ice constituents and TPD to investigate ice evolution and ice desorption.

A typical experiment is as follows: a precursor gas is deposited for a specific thickness and temperature and the resulting RAIRS spectrum is taken. The signal strength can be converted into a surface density. Upon UV irradiation ice constituents will both photodesorp and photodissociate. The corresponding RAIRS spectrum decreases in intensity, and reflects the use-up of the precursor material. To constrain the photodesorption of the ice and thus determine the loss of precursor molecules into the gas phase rather than into photoproducts in the ice, a special method is used. Photodesorption from a multilayer ice is a zeroth order process with respect to photon fluence, since it only depends on the amount of molecules in the surface layers. The photodesorption yield will not change with fluence as long as the original ice is sufficiently thick. Ice photodissociation, however, is a first order process, since it depends on the total amount of ice. Through simultaneous modelling of the ice loss with an exponential decay and a linear function, the two processes can be separated. The photodesorption yield has been determined for CO, H_2O, D_2O and CH_3OH and is with roughly 10^{-3} molecules per UV photon. For CO, this is two orders of magnitude more effective than assumed so far in astrochemical models and has significant consequences for models of protoplanetary disks where grains have grown to large sizes.

Simultaneously with the decrease in the RAIRS signal for the precursor species, new spectral features may appear that correspond with more complex reaction products. Öberg and collaborators found that during UV irradiation of CH_3OH-rich ices, the hot core molecules $HCOOCH_3$, CH_3OCH_3, CH_3CH_2OH and $(CH_2OH)_2$ all form and their formation cross sections have been tabulated between 20–70 K. The formation cross sections display different temperature dependences. The suggested formation mechanism of complex organics is through photodissociation of CH_3OH, followed by diffusion of the radicals, and recombination of the radicals into larger molecules (Fig. 3.39). The chemistry is thus primarily governed by 1) the photodissociation rate of CH_3OH, 2) the photodissociation branching ratio of CH_3OH into CH_2OH, CH_3O and CH_3, and 3) the different diffusion barriers of different radicals. These quantities should not change between the laboratory and astrophysical settings and can thus be used as input in astrochemical models to derive product formation rates and branching ratios appropriate for the ice temperature and UV flux in each astrophysical setting. The combined outcome of the CO hydrogenation and UV methanol photochemistry experiments offers an interesting pathway from simple ice to complex molecules. Once the star starts to heat its surroundings, radicals become mobile, complex ice components are formed and are eventually thermally released into the gas phase.

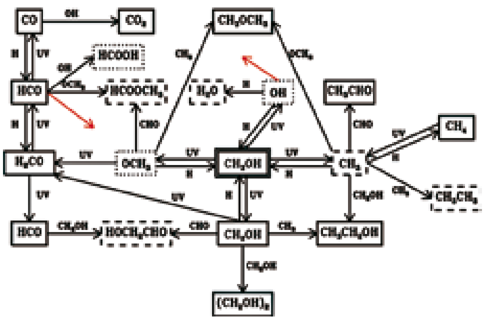


***Figure 3.39*: Proposed reaction scheme to form complex organic molecules following UV-irradiation of pure CH_3OH ice (solid boxes), of CO: or CH4:CH_3OH ice mixtures (dashed boxes) and products whose production could only be constrained with upper limits (dotted boxes) (from: Öberg et al. 2009, A&A, 504, 891).**

3.2.15.6. Photochemistry in complex ices

An important question is how far molecular complexity in ice can go. For this reason Bouwman, Linnartz, Cuppen and Allamandola (NASA Ames, NWO visitor) have been studying ices containing large complex molecules, such as PAHs. These are common throughout the diffuse ISM and condense onto cold icy grain mantles in the dense clouds where they are expected to influence and participate in the ice chemistry. Previous studies have focused on infrared experiments that have the disadvantage of spectral overlap; for different PAH members essentially the same vibrational modes are excited. At visible wavelengths such a problem can be overcome, because electronic energies will be different for different PAH species. Beyond a very limited set of molecules, there is little information on the UV induced, in situ photochemistry and photophysics of PAH containing water rich ices. The new CHESS experiment built by Bouwman offers a unique opportunity to measure the electronic spectra in ices.

A pilot study has been performed on the UV induced photochemistry of the PAH pyrene ($C_{16}H_{10}$ or Py) in a 1:10,000 diluted water ice. Fig. 3.40 shows the 310-500 nm spectrum of the Py:H_2O ice at 10 K after UV photolysis in absorbance mode. Since the spectrum recorded before UV irradiation is taken as reference, bands with positive optical depth values arise from species produced by photolysis while the carriers of negative optical depth bands reflect a density decrease. The spectrum shown is only one snapshot (an averaged spectrum of a few hundred recordings of ~5 ms length). The integrated band intensity can be recorded as a function of time, i.e. as function of fluence, correlating precursor and reaction products and consequently providing insight into possible reaction pathways. Temperature can also be varied. It turns out that ion-mediated processes play a very important role. Py is efficiently converted into Py^+ and the charge remains largely located in the ice, also when the UV photolysis source is switched off. Other products are observed as well illustrating the importance of UV photochemistry in creating more complex species.

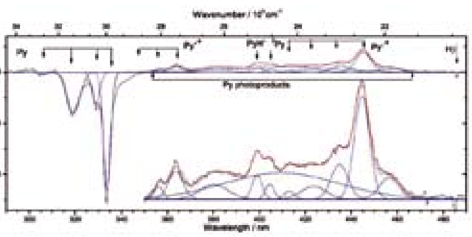


***Figure 3.40*: 310-500 nm spectrum of the Py : H_2O ice at 10 K after UV photolysis in absorbance mode.**

3.2.15.7. Measurements of molecular transients

Wehres (PhD), in collaboration with Linnartz, Tielens and van Winckel (Leuven), has used a special plasma expansion to simulate the physical and chemical conditions in the outflows of the Red Rectangle proto-planetary nebula. A sensitive time-gated fluorescence setup (LEXUS) is used to identify ro-vibronically excited molecular bands for unstable species at low final rotational temperatures. Two narrow emission features, observed on top of an extended red emission, have been assigned for the first time to Swan band transitions of vibrationally excited electronic states of C_2. The laboratory data are used to quantify the physical and chemical processes at different off-sets from the central star.

With the aim to monitor unstable species generated in a plasma expansion, Verbraak has been studying complex ions of astrophysical interest using plasma modulation on SPIRAS. Recently, Guss (NOVA PD) has started the construction of a tunable submillimeter spectrometer on the same set-up in support of HIFI data analysis. Sensitive detection techniques (frequency and plasma modulation as well as cw cavity ring-down) will be used to record complex ions and hydrocarbon radicals in direct absorption.

3.3. Final stages of stellar evolution: physics of neutron stars and black holes

The aim of Network 3 is to study the physics of compact objects (white dwarfs, neutron stars and black holes), including processes related to their formation, such as supernovae and gamma-ray bursts. These compact stellar fossils are important for understanding stellar evolution. In addition, neutron stars contain the densest form of bulk matter known and the equation of state of ultra-dense matter is as yet undetermined. Gravity near neutron stars and black holes is sufficiently strong that general relativistic effects dominate the dynamics, rather than providing small corrections to the classical laws of motion; in this extreme regime the theory of relativity has not yet been tested. The research in Network 3 concentrates on the astrophysics, formation and evolution of compact objects and their host systems by (1) direct observations of compact objects and their surroundings, (2) population studies, and (3) theoretical work on formation and evolution of compact objects and host systems as well as on physical processes near them.

3.3.1. Gamma-ray bursts

3.3.1.1. Gamma-ray burst redshifts and environments

On April 23, 2009, a large international collaboration including Rol (PhD) and Wijers (led by Tanvir, Leicester Univ.) discovered the most distant object in the Universe to date: a gamma-ray burst with a redshift of 8.2 (Fig. 3.41). Its redshift, combined with an age of the Universe of 13.7 Gyr, implies that it occurred only 630 million years after the Big Bang. This, in turn, implies that the process of galaxy formation and star formation in the Universe must have advanced very far already so soon after the Big Bang,

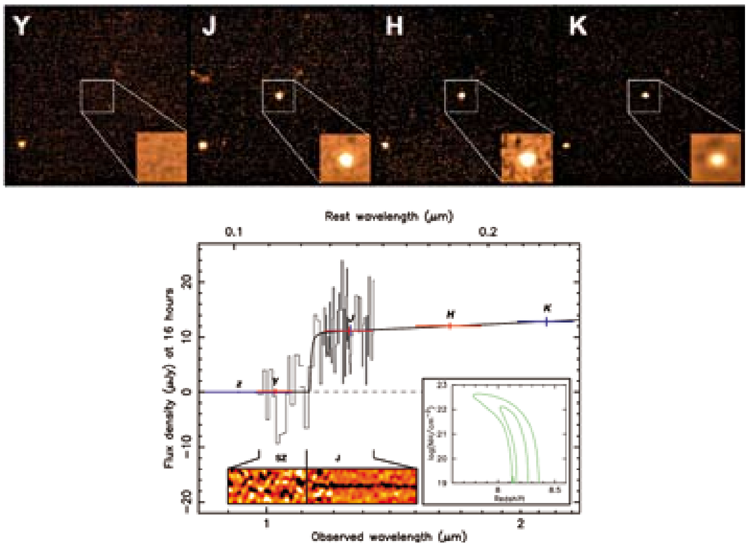


Figure 3.41: Top: multi-band images of the afterglow of GRB 090423. The non-detection in the Y band to deep limits combined with clear detections in J, H, and K was the first indication that the source was at very high redshift. Bottom: the SZ- and J-band 1D and 2D spectra of GRB 090423. In addition the data points obtained with Gemini-N and Gemini-S are shown (from: Tanvir et al. 2009, Nature, 461, 1254).

since the gamma-ray burst signals the explosion of a very massive star. This discovery highlights the current and future potential of GRBs as probes of early stages of structure formation and stellar birth in the Universe.

A detailed study of absorption lines in the afterglow of GRB060206 at z=4.05 by Thoene (Copenhagen), Wijers, and others showed that the interstellar medium in the host is complex, with different components having different ionization states and abundances. This gives rise to some caution in interpreting lower-resolution spectra to deduce the abundances of the progenitor object. It was also shown that the surprising claim by earlier authors of variability in the absorption by intervening galaxy at z=1.48 is contradicted by their data (which have higher S/N and resolution). A detailed study of spectra and photometry of GRB040924 by Wiersema (former PhD, now Leicester), Wijers, and others showed the object to have been a typical long GRB, despite its duration being near the long/short divide: the host galaxy shows [Ne III] emission indicative of very hot stars exciting the ISM, the optical afterglow is typical in shape and energy of a long GRB, and they found a bump in the late light curve consistent with a supernova contribution.

Van der Horst (Huntsville), Rol, Wijers and others re-examined the properties of optically dark GRBs (which are events in which the optical emission is unexpectedly dim given the X-ray flux). They found an improved scheme by which to quickly predict from X-ray data whether an afterglow is of this type, and thus perhaps merits extra investigation to determine the cause of its optical dimness.

Fynbo (Copenhagen), Rol, and others studied a sample of 77 Swift-detected GRBs for which optical spectroscopic follow-up has been secured. They find that no more than 18% of Swift GRBs can be at z>7. However, they also conclude that the sample of Swift bursts with a measured redshift is biased towards brighter bursts on sight-lines with lower than average extinction, so some caution is required in deriving the intrinsic population distribution in redshift from that sample.

Soderberg (Princeton), Rea, and colleagues reported a very bright X-ray outburst in a fairly nearby galaxy with Swift. After initial suspicions that it may be a soft-spectrum GRB, the appearance of a bright supernova at its location after a short time revised this view: the X rays were caused by the shock breakout of an energetic supernova, possibly similar to the first SN-GRB association of SN1998bw/GRB980425. Malesani (Copenhagen), Rol and colleagues also reported the early spectroscopic discovery of a type Ib supernova, 2008D, in the afterglow of this same transient.

3.3.1.2. Theory and observation of GRB light curves

Van Eerten (PhD) and Wijers published their theoretical study of precisely calculated synchrotron afterglows from GRB blast waves. These yield much improved predictions of the light curves of afterglows because the outflow is calculated with a hydro simulation rather than assumed to be a uniform slab of emitting material, and because the synchrotron emission is modeled more accurately. They found that their models fit data well, and yield rather different values for the physical parameters of a given GRB, such as its explosion energy and ambient density, than fits with simplified models. In a follow-up study with Keppens and Meliani (Leuven) they addressed the controversial issue of whether the light curve rebrightens when the blast wave hits a dense layer of gas. It turns out that it does not, and that this is the result of the detailed blast wave structure in such a collision, confirming the need to use good hydrodynamical models in order to derive reliable predictions for the observed behavior of GRB afterglows.

One of the most spectacular gamma-ray bursts to date occurred on March 19, 2008: GRB080319B was at redshift 0.94 (or 8.6 billion light years away), and yet had a peak brightness of magnitude 5.3 (Fig. 3.42). The results on this GRB were reported by an international collaboration including Wijers and Rol. It was thus visible to the naked eye for about 40 seconds. Fortuitously, it was only 10 degrees away in the sky from an event a few hours before, so monitoring cameras caught the radiation right from the start, without slewing delays. As a result, a completely unique data set at wavelengths from gamma rays to radio was assembled, enabling a large collaboration including the Amsterdam GRB group to analyze the physics of this event with unprecedented precision. The extra-ordinary brightness appears to have been due to an extra component of the relativistic jet that was even more narrowly collimated than the normal outflow (opening angle only 0.2°) and having an unusually large Lorentz factor of around 1000. Quite possibly, all GRBs have such a component, because such a narrow component is expected to be aimed at us only about once per decade (and we have now seen one in 12 years of afterglow observations). Otherwise, the event was not unusual: the total energy was around the average of long GRBs.

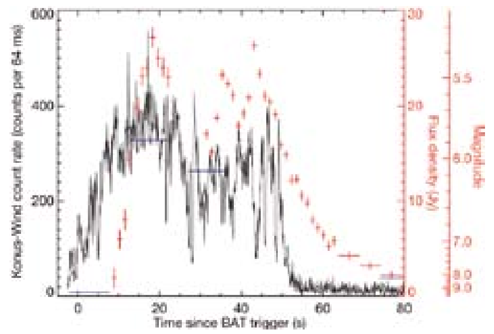


Figure 3.42: The prompt emission light curve of GRB080319B. The black curve shows the Konus-Wind γ-ray light curve, blue the 'Pi of the sky' light curve (white light) and red the TORTORA light curve (V band) (from: Racusin et al. 2009, Nature, 455, 183).

Page (Leicester), Rol, and others published a detailed study of one of the first GRBs to both trigger Fermi and Swift; it was very bright in prompt and afterglow emission and had an unusually high isotropic energy output of $3x10^{53}$ erg, with no evidence of narrow collimation from any jet break in the first 6 days. It has a spectral break between X rays and optical in the afterglow, that evolves in a somewhat puzzling way. In a similar study of GRB080721, Starling (Leicester), Rol and colleagues followed the afterglow until more than a month after the burst, finding no evidence of a jet break. This requires this burst also to have a fairly high true energy and not be too narrowly collimated. Melandri (Liverpool), Rol, and colleagues found that finely tuned late energy injection may be required to explain the peculiar light curve of GRB070419A. Kamble and colleagues found in a detailed analysis of the afterglow of GRB050401 that its puzzling optical to X-ray evolution can be explained if the jet has a very narrow component embedded within the wider and more usually observed jet, similar to the need for a double-jet model in a few other afterglows (such as 030329 and 080319B).

Curran, Wijers, and others analyzed a sample of Swift GRBs for the presence of jet breaks and for the values of the power-law index of the energy distribution of synchrotron electrons. They found that most bursts can be modeled consistently with a simple jetted blast wave model, but that both the electron power-law index and the density distribution around the explosion are quite heterogeneous across the sample.

A study of the radio afterglow of GRB030329 with WSRT and GMRT by Van der Horst, Kamble and others revealed that the afterglow became non-relativistic and uncollimated at about 80 days after the burst. Its energy was quite similar to earlier findings, and the circumburst medium turns out to be uniform at large distance, possibly indicating that the blast wave has exited the region affected by the stellar wind of the progenitor star and is now propagating into undisturbed ISM. Curran and other published a number of studies to improve the analysis of early gamma-ray burst afterglows. The results included a better method to determine the true color and photometric redshift of a burst, and a discussion of late-time flares in the X-ray light curves, which are found to be caused most likely by late re-activations of the GRB central engine. A study of a sample of ten Swift afterglows by Starling, Wijers, and others showed that afterglows occur with similar likelihoods in uniform ambient densities as in fossil stellar winds, showing that their environments are complex and rich in physics. The study also confirmed the earlier finding by the same authors (from pre-Swift bursts) that the particle acceleration mechanism in GRB blast waves varies from burst to burst. A multi-wavelength study of the very bright GRB070125 including WSRT data by Updike (Clemson), Wijers, and others found that this burst was intrinsically fairly energetic and had a well-defined achromatic jet break and a pretty steep energy spectrum of relativistic electrons.

Figure 3.43: The possible X-ray progenitor (left) to the supernova Type Ia source SN2007on (right). The progenitor was detected four years prior to the SN in observations with the Chandra X-ray satellite of the elliptical galaxy NGC1404 (based on: Voss & Nelemans 2008, Nature, 451, 802).

3.3.2. SN-Ia

Nelemans with Voss (MPE) started a program to investigate archival X-ray images of positions of newly found type Ia supernovae in order to search for X-ray signatures or lack thereof from their long sought progenitors. Two classes of progenitor systems are proposed, one accreting (X-ray bright) and one merging (likely X-ray dim). A breakthrough was accomplished with the detection of an X-ray source in archival images of the region of SN2007on in NGC 1404 suggesting an accreting progenitor (Fig. 3.43). Later investigations together with Roelofs (former PhD, now CfA) and Bassa (McGill) showed a slight offset between the best X-ray position and the optical position causing some doubts about the association, although post-SN X-ray observations failed to detect the source. The same collaboration also published interesting upper limits to the X-ray luminosity of the progenitor of SN2007sr in the Antennae galaxies, ruling out some, but not all accreting models.

3.3.3. Supernova remnants

Schure (PhD), Vink, Achterberg and Garcia-Segura (Mexico) performed hydrodynamical simulations of the jets in the young supernova remnant Cassiopeia A. The Cas A explosion may have occurred either when the progenitor star was in the Wolf-Rayet star phase or still in the red super giant phase. The wind structure in both cases was simulated and then a supernova explosion with a jet structure was simulated within this wind configuration. A Wolf-Rayet star phase blows a fast tenuous wind which creates a dense shell, marking the boundary between the Wolf-Rayet star wind and the red supergiant wind. Schure and co-workers found that the jets, which have energies ~10^{48}-10^{49} erg, cannot survive the passage through the dense shell, unless the shell is not very massive. This latter situation corresponds with a Wolf-Rayet star lifetime of 1500-3000 yr. Such a short duration is unlikely given that most Wolf-Rayet star phases last for 10,000-50,000 yr. The conclusion is therefore that the presence of jets in Cas A points either to the formation of a Type Ib supernova without a prior Wolf-Rayet star phase, or the Wolf-Rayet star phase was very short, which could be a result of a common-envelope phase of a binary star, just prior to explosion. Such a common-envelope phase may lead to a brief Wolf-Rayet star phase of the merged stars.

Schure (PhD), Vink, Achterberg and Keppens (Leuven) investigated the evolution and orientation of magnetic fields in supernova remnants using magneto-hydrodynamic simulations. Observations of young supernova remnants show that the magnetic field is radially polarized. While compression of the interstellar magnetic field would leave a preferred tangential component of the magnetic field, stretching of magnetic field lines by the Rayleigh-Taylor instability at the contact discontinuity could explain the preferred radial direction. A high compression ratio at the forward shock is needed to extend the radial polarization signature to the forward shock. They modeled this using the MHD code of the AMRVAC framework.

Kosenko, Vink, Blinnikov (Sternberg Inst. Russia) and Rasmussen (SLAC/Stanford) published a detailed analysis of EPIC-MOS and RGS XMM-Newton observations of the youngest supernova remnant in the Large Magellanic Cloud, 0509-67.5. The RGS spectra show very strong line broadening, with velocities of ~5000 km/s. The X-ray spectra and the images show that the overall emission from iron is low. Type Ia supernovae are expected to produce about 0.5-1 $M_{\odot}$ of iron. However, 0509-67.5 is a young remnant and its reverse shock has not yet heated a substantial part of the iron-rich layers. The study included numerical modeling of the supernova remnant with the SUPREMNA code using Type Ia supernova explosions models as input. The numerical results are in good agreement with the observed properties of 0509-67.5

Vink participated in a gamma-ray study by the HESS collaboration of the supernova remnant RCW 86. RCW 86 is probably the remnant of the oldest historical supernova, SN 185. It is a large object, 40 arcmin. The emission of X-ray synchrotron radiation makes it a promising source of TeV gamma-ray emission. The TeV gamma-ray telescope HESS observed RCW 86 for 38 hr and detected extended gamma-ray emission at the 8.5 sigma level. The source has a flux of 10% of that of the Crab nebula.

Helder (PhD), Vink, Verbunt, Bassa and international collaborators investigated the particle acceleration efficiency of a shock in the RCW 86 supernova remnant. Shocks of supernova remnants are the main candidates for accelerating Galactic cosmic rays. To maintain the Galactic cosmic-ray energy density, they need to convert 10% of their incoming energy into cosmic-ray energy, averaged over their lifetime. This remnant is a TeV gamma-ray source, and this particular shock emits X-ray synchrotron radiation, both signs of active particle acceleration. The efficiency was measured by comparing the kinetic energy of the incoming material with the thermal energy behind the shock front. The former was determined from two epochs of Chandra X-ray observations (Fig. 3.44), which indicate a shock velocity of 6000 ± 2000 km/s. The post-shock temperature was determined by measuring the width of the broad component of the Hα line, which is emitted after charge exchange with hot protons behind the shock front. It appears that, assuming conservation of mass, momentum and energy, the temperature behind the shock front was too low for the shock velocity: without cosmic ray acceleration a temperature of 40-100 keV is expected. The measured post-shock temperature is only 2.2 keV. This difference between expected and actual temperature implies that a large part of the post-shock pressure is provided by cosmic rays, implying a partial pressure in cosmic rays of more than 50% for this shock.

Figure 3.44: Photo montage of Hα emission taken with the VLT/FORS2 instrument (in red) and Chandra X-ray emission (blue) of the northeastern rim of RCW 86. The X-ray emission is dominated by synchrotron radiation. Optical spectroscopy of the Hα filaments indicate a post-shock temperature that is too low for the shock velocity, but is explained by taking into account very efficient particle acceleration (from: Helder et al. 2009, Science 325, 719; Image: ESO/E. Helder & NASA/Chandra).

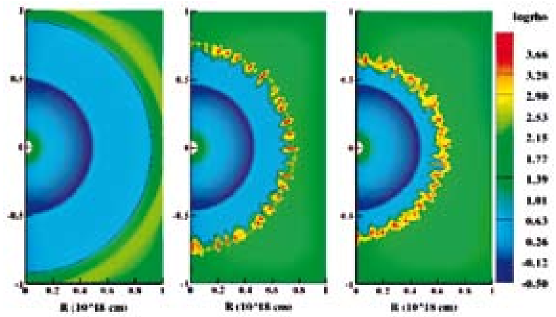


Figure 3.45: The impact of the new cooling curve on hydrodynamic simulations of a circumstellar shell. Left: a circumstellar shell in the absence of cooling. Center: idem, but now using an older cooling curve. Right: idem, using the newly synthesized cooling curve of Schure and co-workers (from: Schure et al. 2009, A&A, 508, 751).

As a by-product of the in-flight calibration of the RGS of XMM-Newton, Kaastra and co-workers used the spectrum of the Crab nebula to determine for the first time accurate abundances of a number of chemical elements in the interstellar medium, because X-rays are able to trace all phases (cold, warm and highly ionized gas; dust). While oxygen and nitrogen show solar abundances, neon is overabundant by a factor of 1.7, supporting recent findings that the solar neon abundance is severely under-estimated.

3.3.4. A new radiative cooling curve based on an up to date plasma emission code

Improvements to the X-ray spectroscopic code SPEX were reported by Kaastra, Werner, Schure, Vink and co-workers. The code now allows to calculate the effects of non-thermal electron distributions on the spectrum, thereby giving a new diagnostic to detect such components in sources like clusters of galaxies, stellar coronae and supernova remnants. Schure, Kosenko, Kaastra, Keppens (Leuven) and Vink produced a new cooling curve based on this SPEX emission package, which they used to calculate radiative cooling rates for a plasma in collisional ionization equilibrium. The new curve predicts higher cooling rates than previously published ones. This can be attributed to the fact that SPEX takes more line transitions into account. Inclusion of radiative cooling can make important differences to the calculation of the evolution of the circumstellar medium (Fig. 3.45). Radiative cooling can cause circumstellar shells to become very thin and hence susceptible to the Vishniac thin shell instability, something that does not appear when cooling is not taken into account.

3.3.5. X-ray binaries

Accreting black holes and neutron stars in X-ray binaries form the brightest X-ray point sources in the sky. Important information about the extreme physical processes related to these compact objects can be obtained by studying the processes around these accreting compact objects.

3.3.5.1. X-ray transients in outburst

Wijnands and co-workers presented an analysis of the Swift Burst Alert Telescope (BAT) and X-ray telescope (XRT) data of GRB060602B, which is most likely an accreting neutron star in a binary system and not a gamma-ray burst. Their analysis showed that the BAT burst spectrum is consistent with a thermonuclear flash (type I X-ray burst) from the surface of an accreting neutron star in a binary system. The X-ray binary nature is further confirmed by the report of a detection of a faint point source at the position of the XRT counterpart of the burst in archival XMM-Newton data approximately six year before the burst and in more recent XMM-Newton data obtained at the end of 2006 September (nearly four months after the burst). They determined that the source is at most at a distance of 6.7 ± 1.3 kpc. For a transiently accreting X-ray binary, its soft X-ray behavior is atypical: its 2-10 keV X-ray luminosity (as measured using the Swift/XRT data) decreased by nearly three orders of magnitude in about 1 day, much faster than what is usually seen for X-ray transients. If the earlier phases of the outburst also evolved this rapidly, then many similar systems might remain undiscovered because the X-rays are difficult to detect and the type I X-ray bursts might be missed by all the sky surveying instruments. This source might be part of a class of very fast transient low-mass X-ray binary systems of which there may be a significant population in our Galaxy.

Degenaar (PhD) and Wijnands report on the spectral analysis of seven X-ray transients, which were found to be active during a monitoring campaign of the Galactic center carried out in 2006 and 2007 using the X-ray telescope aboard the Swift satellite (Fig. 3.46). This campaign detected new outbursts of five known X-ray transients and discovered two new systems. Their 2-10 keV peak luminosities range from 10^{34} to $6x10^{36}$ erg/s, which implies that all seven X-ray transients are subluminous compared to the bright X-ray transients that have peak luminosities of 10^{37-39} erg/s. Two of the sources discussed in this paper are confirmed neutron star systems (AX J1745.6-2901 and GRS 1741-2853), while the five others have an unknown nature. Assuming that those sources are accreting neutron stars and black holes, the authors estimated the time-average accretion rate of the transients, which is an important input parameter for binary evolution models that attempt to explain the nature and origin of these subluminous X-ray transients. Several of the systems have such low estimated mass-accretion rates that they possibly pose a challenge for binary evolution models.

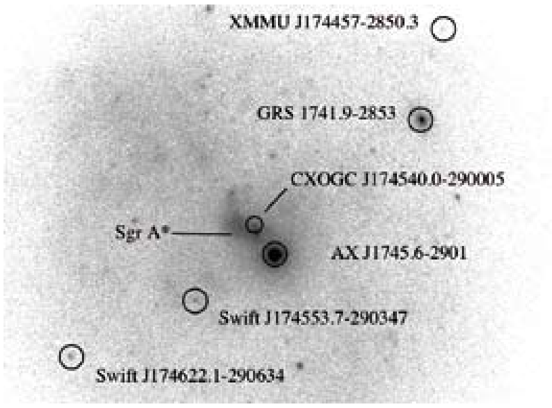


Figure 3.46: Swift X-ray images (0.3-10 keV) of the inner region around Sgr A* using observations carried out in 2006 and 2007. Six of the seven detected X-ray transients are indicated (from: Degenaar & Wijnands 2009, A&A, 495, 547).

3.3.6. X-ray transients in quiescence

Heinke (Alberta), Wijnands and collaborators observed SAX J1808.4-3658, the first accreting millisecond pulsar, in deep quiescence with XMM-Newton. The X-ray spectrum of the source is similar to that observed in quiescence in 2001 and 2006. In the framework of the current theory of neutron star (NS) heating and cooling, the constraints obtained on the thermal luminosity of SAX J1808.4-3658 and another, very similar source, 1H 1905+000, require strongly enhanced cooling in the cores of these NSs. They compiled data from the literature on the mass transfer rates and quiescent thermal flux of the largest possible sample of transient NS low-mass X-ray binaries and identified a thermal component in the quiescent spectrum of the accreting millisecond pulsar IGR J00291+5934, which is consistent with the standard cooling model. The contrast between the cooling rates of IGR J00291+5934 and SAX J1808.4-3658 suggests that the latter may have a significantly larger mass. This can be interpreted as arising from differences in the binary evolution history or initial NS mass in these otherwise similar systems.

In quasi-persistent neutron star transients, long outbursts (lasting years to decades) cause the neutron star crust to be heated out of thermal equilibrium with the rest of the star. During quiescence, the crust then cools back down. Such crustal cooling has been observed (as first reported in 2001 by Wijnands and collaborators) in two quasi-persistent sources: KS 1731-260 and MXB 1659-29. Cackett, Wijnands, Degenaar and collaborators presented an additional Chandra observation of MXB 1659-29 in quiescence, which extends the baseline of monitoring to 6.6 yr after the end of the outburst. This new observation strongly suggests that the crust has thermally relaxed, with the temperature remaining constant over 1000 days.

The quasi-persistent neutron star X-ray transient and eclipsing binary EXO 0748-676 recently started the transition to quiescence following an accretion outburst that lasted more than 24 years. Degenaar, Wijnands and co-workers report on two Chandra and 12 Swift observations performed within five months after the end of the outburst to investigate the cooling of the accretion-heated neutron star crust. From these early data it is already evident that the neutron-star crust in this source cools down significantly slower than what has been observed for other similar sources.

3.3.6.1. Accreting millisecond pulsars

2008 marked the tenth anniversary of the discovery of the accreting millisecond pulsars. Studies of the first known accreting millisecond pulsar SAX J1808.4-3658 (Wijnands and van der Klis 1998) continued apace, with various new contributions by NOVA- and other teams on this prototype system. The total number of scientific papers referring to this object totaled more than 600 by December 2009. A successful international workshop co-sponsored by NOVA and attended by the experts in the field was held in Amsterdam during 2008 to mark this anniversary and discuss the exciting new developments in the field. Two new accreting millisecond pulsars were discovered in 2009, bringing the total number of accreting millisecond pulsars now known to twelve. The discovery during the reporting period of the so-called intermittent pulsations, as well as the relations between accretion and nuclear-burning driven pulsations, both discussed further below, led to very lively scientific debate indeed.

Altamirano and Casella, with Patruno (NOVA PhD), Wijnands and van der Klis obtained several exciting new results in a systematic search for intermittent X-ray periodicities and quasi-periodicities covering more than ten years of observations of X-ray binaries with the Rossi X-ray Timing Explorer. They found a number of intermittent pulsation episodes of the accreting millisecond pulsar SAX J1748.9-2021 in the globular cluster NGC 6440, allowing to establish the identification of the pulsar with the X-ray burst source in the same globular cluster; the pulsations occur in an intriguing pattern that correlates, as found in a further study including the same authors, in a complex way with X-ray bursting episodes of the source (Fig. 3.47). A very surprising discovery was that of 550 Hz pulsations from the long-known neutron star X-ray transient Aquila X-1. These were found in the form of one single 150-second interval of pulsations lurking among 500 000 seconds of data where no pulsations could be found. The mechanism allowing this neutron star to show coherent pulsations so briefly and so sporadically is a mystery at this stage - proposals even extend to the one-off capture by the neutron star of an asteroid.

Watts, Patruno and van der Klis undertook a study of the phase relation between the accretion-driven and the nuclear burning-driven pulsations in the accreting millisecond pulsar XTE J1814-338. Surprisingly it turned out that the nuclear pulsations track the phase fluctuations of the accretion pulsations strictly, indicating that it is not the magnetic field of the neutron star but some action of the accretion flow itself that determines the location where on the

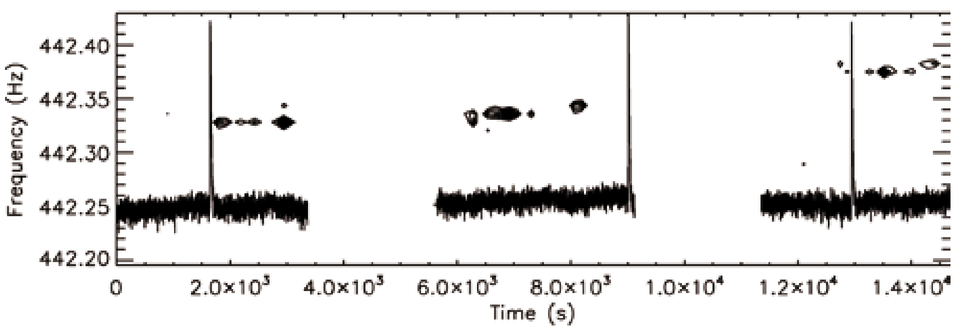


Figure 3.47: Dynamical power spectrum of SAX J1748.9-2021 showing intermittent pulsations (contours). In the light curve (line) three X-ray bursts are seen. The pulse frequency drifts due to orbital Doppler modulation (from: Altamirano et al. 2008, ApJ, 674, L45).

neutron star surface the nuclear burning emission is enhanced. A scenario involving premature nuclear ignition at the accretion column impact point, due to higher local temperatures there, coupled to nuclear burning-front stalling, currently seems to provide the best explanation for this unexpected result.

Altamirano, Patruno, Wijnands, van der Klis and co-workers discovered a second accreting millisecond pulsar in the globular cluster NGC 6440. There are no other globular clusters known to contain even a single accreting millisecond pulsar. The new, 5-millisecond, pulsar is in an ultra-compact binary with a 57 minute orbital period. It has the shortest transient outburst recurrence time yet seen in an accreting millisecond pulsar, about a month, and if this behavior continues the system will become a main target for spin evolution studies.

Markwardt (NASA), Altamirano, Linares with NASA collaborators reported a new 4-millisecond period accreting pulsar IGR J17511-3057. This discovery was reported in the fast online Astronomy Telegram prior to regular publication.

Patruno, van der Klis, Wijnands and co-workers proposed a novel interpretation of the pulse time of arrival residual variations in accreting millisecond pulsars. Contrary to standard accretion theory, which predicts the spin-up to correlate with mass accretion rate in these systems, instead pulse phase correlates with X-ray flux. This prompted them to propose that the time-of-arrival residuals are dominated by variations in hot spot location or emissivity correlating with polar mass accretion rate rather than by accretion torques.

Hartman (MIT), Patruno, van der Klis and Wijnands with further MIT and NASA co-workers reported on ten years of timing SAX J1808.4-3658 with RXTE. The previously reported spin down of the neutron star was found to continue consistent with an interpretation in terms of magnetic dipole spin down mostly during quiescence. A continued increase of the binary orbital period possibly due to gradual mass loss from the system is also confirmed.

The first soft X-ray timing and spectral study of SAX J1808.4-3658 was reported by Patruno, Rea, Altamirano, Linares Wijnands and van der Klis. The high sensitivity of the X-ray telescope used, XMM-Newton, allowed a low energy (<2 keV) tail to be detected in the X-ray emission, providing both spectral and time variability signatures of the accretion disk.

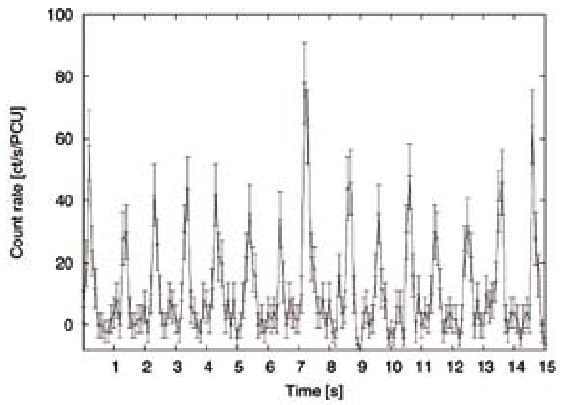


Figure 3.48: The 1 Hz modulation of the X-ray light curve as observed during the 2005 outburst of SAX J1808.4-3658 (from: Patruno et al. 2009, ApJ, 707, 1296).

Patruno, Watts, Klein-Wolt, Wijnands and van der Klis made the first systematic study of the enigmatic, violent 1-second time scale flaring (Fig 3.48) seen in the late stages of several outbursts of SAX J1808.4-3658. The main conclusion is that the flaring can be related with changes in the coherent millisecond pulsations and is best explained by hydrodynamic disk instabilities triggered close to the disk-magnetosphere boundary layer when the system is entering the propeller regime where matter begins to be ejected from the magnetosphere by centrifugal effects.

Bassa collaborated with his former colleagues at McGill in the determination of the optical periodic modulation of the X-ray binary SAX J1808.4-3658 that harbors an accreting millisecond pulsar. The optical period is consistent with the X-ray period, ruling out the possibility of the modulation arising from the accretion disk, although a disk must exist. The finding supports the previous suggestion that the X-ray pulsar becomes rotationally powered in quiescence, with its energy output irradiating the companion star.

Nelemans participated in a large collaboration led by Torres (CfA) observing the 599 Hz accreting X-ray pulsar IGR J00291+5934 during the 2004 outburst and in quiescence. Spectral analysis of the RIJHK broadband photometry shows excess in the near-infrared bands that may be due to synchrotron emission. The Hα emission line profile suggests the orbital inclination is approximately 22-32 degrees.

Linares, Wijnands, van der Klis and co-workers reported on the analysis of the aperiodic rapid X-ray variability of the accreting millisecond pulsar Swift J1756.9-2508. They detected strong flat-topped broadband noise throughout the outburst with low characteristic frequencies (around 0.1 Hz). This makes this source similar to the rest of accreting millisecond pulsars and to other low-luminosity accreting neutron stars when they are in their hard states. They also detected a hard tail in its energy spectrum extending up to 100 keV, fully consistent with such source and state classification.

3.3.6.2. Thermonuclear burning on neutron stars

Thermonuclear X-ray bursts (simply known as bursts) are due to unstable burning of H and He on the surface of accreting neutron stars in low-mass X-ray binaries. During these bursts, the X-ray flux increases by factors of ~10-100 within a second or less, after which it returns back to its pre-burst level over a time-span of tens of seconds, following an approximately exponential decay. In the past decade the volume of data on X-ray bursts has grown tremendously through observations with the Dutch-built BeppoSAX Wide Field Cameras and the US Rossi-XTE. This resulted in the promise of more sensitive studies through stacking of burst lightcurves. A good object for this is the burster GS 1826-24, because its X-ray bursts show a high degree of reproducibility. In 't Zand (SRON), Keek (PhD), Mendez and collaborators have constructed an average time profile of the flux of several tens of X-ray bursts from this object, thus increasing the sensitivity by an order of magnitude. This has revealed a hitherto unknown phenomenon: faint tails that can be followed for one hour, to be compared with the bright burst phases of just a few minutes. It was possible to explain this phenomenon by the inward heating of the neutron star envelope by the thermonuclear flash.

Zhang and Mendez, Altamirano and colleagues discovered a triple-peaked X-ray burst from the low-mass X-ray binary 4U 1636-53 with RXTE. This is the first triple-peaked burst reported from any such system using RXTE, and it is only the second burst of this kind observed from any source. From fits to time-resolved spectra, they found that this was not a radius-expansion burst, and that the same triple-peaked pattern seen in the X-ray light curve was also present in the bolometric light curve of the burst. This triple-peaked burst, as well as the first one observed with EXOSAT and the double-peak bursts in this source, all took place when 4U 1636-53 occupied a relatively narrow region in the color-color diagram, corresponding to a relatively high (inferred) mass-accretion rate. No model presently available is able to explain the multiple-peaked bursts.

Lin (MIT), Altamirano, Wijnands and co-workers report on three X-ray bursts they discovered in the transient Z source XTE J1701-462. One of the bursts was found during the flaring branch state of the source, casting doubts on proposals that the flaring branch is due to unstable nuclear burning of accreted matter.

A prediction of thermonuclear flash theory is that neutron star envelopes can, at the bottom, attain high-enough temperatures (several billion K) for stable helium fusion only if the accretion rate of matter from the companion star is very high. Actually, it would have to be so high that the radiation pressure from the released potential gravitation energy would blow away that matter; an impossible circumstance. Nevertheless, stable fusion is observed. A numerical study of differential rotation in the neutron star envelope by Keek, Langer & in 't Zand has shown that rotational mixing of helium in that envelope may lower the threshold in accretion rate for stable helium fusion by a few tens of percents.

A rare type of burst is the so-called superburst which recurs once a year. It is due to the ignition of thick carbon shells. Currently 10 Galactic superbursters are known. A recent discovery is 4U 1608-522 which was investigated by Keek, in 't Zand and collaborators. It is peculiar because, in contrast to other superbursters, it is not accreting for prolonged periods. This presents a challenge to theory, because it is not understood how a sufficient amount of carbon fuel can be accumulated if the supply rate is so low and, as a secondary effect, the neutron star so cool. Possibly, in the future this can be used to obtain constraints on the composition of the neutron star crust.

Keek and in 't Zand investigated whether superbursts can be detected with the wide field gamma-ray cameras IBIS on INTEGRAL and BAT on Swift. It was found that only superbursts from UCXBs such as 4U 1820-30 give high enough signals at photon energies within the bandpasses of these cameras to be detectable. This involves less than 10% of all superbursts detected thus far.

Kuulkers (ESA), Linares and co-workers studied the puzzling sporadic bursts of 4U 0614+091 using a wide array of X-ray satellites. One of the bursts lasted several hours and hence is a candidate superburst. Ordinary bursts resumed 19 days after the superburst, which is the shortest recovery time yet seen after a superburst. The burst properties are hard to understand if the accreted material is provided by a CO white dwarf companion as previously proposed and instead requires the presence of helium in the accreted matter.

Chemical peculiar companion stars can give rise to peculiar flashes. For instance, if the companion star is deficient in hydrogen such as in an ultra compact X-ray binary (UCXB) with an orbital period less than one hour. The accretion rate in UCXBs is generally small. Together with the lack of hydrogen this results in relatively cool neutron stars. Cooler temperatures imply that ignition conditions in the accreted helium will take longer to develop. As a result, if ignition finally occurs, the amount of fuel is large and the resulting flash much more energetic than for ordinary flashes (although not as large as for superbursts). The flash duration is up to 40 min. This kind of bursts was first recognized in 2005 by in 't Zand, van der Sluys, Verbunt, Pols and collaborators, and a compilation by in 't Zand, Jonker (SRON) and Markwardt (NASA-GSFC) in 2007 turned up 6 new UCXB candidates using that characteristic. in 't Zand, Jonker, Keek, Verbunt and collaborators performed a campaign on the burster 4U 1246-58 with XMM-Newton, RXTE, BeppoSAX and VLT to confirm its UCXB nature.

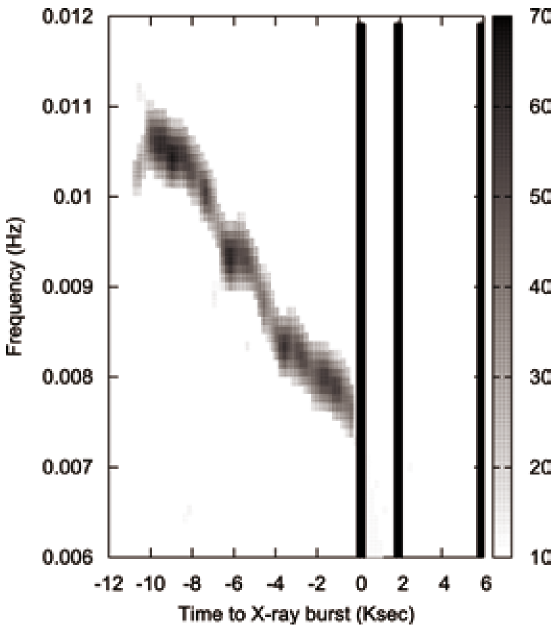


Figure 3.49: Dynamical power spectrum showing the mHz oscillations observed in the neutron star low-mass X-ray binary 4U 1636-53 during the last 12 kiloseconds before an X-ray burst occurred. The three black vertical lines correspond to the times of the occurrence of X-ray bursts. Clearly, the frequency of the mHz oscillations was decreasing before the burst occurred (from: Altamirano et al. 2008, ApJ, 673, L35).

Altamirano, van der Klis, Wijnands and Cumming (McGill) in a study of the marginally stable nuclear-burning generated mHz oscillations of neutron star low mass X-ray binaries discovered an up to now unknown systematic pattern of behavior in these oscillations and their relation to X-ray bursts. In a pattern repeating over and over, first, a systematic frequency drift takes place in the oscillation, and then, within a few kiloseconds after the frequency drops below 9 mHz, a thermonuclear burst occurs (Fig. 3.49). This strongly suggests that the buildup of nuclear fuel on the neutron star surface leads to physical changes in the pre-burst layers that are diagnosed by the mHz oscillations, the burst ignition point corresponding to the 9 mHz oscillation frequency. It is for the first time that such a systematic effect 'predicting' the occurrence of an X-ray burst has been found.

Linares, Watts, Wijnands, Soleri, Degenaar, van der Klis and co-workers reported the capture with Swift of a rare long Type I burst from the new transient X-ray source XTE J1701-407. This establishes the source as a low-magnetic field neutron star. The unusually long, helium powered thermonuclear burst allows to constrain both the composition of the accreted matter and the thermal properties of the neutron star crust.

Watts, Altamirano and Linares and other members of the Amsterdam group (including NOVA PhD Cavecchi) made the first detection of nuclear-powered pulsations (burst oscillations) from the intermittent accretion-powered millisecond pulsar HETE J1900.1-2455. Their properties were totally unlike those seen in other pulsars, where the magnetic field is thought to play a major role during the burst. Either the magnetic field has been buried to a depth where it cannot affect thermonuclear bursting, or the magnetic field is not essential to the development of nuclear-powered pulsations.

3.3.6.3. Relativistic iron lines

An international team led by Cackett (U. Michigan) including van der Klis using the Japanese Suzaku satellite found broad asymmetric X-ray iron lines in three neutron star low mass X-ray binaries. Applying techniques commonly used for similar lines in black holes they found values for the inner radius of the accretion disk between 14.5 and 16.5 km, in agreement with expectations and supporting a similar inner disk origin and similar formation mechanisms for such spectral features in neutron stars and black holes. In addition, the Fe K lines observed in these neutron stars are narrower than those in the black holes that are thought to be close to maximally spinning, as one would expect if inferences for spin are robust. Further work along these lines by Cackett, Altamirano, Patruno, Linares, Wijnands and co-workers led to the discovery of a relativistic Fe line in the accreting millisecond pulsar SAX J1808.4-3658. This allowed estimating the inner radius of the accretion disk in this source to be 13.2 ±

2.5 GM/c^2. Magnetospheric disk truncation to this radius requires a 3x10^8 Gauss dipole field strength, consistent with previous estimates from the pulsation studies.

Blum (U. Mich.), van der Klis and co-workers measured the relativistic Fe line in GRS 1915+105 and used relativistic disk reflection models to constrain the black hole spin, excluding a zero spin at 4σ confidence.

In an effort at critically evaluating the meaning of broad Fe line results, Hiemstra, Soleri, Mendez, Wijnands and co-workers report the discovery of a broad iron line in the black hole candidate Swift J1753.5-0127, with the XMM-Newton satellite. While previous claims were that the accretion flow of this source could be modeled with a disc extending to close to the hole even in the hard state at low X-ray luminosity they found that other models allow the disk to be truncated further out. In further work along these lines Altamirano, Mendez, Hiemstra and co-workers studied the combined properties of broad Fe line and kHz QPOs in the neutron star 4U 1636-53, combining data from XMM-Newton, Chandra and Rossi XTE. They found that the Fe line properties do not correlate well to spectral state, and that the inner disk radius derived from the Fe line and from the QPO frequency sometimes differ, and conclude from this that standard analysis of the Fe lines provides no reliable measurement of the disk geometry.

3.3.6.4. **Jets**

A series of investigations into the physical links between the accretion disk inflows and the relativistic jet outflows in X-ray binaries came to fruition during the reporting period. The work concentrated on comparing these flows and their connections as seen in neutron stars with those observed in black holes, so that characteristics unique to either type of compact object could be distinguished from those that are generic to accretion flows onto compact objects in general.

Tudose, Fender, van der Klis and co-workers using European VLBI radio data combined with observations with RXTE probed the behavior of the X-ray binary Cygnus X-3, famous for its giant radio outbursts first discovered in the early 1970's. The data allow disentangling the radio emission at milliarcsecond scales of the system core from that of the relativistic jet, and showing that contrary to earlier expectations in the active states the radio emission is dominated by the jet emission and hence is not a direct tracer of the accretion state.

Tudose, Fender, Linares, Maitra and van der Klis made a detailed study of the milliarcsecond radio, X-ray and infrared variability of Aquila X-1 with the aim to compare the jet properties of this certified low (but not zero)-magnetic field neutron star with those of black holes. Surprisingly, and at variance with other results on neutron stars, the jet properties in terms of the radio/X-ray flux correlations were found to be rather similar to those seen in black holes, indicating the process generating this aspect of disk/jet correlations is generic and does not critically depend on the central object.

Soleri, Tudose, Fender, van der Klis and Jonker studied the peculiar neutron star low-mass X-ray binary Circinus X-1, well known for its many similarities in both X-rays and radio to black holes, and displaying a wide variety of X-ray phenomena often considered characteristic for either Z or atoll source neutron stars. The data argue against a simple causal relation between disk and jet emission in this source, in ways reminiscent to those recently observed in the black hole candidate GX 339-4. This may be related to the highly eccentric 17-day orbit with enhanced mass transfer in periastron that uniquely characterizes this object.

In a related study of this object, Soleri, Fender, Wijnands, Tudose, Altamirano, Jonker, van der Klis, Casella and co-workers detected both the

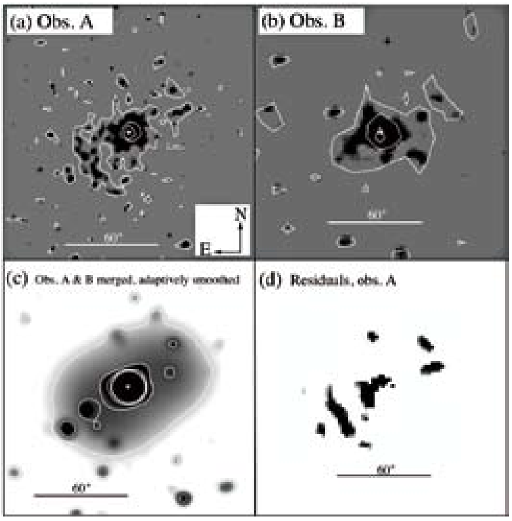


Figure 3.50: Chandra X-ray image of Cir X-1. Top left: image obtained on 2007 April 21; top right: image obtained on 2007 May 16th; bottom left: image of the merger of both observations, adaptively smoothed; bottom right: image of the residuals obtained after fitting the source image clearly showing the diffuse emission associated with the outflow (from: Soleri et al. 2009, MNRAS, 397, L1).

approaching and the receding jet in Circinus X-1 in X-rays using the Chandra satellite (Fig. 3.50). The X-ray emission is consistent with a synchrotron origin. This detection shows that neutron star binaries are as efficient as black hole binaries in producing X-ray outflows, despite their shallower gravitational potential.

Casella and Péer made a detailed theoretical study of the effects of differences in jet magnetic field strength on jet emission spectra and the resulting radio/X-ray correlations. They found that radio flux is not necessarily a measure of jet power and that the magnetic field reaching a critical value can explain the observed spectral transitions out of the hard state. They distinguish at least five qualitatively different emission regimes based on differences in jet width and field strength, which may explain some of the varied observational results obtained in the campaigns described above.

Caballero-Garcia (Cambridge), van der Klis and co-workers performed simultaneous INTEGRAL and XMM-Newton spectroscopy of the black-hole candidate GX 339-4. The time sequence of spectra is interpreted in terms of an ejection of the coronal material responsible for the hard X-ray emission in the form of plasma ejection events in the jets.

Russell and Fender, using the VLT and UKIRT, discovered intrinsic polarization in the infrared emission from two X-ray binaries: the brightest X-ray source in the sky, the neutron star system Scorpius X-1, and, for the first time, from the black hole system GRO J1655-40. This is interpreted as optically thin synchrotron emission from the collimated relativistic jets in these systems indicating the existence of a partially ordered magnetic field is present in the inner regions of the jets, providing further clues to the mechanism leading to the near-light speed bulk velocities in these jets.

In the last decade, a tight correlation between radio and X-ray luminosity has been discovered in accreting black hole binaries, that seems to extend to supermassive black holes as well, in what has been termed the "Fundamental Plane of Black Hole Accretion". Assuming that radio and X-ray luminosities are suitable proxies for jet power and accretion power, respectively, a broad fundamental connection between accretion and jet production is implied. In an effort to refine these links and enhance their power, Gültekin, Markoff and collaborators have explored the above relations exclusively among black holes with direct, dynamical mass-measurements, eliminating systematic errors incurred by using secondary mass measurements. They found Fundamental Plane coefficients similar to prior efforts, and because their sample is so high-precision in mass, it can be inverted into an effective mass predictor. In particular, if obscured active galactic nuclei are excluded, the plane is potentially a better predictor than other scaling measures such as the M-sigma relation.

Maitra, Markoff and co-workers have incorporated for the first time the effects of disk irradiation into a steady-state jet model for the low-luminosity "hard state" of accreting black hole X-ray binaries. They compiled two quasi-simultaneous data sets including radio, IR/optical and X-ray data, in order to apply the model, and derived new constraints on the accretion geometry including the outer disk for the first time. In one case, the best-fitting radius of the outer edge of the disc is consistent with the Roche lobe geometry of the system, and the temperature of the outer edge of the accretion disc is similar to those found for other XRBs, and irradiation of the disc by the jet is found to be negligible. Although in a similar state, the other source shows no disk components at all, suggesting that there is significant diversity in geometry and radiative properties represented by the accretion states, even with jets.

Jonker and Nelemans collaborated with Miller-Jones (NRAO) on radio studies of the black hole X-ray binary V404 Cyg parallax and determined a precise proper motion and later parallax using radio VLBI measurements. The new distance of 2.39 ± 0.14 kpc, is much closer than earlier estimates. More importantly, it was shown that accurate distance measurements to black hole binaries are possible. The new distance, combined with the proper motion, allows determination of the 3D space velocity of the system and puts constraints on the question of how black holes are formed and if they get asymmetric kicks just like neutron stars or not. The velocity suggests that the black hole was formed in a supernova (rather than a complete collapse), but with no or very small asymmetric kick.

3.3.6.5. Accretion processes in X-ray binaries

Klein-Wolt and van der Klis made a big study of the relations between black hole and neutron star broad-band variability power spectra based on a homogeneous analysis of 8.5 Msec of RXTE data. The similarities between the neutron star and the black hole systems are found to be strong, which is in line with the expected similar accretion flow patterns around these similarly-sized compact objects, but important differences are also revealed: black holes have more power at low frequency and less at high frequency than neutron stars, and have lower maximal frequencies in their variability. These differences occur by making the same variability components weaker respectively stronger between neutron stars and black holes and do not require the presence of unique types of broad-band variability in either type of compact object. These findings are in general accordance with the scenario that, in addition to similar accretion flow patterns around neutron stars and black holes producing the observed similar variability components, the characteristic frequencies of the variability scale inversely with mass (as expected for the general relativistic orbital and epicyclic frequencies) and the modulation strengths are affected by the presence or absence of a material surface to provide a one-to-one conversion between accretion flow modulation and X-ray flux modulation.

Maitra and Bailyn (Yale) presented simultaneous optical and near-IR observations of the major outbursts of Aquila X-1 from almost a decade of coverage from summer 1998 - fall 2007. Their data suggests that within the same source, fundamentally different accretion modes are present. In addition, the observed time evolution of the measured fluxes is compatible with thermal heating of the irradiated outer accretion disk. No signature of X-ray spectral state changes or any compact jet are seen, showing that the optical/near-IR color-magnitude diagram can be used as a diagnostic tool to separate thermal and non-thermal radiation from X-ray binaries.

Fender, Russell and collaborators report an anti-correlation between continuum luminosity and the equivalent width (EW) of the Hα emission line in X-ray binary systems. The effect is evident both in a universal monotonic increase in Hα EW with time following outbursts, as systems fade, and in a comparison between measured EWs and contemporaneous X-ray measurements. The effect is most clear for black hole binaries in the low/hard X-ray state, which is prevalent at X-ray luminosities below ~1% of the Eddington luminosity. Comparison with previously established correlations between optical and X-ray luminosity suggests that the line luminosity is falling as the X-ray and optical luminosities drop, but not as fast. They briefly discussed possible origins for such an effect, including the optical depth, form of the irradiating spectrum and geometry of the accretion flow. Further refinement of the relation in the future may allow measurements of Hα EW to be used to estimate the luminosity of, and hence the distance to, X-ray binary systems.

Soleri, Belloni (INAF) and Casella presented the results of the timing analysis of five RXTE observations of the black hole candidate GRS 1915+105 between 1996 September and 1997 December to study the quasi-periodic oscillations in this source. For the first time they detected a so-called type B quasi-periodic oscillation in GRS 1915+105. Since in other systems this phenomenon has been found to appear during spectral transitions from hard to soft states and these spectral transitions have been associated to the emission and collimation of relativistic radio-jets, their presence in the prototypical Galactic jet source strengthens this association.

3.3.6.6. A bow shock nebular associated with a neutron-star low-mass X-ray binary

In a multi wavelength program dedicated to identifying optical counterparts of faint persistent X-ray sources in the Galactic bulge, Wiersema (Leicester), Russell, Degenaar, Klein-Wolt, Wijnands and co-workers found an accurate X-ray position of SAX J1712.6-3739 through Chandra observations, and discovered its faint optical counterpart using data from EFOSC2 on the ESO 3.6-m. They found this source to be a highly extincted neutron star low-mass X-ray binary with blue optical colors. They serendipitously discovered a relatively bright and large bow shock shaped nebula in their deep narrow-band Hα imaging (figure on back cover), most likely associated with the X-ray binary. A nebula like this has never been observed before in association with a low-mass X-ray binary, and as such provides a unique laboratory to study the energetics of accretion and jets.

3.3.6.7. Low-luminosity persistent X-ray binaries

Kaur, Wijnands, Patruno, Degenaar and collaborators presented results from Chandra and XMM-Newton observations of two low-luminosity X-ray pulsators SAX J1324.4-6200 and SAX J1452.8-5949 which have spin periods of 172 and 437s, respectively. During their XMM-Newton observations, SAX J1324.4-6200 is detected with coherent X-ray pulsations at a period of 172.86 ± 0.02 s while no pulsations with a pulse fraction greater than 18% (at 95% confidence level) in 0.2-12 keV energy band are detected in SAX J1452.8-5949. The spin period of SAX J1324.4-6200 is found to be increasing on a time-scale which would suggest that the accretor is a neutron star and not a white dwarf. Using subarcsec spatial resolution of the Chandra telescope, possible counterparts are seen for both sources in the near-infrared images obtained with the NTT. The X-ray and near-infrared properties of SAX J1324.4-6200 suggest it to be a persistent high-mass accreting X-ray pulsar at a distance <8 kpc. They identified the near-infrared counterpart of SAX J1452.8-5949 to be a late-type main-sequence star at a distance <10 kpc, thus ruling out SAX J1452.8-5949 to be a high-mass X-ray binary.

A compilation of persistently active bursting low-mass X-ray binaries by in 't Zand, Jonker & Markwardt revealed an exceptional case, 1RXS J171824.2-402934, which appeared to have the lowest known average accretion rate. To confirm this nature, in 't Zand, Keek et al. performed a 3 year observation campaign with Chandra, Swift-XRT and RXTE to monitor its accretion rate. The consistently low accretion rate was confirmed. Furthermore, the second-ever X-ray burst was detected. Inferences from the 2 bursts on the average burst recurrence time are in line with the low accretion rate (which equals the average fuel supply rate for X-ray bursts). The low accretion rate, if interpreted within accretion disk instability theory, suggests a very short orbital period of less than 7 min.

3.3.6.8. Extra-galactic ultra-luminous X-ray sources

Casella, Patruno and collaborators described a new method to estimate the mass of black holes in Ultra-luminous X-ray Sources (ULXs). The method is based on the recently discovered `variability plane', populated by Galactic stellar-mass black-hole candidates and supermassive active galactic nuclei, in the parameter space defined by the black-hole mass, accretion rate and characteristic frequency. They applied this method to the two ULXs from which low-frequency quasi-periodic oscillations have been discovered, M82 X-1 and NGC 5408 X-1. For both sources they obtained a black-hole mass in the range 100-1300 solar masses, thus providing evidence for these two sources to host an intermediate-mass black hole.

Patruno and Zampieri (Padova) presented evolutionary tracks of binary systems with high-mass companion stars and stellar-through-intermediate mass black holes (BH). Using Eggleton's stellar evolution code, they computed the luminosity produced by accretion from the donor during its entire evolution as well as the evolution of the optical luminosity and colors of the binary system taking the disc contribution and irradiation effects into account. The calculations presented can be used to constrain the properties of the donor stars in ultraluminous X-ray sources by comparing their position on the Hertzsprung-Russell or color-magnitude diagrams with the evolutionary tracks of massive BH binaries. This approach may actually provide interesting clues also on the properties of the binary system itself, including the BH mass. They found that, on the basis of their position on the color-magnitude diagram, some of the candidate counterparts considered can be ruled out and more stringent constraints can be applied to the donor masses.

3.3.6.9. X-ray sources in globular clusters

Verbunt, Bassa et al. used Chandra, HST and VLT to observe a number of globular clusters with low core densities, in which X-ray sources evolved from primordial binaries are expected to dominate over binaries formed in stellar encounters. A sensitive statistical test was developed and applied to these data, together with older data, to prove significantly that the population of low-luminosity X-ray binaries in globular clusters is a linear function both of the number of stellar encounters and of the total cluster mass. It was also shown that a dozen sources, hitherto classified as active binaries based on their main-sequence optical colors, are orders of magnitude more luminous in X-rays than similar systems in the galactic disk. The nature of these systems is now in doubt: either they are super-luminous active binaries, or they are cataclysmic variables that even in the ultraviolet have main-sequence colors.

3.3.7. High-mass X-ray binaries

Gies (Georgia), Kaper and collaborators obtained ultraviolet spectra of the high-mass X-ray and black hole binary system Cyg X-1 with HST. The spectra were obtained at both orbital conjunction phases in 2002 and 2003, when the system was in the X-ray high/soft state. The UV stellar wind lines suffer large reductions in absorption strength when the black hole is in the foreground due to the X-ray ionization of the wind ions. They constructed model UV wind line profiles assuming that X-ray ionization occurs everywhere in the wind except the zone where the supergiant blocks the X-ray flux. The good match between the observed and model profiles indicates that the wind ionization extends to near the hemisphere of the supergiant facing the X-ray source. They also presented contemporaneous spectroscopy of the Hα emission that forms in the high-density gas at the base of the supergiant's wind and the He II 4686 Å emission that originates in the dense, focused wind gas between the stars. The Hα emission strength is generally lower in the high/soft state than in the low/hard state, but the He II 4686 Å emission is relatively constant between X-ray states. The results suggest that mass transfer in Cyg X-1 is dominated by the focused wind flow that peaks along the axis joining the stars, and that the stellar wind contribution from the remainder of the hemisphere facing the X-ray source is shut down by X-ray photoionization effects (in both X-ray states). Caballero-Nieves (Georgia), Kaper and others studied the photospheric spectrum of the O-supergiant

Figure 3.51: Three-color Chandra X-ray image around Sgr A*. Red is 1-3 keV, green is 3-5 keV, and blue is 5-8 keV. The field-of-view is approximately 2° x 0.8° (from: Muno et al. 2009, ApJS, 181, 110).

in the high-mass X-ray binary HD 226868 / Cyg X-1. Based on the HST/STIS UV spectra and ground-based optical spectra they determined the effective temperature and gravity of the O9.7 Iab supergiant. Using non-LTE, line-blanketed, plane-parallel models from the TLUSTY grid, they determine Teff = 28.0 ± 2.5 kK and log g ~3.00 ± 0.25, both parameters were found to be lower than in previous studies. The optical spectrum is best fit with models that have enriched He and N abundances. The model spectral energy distribution has been fitted for this temperature and gravity to the UV, optical, and IR fluxes to determine the angular size and extinction toward the binary. The angular size then yields relations for the stellar radius and luminosity as a function of distance. By assuming that the supergiant rotates synchronously with the orbit, they used the radius-distance relation to find mass estimates for both the supergiant and BH as a function of the distance and the ratio of stellar to Roche radius. Fits of the orbital light curve yield an additional constraint that limits the solutions in the mass plane. They obtained a mass $23^{+8}_{-6}\ M_{\odot}$ for the supergiant and $11^{+5}_{-2}\ M_{\odot}$ for the black hole.

Muno (Caltech) and a large team of international collaborators including Wijnands presented a catalog of 9017 X-ray sources identified in Chandra observations of a 2 by 0.8 degree field around the Galactic center (Fig. 3.51). This enlarges the number of known X-ray sources in the region by a factor of 2.5. The catalog incorporates all of the observations as of 2007 August, which total 2.25 Ms of exposure. At the distance to the Galactic center (8 kpc), they are sensitive to sources with luminosities of 4×10^{32} erg s^{-1} (0.5-8.0 keV) over an area of 1 square degree, and up to an order of magnitude more sensitive in the deepest exposure (1.0 Ms) around Sgr A*. Comparison of the spatial distribution of X-ray sources to a model for the stellar distribution shows 2.8 σ evidence for excesses in the numbers of X-ray sources in the region of recent star formation encompassed by the Arches, Quintuplet, and Galactic center star clusters. These excess sources are also seen in the luminosity distribution of the X-ray sources, which is flatter near the Arches and Quintuplet than elsewhere in the field. These excess point sources, along with a similar longitudinal asymmetry in the distribution of diffuse iron emission that has been reported by other authors, probably have their origin in the young stars that are prominent at l = 0.1°.

Law published his study of the Galactic Center region in radio and mid-IR in a series of papers. The study shows a very rich diversity of physics, with both thermal-like emission from HII regions and massive star formation activity, and non-thermal filaments from energetic processes. The mid-IR data allow one to relate specific features in more detail to star-forming activity and heavily extinct regions. Follow-up study using OH maser emission and IR spectroscopy led to the identification of a population of red supergiants in the young cluster RSGC1.

The Galactic Bulge Survey is a 12 square degree optical/X-ray survey of the Bulge, 1 degree above and below the Galactic plane to avoid the most extreme interstellar reddening (Fig. 3.52). The X-ray survey detected 1700 sources in the 8 square degree done so far, while the completed optical survey produced photometry of 60 million objects. Jonker (SRON), Bassa and Nelemans presented the first results.

The European Galactic Plane Surveys (EGAPS) are rapidly gaining momentum, both on the observational side as well as in science exploitation. For the northern red part (IPHAS) only a few fields remain to be done, and a first data release was organized by the IPHAS consortium, where the description of the data was led by Gonzales-Solares (Cambridge), Greimel (Graz) and Walton (Camdridge) with the participation of Groot. Scientific results from the IPHAS survey include the first catalog of Hα emission line objects by Witham (Southampton), a study of young planetary nebulae by Viironen (IAC), of symbiotic by Corradi (IAC), of a new method to derive a 3D dust map of our Milky Way Galaxy based on the IPHAS data by Sale (Imperial) and the application of this method to the structure of the outer Galactic disk, and the discovery of extremely red objects by Wright (UCL) and collaborators, all including Groot. Deacon and Groot published the

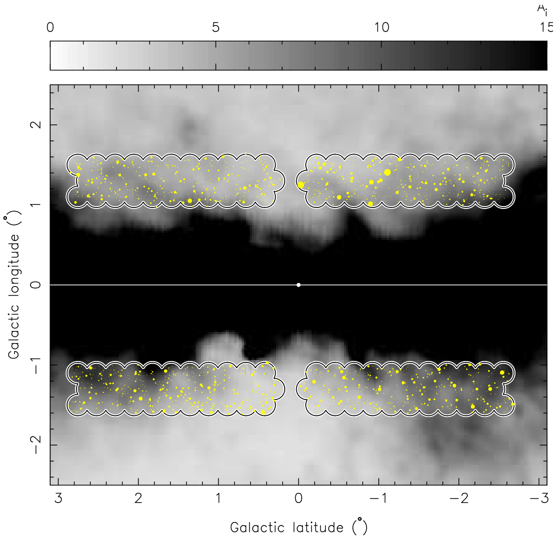


Figure 3.52: Map of the GBS area near the Galactic center ('bubbles'), overlayed on top of a dust extinction map (on the gray scale on the right). Within the GBS area the detected X-ray sources are shown with radius according to intensity (from: Jonker et al. in prep).

first high quality catalog of objects with detectable proper motions in the Galactic plane based on a cross-match between the IPHAS data and POSS-I plates. This catalog uncovers a significant population of cool, nearby white dwarfs in the Galactic Plane, which will be used to construct a more accurate and homogeneous white dwarf luminosity function.

The IPHAS Hα observations are also crucial in the remarkable discovery of the fact that Nova Vul 2007 (V458 Vul) resides inside a planetary nebula, only the second known system, which raises large questions on the progenitor history of the system, and which has been published by Wesson (UCL) and collaborators, including Groot. The IPHAS Hα observations were obtained only six weeks before the nova went off (Fig. 3.53): a nice example of the legacy value of the first multi-color digital survey of the Galactic Plane.

The Northern blue survey part of EGAPS, the UVEX survey, entered into the full observations mode on the Isaac Newton telescope and is now 33% complete. A description of the survey and a first analysis of the data quality is given by Groot, including Verbeek, de Groot, Deacon and Nelemans. Deacon and collaborators used the available southern IR wide-field surveys to constrain the initial mass function of the lowest mass stars and brown dwarfs, and discovered a significant new number of T-type brown dwarfs using the UKIDSS.

3.3.8. Post-common envelope binaries

Maxted (Keele), in collaboration with Nelemans and others published a study aimed at finding new post-common envelope binaries. A new method, in which GALEX UV data are combined with SDSS optical data, is used to select candidates. Follow-up observations of 36 candidates show that at least three are short period binaries, while two are rapidly rotating K-dwarfs.

In a related study, Augusteijn (NOT), Greimel (Graz), Van den Besselaar and Groot showed that the SDSS is also an excellent hunting ground for the related population of detached red-dwarf white-dwarf systems, which are the possible progenitors of the Cataclysmic Variables and whose population characteristics will lead to direct limits on the physics of the common-envelope.

3.3.9. AM CVn-type ultra compact binaries

Groot and Nelemans, together with Roelofs (CfA), Rau (Caltech) and collaborators selected from the Sloan Digital Sky Survey (SDSS) photometric database a sample of 2000 candidates for AM CVn-type ultra compact binaries. For these candidates spectroscopic identification has been obtained using an array of telescopes around the world (including the ING, Keck and VLT telescopes) and five new AM CVn-type binaries were found so far. This appears to be significantly lower than the 50-odd systems predicted to be present in the sample which may indicate an even-lower than expected space density of these rare ultra compact binaries. Using phase resolved spectroscopy the orbital period of two of these newly selected systems (SDSSJ0804+16 and SDSSJ0902+32) were determined.

The nature of the most extreme ultracompact binaries with orbital periods less than 10 minutes (HM Cnc & V407 Vul) remains a puzzle. Wood simulated

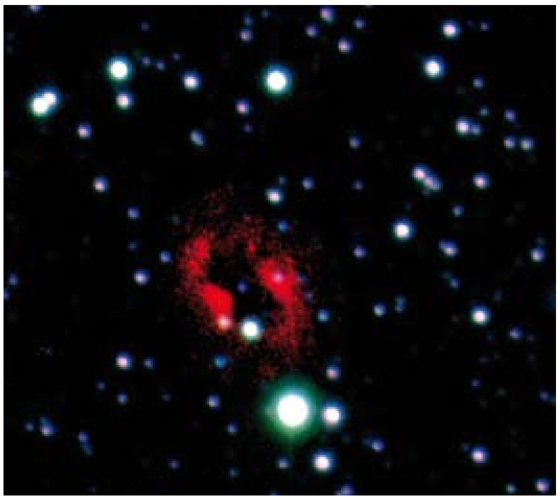


Figure 3.53: Hα IPHAS image of the area surrounding Nova Vul 2007, before it went off, showing the planetary nebula present (from: Wesson et al. 2008, ApJ, 688, L21).

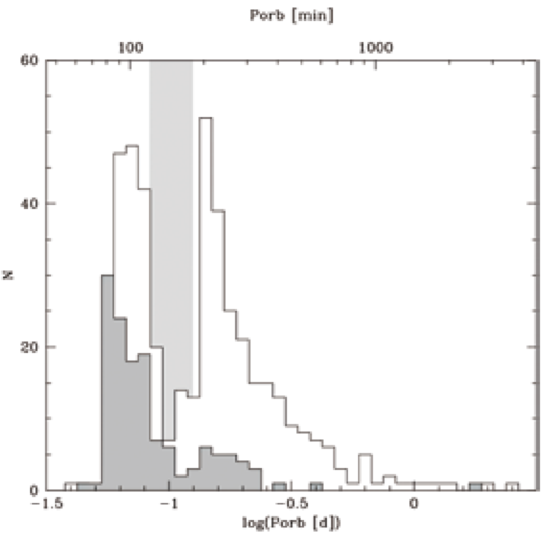


Figure 3.55: Histogram showing the before-SDSS orbital period distribution of CVs (white) and the SDSS CVs (gray). The large asymmetry below and above the period gap at 2-3 hrs is clear in the SDSS distribution and similar to that predicted by theory (from: Gänsicke et al. 2009, MNRAS, 397, 2170).

the direct impact onto the white dwarf accretor using an equatorial accretion belt and was able to qualitatively explain the optical and X-ray lightcurves of these systems. This clearly points to an interacting binary nature of these enigmatic systems.

The suspected ultra compact system V445 Puppis is the only known helium nova (Nova Puppis 2000). Using the adaptive optics facilities on the VLT the system was imaged by Woudt (Cape Town) and collaborators including Groot and Nelemans, over the course of four years (Fig. 3.54). These exceptional observations show the bipolar expansion of the nova shell, and a very thick dusty torus in the mid-plane as well as a knot of high-velocity material being ejected from the system about half a year after the nova explosion. Combining pre-nova observations with the kinematics of the nova shell allowed the determination of the mass of the white dwarf (1.3 $M_\odot$) which makes this a good supernova Type Ia progenitor.

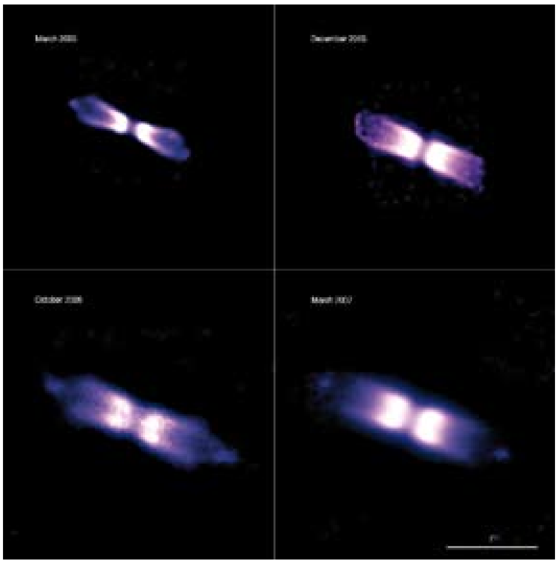


Figure 3.54: Four year composite of VLT adaptive optics observations of the expanding shell around the unique helium nova V445 Puppis. The expansion of the shell in a bipolar jet is clearly evident, as well as a high velocity knot shooting out of the cone, and the thick dust torus around the middle (based on: Woudt et al. 2009, ApJ, 706, 738).

3.3.10. Cataclysmic variables and detached red-dwarf white-dwarf systems

The evolution of Cataclysmic Variables, hydrogen-rich interacting white dwarf - red dwarf binaries, has been a long-standing puzzle in binary evolution, in particular the (non-)existence of the pile up of systems near the orbital period minimum of 80 min. In a seminal study of the population of Cataclysmic Variables Gänsicke (Warwick), in collaboration with Groot and Nelemans, showed that the depth of the SDSS unveils a class of low-luminosity CVs, whose orbital period distribution does show the expected pile-up of systems near the orbital period minimum (Fig 3.55). Wood and collaborators used a smooth-particle-hydrodynamics code to explain the light curves of negatively superhumping Cataclysmic Variables as due to an out-of-the-plane tilt of the accretion disk in the system.

3.3.11. Super-soft X-ray binaries

Van den Heuvel continued his work on the relation between Supersoft Binary X-ray Sources and Type Ia supernovae and on the origins of binary radio pulsars, which resulted in one paper in Nature and one in Science, respectively. He also continued his work on the possible binary origins of long-duration Gamma-ray Bursts. Together with Yungelson (Moscow), Portegies Zwart, Vink and de Koter, he studied the evolution of super-massive stars (masses of ~1000 $M_\odot$) in order to examine whether such stars might, at the end of life, produce intermediate-mass black holes, with masses of several 100 to 1000 $M_\odot$. It was found that due to the extremely strong stellar wind mass loss from these stars, the resulting black holes have masses below 100 $M_\odot$, and that therefore intermediate-mass black holes, if they exist, cannot be the products of super-massive stars.

3.3.12. White dwarfs

Kaastra and collaborators studied the soft X-ray spectrum of the white dwarfs Sirius B and HZ43A and found that it is close to a pure hydrogen atmosphere. In addition tight limits to the amount of helium or the thickness of a hydrogen layer in both stars were obtained. The upper limit to the helium abundance in Sirius B is four times below the previous detection based on EUVE data. They also found that their results are sensitive to the adopted cut-off in the Lyman pseudo-continuum opacity in Sirius B. They obtained the best agreement with a long wavelength cut-off.

3.3.13. Binary and stellar evolution

3.3.13.1. Chemical evolution of donors

Nelemans finished his long term project in collaboration with Yungelson, van der Sluys and Tout, to determine the chemical composition of the donors in ultra-compact binaries. Three different formation channels have been proposed for the formation of ultra-compact binaries (AM CVn stars with white dwarf accretors or ultra-compact X-ray binaries with neutron star accretors). The study shows that the detailed abundances can in principle distinguish between the three different formation channels and thus provide a tool to couple the observed systems to their formation channels and test binary evolution theory. The current observational limits (as determined in the groups of Groot and Nelemans) provide conclusive determination of the donor type in just a few systems.

3.3.13.2. AGB nucleosynthesis

The work of Lugaro, van Raai and Karakas (Mt Stromlo) focused on the evolution and nucleosynthesis of asymptotic giant branch (AGB) stars of intermediate mass, between 4 and 8 $M_\odot$. They computed detailed models for such stars and used these to interpret observations of lithium, zirconium, and rubidium in massive AGB stars in the Magellanic Clouds. They confirmed qualitatively that the main neutron source nucleus in these stars is ^{22}Ne and that lithium can be either produced or destroyed, depending on the stellar mass and the evolutionary timescale.

With other collaborators, they also compared their models to observed abundances in planetary nebulae, in particular of selenium and krypton. Their work confirmed that so-called Type I planetary nebulae, those that are rich in helium and nitrogen, are indeed likely to descend from intermediate-mass AGB stars. Furthermore, they demonstrated that an intermediate-mass AGB star is a good candidate for having produced short-lived radioactive nuclei in the early solar system, such as ^{26}Al and ^{60}Fe, suggesting that a nearby AGB star influenced the formation of the solar system.

3.3.13.3. Carbon-enhanced metal-poor stars

Very metal-poor stars in the Galactic halo are important probes of the formation and early evolution of our Galaxy. The discovery that a large fraction of these stars are surprisingly enriched in carbon (by a factor of 10 or more, relative to iron) has started a vivid debate about their possible origin. The majority of these carbon-enhanced metal-poor (CEMP) stars occur in binaries and are also enriched in heavy s-process elements normally produced in asymptotic giant branch (AGB) stars, suggesting mass transfer from a more massive AGB companion as a likely formation scenario. Lugaro, de Mink (NOVA PhD), Izzard, Pols and collaborators demonstrated that this scenario provides an explanation for the first detection of an enhanced abundance of fluorine in a metal-poor star, HE 1305+0132. Fluorine is produced alongside carbon in metal-poor AGB stars and transferred to a low-mass binary companion. Using binary population simulations, they show that nearly all CEMP stars formed via the mass transfer scenario are expected to be enriched in fluorine.

The CEMP stars make up between 10 and 25% of the metal-poor population. Several studies have argued that this large fraction can only be explained if the initial mass function in metal-poor populations was different than for stars in the disk of our Galaxy, favoring the formation of AGB stars more massive than the Sun. In a population synthesis study, Izzard, Glebbeek, Stancliffe (Cambridge, UK) and Pols investigated whether the observed properties of CEMP stars can be understood without such a change in the initial mass function, but accounting for the inherent physical uncertainties in their evolution. Their population synthesis models confirm that standard AGB models cannot explain the large CEMP frequency, but if allowance is made for efficient dredge-up of carbon in low-mass AGB stars the predicted number approaches what is observed. At the same time, their models reproduce the observed paucity of very nitrogen-rich stars.

In an effort to understand how the surface abundances of CEMP stars evolve after the accretion of AGB-processed material, Stancliffe and Glebbeek studied the combined effect of thermohaline convection (which tends to mix the accreted material inwards due to its higher molecular weight) and gravitational settling, which can suppress such mixing. They found that thermohaline mixing is indeed inhibited if gravitational settling acts long enough to set up a stabilizing molecular weight gradient, or if the amount of accreted material is small. However, the effect of gravitational settling after the accretion has ended strongly changes the surface abundance and depletes surface carbon even more strongly than thermohaline mixing alone.

3.3.13.4. Binaries and galactic chemical evolution

With Sansom and Ocvirk (Preston, UK), Izzard investigated the observational consequences of incorporating binary-star yields into galactic chemical evolution. In particular the effect of including binaries on unresolved galactic spectra was compared to observational errors and found to be of the same order of magnitude. However, the study highlighted the need for a more quantitative study of type Ia supernova rates and yields compared to the traditional semi-analytic Galactic chemical evolution approach.

3.3.13.5. Massive single and binary stellar evolution

Recent observations have triggered a vivid debate on the efficiency of rotational mixing in massive stars. De Mink (NOVA PhD), Cantiello, Langer, Pols, Brott and Yoon (Santa Cruz) argued that detached eclipsing binaries may provide strong test cases for rotational mixing and they provide predictions for the surface abundances of typical systems. They also discussed the possibility that mixing in close massive binaries can be so efficient that the stars stay compact and avoid Roche-lobe overflow altogether. They proposed that these effects provide a new evolutionary channel for the formation of close Wolf-Rayet binaries and is potentially interesting for the explanation of some intriguing high-mass black-hole binaries.

An exciting recent discovery is the presence of multiple stellar populations in globular clusters. If these populations would differ in age by a few hundred million years, one would expect to see this in the color-magnitude diagram of younger massive clusters, such as the well-populated intermediate-age clusters in the Large Magellanic Cloud. Several authors started looking for this effect and indeed reported the appearance of a spread in the color-magnitude diagram near the turn-off. Bastian (Cambridge, UK) and de Mink pointed out that the stars near the turn-off of these clusters typically rotate rapidly. Using simple estimates they demonstrated that the effects of rotation on the luminosities and effective temperatures of stars cause a similar spread in the color-magnitude diagram and they concluded that rotational effects can mimic the presence of a spread in age. In the old globular clusters, however, rotational effects are not thought to be important.

Besides the color-magnitude diagram, evidence for multiple populations comes from variations in the surface abundances among stars in globular clusters. It has been proposed that the more massive stars, which were originally present in the cluster, polluted the cluster with their ejecta. Out of these ejecta a second generation of stars was formed which shows these particular abundance patterns. One of the main problems with this idea is that the two proposed sources, asymptotic giant branch stars and fast-rotating massive stars, can not provide enough polluted material to form a second generation that is as numerous as is observed. De Mink, Pols, Langer and Izzard proposed that interacting binaries are a promising alternative source of pollution. They argued that mass shedding from binaries may be a rather common phenomenon and showed with an example model that the ejected material indeed shows most characteristics of the observed abundance patterns. They estimated that this source of pollution probably dominates over the contribution of the two previously proposed sources (Fig. 3.56).

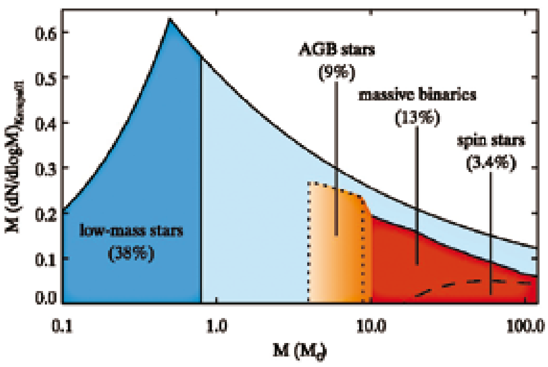


Figure 3.56: Mass-weighted initial mass function. The surface areas indicate the mass contained in the first generation of long-lived low-mass stars (dark blue), the ejecta of AGB stars (dotted line), spin stars, i.e. fast-rotating massive stars (dashed line), and massive (red) and intermediate-mass (orange) binaries. Percentages indicate the fraction of mass relative to the total mass contained in stars of the first generation (from: de Mink et al. 2009, A&A 507, L1).

3.3.13.6. Evolution of stellar collision products

Blue stragglers in dense star clusters can form by several mechanisms, the most important of which is the direct collision and merging of stars. The blue straggler population is an important diagnostic of cluster evolution, because it can provide valuable insight in the dynamical history of star clusters and help test models of their evolution. Glebbeek, Pols and Hurley (Swinburne) computed detailed models of blue stragglers formed through stellar collisions in a previously published N-body calculation of M67. They compared their models with the simpler stellar evolution prescriptions used in the N-body code. They found that these simple recipes, based on formulas that are fit to standard stellar evolution tracks, over-predict the blue straggler lifetime by up to a factor of two. In a follow-up paper, Glebbeek and Pols conducted a systematic study of the parameter space for stellar collisions. They provide a prescription that can be used to improve the stellar evolution recipes so that they are in better agreement with the detailed models.

Glebbeek, Gaburov, de Mink, Pols and Portegies Zwart studied the outcome of a runaway sequence of collisions between massive stars in a dense cluster. Such collision runaways had previously been proposed to lead to the formation of intermediate-mass black holes. Using the tools and experience from their study of blue stragglers these authors modeled the evolution of a number of published merger sequences in detail. They concluded that mass loss from the collision product due to stellar winds prevents the formation of a very massive star and, therefore, of an intermediate-mass black hole. However, the material that is lost may contribute to the enrichment of the interstellar medium early in the evolution of the cluster. The authors briefly discussed the possible implications for the observed abundance anomalies in globular clusters.

3.3.14. Pulsars

Exciting results in the area of gamma-ray pulsars were obtained with the new Fermi satellite LAT instrument by Rea as a member of the large international Fermi-LAT collaboration. The new Fermi results were reported in three papers in Science. (I) in a search among all known millisecond pulsars outside globular clusters, strong gamma-ray pulsations were discovered in eight of them. The gamma-ray pulse profiles and spectral properties resemble those of young gamma-ray pulsars, and it was concluded that the basic emission mechanism is apparently the same for millisecond radio pulsars and young pulsars, with the emission originating in regions far from the neutron star surface. (II) the globular cluster 47 Tucanae, known to harbor at least 23 millisecond pulsars, was found to be a strong 200 MeV gamma ray source with a spectrum consistent with a population of millisecond pulsars and allowing to set an upper limit of 60 on the number of millisecond pulsars present in this cluster. (III) a search for gamma-ray periodicities in the emission from several 100 selected sky locations led to the discovery of 16 gamma-ray pulsars with pulse frequencies between 2 and 20 Hz.

3.3.14.1. Low frequency pulsar searches and studies

Hessels, Van Leeuwen, Coenen (NOVA PhD), and Alexov (NOVA postdoc) are working closely with engineers and software developers at ASTRON to commission the LOFAR telescope for low-frequency observations of pulsars and fast transients. This includes designing and testing the online LOFAR "pulsar pipeline" as well as developing the offline pipeline that will search the data from a soon-to-start all-sky survey for pulsars and fast transients. Such a survey will discover hundreds of pulsars and will be sensitive to any transient events on millisecond to second timescales. Many impressive observational milestones have already been achieved during this commissioning, including the widest-band low-frequency pulsar observations ever made (Fig. 3.57). The data quality is being scrutinized from a scientific standpoint to identify and correct potential problems in the online data analysis.

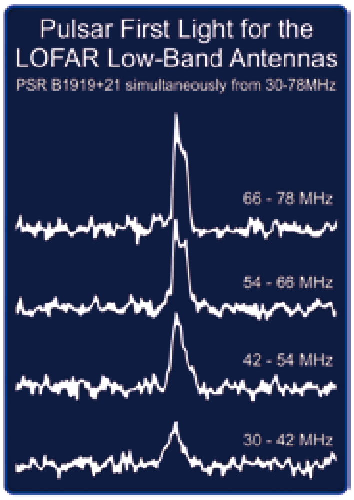


Figure 3.57: The first pulsar observation with the LOFAR low-band antennas (LBAs) on PSR B1919+21. This is the largest bandwidth observation of a pulsar ever made at these frequencies. Figure courtesy van Leeuwen.

Karuppusamy (NOVA PhD) observed the Crab pulsar using the PuMa-II machine (NOVA Instrument) with the low-frequency (LFFE) receivers on the Westerbork radio telescope to characterize the giant pulses of this famous young pulsar and to understand the nature of the radio emission mechanism itself. This work will be continued with the much higher sensitivity of LOFAR.

Serylak and collaborators introduced a new "sliding fluctuation spectrum" technique to characterize drifting subpulses seen in radio pulsars. When applied to three bright pulsars, temporal changes in the drifting subpulse behavior were detected with PuMa at Westerbork. Furthermore, this team has investigated the simultaneous single-pulse properties of the radio emitting magnetar/anomalous

X-ray pulsar XTE J1810-197. A high degree of intensity fluctuations on day-to-day time-scales and dramatic changes across pulse phase were found.

3.3.14.2. Finding pulsars

Janssen, Rubio, Van Leeuwen and team report on the first Dutch discovery of radio pulsars. Pioneering a novel interferometric observing mode, multiple simultaneous digital beams were formed using PuMa+PuMa-II at Westerbork to provide high sensitivity over a large field of view. Three pulsars were newly discovered. Such techniques will be crucial for finding pulsars with the next generation of radio telescopes, and eventually the SKA.

Hessels, Van Leeuwen, Kondratiev and the GBT350 team discovered PSR J1023+0038, a radio pulsar/X-ray binary evolutionary missing link (Fig. 3.58). This nearby radio millisecond pulsar is in a circular binary orbit with an optically identified companion star. Optical observations indicate that an accretion disk was present in this system within the past decade. The millisecond radio pulsars appear to have turned on after a recent low-mass X-ray binary phase.

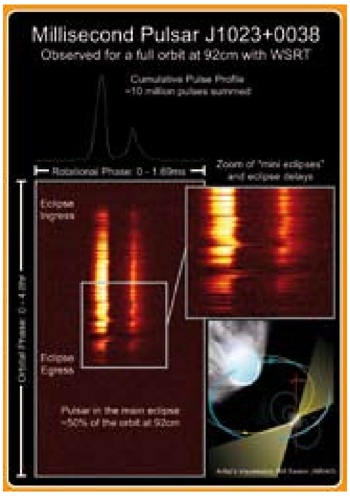


Figure 3.58: PSR J1023+0038 is the recently discovered radio millisecond pulsar that provides a unique view of the evolutionary link between the accreting "low-mass X-ray binaries" and their descendants, the radio millisecond pulsars. Shown are the eclipses that are likely due to material orbiting in the system, as observed with PuMa-II. Figure courtesy van Leeuwen.

Hessels, Van Leeuwen and the PALFA team presented the Arecibo discovery of a young, energetic, "Vela-like" pulsar J1856+0245. This pulsar is a likely counterpart to the previously unidentified TeV gamma-ray source HESS J1857+026, providing a convincing solution to the mystery of this source's nature.

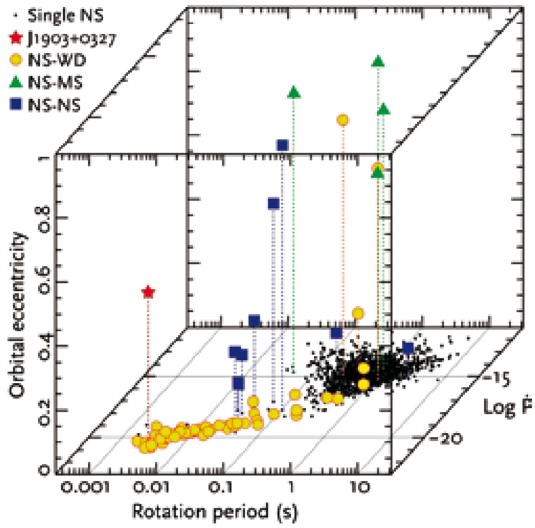


Figure 3.59: Rotation periods, period derivatives, and orbital eccentricities of pulsars in the disk of the Galaxy. The red star is PSR J1903+0327, which occupies a unique place in the diagram, and whose evolution is unexplained (from: Champion et al. 2008, Science, 320, 1309).

Champion (McGill), Van Leeuwen, Hessels, Kondratiev and the PALFA team found PSR J1903+0327, a fast radio millisecond pulsar in a highly eccentric (e = 0.44) 95-day orbit around a solar mass companion. Conventional binary stellar evolution models predict neither large orbital eccentricities nor main-sequence companions around millisecond pulsars (Fig. 3.59). An unknown alternative formation scenario must be involved. The pulsar is also unusually massive, which is interesting from an evolutionary point of view.

3.3.14.3. Studying pulsar systems

Janssen and collaborators were able to constrain the masses in the double neutron star system PSR J1518+4904, finding one of the lightest neutron stars known to date, using PuMa+PuMaII at Westerbork. Hessels et al. performed follow-up observations of the young pulsar J1856+0245 (see above) with the XMM-Newton to discover a compact pulsar wind nebula. Together with the TeV emission likely associated with this object, this provides information of how pulsars liberate the majority of their energy, in the form of a relativistic particle wind.

Rea and team reported on the discovery of a peculiarly shaped region of X-ray emission around the rotating radio transient J1819-1458. The most plausible interpretation is a nebula powered by the pulsar's high magnetic field.

3.3.15. Magnetars

Rea and co-workers used X-ray and gamma-ray data from XMM-Newton and Integral to study the physical processes that make magnetars emit X-rays. Magnetars form a class of neutron stars with ultra-strong magnetic fields. With magnetic fields a 10^{15} times stronger than that of the Earth, they are the strongest known magnets in the cosmos. They differ from "ordinary" neutron stars (whose magnetic fields are a thousand times weaker) because their magnetic field is strong enough to twist the stellar crust and produce hot plasma that fills the magnetosphere. The spectral analyses of Rea et al. of 10 of these magnetars show that the X-rays are produced by inverse cyclotron scattering on this hot plasma of photons emitted by the stellar surface.

Rea led a large collaboration including van der Klis which performed a detailed study of the first outburst of a new magnetar candidate, the soft gamma ray repeater SGR 0501+4516, using the XMM-Newton, Swift, Suzaku and INTEGRAL satellites. They discovered a variable hard X-ray component out to 100 keV fading in less than 10 days after the bursting activation and were able to do a fully phase coherent X-ray timing analysis covering 160 days.

Watts and Steiner (Michigan) studied the effects of crust composition on the global seismic vibrations excited by giant flares on magnetars. Mode frequencies turned out to be surprisingly sensitive to uncertainties in the nuclear composition of the crust. Seismic calculations using older crust models had inferred a worryingly low mass for magnetars, contradicting the predictions of supernova simulations. The new models lead to revised mode identifications and more reasonable masses. The researchers also showed that neutron star seismology complements results expected from laboratory experiments aimed at measuring the neutron skin thickness of lead. Together they can pin down the density dependence of the symmetry energy, a major unknown in dense matter physics.

An exciting new source was discovered in gamma-rays with SWIFT, for which Castro-Tirado, Markoff, Leventis and collaborators triggered a multi-wavelength campaign expecting a typical gamma-ray burst. Instead, they detected very unusual flaring behavior, with over 40 optical flares in the following few days, as well as a faint infrared flare before the source returned to quiescence, while no radio emission was detected. Energetically such a scenario could be consistent with an ejection event by an X-ray binary, but the favored scenario is that this source is a new magnetar that looks like a soft gamma-ray repeater (SGR), except in the optical bands rather than the gamma-rays, where only one burst was detected. If true, this would be the first detection of an SGR at optical wavelengths. Only further bursts will determine its true nature.

Vink and Bamba (ISAS/JAXA, Japan) reported the discovery of an X-ray nebula around the magnetar AXP 1E1547.0-5408 (Fig. 3.60). The nebula is likely the pulsar wind nebula blown by the magnetar. Its X-ray luminosity is about 1% of the rotational energy loss of the magnetar, a fraction that is similar to other young pulsars. The discovery of a pulsar wind nebula offers a possibility to investigate the origin of the strong magnetar magnetic fields, as a pulsar wind nebula contains information about the history of the rotational energy loss.

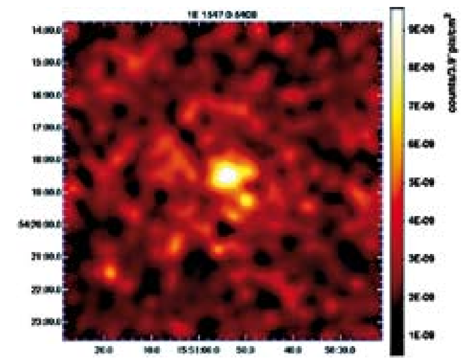


Figure 3.60: Chandra X-ray image of the pulsar wind nebula around the magnetar 1E1547.0-5408. The emission from the magnetar itself has been removed. The nebula has a radius of ~40 arcsec. One can also discern very faint X-ray emission from the shell of the associated supernova remnant G327.24-0.13, with a radius of about 100 arcsec (from: Vink & Bamba, ApJ 707, L148).

Hermsen continued with Kuiper (SRON) and den Hartog his studies of non-thermal X-ray emission from magnetars and radio pulsars. Detailed high-energy characteristics of Anomalous X-ray pulsars AXP 4U 0142+61 and 1RXS J170849-400910 were published exploiting multi-year observations with INTEGRAL, RXTE, XMM-Newton and ASCA. The spectra of the total pulsed and unpulsed emissions were derived, as well as the variations of the pulsed-emission spectra with pulsar phase. It was shown that genuinely different pulsed components with different spectra contribute to the total pulsed emission. The results provided stringent constraints on the geometry of the production sites in the magnetar magnetosphere as well as the required different production processes. None of the presently proposed models satisfactorily explains the luminous non-thermal hard X-ray emission.

The only rotation-powered pulsar which showed a radiative outburst with magnetar-like bursts, is the high-B-field pulsar PSR J1846-0258, located in supernova remnant Kes 75. Multi-year RXTE and INTEGRAL observations crossing the outburst in June 2006 were studied in detail. Kuiper and Hermsen showed that the varying temporal and spectral characteristics of PSR J1846-0258 can be explained in a scenario of a young high-B-field pulsar in which a major glitch triggered a sudden release of energy, and resonant cyclotron up-scattering and synchrotron emission are responsible for the measured radiative outburst at higher X-ray energies.

3.3.16. Radio transients

Hyman (Sweet Briar), Wijnands and co-workers reported the detection of a new transient radio source, GCRT J1742-3001, located ~1 degree from the Galactic center. The source was detected 10 times from late 2006 to 2007 May in their 235 MHz transient monitoring program with the Giant Metrewave Radio Telescope (GMRT). The radio emission brightened in about one month, reaching a peak observed flux density of ~100 mJy on 2007 January 28, and decaying to~50 mJy by 2007 May when the last monitoring observation was made. Based on non-detections in observations obtained simultaneously at 610 MHz, they deduce that the spectrum of GCRT J1742-3001 is very steep, with a spectral index less than about -2. No X-ray counterpart is detected in a serendipitous observation obtained with the X-ray telescope aboard the Swift satellite during the peak of the radio emission in early 2007. Thus, GCRT J1742-3001 is either a new member of an existing class of radio transients, or is representative of a new class, possibly having no associated X-ray emission.

Spreeuw, Scheers, Wijers, and others studied the enigmatic radio source GCRT J1745-3009. It is located near the Galactic Center in the sky and was discovered in a 330MHz VLA survey. Attempts to observe it almost always yield non-detections, despite many attempts by VLA, GMRT, and WSRT. On rare occasions when it is detected, it shows periodic outbursts lasting about 10 min every 77 min. By a much-improved analysis, they determined a more accurate period and established a more detailed shape of the outbursts. Theories on the nature of the source vary from a distant white-dwarf pulsar to a nearby exoplanet. The work is also a pathfinder for LOFAR transients studies, and demonstrates that accurate imaging of wide fields of view at low radio frequency is possible, though difficult, even within the complex background of the Galactic Plane.

3.3.17. Asteroseismology

The launch of the CoRoT satellite opened a new era for the asteroseismology of massive stars from space. Aerts and collaborators have been heavily involved in the preparation of CoRot for β-Cephei pulsators, among others on MOST data of Spica, ground-based data on the CoRoT main target HD180642, and on pulsating stars in the open clusters M67 and NGC884. First CoRoT results were obtained on the interacting binary AU Mon and on 358 candidate B-star pulsators.

Hu finished her thesis using asteroseismology to determine the formation of sub dwarf B stars. Together with a.o. Nelemans, Aerts and Groot she studied the formation of the short period, eclipsing sdB + M stars binary NY Vir and concluded that the sdB star is likely formed via a helium flash, at least if the common-envelope is governed by the energy balance, instead of the angular momentum balance.

A study led by Hu and including Aerts and Nelemans of the power of asteroseismology to distinguish the different formation channels for sdB stars was published. It shows that seismology, in combination with determination of surface temperature and gravity can distinguish between progenitors with non-degenerate cores and those with degenerate cores, at least if the modes of the frequencies are determined.

In a further study, Hu, Nelemans, Aerts and others significantly improved the stellar evolution models used in asteroseismology by implementing atomic diffusion in the calculations. The new models were used to study the influence of helium diffusion on the seismic properties of sdB stars and models with diffusion are in better agreement with the observations. Also, the possibility was investigated of using asteroseismology to probe the details of the helium flash.

3.3.18. Gravitational waves

Watts and collaborators carried out the first rigorous assessment of the detectability of gravitational waves from known accreting neutron stars, a major target for new detectors such as LIGO and VIRGO. Uncertainties in parameters such as spin and orbital period were found to have a potentially devastating effect. The astronomical, astrophysical, technological and computational challenges to be overcome were quantified, and efforts are now underway to mitigate these problems and open up this new frontier.

Nelemans reviewed the Galactic gravitational wave foreground for the International LISA conference, with particular emphasis on complementary electro-magnetic observations. The Galactic plane and Galactic Bulge surveys in which the groups of Groot and Nelemans participate will be particularly interesting from that point of view.

Nelemans and Stroeer (Birmingham) published the results of their investigation into the influence of short term variations in interacting binaries on their gravitational wave signal, in particular for LISA. They conclude that short-term may significantly alter the frequency evolution and may hamper parameter estimation of the binaries.

3.3.19. Super-massive black holes

Markoff and co-workers led an unprecedented simultaneous broadband campaign on the weak, nearby active galactic nucleus M81*, using the Chandra High Energy Gratings, along with the ground based instruments GMRT, VLA/VLBA, PdBI, SMA and the Lick Observatory. Several exciting results came out of this program, but the highlight was the intriguing detection of strong and highly variable submm emission, suggesting that M81* may also have a strongly polarized synchrotron "bump" originating from hot plasma very

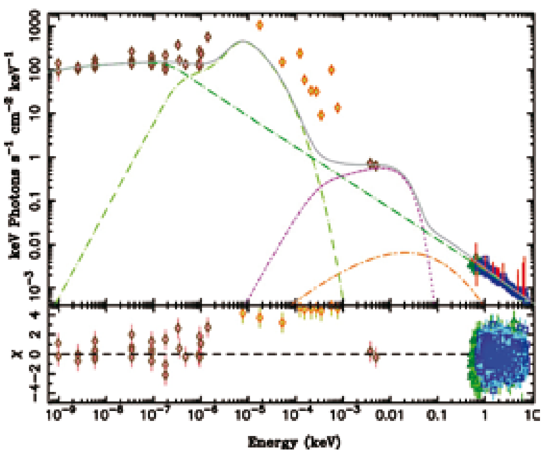


Figure 3.61: Model fit to combined set of all broadband observations of M81*. The symbols represent the data, while the solid red line is the model fit in detector space. Solid (gray): total spectrum, Dot-long-dashed (light green): pre-acceleration inner jet synchrotron emission, Dot-long-dashed (darker green): post-acceleration outer jet synchrotron, Dot-long-dash-short-dash (orange): Compton emission from the inner jet (including external disk photons as well as synchrotron self-Compton), Dots-short-dash (magenta): thermal multicolor-blackbody disk mode (from: Markoff et al. 2008, ApJ, 681, 905).

close to the central black hole. This feature has only been seen in Sgr A* so far, and was one of the motivating factors for the campaign on M81*, in order to help "place" Sgr A* in context with other weakly accreting local galactic nuclei. Even more exciting, the broadband spectrum can be well fit by exactly the same outflow-dominated model that successfully describes the low-accretion state in accreting black hole X-ray binaries, with the same physical parameters except for a larger mass (Fig. 3.61). Such a result strongly supports the idea that accretion physics scales predictably with mass, and suggests that the low-luminosity AGN class is a longer-lived analog of the transient "hard state" in X-ray binaries, and opens the door for more correspondences between AGN classifications and X-ray binary states.

The black hole at the Galactic Center, Sgr A*, is the prototype of a galactic nucleus at a very low level of activity. Its radio through submm-wave emission is known to come from a region close to the event horizon, however, the source of the emission is still under debate. In the context of a jet model, scaled down in power from what is expected in AGN, Falcke, Markoff and Bower (Berkeley) used all current available VLBI data to derive the intrinsic wavelength-dependent size of Sgr A*'s photosphere, and calculate the expected frequency-dependent time lags of radio flares. The combination of time lags and size measurements imply a mildly relativistic outflow and are reproduced well by a pressure-driven jet model without any major fine tuning. Their results therefore further strengthen the case for the cm-to-mm wave radio emission in Sgr A* as coming from a mildly relativistic jet-like outflow, as would be expected based on similarities to other nearby low-luminosity AGN.

The source of emission from Sgr A* is still unknown, but flares and data from multi wavelength campaigns are providing the best clues for use in models, especially when time dependence is considered. Maitra, Markoff & Falcke have developed a new time-dependent jet model, which for the first time allows one to compare the model predictions with flare data from Sgr A*. Taking into account relevant cooling mechanisms, the frequency-dependent time lags and photosphere size expected in the jet model are calculated. They showed that a time-dependent relativistic jet model can successfully reproduce: (1) the quiescent broadband spectral energy distribution of Sgr A*; (2) the observed 22 and 43 GHz light curve morphologies (Fig. 3.62) and time lags; and (3) the frequency-size relationship. The results suggest that the observed emission at radio frequencies from Sgr A* is most easily explained by a stratified, optically thick, mildly relativistic jet outflow. Frequency-dependent measurements of time-lags and intrinsic source size provide strong constraints on the bulk motion of the jet plasma. The model also predicts light curves and structural information at other wavelengths which could be tested by observations in the near future.

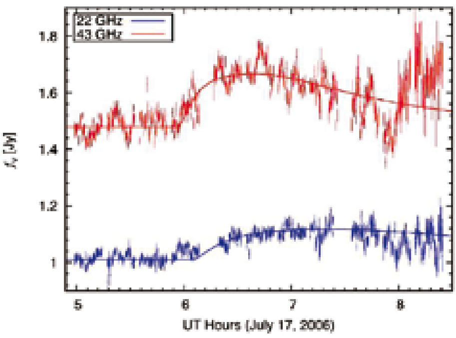


Figure 3.62: Comparison of time-dependent jet model with data for the radio flare on 2006 July 17 at 43 and 22 GHz. The 43 GHz data with error bars from Yusef-Zadeh et al. 2008 are shown in red, and 22 GHz data + model in blue (from: Maitra et al. 2009, A&A, 508, L13).

Together with Brunthaler (MPIfR) and colleagues, Falcke worked on precise astrometric measurements of nearby galaxies to obtain extragalactic proper motion measurements. This allows one to constrain the history and matter distribution of the local Universe. As a by-product they detected a radio transient in M82, which turned out to be one of the radio supernovae, whose expansion can be (and is being) traced by direct VLBI radio imaging, thereby promising detailed insight into the physics of supernova explosions.

Reynolds (Maryland), Markoff and co-workers presented a “mega-campaign” at X-rays on the low-luminosity active galactic nucleus (LLAGN) in NGC 4258 using data from Suzaku, XMM-Newton, and the Swift/Burst Alert Telescope survey. They found surprisingly weak signatures of X-ray reprocessing by cold gas: a weak, narrow fluorescent Kα emission line of cold iron is robustly detected in both the Suzaku and XMM-Newton spectra but at a level much below that of most other Seyfert-2 galaxies. They concluded that the circumnuclear environment of this AGN is very “clean” and lacks the Compton-thick obscuring torus of unified Seyfert schemes, and constrain the line to be emitted within ~10^{3-4} r_g from the black hole. The observed properties of the line can be best explained if it originates in a warped accretion disk, as known to exist in this source, and they modeled the expectations from a Lens-Thirring precession warp. The Suzaku data also show significant fast variability, which if associated with accretion disk processes requires an origin in the innermost regions of the disk ($r \approx 10$ r_g or less).

Detmers, Kaastra, Verbunt and collaborators studied the variability of the photo-ionized, X-ray absorbing and emitting gas from AGN outflows. In NGC 5548, the changes between two spectra taken three years apart lead to a distance estimate for the narrow line region of 1 pc. UV spectra taken by HST show also the presence of a new, intermediate width line region in this source. In a less massive source, NGC 4051, the signatures of recombination after a sudden flux were found to decrease by a factor of five. This leads to a range of 0.02 - 1 pc for the various outflowing components in this source.

3.3.20. X-ray clusters

Wise continued his studies of central galaxies in clusters, with a publication in which the jet power of the radio galaxy, as inferred by the cavity it has blown into the cluster gas, is shown to scale with its radio luminosity. He also participated in a study showing that most Spitzer IR sources in a field near the Galactic Center are not correlated with Chandra X-ray sources.

Kirkpatrick (Waterloo), Wise and others observed the Hydra A galaxy cluster with Chandra, and found that the material ejected by the AGN into the cluster medium is more metal-rich than the cluster gas itself. McNamara (Waterloo), Wise, and colleagues determined that the central AGN in cluster MS0735.6+7421 must have injected about 10^{62} erg of energy into the cluster gas over the past 100 Myr via its jets. Given the low current brightness of the AGN and the small amount of gas near its center, they surmise that the large mechanical power of the jet is supplied from the rotational energy of the black hole rather than by accretion. With Kirkpatrick and others, Wise also analyzed the Chandra observations of Abell 1664. The large mass of hot gas near the center appears to be cooling into cold molecular gas in the central brightest cluster galaxy and giving rise to rapid star formation.

3.3.21. CMB cosmology

Meerburg, Van der Schaar and Corasaniti studied a particular variation on models for the very earliest evolution of the Universe after the Big Bang, namely initial-state modifications of the inflation field. They found that by analyzing the bi-spectrum statistics of CMB fluctuations, one can discover the imprint of such models on the CMB and even distinguish them from imprints caused by other types of models.

3.3.22. Cosmic rays and neutrinos

Falcke and Hörandel together with Horneffer and the Pierre Auger Collaboration continued investigations of the properties of the highest-energy cosmic rays. Correlations with the positions of nearby AGN have been pursued. The sources of the cosmic-ray particles seem to be correlated with the general distribution of matter in the Universe, for which the AGNs act as tracers. New upper limits on the fluxes of ultra high-energy neutrinos and photons have been derived. In the energy spectrum of cosmic rays, a depression of the flux at energies exceeding 4×10^{19} eV has been measured. This is a hint towards an interaction of ultra high-energy cosmic rays with the cosmological microwave background (GZK effect).

Hörandel and the AIRFLY Collaboration continued the measurement of the fluorescence light yield of electrons in air. This light yield is important to set the absolute energy scale of the data registered with the Pierre Auger Observatory. The dependence of the light yield on particle energy, gas pressure, temperature and humidity has been measured.

Falcke, Hörandel, and Kuijpers together with Horneffer, Nigl and the LOPES collaboration continued the investigation of radio emission from extensive air showers. Frequency spectra have been measured and the reconstruction of air showers, based on the observed radio signals, has been optimized. This is important preparatory work for measurements of radio emission with the LOFAR telescope. Together with Lafebre (PhD), the prospect to determine the mass of cosmic rays via the Gerasimova-Zatsepin effect has been investigated.

Falcke and Kuijpers together with Buitink (PhD) further developed the detection of neutrinos by measurements of radio emission from the Moon. A new upper limit on the ultra high-energy neutrino flux, based on measurements with the Westerbork telescope has been published.

Falcke investigated the feasibility of building a radio telescope on the Moon. He published together with Jester a large review of current and past studies on this topic and discussed new science areas, where a lunar telescope would produce unique science, including a study of the dark ages of the Universe, ultra-high energy neutrino detection, and exoplanet search.

Hörandel and the KASCADE-Grande collaboration continued their investigations of galactic cosmic rays. An update has been given on the energy spectra for groups of elements in cosmic rays with energies exceeding 10^{15} eV. It could be confirmed that the mean mass of cosmic rays increases as function of energy. The tests of hadronic interaction models used for the simulation of the development of extensive air showers in the atmosphere have been continued. The newly available model EPOS is not compatible with the observed data and a new method has been developed to measure the attenuation length of hadrons in extensive air showers.

Falcke, Hörandel, and Kuijpers together with Lafebre worked out the universality of electron-positron distributions in extensive air showers. Hörandel (partly with collaborators) reviewed the present status of galactic and extra-galactic cosmic-ray research. They also continued the investigation of galactic cosmic rays at energies below 10^{14} eV. With the TRACER balloon experiment the energy spectra of individual elements in cosmic rays from oxygen to iron have been measured. Also, the effects of solar activity on the flux of low-energy cosmic rays observed at Earth have been observed and recent Forbush decreases have been analyzed.

3.3.23. Computational astrophysics

Portegies-Zwart and his computational astrophysics group at Leiden (previously Amsterdam) works on a wide variety of aspects related to numerical stellar dynamics and other computationally oriented astrophysics problems. A wide range of spatial and temporal scales is investigated, from planetary dynamics to cosmology, from processes that operate on time scales of hours to millions of years.

The Astrophysics Multipurpose Software Environment (AMUSE) for simulating astrophysical systems (see {\em http://muse.li}) is under development. The source code can be downloaded free of charge and used by any researcher or student to conduct his or her research. The package includes stellar dynamics, stellar evolution, gas/hydro dynamics and radiative transport. In the last year the team has professionalized the development of AMUSE, by hiring a software engineer, a postdoc and two programmers. The AMUSE component library will provide easy access to individual packages and allow scientists to use combinations of codes to solve coupled problems (such as hydrodynamics and radiative transfer or stellar evolution and stellar dynamics) without the need to write new codes or significantly alter existing codes.

Considerable work has been put into the development of a cosmological Tree/Particle-Mesh integrator which is capable of running across multiple supercomputers. Test runs have been performed between two supercomputers, one in Amsterdam and one in Tokyo. These tests show that their simulation indeed scales well across multiple supercomputers, and that the communication overhead is limited to ~10% for production-scale problems. However, arranging dedicated network paths and compute time across different supercomputers turned out to be much more time-consuming and politically challenging than we initially anticipated.

The first science application is a very large-scale cosmological simulation containing about 10 billion particles, using a few thousand processes across two supercomputers which are interconnected by a dedicated 10Gb/s light path. Groen was mostly responsible for developing and testing the low-level socket communication library which is used for sending data efficiently over the light path.

In collaboration with Stolte (Cologne), the team has worked on creating a realistic N-body model of the Arches cluster. For this purpose, a large number of simulations were systematically compared with the available observational data. The first step was to constrain the initial conditions of the cluster, in particular the mass function of the Arches cluster which has been discussed as an example of a non-universal IMF. However, they were able to show that the observed mass function can be perfectly explained with the normal (Salpeter) IMF taking into account the dynamical evolution of the cluster.

3.3.24. LOFAR development work

The ultimate aim of the LOFAR pipeline group is to use the International LOFAR Telescope to identify, classify, monitor and respond to astronomical transients as automatically as possible. Throughout 2009, development has continued on the necessary infrastructure; to a large extent, this has focused on LOFAR's 'Standard Imaging Pipeline' (SIP), which accepts raw data from the LOFAR correlator and processes it to make images---a computationally demanding task.

It is clear that existing image formats (e.g. FITS) were inadequate for the quantity of data that LOFAR will produce. A new specification for image cubes using the HDF5[1] system has been developed (Anderson and Alexov): this will be the standard way in which LOFAR delivers images, and it is hoped that it will be widely adopted in the astronomical community at large.

Development of the SIP is based at ASTRON. However, members of Amsterdam pipeline group have play key roles. Swinbank and others have developed a 'pipeline framework': a system of running all the various required components in a coordinated way across the LOFAR compute cluster, so that they can be reliably controlled and efficiently managed. This framework is now in regular use processing test data from LOFAR hardware; eventually, it will become standard for many LOFAR data processing tasks.

A fast, accurate system has been developed by Spreeuw over the last few years to identify and measure sources in astronomical images. This code is now in operation as part of the SIP; it will also be directly used in the transient detection system. The source measurement system feeds into a large database of astronomical sources. This database has been developed by Scheers in conjunction with the Centrum voor Wiskunde en Informatica in Amsterdam, and is now entering use as part of the LOFAR system. Eventually, this will form the basis for a huge public database of transient lightcurves detected by LOFAR.

All of this development is of little use without proper testing. An automated system for running the various pipeline components and ensuring their correct operation has been developed. Results can be made available on a website, so that all the users and developers can study and act upon the results. The group has also begun building systems for communicating the results of the search for transients to other facilities. In particular, they are developing a VOEvent based system, which has undergone its first tests over the course of this year. Eventually, this will provide near real-time alerts of astronomical events to the community, thereby facilitating the most exciting possible science. In addition to work on the pipeline, effort is put into making cross-triggering agreements with other wide-field or fast-responding instruments such as MAGIC (TeV gamma), Fermi (keV-GeV), Liverpool Telescope (optical), and others.

[1]) http://www.hdfgroup.org/HDF5/

4. PhD's in astronomy awarded in 2008 - 2009

In 2008 a total of 24 PhD's in astronomy were awarded in the Netherlands and 33 were awarded in 2009. Of these PhD's 11 were obtained through funding or co-funding from NOVA. The table below lists all PhD's in astronomy over 2008-2009 specified for each university.

	PhD date	Funding	Promotor	Thesis title
UvA				
D. Altamirano	23/04/2008	NOVA / UvA	van der Klis	Different manifestations of accretion onto compact objects
P. Curran	05/09/2008	NWO	Wijers	Multi-wavelength analyses of gamma-ray bursts: Features of swift GRBs and the blast wave model
E.Gaburov	04/11/2008	NWO	Wijers, Sloot co: Portegies Zwart, Pols	Stellar collisions in young star clusters
P. den Hartog	21/05/2008	other	Hermsen co: van der Klis	Non-thermal x-ray emission from anomalous x-ray pulsars
D. Paszun	17/10/2008	NWO	Dominik	The collisional evolution of small dust aggregates
G.H. Janssen	25/03/2009	NWO	van der Klis co: Stappers	High precision radio pulsar timing
R. Karuppusamy	13/11/2009	NOVA	van der Klis co: Stappers	A study on giant radio pulsars
M. Linares Alegret	16/09/2009	NWO	van der Klis	Accretion states and thermonuclear bursts in neutron star X-ray binaries
A. Patruno	09/06/2009	NOVA	van der Klis co: Wijnands	Accreting millisecond X-ray pulsars: from accretion disk to magnetic poles
A. Verhoeff	10/11/2009	NWO	Waters, Tielens co: Pel	Dusty disks around young stars
RuG				
P.A. Araya Melo	19/05/2008	RuG	van de Weijgaert	Formation and evolution of galaxy clusters in cold dark matter cosmologies
W.F. Frieswijk	28/03/2008	RuG / SRON	Spaans co: Shipman	Early stages of clustered star formation : massive dark clouds throughout the Galaxy
P. Kamphuis	07/11/2008	RuG	Peletier, van der Kruit	The structure and kinematics of halos in disk galaxies
J.W. Kooi	22/12/2008	other	Wild, Klapwijk	Advanced receivers for submillimeter and far infrared astronomy
C.W. Ormel	10/10/2008	RuG	Tielens, Spaans	The early stages of planet formation: how to grow from small to large
P. Serra	11/04/2008	RuG	Trager co: Oosterloo, Morganti	Stars, neutral hydrogen and ionised gas in early-type galaxies
M. Barnabe	27/03/2009	NWO	de Bruin, Koopmans	Combined gravitational lensing and stellar dynamics analysis of early type galaxies
A. Berciano-Alba	09/11/2009	RuG / ASTRON	Koopmans, Garrett, de Bruyn	Strong gravitational lensing in the radio domain
C. Boersma	11/12/2009	NOVA	Tielens, Waters co: Allamandola	Infrared emission features: probing the interstellar PAH population and circumstellar environment of Herbig Ae, Be stars
J.S. Heiner	06/04/2009	RuG	van der Kruit, Allen	Large-scale photodissociation regions in nearby spiral galaxies
Y.S. Li	30/01/2009	NWO	Helmi	Local group galaxies in a lambda CDM universe
A.F. Loenen	23/10/2009	NWO	Spaans, Baan	Star formation and the ISM : interactions in the Milky Way and other galaxies
E. Platen	13/11/2009	NOVA	van de Weijgaert, Jones	A void perspective of the cosmic web
G. Sikkema	13/03/2009	RuG	Peletier, Valentijn	The influence of the environment on the evolution of galaxies
R.M. Thomas	20/03/2009	RuG	Zaroubi co: Koopman	Cosmological reionization simulations for LOFAR
A. Villalobos Coffre	25/05/2009	NWO	Helmi	Simulations of the formation of thick discs in galaxies
UL				
S. Albrecht	17/12/2008	NWO / EU	Quirrenbach co: Snellen	Stars and planets at high spatial and spectral resolution
R. van de Bosch	10/09/2008	NWO	de Zeeuw	Giant elliptical galaxies

	PhD date	Funding	Promotor	Thesis title
UL				
C. Brinch	22/10/2008	UL / EU	van Dishoeck co: Hogerheijde	The evolving velocity field around protostars
T. van Kempen	09/10/2008	NWO	van Dishoeck co: Hogerheijde	Probing protostars: The physical structure of the gas and dust during low-mass star formation
D. Schnitzeler	15/05/2008	NWO	Miley, de Bruyn co: Katgert	Faraday tomography of the galactic ISM with the WSRT
L. van Starkenburg	04/12/2008	NOVA	Franx co: Van der Werf	Dynamics of high redshift disk galaxies
C. Tasse	31/01/2008	UL	Miley co: Röttgering	Host galaxies and environment of active galactic nuclei
H. Verbraak	10/09/2008	FOM	Stolte co: Linnartz	High resolution infrared spectroscopy of ionic complexes
H.T. Intema	31/07/2009	NOVA / KNAW	Miley, co: Röttgering	A sharp view on the low-frequency radio sky
D. Lommen	15/04/2009	NOVA /NWO	van Dishoeck, co: van Langevelde, Wright	The first steps of planet formation
E.R. Micelotta	15/05/2009	UL / EU	Israel, Tielens	PAH processing in space
K.I. Öberg	31/08/2009	NWO / EU	van Dishoeck, Linnartz	Complex processes in simple ices
O. Panic	15/08/2009	NWO / EU	van Dishoeck, co: Hogerheijde	High angular resolution studies of protoplanetary discs
A.H. Pawlik	30/09/2009	EU / UL	Röttgering, co: Schaye	Simulating cosmic reionisation
D. Raban	28/02/2009	NWO	Röttgering, co: Jaffe	Infrared interferometric observations of dust in the nuclei of active galaxies
E.N.C. Taylor	31/08/2009	NWO	Franx, co: van Dokkum	Ten billion years of massive galaxies
R. Visser	31/10/2009	NWO	van Dishoeck	Chemical evolution from cores to disks
N. de Vries	31/08/2009	UL	Schilizzi, co: Snellen, Röttgering	The evolution of radio-loud active galactic nuclei
A-M. Weijmans	31/07/2009	NWO	de Zeeuw	The structure of dark and luminous matter in early-type galaxies
UU				
E. Glebbeek	25/06/2008	NWO	Langer co: Pols, Portegies Zwart	Evolution of the remnants of stellar collisions
L. Keek	01/12/2008	NOVA	Langer co: In 't Zand, Méndez	Probing thermonuclear burning on accreting neutron stars
N. Werner	13/05/2008	NWO	Verbunt co: Kaastra	X-ray spectroscopy of clusters of galaxies and of the cosmic web
M. Cantiello	06/11/2009	NOVA / UU	Langer	Observational consequences of Unstable Stellar Interiors
M.R. Duvoort	02/11/2009	UU	Achterberg, Heise co: van Eijndhoven	A search for gamma ray burst neutrinos in AMANDA
R.A. Scheepmaker	16/06/2009	NOVA / UU	Lamers	Star clusters in the Whirlpool Galaxy
F. Snik	26/10/2009	UU	Keller	Astronomical polarimetry: new concepts; new instruments; new measurements & observations
RU				
S.J. Lafebre	19/12/2008	FOM	Kuijpers, Falcke	From cosmic particle to radio pulse
A. Nigl	22/01/2008	ASTRON	Falcke, Kuijpers	Fast radio flashes observed with LOFAR prototypes
S.J. Buitink	01/10/2009	RU	Falcke, Kuijpers	Radio emission from cosmic particle cascades
R.A. Hijmering	21/12/2009	ESTEC	Groot co: Verhoeve, Martin	Distributed read-out imaging device array for astronomical observations in UV/VIS
H. Hu	06/10/2009	RU (convenant RU/KU Leuven)	Aerts co: Nelemans	Backtracking the evolution of subdwarf B stars with asteroseismology

5. Instrumentation Program

5.1. ALMA high-frequency prototype receiver

The NOVA-ALMA group at RuG and SRON is involved in two projects: the development and prototype production of the 600-720 GHz receiver cartridges for the ALMA project and the development of 600-720 GHz side-band separating mixers. The first project is discussed here, while the other is discussed in sections 5.1.2.

5.1.1. NOVA-ALMA Band-9 receiver cartridge

The Atacama Large Millimeter Array (ALMA) is a collaboration between Europe, North America, East Asia, and Chile, to build an aperture synthesis telescope consisting of at least 66 antennas at the 5000 m altitude Chajnantor plateau in northern Chile. When complete, ALMA will observe in 10 frequency bands between 30 and 950 GHz, with a maximum baseline of up to 14 km, offering unprecedented sensitivity and spatial resolution at millimeter and sub-millimeter wavelengths. Within the Netherlands, a collaboration of NOVA, the RuG, SRON, and the Kavli Institute of Nanoscience in Delft is building and testing heterodyne receivers for ALMA to operate at frequencies between 602 and 720 GHz. The work is done under a contract between the European Southern Observatory (ESO) and NOVA. As the highest frequency band in the baseline project, these so-called Band-9 receivers will provide the observatory's highest spatial resolutions and probe higher temperature scales to complement observations in the lower-frequency bands (between 84 and 500 GHz).

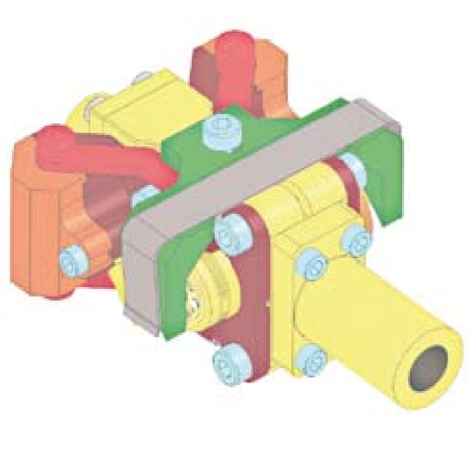
The final 8 pre-production phase cartridges were delivered in June 2008. Also in 2008 all contracts with suppliers were finalized. The request from ESO to accelerate the cartridge deliveries resulted in a contract amendment that was signed in April 2009. According to the amendment the last cartridge (#73) will be delivered in March 2012. This implies a gradual increase in cartridge production and testing from 1 cartridge every 3 weeks to 1 per 2.5 weeks. As of end 2009 the deliveries are well on schedule.

Most hardware procurement items are received or well underway to completion. Some items remain critical like the corrugated horns and the coin silver waveguides. These suppliers need and are getting much attention. Also the supply of junctions needs attention, in close contact with the Delft group the situation remains under control.

The ALMA Band-9 group in Groningen consists of the following persons: Jackson (project manager until 31-12-2009), Jager (project manager from 1-1-2010), Baryshev (project scientist), Adema, Barkhof, Bekema, v.d. Bemt, Gerlofsma, R. de Haan, M. de Haan (0.4 fte from Sept 09) Hesper, Keizer, Koops, Koops van het Jagt and Panman. The SIS junction group in Delft included Klapwijk (group leader), Lodewijk, Loudkov, Zijlstra and Zhu.

5.1.2. ALMA R&D phase-3

The main advantage of a sideband-separating (2SB) receiver compared with a double sideband (DSB) receiver is that it cuts out the atmospheric noise of the unwanted image sideband, which is significant at submillimeter wavelengths even at the best observing sites. Improvements in observing speed of up to a factor of two can be achieved under typical weather conditions at the ALMA site. This NOVA Phase-3 project (Fig 5.1) is based on the successful



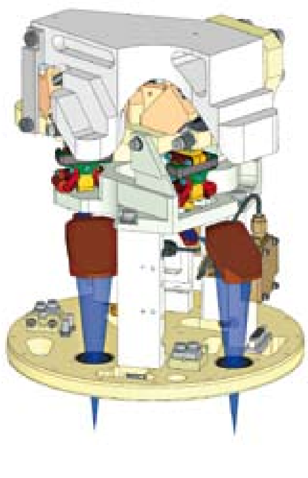


Figure 5.1: Left: the design of the ALMA band-9 2SB mixer concept. Right: layout of the ALMA band 9 2SB cartridge optics block.

development of the previous NOVA Phase-2 R&D project, which has demonstrated a working prototype of a 2SB mixer for the ALMA band-9 (602-720 GHz) atmospheric window. Performance of this prototype already meets ALMA specifications both for sensitivity and sideband ratio. The project is being done at the Kapteyn Astronomical Institute (RuG) in close collaboration with SRON and the Technical University of Delft. Spaans is the project PI and key people are Baryshev, Hesper, Gerlofsma, Jagers and Adema. In May 2008, P. Mena has left the NOVA group. He continued his involvement as assistant professor at the University of Chile, building up an astronomical instrumentation group. A collaboration between the two groups is being set up on prototyping the 2SB mixer. The NOVA project also benefited significantly from pan-European collaboration within the FP6 and FP7 RadioNet AMSTAR+ initiatives.

The NOVA Phase-3 projects aims to develop a prototype of a compact 2SB mixer module that fits into the current ALMA band-9 receiver cartridge. The main idea behind the design is to be able to upgrade the existing ALMA band-9 receivers, which are currently double sideband, into 2SB versions while reusing most of the existing components and with as little modification as possible. During the 2008 - 2009 period, a detailed mechanical mixer design has been made and the ALMA band 9 cartridge design has been modified to fit the 2SB option. It was demonstrated that it is possible to improve the existing cartridge such that all elements fit together in the space available. Based on this, the project proceeded further to build the first mechanical prototype of the new 2SB mixer in order to study its manufacturability and to provide valuable feedback to further optimize the design towards a small series production. The latter is required for a possible ALMA band-9 upgrade or for large format focal plane array production. Conveniently, the ALMA band-9 DSB SIS mixer parts can be reused in this. The ALMA band-9 2SB mixer concept and the cartridge optics block lay-out are illustrated in Fig 5.1.

5.1.3. Allegro

Following its establishment in 2005, Allegro (ALMA Local Expertise Group), the Dutch node of the European ALMA Regional Center (ARC) network, made significant progress in 2008 and 2009. The ALMA project itself underwent a 'phase transition' with the first (provisional) acceptance of antennas by the project, the transportation of the first 3 antennas from the Operations Support Facility to the Array Operations Site, and the establishment of three-element interferometry by late 2009. Currently, the process of assembly/integration/verification and commissioning/science verification is going ahead full-speed; a call for early science is planned for late 2010 with early science starting in mid-2011; and completion of the array is foreseen for 2013.

In Europe, the ALMA Regional Center network was formalized by the signing of a Memorandum of Understanding in the Summer of 2008 between the nodes (ESO/Garching, Allegro, Bonn/Cologne/Bochum, Manchester, Bologna, IRAM, and Onsala); a seventh node in the Czech Republic is being set up. An Implementation Plan, agreed on in the Fall of 2009, further details the activities of the central core at ESO and the various nodes of the European ARC. Specific attention is given to a uniform presentation of information to the prospective ALMA users, e.g., through the design of a single (set of) logos. The European ARC web site (http://www.eso.org/sci/facilities/alma/arc/) describes the ARC network.

In the Netherlands, the activities of Allegro cover both face-to-face user support for the general user, and specialist support in three areas. These are (1) observing at high frequencies, (2) obtaining data at high dynamic range and of wide fields, and (3) providing access to advanced science analysis tools for the interpretation of atomic and molecular line data from ALMA.

In 2008 and 2009, the Allegro staff consisted of Hogerheijde (coordinator), van der Tak (focusing on maintaining the molecular database), Hill (postdoc until February 2008), Frieswijk (postdoc since May 2008, focusing on high-frequency observing and software testing), and Brinch (NWO funded postdoc since September 2009, focusing on hardware and software). In addition, Schleicher joined Allegro on an ESO fellowship funded by the European Union. Significant efforts were spent to try and find a suitable candidate for a 5-year fellowship, two of which to be spent in Chile as part of the ALMA commissioning team; given the highly competitive labor market in this field, it took until late 2009 to reach agreement with a good candidate (van Kempen) who is expected to start in the second half of 2010.

The activities of Allegro in 2008 and 2009 centered on three themes: (1) the development of a website with user information, (2) participation in testing of software for ALMA, in particular the CASA offline reduction package and the OT observing preparation package, and (3) the use of APEX/CHAMP+ and enhanced-SMA (the interferometric link up of the Submillimeter Array, James Clerk Maxwell-Telescope, and the Caltech Submillimeter Observatory) data as testbed for high-frequency submillimeter and interferometric observations. The APEX/CHAMP+ observations resulted in a memo describing a list of AGB stars suitable as line calibration targets for ALMA.

An important step in the development of Allegro in 2008-2009 was the proposal submitted by Hogerheijde and van Dishoeck to NWO to secure long-term funding for Allegro. This proposal was successful, and funding has been secured at a 5-fte level. The funding starts with a ramp-up in 2009, reaches its full level in 2012, and is subject to periodic review. As part of the agreement with NWO, Allegro is currently in the process of reforming its 'steering committee' (currently consisting of Barthel, Oosterloo, van Langevelde, Roelfsema, and van Dishoeck) into a more formal Board.

5.2. OmegaCAM

OmegaCAM is the wide-field camera for the VLT Survey Telescope (VST). Its focal plane contains a 1x1°, fully corrected field of view, which is tiled with 32 CCD detectors (2048x4096 pixels) for a total of about 16,000 x 16,000 pixels – a quarter of a gigapixel. The camera and telescope are designed specifically for good image quality, and the detector array will sample the excellent seeing on Paranal well with 0.2 arcsec per pixel. The total cost of the instrument is of the order of 6 M€. NOVA leads the project, and contributes about 1/3 of the funding. Other partners in the project are the university observatories of Munich, Göttingen and Bonn in Germany, Padua and Naples in Italy, as well as ESO who developed the detector and associated cooling systems.

OmegaCAM and the VST are expected to have an operational lifetime of at least 10 years. By way of payment for the instrument, ESO grants guaranteed observing time. For NOVA its share is about four weeks of VST time per year, over the lifetime of the instrument.

The key NOVA deliverable to the project has been the development of the data processing software that will run in ESO's data flow system. Building on this experience, a data center for OmegaCAM, OmegaCEN, was set up in Groningen in order to support scientific use of OmegaCAM in the form of calibration and archiving, data processing and expertise. OmegaCEN activities are described in more detail below.

In 2006 OmegaCAM was completed and delivered to ESO. Unfortunately the telescope project was hit by a series of delays, most recently a shipping accident involving the primary mirror cell. The cell is now being refurbished and is expected back on Paranal in early summer 2010. Commissioning of telescope and camera should start before the end of 2010.

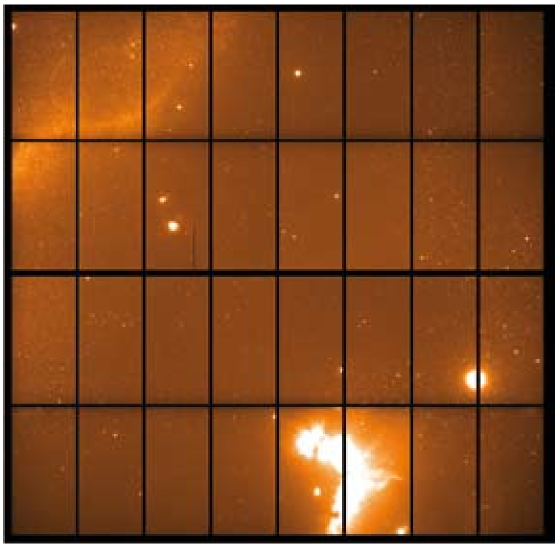


Figure 5.2: 256 Mega pixel test image of OmegaCAM.

5.2.1. OmegaCEN data center

5.2.1.1. Data center

OmegaCEN is the national datacenter for wide-field imaging and the expertise center for astronomical information technology. It is situated at the Kapteyn Astronomical Institute of the RUG and its core staff is funded by NOVA. The center is headed by Valentijn and brings together astronomers and astronomical IT experts. About 15 scientists (staff, postdocs, PhD students and scientific programmers) work at the center. OmegaCEN is partner in various optical and radio wide field surveys, conducted by international collaborations. The largest of these is the Kilo Degree Survey (KiDS).

OmegaCEN is coordinator of Astro-WISE, a unique, advanced survey information system for astronomy. Astro-WISE connects in real-time databases, compute and storage grids available at national datacenters and satellite nodes in the Netherlands, Germany, Italy and France. Geographically-spread survey teams collaborate in this single virtual research environment. Here, they calibrate astronomical wide field imaging data up to the Petabyte regime, do research analysis and publish the results. The KiDS team is ready to use Astro-WISE for the KiDS survey processing.

Figure 5.3: The picture shows a small region of the merging galaxy cluster A2RXCJ0014.3-3022. Contours indicate surface densities of blue and red galaxies. The red contours form a part of the outer regions of the cluster. The blue contours represent an over density of blue galaxies in the inter cluster space. The labeled galaxies are very bright blue galaxies found in the outskirts of the cluster which appear to flame up when falling from outer inter cluster space into the cluster, suggesting the witness of the morphological transitions of galaxies when they fall into the cluster domain. The galaxy evolution part of the KIDS program plans, among other things, to locate and study galaxies during their transitional phases (from: Braglia et al.2007, A&A, 470, 425).

The Astro-WISE system is ready to be filled with 100's of Terabyte of imaging data by the teams of public and GTO surveys of VST/OmegaCAM and VISTA/VIRCAM. The Astro-WISE astrometric pipeline is thoroughly tested (Astro-WISE astrometry report, McFarland et al., 2008). The experience with processing and quality control of an extensive subset of CFHT Legacy Survey, in the summer 2009, was used to write a detailed OmegaCAM Surveys Operations Plan. This Operations Plan will be applied to the survey operations for the KiDS 1500 square degree survey and its VISTA near-IR complement, the VIKING survey (5 filters: Z, Y, J, H, and K_s).

The extensive (web)services for database browsing, processing and publishing were improved. A new web service, Quality-WISE, serves as a single portal for scientists to efficiently qualify survey data (see Verdoes Kleijn et al., 2009). The Astro-WISE Grid was integrated with the EGEE Grid which enables the Astro-WISE applications to run on the EGEE Grid as a preparation for LOFAR operations. This merging of grid technologies has been published in a refereed computational science journal.

NOVA-OmegaCEN is the national representative for European Virtual Observatory (EURO-VO) programs. In the framework of these programs OmegaCEN developed the infrastructure to access data residing in Astro-WISE through the Virtual Observatory. To access the Virtual Observatory resources from within Astro-WISE a package was built using the Plastic/SAMP communication protocol (PhD Buddelmeijer). This is part of OmegaCEN's R&D track to build a query-driven visualization infrastructure for very large, multi-dimensional datasets.

5.2.1.2. R&D astronomical information technology

The goal at OmegaCEN in this research area is to enable astronomers to efficiently run their mining algorithms, specialized processes and to publish results for a Petabyte-sized ocean of data. All steps are executed while keeping track of the processing configuration and propagation of data. Research is performed on Extreme Data Lineage in a distributed environment (Nuffic-PhD Mwebaze). The aim is to exploit data lineage in scientific pipelines to the subimage level and eventually couple applied methods and programs to the data in a database. A review of the usage of data lineage in scientific processing and OmegaCEN's approach was published in a refereed computational science journal.

Query-driven visualization of very large catalogues was developed by PhD Buddelmeijer in collaboration with the Scientific Visualization group of the Computing Science department (PhD Ferdosi).The goal is to give within the visualization process direct access to multi-dimensional 10-100 Tbyte datasets, which current visualization techniques cannot handle 'stand-alone'. It is leading research in a new domain called 'query driven visualization' which is currently emerging. A first prototype for query-driven visualization was designed and implemented in Astro-WISE.

The unique e-science aspects of the system triggered other parties to use it as a platform as well. In particular, the novel concept of 'entire backward chaining' (the linking of data products to the input raw data) has drawn attention as it provides a backbone for the

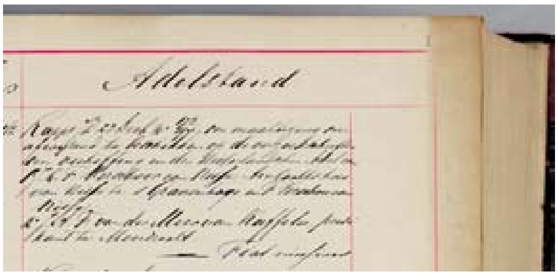


Figure 5.4: The first example of the Astro-WISE information system being used outside astronomy: images of handwritten texts from the Dutch government are currently being analyzed using Astro-WISE, aiming to provide easy access to the hundreds of meters of paper archives by means of intelligent computing. Handwriting recognition code is run on the IBM Blue Gene supercomputer to interpret the archives of the Kabinet van de[n] Koning[in].

infrastructure for advanced distributed e-science. This NOVA-funded development has culminated in a large spin-off in 2009: the Target program, coordinated by Valentijn. Target is a collaboration between five science/research groups (OmegaCEN, ASTRON/LOFAR, Artificial Intelligence (RuG), Donald Smits Center for Information Technology (RuG) and the University Medical Center at RuG) and 5 high-tech business enterprises (including IBM and Oracle). The Target partners drew up an innovative 32 M€ four year program. The Ministry of Economic Affairs, Samenwerkingsverband Noord Nederland (SNN), Sensor Universe, the provinces of Groningen and Drenthe and the city of Groningen have awarded the program with grants over 16 M€ in total. The rest is fully co-financed by the partners. Scientific research groups and businesses jointly develop and improve complex and scalable information systems aimed at very large datasets for scientific and commercial usage. The program has been presented at numerous occasions, ranging from Sensor Universe Bestuurlijk platform, SSN program committee, XLDB meeting (Lyon), Nikhef (Amsterdam), Akkoord van Groningen (mayor Groningen and city council), and privately to the Prime Minister, Balkenende.

Within the Target program OmegaCEN designed and built the Long Term Archive for LOFAR. The prototype was delivered in December 2008 and the archive in December 2009. A first rehearsal, filling the Long Term Archive while off-loading the LOFAR central processor was conducted successfully in November 2009. Within the Target framework, OmegaCEN led the data-handling study for

Figure 5.5: Meeting with the board of the University at the awarding of the Target grant. From left to right: Poppema (President RuG), Valentijn (Head OmegaCEN and Target), Janz (General manager Donald Smits Center for Information Technology), and Duppen (Member of the Executive Board of RuG).

the proposed ESA Class-M mission EUCLID. The Euclid Science Study team, of which Valentijn is a member, delivered the Euclid study report for ESA's down-selection procedure. Through NOVA,

OmegaCEN also contributed to the Phase-A study for MICADO instrument, which is proposed for the E-ELT. OmegaCEN provided the first design for its data flow system.

An international panel, chaired by O'Mullane (ESA), reviewed OmegaCEN in the fall of 2008. Its assessment was very positive. They pointed at two critical areas: understaffing of the center (now counterbalanced by the Target program) and the lack of an operation plan for VST data handling (now produced and delivered - see above).

5.2.2. Science to be done with OmegaCAM & OmegaCEN

A number of large surveys were planned for Omega CAM, three of which had a significant Dutch involvement:

- KiDS, and its counterpart on VISTA named VIKING, is the most challenging of the VST surveys. It will cover 1500 square degrees in 9 bands from U to K, and is designed as a combined weak gravitational lensing/photometric redshift survey. Also the growth of the amplitude of large-scale structure can be studied with KiDS: this provides one of the most powerful ways to study the expansion history of the universe and hence the nature of the dark energy. Additional scientific rewards from KiDS/VIKING will include samples of very high redshift quasars, very faint brown dwarfs, and Galactic halo stars, as well as a detailed study of galaxy population statistics as a function of environment.

- The second-largest VST public survey, the Galactic Plane Survey VPHAS+, significantly involves the Nijmegen Department for Astrophysics (co-PI Groot). It complements a similar survey of the Northern Galactic plane carried out with the Isaac Newton Telescope on La Palma.

- The largest Dutch guaranteed time project on OmegaCAM is VESUVIO, a study of the galaxy population in nearby superclusters. Staff of the Kapteyn Institute (Heraudeau, Trager, Valentijn, Peletier, and van de Weijgaert) designed an extensive observing program of nearby superclusters. This program will start with a deep 12 square degree survey of the Hercules supercluster and will be extended later with a large 100 square degree survey of the Horologium supercluster. For this

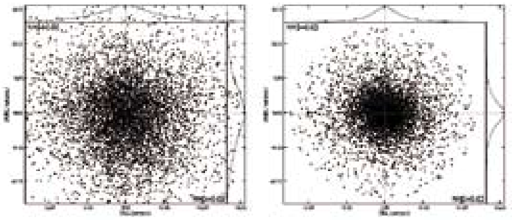


Figure 5.6: Astro-WISE global astrometry at work. Improvement from the local (chip-by-chip) astrometric solution to the global (all chips and pointings at once) astrometric solution. The two-dimensional RMS of the source position residuals from astrometrically corrected frames improves from 0.077 arcsec for the local solutions (left panel) to 0.041 arcsec for the global solution (right panel).

multispectral study also X-ray XMM-Newton observations (Bohringer, Kaastra) and HI observations (Valentijn, van Gorkom) are planned.

The public surveys with OmegaCam are now under internal review, due to the large delays. These large projects involve international consortia, and in the current situation, with many competitor surveys starting, they need to be re-evaluated. The scientific niche is still open, but a number of consortium partners are no longer able to guarantee their original commitment of manpower to the project. The OmegaCAM Consortium has therefore started a process, also involving ESO, to reorganize these projects.

Astronomical research using the Astro-WISE system in the Netherlands was carried out by Valentijn, McFarland, Belikov, Verdoes Kleijn, Peletier, den Brok, Sikkema, Buddelmeijer, Nelemans and Spooren. In Groningen it focused on the area of galaxy evolution as a function of environment: in the Coma cluster using the HST/ACS Coma Legacy Survey by den Brok (PhD); in nearby superclusters and field using a WFI survey by Sikkema (PhD) and of large volumes of the nearby universe using UKIDSS/SDSS catalogs (Buddelmeijer, PhD). In Nijmegen Galactic compact binaries were studied by Spooren (student).

5.3. Sackler Laboratory for Astrophysics

The Sackler Laboratory for Astrophysics is one of the few places world wide where experimental research is fully dedicated to the study of inter- and circumstellar matter. The laboratory comprises seven experiments – five solid state experiments (SURFRESIDE, CRYOPAD, CESSS, HV-setup, MATRI²CES) and two gas phase setups (LEXUS, SPIRAS) - focusing on processes in inter- and circumstellar ice analogues and molecular transients of astrophysical interest. The Laboratory led by Linnartz, since 2008 also associated with the Laser Center at Vrije Universiteit in Amsterdam on a special chair of 'Molecular Laboratory Astrophysics', is fully embedded within the infrastructural settings of Leiden Observatory. Science results are described in section 3.2.15 and here recent instrumentation developments are summarized.

5.3.1. SPIRAS - Supersonic Plasma InfraRed Spectrometer

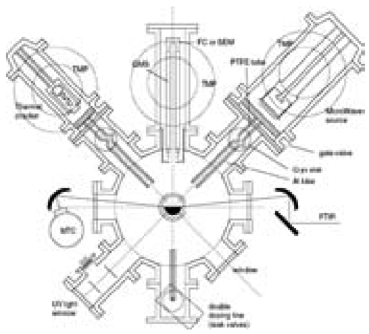
At SPIRAS (Supersonic Plasma InfraRed Spectrometer) a new sensitive detection technique is implemented based upon cw cavity ring-down spectroscopy using a new tunable OPO based infrared laser system, financed through a NWO-M grant. The system allows studying molecular transients of astronomical interest in direct absorption with absolute accuracies of the order of 20-50 MHz (in the infrared). The results will be used to guide tunable far infrared work (200-750 GHz) on SPIRAS and in support of identifying upcoming HIFI data.

5.3.2. MATRI²CES - Mass Analytical Tool of Reactions in Interstellar ICES

MATRI²CES (Mass Analytical Tool of Reactions in Interstellar ICES), combines solid state and gas phase techniques with the aim to monitor chemical reactions in inter- and circumstellar ices in situ and in real time with a sensitivity that should be orders of magnitude higher than with regular surface techniques. All major parts have arrived and the setup is currently assembled.

5.3.3. SURFRESIDE - SURFace REactions SImulation Device

SURFRESIDE (SURFace REactions SImulation Device; Fig. 5.7) is currently extended with a second beam line in which O- and N-atoms are generated in a continuous microwave discharge source to simultaneously bombard an interstellar ice analogue with different atoms (H+O or H+N). This makes it possible to study new and more complex reaction pathways. A simultaneous bombardment of CO ice with H- and O- or N-atoms may lead, for example, to the formation of ethylene glycol ($HOCH_2CH_2OH$) or amino methanol (NH_2CH_2OH), respectively. As all experiments are performed time resolved, reaction rates can be determined.



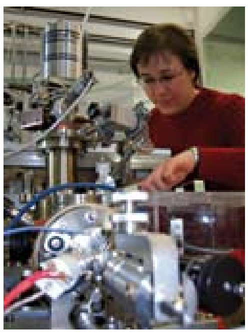


Figure 5.7: Left: A schematic of the extended version of SURFRESIDE – as currently under construction – in which a second atomic beam line is added to study simultaneous H/N or H/O addition reactions. Right: NOVA postdoc Claire Romanzin at work at SURFRESIDE.

5.4. JWST-MIRI

The Mid-Infrared Instrument (MIRI) is a combined imager / integral field spectrometer covering 5-28 μm on board the James Webb Space Telescope (JWST), the successor of HST to be launched around 2014. The Netherlands, led by NOVA (PI: van Dishoeck, deputy-PI: Brandl) with ASTRON and TPD as subcontractors and with contributions from SRON, is responsible for the camera and dispersion optics of the spectrometer. With its unprecented combination of sensitivity, spatial and spectral resolution, MIRI will provide a huge discovery space and will have tremendous power for studying the mid-infrared sky. It will make key contributions to science themes ranging from the `first light' in the Universe to the assembly of galaxies, the birth of stars and proto-planetary disks, the evolution of planetary systems and the organic material contained within them, and exo-planetary atmospheres.

The main aims of the NOVA project are:
1. design, build and deliver the Dutch part of the spectrometer to the European consortium according to specifications;
2. ensure strong Dutch participation in the scientific exploitation of MIRI;
3. retain and further develop mid-infrared scientific and technical expertise in the Netherlands, important for securing a Dutch role in future infrared instruments.

The MIRI instrument is designed and built by a joint US/European consortium. The European Consortium is led by the UK (PI G. Wright), with Germany, France, The Netherlands, Belgium, Spain, Switzerland, Ireland, Sweden and Denmark as partners. Europe is building the entire camera/spectrometer unit, the so-called Optical Bench Assembly (OBA). Scientific oversight is through the joint NASA-ESA MIRI Science Team (MST, co-chairs: G. Rieke, G. Wright), of which van Dishoeck was a member up to 2008, and in which Brandl participates as instrument scientist. Significant MST activities in 2008-2009 included updates of the MIRI calibration and operation plan documents, time assessment tables and overheads, observing modes including optimal dither patterns, selection of the flight detector arrays and their spares, analysis of MIRI Verification Module (VM) test data and their software, and planning of the guaranteed time.

The Dutch project office is located at NOVA-ASTRON, with R. Jager as the Dutch project manager. NOVA-ASTRON leads the optical and mechanical design of the Dutch part of MIRI, and does the end-to-end modeling, prototyping, testing and manufacturing. TPD's contribution was in the optical design in the early stages. SRON has a consultancy role, and provides support in the area of space qualified design, and PA/QA.

Funding for the Dutch contribution of MIRI was secured in 2003 by commitments from NOVA, a NWO-Groot proposal and in-kind contributions from the universities, ASTRON and SRON. The ESA-SPC confirmed the European contribution to JWST and the MIRI consortium in late 2003, and NOVA signed the Formal Agreement with ESA on behalf of the Netherlands. A European MIRI steering committee with representatives from the various agencies contributing financially to MIRI oversees the project, including Boland on behalf of NOVA. In late 2007, NOVA provided through its Phase-3 program for a calibration scientist in the post-delivery phase, participating in the ground testing and calibration (including deriving a well characterized relative spectral response function before launch) and developing data reduction algorithms for the integral field spectrometer.

5.4.1. Technical progress in 2008-2009

5.4.1.1. Hardware

The light from the JWST focal plane is split spectrally into four paths by sets of dichroic filters mounted in a wheel. The resulting four passbands are fed into four IFU's where the images are sliced and reassembled to form the entrance slits for the spectrometers. The light from each IFU is separately collimated and dispersed. The spectra from pairs of gratings are then imaged by two cameras onto two 1024x1024 Si:As detector arrays cooled to 7 K. This results in a division of the full 5-28.3 μm wavelength range into four equal channels. Full wavelength coverage is obtained in three grating moves using a single grating wheel mechanism. The spectrometer input/pre-optics (SPO) with the dichroics and IFU's are provided by the UK whereas the actual spectrometer main optics (SMO) with collimator-grating camera optics are the responsibility of the Netherlands. The gratings mechanism is contributed by Germany and the detector units are US responsibility.

In 2008, both the Long Wave (LW) and Short Wave (SW) arms of the flight model (FM) SMO hardware, constructed in 2007, were optically tested at ASTRON before and after vibration and thermal vacuum cycling. No significant changes in the optics were found. Delivery of the SMO to the Rutherford Appleton Laboratory (RAL) took place on August 20 2008, the first major FM hardware to be delivered. Following delivery, additional qualification

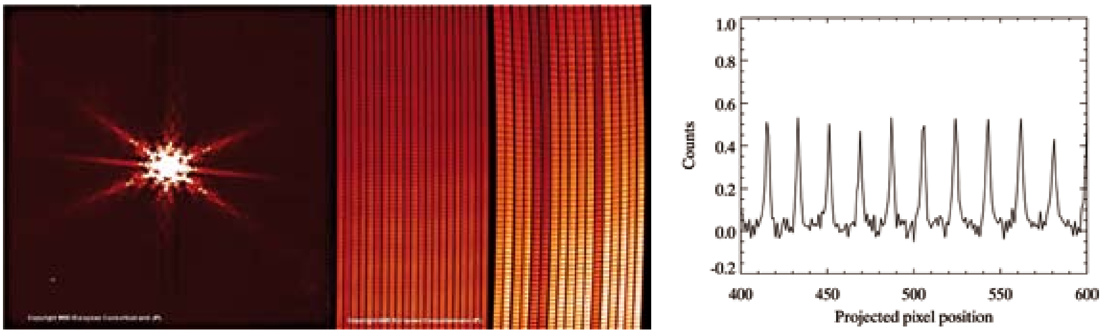


Figure 5.8: MIRI VM spectrometer test results obtained in the cryo-vacuum chamber at RAL in 2008. The individual image slices are clearly seen. The strong fringing in the spectral (vertical) direction is well characterized and analyzed by Lahuis. These data verify many of the MIRI optical design and performance parameters. Right: VM2 test spectrum of one of the IFU slices obtained in the cryo-vacuum chamber at RAL in September 2008. The estimated spectral resolution is consistent with that predicted by the optical model. Data are taken and reduced by NOVA PhD student Rafael Martinez.

tests were required for the gold coating.
The Grating Wheel Assemblies (GWA) were delivered to MPIA at Carl Zeiss late June 2008. Due to very late delivery of the last grating for channel 3 from Carl Zeiss Optronics (ZeO) to NOVA-ASTRON, the Dutch testing activities concentrated on optical tests only. A new US supplier was found for the channel 4 gratings, which were delivered in January 2009, in time to include them in the grating wheel that was returned from Zeiss to ASTRON for this purpose. The Delivery Review was formally closed in February 2009.

5.4.1.2. Testing and software

Planning for integration, testing and calibration on the ground and in-orbit ramped up considerably in 2008-2009. The MIRI EC has developed a plan for post-delivery support of MIRI, covering the periods of the VM and FM testing and other pre-launch activities up to 2013, as well as post launch activities including in-orbit commissioning, calibration and science verification. This support is essential to maintain a visible European role within the JSWT project during the long period between instrument delivery to Goddard and launch some 4 years later, as well as to reap the scientific benefits immediately after launch.

A significant part of the activities focused on obtaining and analyzing the VM test results obtained in 2008, by Kendrew (NOVA PD), Martinez (NOVA PhD), and Lahuis (NOVA SRON/Leiden). After receiving full training at RAL on the test operations, software and scripting language, they have participated in the design and execution of the VM1 and VM2 test campaigns and are well prepared for FM testing in late 2010. The Dutch test team focused on the characterization of the spectrometer performance, in particular the wavelength calibration, spectral resolution, line shape analysis, fringing and related issues (Fig. 5.8).

Lahuis is taking the lead in defining software requirements for high-level analysis of the FM test data and in outlining a roadmap toward the development of the MIRI science pipeline and offline packages, in collaboration with partners, with a focus on the medium resolution spectrometer modes. In June 2008 a meeting was organized between representatives of the MIRI-EC and STScI to discuss collaborations and Lahuis has since that time been the main point of contact between the MIRI-EC and the STScI for software development.

5.4.2. Science preparation

A Dutch national 'Science with JWST-MIRI' discussion day was held in Leiden in December 2008, to which the entire Dutch community was invited. Waters, Kamp and van der Werf were selected as the Dutch science co-Is. Together with van Dishoeck, Brandl and the Dutch MIRI test team members, they are part of the European consortium science team that defines the guaranteed time program. All Dutch science team members have leading roles in the main science themes on the high redshift Universe, protoplanetary disks, protostars and exoplanets. A joint meeting with the US MIRI mission scientists was held in June 2009.

5.5. Multi Unit Spectroscopic Explorer, MUSE

5.5.1. General description of the project

MUSE, the Multi Unit Spectroscopic Explorer, is a second-generation panoramic integral-field spectrograph for the VLT, due to begin operation in 2012. The instrument consists of 24 combined identical integral-field spectrograph units, covering simultaneously the spectral range 0.465-0.93 µm. MUSE will have two modes of operation, both of which are explicitly designed to exploit a complex multi-laser guide star (LGS) Adaptive Optics (AO) system, called GALACSI (Ground Atmospheric Layer Adaptive Corrector for Spectroscopic Imaging), envisioned as part of the approved VLT AO Facility (AOF), at the heart of which is the development of a Deformable Secondary Mirror (DSM) for the VLT.

The primary mode of MUSE has a wide (1 x 1 arcmin) field of view, is able to operate with or without the AOF, and will be used for conducting uniquely sensitive deep-field surveys with the key goal of understanding the progenitor population of present-day

Figure 5.9: Left: AM1 under test at AMOS, the manufacturer of AM1. Shown is AM1 after its spherical lapping. In its final shape, AM1 will be an 1.7-meter aspherical mirror with a standard aluminum coating. Right: the support for AM1, manufactured at Boessenkool, in Almelo. This is the support without surface protection.

'normal' galaxies. The second mode of MUSE aims to provide the unique capability of near-diffraction limited spatial resolution at optical wavelengths over a large 7.5 x 7.5 arcsec field. This will be used for a variety of science goals, including monitoring solar-system bodies; studying the complex emission regions of Active Galactic Nuclei (AGN), and studying young stellar objects.

Critical to ESO's DSM development (and therefore also to MUSE) is ASSIST: Adaptive Secondary Setup and Instrument STimulator. This facility will act as the primary test-bench for ESO's DSM development, used for verifying control algorithms and hardware, functional validation of AO-Facility instruments, and ensuring the DSM operates at specification before being deployed at the VLT. ASSIST will be developed and assembled in Leiden and is due to start operation at ESO, Garching, at the end of 2011, given by the delivery of the DSM.

NOVA's involvement in the MUSE instrument is many-fold, distributed across three inter-related areas of the MUSE project:

- **The MUSE spectrograph scientific impact:** participation in the MUSE science team and Guaranteed Time Observation (GTO) allocation, providing key operations-based deliverables, like the MUSE Exposure Time Calculator (ETC), and estimating the achievable sensitivities in the different instrumental and target configurations.
- **The Interface Control (Document) [ICD]:** controls all aspects of interfacing MUSE with the GALACSI AO system and VLT AO Facility. This also involves the development of tools required for optimal use of the AO system for scientific use.
- **The Adaptive Secondary Setup and Instrument Stimulator [ASSIST]:** This facility will act as the primary test-bench for ESO's DSM development, used for verifying control algorithms and hardware, functional validation of AO-Facility instruments, and ensuring the DSM operates at specification before being deployed at the VLT. ASSIST is developed and will be assembled in Leiden and is due to start operation at ESO, Garching, at the end of 2011.

5.5.2. Progress in 2008-2009

MUSE has passed its Final Design Review (FDR) and is now in the Manufacturing Phase, to be closed with the Preliminary Acceptance Europe in July 2011. Nearly all optical components have been ordered and the first of the 24 spectrographs has been received and tested. The spectrographs are, together with the detector system, the most critical components, since there are 24 of them which each need to be assembled, tested and characterized.

ASSIST, the test facility for both the DSM as well as the two AO systems GALACSI and GRAAL, has passed its Final Design Review and is, like MUSE, currently in its Manufacturing Phase. All optics have been ordered (see the main optical element AM1 being polished at AMOS in Fig. 5.9, as well as the first mechanical components, like the AM1 support structure).

NOVA also maintains the interfacing between the simulations of the AO system and the MUSE instrument. NOVA has introduced PAOLA, a fast, Fourier-based Adaptive Optics simulation tool that enables one to predict the performance of MUSE under a large number of conditions. PAOLA has been benchmarked with the full end-to-end model, 'Octopus', from ESO. Octopus has been used by the GALACSI team to predict the performance of GALACSI (plus MUSE) in a number of test conditions, but the simulation speed of Octopus inhibits the simulation of a large range in parameter space. The results from Octopus and POALA were found to be nearly identical. The results from PAOLA are now used to run a full end-to-end model of MUSE and are implemented in the Exposure Time Calculator, also developed by NOVA and now implemented by ESO.

Both the MUSE and ASSIST projects are governed by their individual agreements with ESO. The two projects together will yield a total of 255 nights of

GTO time for the MUSE consortium on MUSE, to be used mainly for a coordinated deep survey. In parallel with the development of the MUSE instrument, several science team meetings have been held to discuss the use of the GTO time and required preparatory observations. Furthermore, the science team has been keeping a close eye on the impact of the design of MUSE with regards to the scientific performance of MUSE.

The MUSE team in the Netherlands is led by Schaye together with Franx, the MUSE Survey Scientist. Furthermore, Serre (NOVA postdoc) works full-time on MUSE, developing, among other things, the MUSE Exposure Time Calculator and he is working on the problems of data calibration and de-convolution. Further contributions to the MUSE science were made by Brinchmann (also member of the MUSE Science Team), Van de Voort (PhD, virtual deep Ly-α fields and cosmological simulations) and Rakic (PhD, explored what MUSE can do to study the interaction between galaxies and the intergalactic medium). The MUSE Local Project Manager and ASSIST Project Manager is Stuik. The simulations of the Adaptive Optics performance for both MUSE/GALACSI as well as ASSIST were done by Jolissaint. The development of ASSIST was done by Molster (deputy project manager), Hallibert (optical design), Deep (Assembly, Integration and Testing), Wiegers (mechanical construction), Kendrew (analysis) and Pauwels (Product Assurance). The mechanical design of ASSIST was done in collaboration with (mainly) Hans Ellermeijer (UvA).

5.6. X-shooter

X-shooter is the first second-generation instrument for the ESO Very Large Telescope and the most powerful optical and near-infrared medium-resolution spectrograph in the world, with a unique spectral coverage from 300 to 2500 nm in one shot. The Dutch contribution to X-shooter is one of the three spectrographs: the near-infrared arm, designed, constructed and tested at ASTRON and its cryogenic enclosure at the Radboud University in Nijmegen. This has been delivered to ESO in March 2009 and the whole X-shooter is available for the user community since October 2009. The strong demand for VLT/X-shooter has been demonstrated by the two first Calls for Proposals from the ESO user community. More than 150 proposals were received for both (semester) calls, making X-shooter the one but most demanded instrument (of the 11) on the VLT. The pressure factor on X-shooter observing time is comparable to that on Hubble Space Telescope. The X-shooter consortium members are from Denmark, France, Italy, The Netherlands and ESO. Kaper is the Dutch PI and member of the Project Board, Groot is co-PI and chairman of the X-shooter Science Team, and Navarro (ASTRON) is the NL Project Manager.

Figure 3.10: The X-shooter spectrograph at the Cassegrain focus of Unit Telescope #2 of the ESO Very Large Telescope.

X-shooter has a broad and varied usage ranging from nearby intrinsically faint stars to bright sources at the edge of the Universe. The unique wavelength coverage and unprecedented efficiency opens a new observing capacity in observational astronomy. At the intermediate resolution of X-shooter 80-90% of all spectral elements are unaffected by strong sky lines, so that one can obtain sky continuum limited observations in between the sky lines within a typical exposure time. Key science cases to be addressed with X-shooter concern the study of brown dwarfs, the progenitors of supernovae Type Ia, gamma-ray bursts, quasar absorption lines, and lensed high-z galaxies, intimately linked to the NL science interests. The advantage of the large wavelength cover-

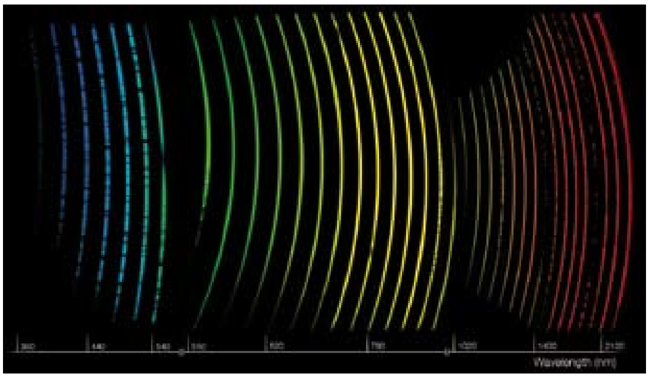


Figure 5.11: The unique wavelength coverage of VLT/X-shooter demonstrated by the ultraviolet, visual and near-infrared spectrum of a quasar.

age is that e.g. the redshift of the target does not need to be known in advance (such as in the case of GRBs); also, the study of Lyman alpha in high-redshift galaxies will be possible in the redshift range $1.5 < z < 15$.

5.7. Spectro-Polarimetric Exoplanet Research (SPHERE)

5.7.1. Overall status of the project

The second generation VLT instrument SPHERE (Spectro Polarimetric High contrast Exoplanet REsearch) is an extreme adaptive Optics facility aimed at the direct detection and characterization of exo planets. SPHERE is optimized to detect gas giant planets in wide orbits, but will also contribute to the study of proto-planetary disks and the envelopes surrounding evolved stars. The extreme AO system feeds three science arms, IRDIS and IFS for near-IR detection of thermal emission from young gas giant planets, and ZIMPOL for the detection of old gas giant planets in polarized reflected light. The Netherlands is contributing to the ZIMPOL system, which is a sensitive imaging polarimeter to detect the faint reflected light signal from extrasolar gas planets in wide orbits. The ZIMPOL group is led by the ETH in Zurich (Schmid), the Dutch PI for ZIMPOL is Waters (UvA), system engineer is Roelfsema, project manager is Pragt (NOVA-ASTRON). NWO, NOVA, the UvA, ASTRON and Utrecht University are contributing to the project. In the reporting period 2008-2009, work on SPHERE focused on the finalization of the full design of the instrument, which resulted in the successful passing of the Final Design Review (FDR) in December 2008. In 2009, procurement and manufacturing of the different components was taken up.

5.7.2. Instrument progress and status

The top-level science requirements for ZIMPOL (a contrast ratio of 10^{-8} between the polarized flux of the planet and the flux of the star) set strict limits on the performance of some key optical elements. In particular, ZIMPOL performance simulations show that the Ferro-electric Liquid Crystal (FLC), used to convert the polarized signal into a time dependent intensity signal, and a Half-Wave-Plate, used to reduce instrument polarization, have a strong impact on the final performance of ZIMPOL. A large effort has therefore been made to study these components. A first batch of FLCs did not meet the requirements. However, in collaboration with the supplier, new FLCs were manufactured that are of a sufficient quality to meet the top level requirements. The measured quality of FLC and Half Wave Plates show that ZIMPOL should reach the photon noise limit.

In 2008 the instrument design developed towards the FDR at the end of the year. The design was detailed optically, mechanically and electrically. Testing and calibration plans were defined and several interfaces and shared work packages with other teams were described in detail such as the total optical performance including extreme AO together with LAOG in Grenoble, data reduction software together with MPIA in Heidelberg, and control software with INS in Padova. The coronagraph was more detailed in cooperation with institutes in Nice and Paris.

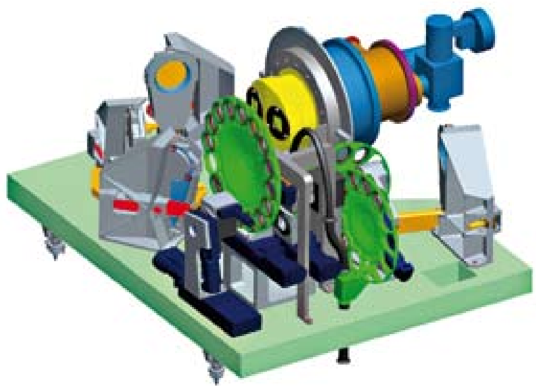


Figure 5.12: The ZIMPOL sub-system: overview of the optical bench.

After the successful passing of the FDR in December of 2008, the project proceeded in 2009 with the actual construction of the hardware (optical, mechanical, and electronic). At the end of 2009, all optics was delivered, but unfortunately several components were rejected mainly on the basis of poor coatings (scratch-dig). An engineering detector in the final cryostat and with NGC controller is in a test phase. The ZIMPOL optical bench is equipped with several parts and all crucial optics is aligned. The two science detectors have been delivered and are now at ESO where their performance is tested. A crucial part of the detector unit is the so-called Micro Lens Array (MLA), which focuses the incoming light on detector pixels. The MLA will be assembled early 2010. Data Reduction and Handling software of MPIA and control software of INS is in progress and computers are available to run the software with ZIMPOL.

5.7.3. Preparing for science with SPHERE

The international SPHERE science team has identified four areas in which the team wishes to spend its guaranteed time: searches for young gas giant planets (using IRDIS and IFS), searches for old gas giant planets (using ZIMPOL), studies of proto-planetary disks, and “other science”, the latter mostly focusing on evolved stars. In all these areas members of the science teams are busy with simulations of instrument performance and feasibility.

The SPHERE science team stepped up its activity in 2008 and more so in 2009 by organizing a series of telecons to discuss the guaranteed time observing programme, and a full science team meeting was held in December 2009 in Grenoble. In addition, a workshop on imaging polarimetry of protoplanetary disks was held in November 2009, hosted by Utrecht University. In preparation of the planet search programmes planned for the guaranteed time, a Large Program was approved by ESO using the VLT and NACO, searching for faint companions that are in reach of the NACO system. The ExPo instrument attached to the 4.2m WHT telescope (P.I. Keller) is providing exciting new results that are very relevant for the definition of the SPHERE program. On a national level, the Dutch SPHERE science team met two times in the context of national exo-planet science days.

5.8. LOFAR for Astronomy

LOFAR, the Low Frequency Array, is a next-generation low frequency radio telescope that will observe in the frequency range of 10 to 240 MHz. The Dutch part of the array will be finished in 2010 and will comprise of 36 stations distributed over an area of diameter of 100 km. In addition, at least eight stations will be built in a number of European countries (Germany, UK, Sweden, and France). The design of LOFAR has been driven by four astrophysical applications that fit excellently with the expertise and scientific interest of the four participating Dutch university astronomy groups. These Key LOFAR Science Projects (KSPs) are:

Epoch of Reionization (de Bruyn, Koopmans and Zaroubi): One of the most exciting applications of LOFAR will be the search for redshifted 21cm line emission from the Epoch of Reionization (EoR). LOFAR will address a number of key questions related to the EoR, including: (I) what is the redshift range in which the bulk of the neutral hydrogen became ionized? (II) What are the characteristics of the spatial distribution of heated and still cold IGM and their evolution? (III) What is the nature of the first objects that ended the Dark Ages and reionised the IGM?

Deep Extragalactic Surveys (Röttgering, Barthel, Best, Brüggen, Brunetti, Chyzy, Conway, Jarvis, Lehnert, Miley, Morganti and Snellen): Deep LOFAR surveys of the accessible sky at a number of key frequencies will provide unique catalogues of radio sources for investigating several fundamental questions in astrophysics, including the formation of massive black holes, galaxies and clusters of galaxies. Because the LOFAR surveys will probe unexplored parameter space, it is likely that new phenomena will be discovered. The design of the surveys has been driven by 3 important topics: (i) z>6 radio galaxies, (ii) diffuse radio emission in galaxy clusters, and (iii) distant star forming galaxies.

Transient Sources (Wijers, Fender and Stappers): LOFAR's large instantaneous beam will make it uniquely suited to efficiently monitor a large fraction of the sky, allowing sensitive unbiased surveys of radio transients for the first time. Averaging of the data will provide information on a variety of time scales, ranging from seconds to many days. The resolution attained will be sufficient for the crucial task of rapid identification of bursts at optical and X-ray wavelengths. Classes of objects known or expected to exhibit variable radio emission include Gamma-Ray bursts, Galactic black-hole/neutron-star systems and exo-planets.

Cosmic rays (Hörandel, Falcke and Kuijpers): LOFAR offers a unique possibility for studying the origin of high-energy cosmic rays (HECRs) at energies between 10^{15} – $10^{20.5}$ eV. The uniqueness of LOFAR as a CR detector lies in its capacity to measure: (I) the composition of CRs by measuring the depth of the shower maximum; (II) point sources of high energy CRs via the detection of energetic neutrons; (III) high-energy neutrinos in horizontal showers as well as from the lunar surface regolith. These studies will be very important for our understanding of both the source origin and the acceleration processes of these particles.

5.8.1. Progress of the LOFAR project

The LOFAR radio telescope is being built by a Dutch

Figure 5.13: The LOFAR superterp as seen in August 2009. This image shows the sites for the 6 LOFAR stations which are being constructed in this central core area. This compact configuration is not only important for calibration but also for monitoring a large fraction of the radio sky at low angular resolution.

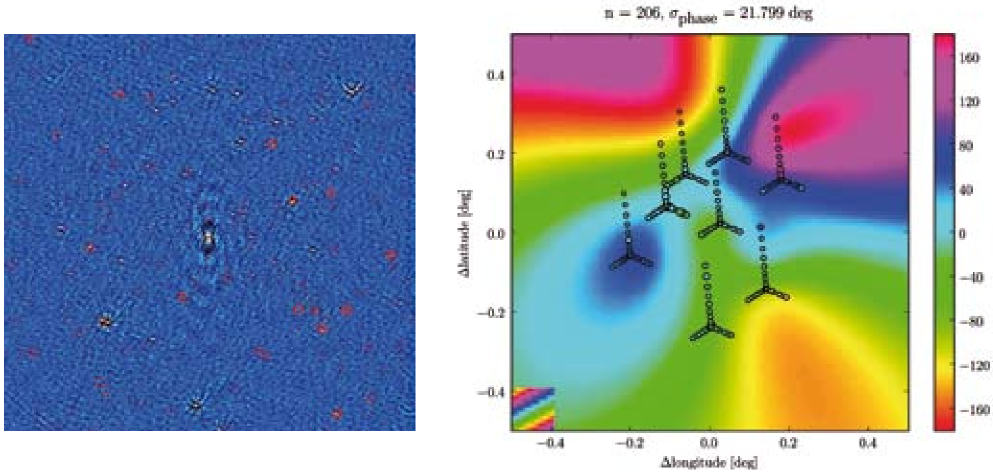


Figure 5.14: (left) Part of an image of the field of 3C196 made from 5 stations. The observations were conducted with 24 MHz bandwidth spread over a 30-75 MHz frequency range. The full field of view is ~ 6 x 3 degrees of which only 20% is shown. The red circles indicate indentified astronomical sources. (right) Example of an ionospheric phase screen model fit. The color map represents an ionospheric phase screen fitted to 10 seconds of 74 MHz VLA data. The axes represent angular distances, with East- and Northward offsets being positive. The overall phase gradient was removed and is depicted in the bottom-left corner. The collection of pierce points from all array antennas to bright sources in the field of view are depicted as small circles.

consortium led by ASTRON. A main emphasis of the LOFAR project during 2008 and 2009 was the roll-out of the LOFAR station hardware. At the end of 2009, the hardware of 20 stations had been placed in the fields and connected to the central processor. Six of these stations are located in the 'superterp' (Fig. 5.13). The full complement of the 36 stations in the Netherlands is expected mid 2010. Rollout of the LOFAR international stations has also continued to make excellent progress with at the end of 2009 the Effelsberg station fully online and the Tautenburg and Unterweilenbach stations awaiting HBA tiles. In parallel with the station rollout, deployment of the first phase of LOFAR's dedicated processing hardware was completed. This first installment of hardware provides roughly 10 TFLOPS of processing power and 2 PB of storage space. The system is currently configured to support both a production version of the processing software as well as an active development version. A first version of the LOFAR imaging pipeline was installed on the new hardware and is currently being used to support commissioning activities.

5.8.2. Development and Commissioning of LOFAR for Astronomy (DCLA)

The DCLA project is being carried out at the four participating universities (Amsterdam, Groningen, Leiden, and Nijmegen). It consists of two main tasks that need to be accomplished in order to enable LOFAR to perform its science. These tasks are:

1. Optimizing the observation and calibration techniques needed to do LOFAR science;
2. Development of algorithms and software pipelines necessary to make astronomy possible.

In the period 2008-2009, the four teams of the key projects made significant progress:

Epoch of Reionization: Members of the EoR group worked on technical, software and astronomical commissioning and preparation. Bernardi (NWO/NOVA postdoc, now at CfA, Cambridge) finished the calibration of three 72h WSRT 138-157 MHz datasets to image Galactic EoR foregrounds and to test aspects of LOFAR calibration methods in AIPS++ and the LOFAR reduction pipeline BBS. Pandey (SNN/NOVA postdoc) concentrated on (helping with) the design, development, testing and benchmarking of the pre-processing (including RFI flaggers) and BBS steps. Other tasks included global band-pass calibration, implementing ionospheric and station beam models and preparing for the first all sky surveys. Yatawatta (NOVA postdoc) spearheaded the fundamental issues related to calibration, imaging and deconvolution using shapelets of very bright sources. He also helped with simulating array configuration issues (splitting and rotating HBA stations, grating lobe issues) and assisted Labropoulos (RuG PhD-student) with the design of an end-to-end EoR pipeline, now ready for serious testing. Finally, Vibor Jelic extensively worked on modeling the EoR foreground modeling for the EoR pipeline and Maaijke Mevius (EU SKA postdoc) was involved in ionospheric modeling in BBS.

Surveys: The focus of the survey team was on three important topics: (I) testing and commissioning of LOFAR data, (II) building software for the source extraction and characterization and for simulation of the LOFAR sky and (III) ionospheric calibration. Birzan and Rafferty (NOVA postdocs) were deeply involved in taking and reducing first LOFAR data and testing the BSS reduction pipeline. While Birzan concentrated on reducing VLA data with BBS as a test of the software system, Rafferty worked on comparing the various methods to deal with Radio Frequency Interference. Mohan (NWO Postdoc) worked on his source extraction pipeline. The methods are now sufficiently robust that they deliver science quality source lists. For their PhDs Intema (now Jansky fellow at NRAO) and vd Tol designed and tested a method to take out ionospheric disturbances from low frequency radio data. Extensive testing on VLA 74 MHz data showed improvements of up to a factor of 2 in dynamic range over classic methods (Fig. 5.14). As a NOVA postdoc, van der Tol is now implementing these methods in the standard BBS pipeline.

Transients: Swinbank (NOVA postdoc), Spreeuw (NOVA PhD) and Scheers have written a first version of a transient detection pipeline and extensively tested it on simulated data. Rol and Anderson (NOVA PDs) are developing and testing HDF5 image data formats and testing the imager in the pipeline. The prototype will be deployed on the LOFAR cluster in Groningen for testing early in 2010. Development of the first LOFAR pulsar pipeline has also continued to make excellent progress. Tests on data from an LBA station showed that pulsars can be studied down to the atmospheric cut-off. The new fully optimized version of the code could potentially allow hundreds of simultaneous pulsar observations. A high performance data writer has been developed to process the pulsar data streams from central Blue Gene supercomputer, down-sample the data as required, and produce standard LOFAR pulsar data products in HDF5 format.

Cosmic rays: the Cosmic Rays KSP has been making progress on developing the pipeline for detecting cosmic rays. Activities included testing the LCU event trigger code, testing and improving the HDF5 Transient Buffer Board (TBB) data writer, and debugging the SkyMapper tool used to create near-field image cubes from TBB data (Fig. 5.15); Horneffer, Bahren NOVA PDs). Initial work has also begun on the design for the Blue Gene/P super computer online trigger algorithm. Also plans were developed for an array of particle detectors to be deployed in the LOFAR core to act as an anti-coincidence monitor for CR events.

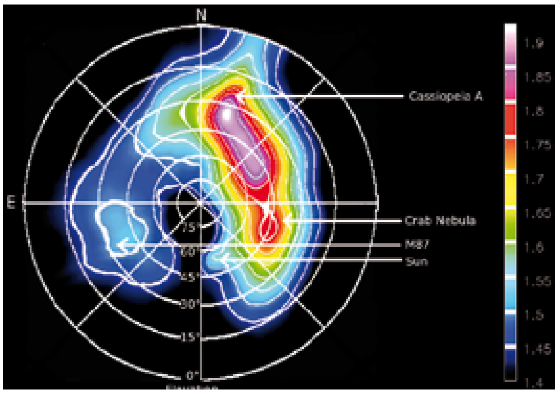


Figure 5.15: All-sky image made from 5ms of data with the cosmic ray imaging software from raw transient buffer data using 43 low band antennas of a single LOFAR station (CS 302 on 29-7-2009, 12:20:03). North is up and East is left. The full outer circle is the horizon and each consecutive inner circle is 15 higher up. The position of a number of strong sources is indicated. The main signal traces the plane of the Milky Way

5.9. Photometric instrument algorithms for the Gaia mission

Gaia is the European Space Agency mission which will provide a stereoscopic census of our Galaxy through the measurement of high accuracy astrometry, radial velocities and multi-colour photometry. Gaia is scheduled for launch in 2012 and over the course of its five year mission will measure parallaxes and proper motions for every object in the sky brighter than magnitude 20 - amounting to about 1 billion stars, galaxies, quasars and solar system objects. It will achieve an astrometric accuracy of 12–25 μas, depending on colour, at 15th magnitude and 100–300 μas at 20th magnitude. Multi-colour photometry will be obtained for all objects by means of low-resolution spectrophotometry between 330 and 1000 nm. In addition radial velocities with a precision of 1–15 km/s will be measured for all objects to 17th magnitude, thus complementing the astrometry to provide full six-dimensional phase space information for the brighter sources.

The primary scientific aim of the mission is to map the structure of the Galaxy and unravel its formation history. Deciphering the formation history of our Galaxy requires a detailed mapping of the structure, dynamics, chemical composition, and age distribution of its stellar populations. Ideally one would like to `tag' individual stars to each of the progenitor building blocks of the Galaxy. The Gaia mission is designed to provide the required fundamental data in the form of distances (through parallax), space velocities (through proper motions and radial velocities) and astrophysical characterization (through multi-colour photometry) for massive numbers of stars throughout most of the Galaxy.

Unlike other ESA missions both the spacecraft and science instruments will be paid for and built by the agency. The ESA member states contribute to Gaia through the on-ground processing of the Gaia measurements.

This project forms the Dutch contribution to the

Gaia Data Processing and Analysis Consortium (DPAC) which will be responsible for all the aspects of the processing and calibration of Gaia measurements, from the spacecraft telemetry to the final catalogue data. The work within this project will lead to the definition, design, validation and provision of a complete software package for the processing of the dispersed images from Gaia's photometric instrument. The algorithms will be delivered to DPAC as software modules to be integrated in the photometric processing pipeline which will be used during the operational phase of the Gaia mission. These algorithms are crucial to the success of the mission and are essentially an instrument in themselves. The Dutch contribution forms part of the core processing algorithms for both the photometric and astrometric measurements of Gaia.

Although this project is concentrated on researching and developing the photometric data analysis algorithms, the highly integrated nature of the overall data analysis effort for Gaia ensures that the participants will have an intimate knowledge of all aspects of the Gaia data. This combined with extensive scientific preparations will put the Dutch community in an excellent position to promptly and optimally exploit these data. In addition this project will generate a lot of expertise in the handling of large and complex data sets, specifically through the use of sophisticated database architectures. This expertise can be used in exploiting other large data sets (such as SDSS and RAVE).

Staff in the Netherlands contributing to the Gaia preparations include Brown, Busso, Marrese, Prod'homme, Risquez, Levin, Le Poole, Snellen, Portegies Zwart (Leiden); Helmi, Trager, Tolstoy (Groningen); Kaper (Amsterdam); Pols (Utrecht); and Nelemans (Nijmegen).

Internationally this work is done in the context of the Gaia Data Processing and Analysis Consortium, specifically the photometric coordination unit in this consortium. The main international partners are located at the universities of Cambridge in the UK, Barcelona in Spain, and Bologna, Rome and Teramo in Italy.

5.9.1. Progress and achievements in 2008–2009

Funding: During this period the positions of Busso and Marrese at Leiden Observatory were funded through the NOVA Phase 3 instrumentation program. Additional funds for research related to the Gaia mission were obtained through an EU-funded research training network, named ELSA for 'European Leadership in Space Astrometry'. The network involves 14 nodes of which two, Leiden and Dutch Space, are in the Netherlands. The funding is available from 2006 to 2010 and has enabled the appointment of 9 PhD students and 5 PDs distributed over the 14 network nodes in Europe. One PhD student (Prod'homme) and one PD (Risquez) are located in Leiden. Brown was a co-I on a successful proposal to fund a European Science Foundation Research Networking Programme called GREAT for 'Gaia Research for European Astronomy Training'. The GREAT funding will be available from 2010 to 2015 and will enable networking activities (conferences, workshops, exchange visits) aimed at preparing for the scientific exploitation of the Gaia catalogue data.

Photometric instrument and algorithms: Gaia's photometric instrument consists of two prisms dispersing all the light entering the field of view. One disperser - called BP for Blue Photometer - operates in the wavelength range 330–680 nm; the other - called RP for Red Photometer - covers the wavelength range 640–1050 nm. The dispersion of the prisms ranges from 3 to 29 nm/pixel for BP and from 7 to 15 nm pr/pixel for RP. One of the major data processing challenges that the teams in Leiden, Rome, and Teramo (all led by Brown) are dealing with is the disentangling of overlapping dispersed images and the treatment of radiation damage effects (see below) in the photometric data.

Over the past two years the IT infrastructure for the photometric processing pipeline has been extensively developed, including the hardware and database facilities located in Cambridge. The photometric processing algorithms developed in Leiden, Rome, and Teramo have been successfully integrated into this pipeline and a first test of the algorithms on a 30 million star data set was run without significant problems. The algorithms are undergoing continuous upgrading in 6 month cycles and will be ready to run in simplified form during the DPAC wide end-to-end tests which will be conducted in 2010. Specific algorithmic developments include the deblending of overlapping dispersed images, the measurement of colour information from the BP/RP data, and the integration of the latter in the initial data treatment pipeline (where the colours are needed for accurate astrometric data processing). The photometric data processing algorithms will continue to undergo development and further sophistication until after Gaia is launched (to cope with unforeseen features in the actual mission data).

ELSA research: A major issue for the Gaia mission is the increasing effect of charge transfer inefficiency (CTI) caused by radiation damage to the CCDs accumulated during the mission. The effect of solar wind particles passing through the CCDs is that so-called traps are created which can hold electrons in the same position on the CCD for a while before releasing them again. This has two effects on a PSF image: (1) some fraction of the signal charge will be lost from the PSF, and (2) The PSF will be distorted into an asymmetric shape. For all Gaia measurements this will lead to large flux losses towards the end of the mission, which will cause a decrease in their precision. For the astrometric data the PSF distortion will lead to biases in the centroid measurement of the images from the astrometric field in the focal plane. At present the detailed physics of CTI is poorly understood and the experience from other space missions cannot be used directly. The goal of Prod'homme's research is to develop a detailed understanding of CTI effects, and how this should be incorporated into the data processing, through a combination of experimental results and physical modelling. This issue is of fundamental importance to the success of the Gaia mission and the expertise gained through this research can also be applied to other astronomical projects requiring high imaging precision, such as weak-lensing surveys.

During 2008–2009 Prod'homme has developed a platform for the simulation of charge transfer inefficiency effects in astronomical CCDs. This platform hosts various CTI models, included a very detailed Monte Carlo model developed by Prod'homme. The CTI modeling has been used in various ways: to analyze laboratory test data from EADS-Astrium in order to better understand the physics; to support the detailed analysis of these test data; to develop and validate approximate but faster models (needed for the data processing); and to conduct a study of the effects of radiation damage on the weak-lensing survey planned for the proposed EUCLID space mission. In addition Brown and Prod'homme were asked as outside experts to advise the company Cosine on a bid for a contract with ESA to study the effects of radiation damage on EUCLID mission CCDs. This demonstrates the benefits of involvement in the preparations for a specific space mission to other areas of interest to the Dutch industry and astronomical community.

Risquez worked on the detailed physical understanding of the dynamics of a continuously rotating space platform. This will be used for high quality spacecraft attitude modeling which is needed to reach the astrometric goals of the Gaia mission, as the reconstructed attitude provides the reference frame relative to which the astrometric measurements are obtained. The results of this study will be used in understanding the dynamics of the satellite once it is in operation, and to incorporate that understanding in the core astrometric processing for the Gaia mission. Risquez developed various algorithms that simulate the effects of external physical disturbances on Gaia, such as the solar radiation, the impacts of micrometeoroids, and the thermal infrared emission from the focal plane radiator. In addition he implemented a detailed model of Gaia's micro-propulsion system.

During 2008 Brown was a member of the management team of the photometric coordination unit of DPAC. In 2009 Brown again became a member of the Gaia Science Team. In addition Brown is a member of the working groups dealing with the on-ground and in-orbit calibration of the Gaia instruments and the treatment of the effect of radiation damage to Gaia's CCD detectors.

5.10. Matisse

MATISSE (Multi-AperTure mid-infrared SpectroScopic Experiment) is a 2nd generation Very Large Telescope Interferometer (VLTI) instrument intended to be installed at ESO's Cerro Paranal Observatory in 2015. It is intended to be a complete mid-infrared VLTI instrument in that it uses all four 8-meter Unit Telescopes to measure 6 simultaneous baselines, and it can measure in three different mid-infrared bands, L(3μm), M(5μm) and N(10μm). It can be viewed as a major upgrade to the MIDI instrument which only measured one baseline in one band (N). The maximum spatial resolution of MATISSE is 2 milliarcsec

MATISSE is being built by a corsortium with as major partners: Observatoire de Cote d' Azur (OCA, Nice, PI), NOVA, Max Planck Institute für Astronomie (MPIA, Heidelberg) and Max Planck Institute für Radioastronomie (MPIfR,Bonn); there are a number of European and American minor partners. The principal involvement of NOVA in the project is the design and construction of the cryogenic optics Cold Optical Bench (COB) at ASTRON. The Dutch Co-PI for MATISSE is Jaffe; the Dutch Project Manager is Navarro. ESO will provide several important hardware components of MATISSE as well as the VLTI infrastructure at Cerro Paranal. The Dutch contribution to the instrument will be roughly 23% of the total hardware costs plus manpower.

Mid-IR astronomical instruments are most useful for observing dust and gas structures with temperatures of a few hundred to a few thousand Kelvin. The most exciting applications of a mid-IR instrument with extreme spatial resolution are imaging the protoplanetary disks around young stars, the complex obscured regions in which massive stars form, and the structures that feed and hide the supermassive black holes in the centers of Active Galactic Nuclei (AGNs).

The multiple baseline-multiple wavelength capabilities of MATISSE will allow high dynamic range imaging of these targets so that complex, asymmetric, and time variable structures can be discerned. Previous interferometers could only measure a few visibility points, and the true morphology could only be surmised by indirect modelling. With the new capabilities we hope, for instance, to map the asymmetries in protoplanetary disks driven by massive protoplanets. It may prove possible to detect directly the emission from hot massive planets.

The conceptual design (Phase A) was accepted by ESO in November 2008. In December 2009 the ESO Council accepted MATISSE as a major project including the allocating of Guaranteed Observing Time to the consortium.

The Netherlands will provide the COB for MATISSE, building on the expertise gained on the contribution to MIDI. The design and fabrication will be done by the Optical-IR instrumentation group. The required total staff effort to design, build and test the COB is of order 20 staff years. Project costs for the Netherlands are 2.5 M€ with contributions from NOVA (~2.1 M€, mainly staff effort) and NWO (450 k€). In addition international partners and ESO will contribute ~800 k€ to the hardware costs of the COB.

MATISSE is a highly complex instrument consisting of 12 spectrally dispersed interferometers (6 baselines, two wavelength regimes) in two cryostats that must operate at a temperature of 40 K to suppress thermal background noise. Thermal and mechanical stability are required to keep components aligned to better than 1 μm. The limitations on cryostat size require multiple folding of the beams and bring the total number of cold optical elements to about 300. It would be technically impossible to align this system by conventional means: the physical adjustment of optical surfaces at room temperature, followed by cooling to operating temperature. For this reason the project in cooperation with Dutch industry developed an innovative cryogenic alignment technology: adjustable tip-tilt and optical path mirrors driven by piezoelectric stepping motors which maintain position when power is off. In total 90 such mechanisms are needed in the MATISSE COB. These devices allow a quick manufacture, assembly, integration and testing of the COB.

The MATISSE PDR was held on November 17-18, 2009 at ESO. The general concept was found to be good, but the review board had several criticisms:

1. The end-to-end performance analysis was not sufficiently detailed to show whether the high level specifications were met;
2. The design assumed VLTI infrastructure performance at delivery that is better than the current state of the VLTI (mirror vibration/pupil stability);
3. The design is very complicated and could perhaps be simplified.

The review board recommended a delta-PDR in ~6 months, after fixing these issues. The team agrees with comments on (1) and (3) but believes that it is necessary for ESO to improve the VLTI performance. The date for a delta-PDR is being negotiated with ESO.

5.11. S^{5}T

5.11.1. Project overview

The Small Synoptic Second Solar Spectrum Telescope (S^{5}T) will study the temporal variation of the weak turbulent magnetic field that covers the entire solar surface but is invisible to traditional magnetic field measuring instruments. While this turbulent field is weak compared to magnetic fields in sunspots, the total magnetic flux emerging through the solar surface in the turbulent field is orders of magnitude larger than the amount of flux emerging in sunspots, even at the peak of the solar activity cycle. Understanding the origin and dynamics of this turbulent field and its interaction with the sunspot cycle is not only important to solve the enigma of the 11-year solar cycle and the variations of the Sun's energy output that ultimately affect life on Earth, but it is also crucial for our understanding of magneto-hydrodynamic turbulence in an astrophysical plasma with applications to much larger scales, such as the galactic magnetic field of which the origin has also not yet been established.

By measuring the linear polarization parallel and close to the solar limb as a function of wavelength, the properties of the weak, turbulent field can be deduced via the Hanle effect, even without spatially resolving the characteristic length scales of this field. Daily measurements with high sensitivity and accuracy with the same instrument during at least one solar cycle (11 years) in combination with advanced radiative MHD numerical simulations will reveal the nature of the ubiquitous weak magnetic field and its relation to the strong fields observed with traditional methods.

The key component of the S[5]T is the theta cell, which converts linear polarization with an azimuthal (or radial) symmetry in the focal plane into a uniform linear polarization pattern, which in turn can be analyzed by a regular polarimeter. This allows for a 'one-shot' observation of the entire solar limb polarization by channelling all the relevant light through the theta cell, the precision polarimeter, and finally into a fiber-bundle-fed spectrometer, which integrates the signal from the entire limb into a single spectrum. Therefore there is no need for a large-aperture telescope to achieve the required signal-to-noise ratio for highly sensitive spectropolarimetry. A variety of calibration routines ensure the required polarimetric accuracy and stability.

5.11.2. Technical progress in 2008 – 2009

The S[5]T concept was conceived in 2007, and a prototype was constructed. After the successful observations with this prototype operated at the Sonnenborgh observatory in the center of Utrecht, the full instrument was selected for funding by NOVA, with support from Utrecht University. PhD student Helena Becher was hired in 2008 to design, build and test the instrument, commission it at Kitt Peak, and analyze the first two years' of S[5]T data, together with Christoph Keller and Frans Snik (UU). The design review was passed in March 2009. All mechanical parts were completed by the UU workshop in autumn 2009, and currently the instrument is being integrated and tested in the lab. The instrument is on schedule for commissioning mid 2010.

5.12. Seed funding projects

The NOVA instrumentation program also includes a funding line to explore new opportunities that might develop towards full instrumentation projects in the future. Proposals that get funded should fulfill several criteria including (1) a challenging science goal that fits within the strategic plan for astronomy in the Netherlands, (2) technical and managerial feasibility, (3) perspective on an attractive Dutch role (like PI or co-PI), and (4) the PI has to be affiliated to one of the astronomical institutes participating in NOVA.

Two seed funding projects are already approved which are described below. The seed funding line also provides a financial contribution to pay for the membership of the European SKA Consortium (ESKAC) to allow university astronomers in the Netherlands to participate in the organization and design studies of the next generation observing facility for radio astronomy, the Square Kilometer Array (SKA).

5.12.1. Auger Radio, radio detection of cosmic rays

Falcke and collaborators, along with groups in Germany and France, are deploying detectors at the Pierre Auger Observatory in Argentina for radio detection of high-energy cosmic rays. The detectors utilize very short timescale radio-frequency emissions from cosmic ray air showers to measure the direction, energy, and composition of cosmic rays as they interact in the atmosphere. The radio technique offers a highly promising detection method which can, with high precision and lifetime, supplement existing cosmic ray techniques such as water Cherenkov tanks and fluorescence telescopes, with the ability to instrument huge areas in a cost-effective manner.

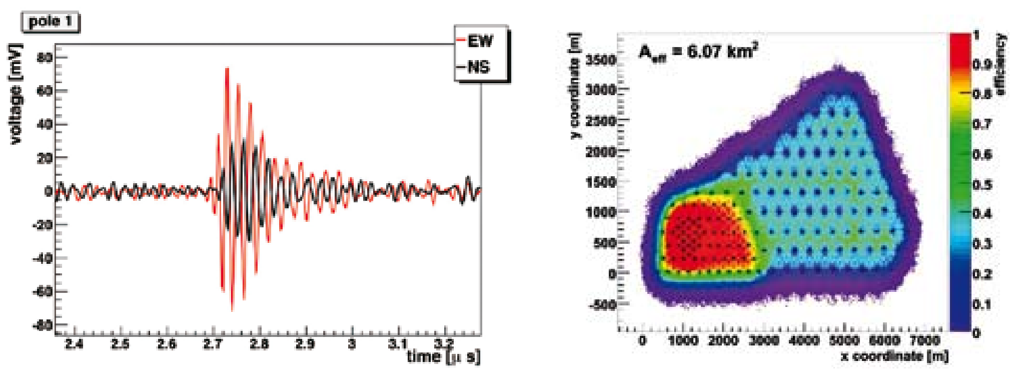


Figure 5.16: Left: radio pulse in two polarizations from a 2 EeV cosmic ray air shower, measured in coincidence with the Auger surface detector. Right: AERA array layout and simulated detection efficiency for a 1 EeV air shower.

The project is transitioning from a prototyping phase, with several test stations currently collecting data in Argentina, to a larger array instrumenting approximately 20 km^2. The new array, AERA (Auger Engineering Radio Array), starts deployment in 2010 with the installation of the initial 25 radio detector stations. Hörandel and Kelley (postdoc) are leading international efforts in system integration and electronics, respectively. Technical developments in the station design include the construction and field testing of a high-speed digitizer (with NIKHEF) and improvements in algorithms for noise rejection and self-triggering.

Simulations of the efficiency, effective area, and expected event rates have been employed to optimize the array layout (Fig. 5.16). A conservative estimate of the energy threshold ($\log_{10}$ E/eV = 17.2) leads to an expected event rate of ~5000 events/year for the completed array (150 stations). AERA will calibrate the radio emission, using hybrid events detected in conjunction with other Auger components, leading to a better understanding of the different emission mechanisms (geomagnetic, charge excess, moving dipole, etc.).

5.12.2. The Cherenkov Telescope Array (CTA)

CTA is a future European gamma-ray telescope based on imaging Cherenkov light induced from gamma-rays entering the Earth's atmosphere. CTA will be a natural successor to the highly successful European Cherenkov telescopes H.E.S.S. and MAGIC. H.E.S.S. and MAGIC are proprietary telescopes, but CTA will have a significant fraction of its observing time open to all astronomers. Currently it is envisioned to build an array both in the Southern and Northern Hemisphere. CTA will have a sensitivity that is an order magnitude better than H.E.S.S. and MAGIC. The main gain in sensitivity is due a significant increase in the number of telescopes employed in the array. For example H.E.S.S. currently has 4 telescopes, which image the Cherenkov shower from different angles. CTA is planned to consist of as much as 40 small and large telescopes. The large telescopes (20 meter class) are optimized to detect faint Cherenkov light caused by low energy gamma-rays (< 100 GeV), whereas many 6 and 12 meter class telescopes will be placed such that the array captures a large part of the sky in order to optimize the number of high energy photons. Note that the actual effective area of the telescope is determined by the sky coverage, the atmosphere acting as the primary detector. At high photon energies the sky coverage is important as sources are usually photon starved.

CTA is now listed under 'High Priorities New Projects' in the ASTRONET Infrastructure Roadmap 2008, in the ESFRI Roadmap 2008, and in the ASPERA Astroparticle Physics Roadmap 2008. In May 2009, during a general CTA meeting in Cracow, the CTA consortium got a more formal structure, with Hofmann (MPI-K, Heidelberg) and Martinez (IFAE, Barcelona). The CTA design studies are now in full swing. The Netherlands is not involved as a full partner in CTA, but is considered to be one of the participating countries. From the Netherlands Markoff and Vink are active participants in the CTA consortium meetings, and have given several oral contributions at CTA meetings concerning science issues with CTA and multi-wavelength aspects of CTA science. Markoff leads the multi wavelength sub-task and Vink participates in the physics working package, which defines the CTA design goals, such as tradeoffs between sensitivity at high and low gamma-ray energies. Their efforts for CTA are supported by NOVA in the form of seed funding. At least one of them always participated in the general CTA meetings.

5.13. Other instrumentation projects

5.13.1. Superconducting tunnelling junction device

The PhD project of Hijmering (PhD) and Groot together with ESTEC was successfully concluded. They worked together with ESTEC and collaborators in Lancashire on the development of an array camera based on Superconducting Tunneling Junction (STJ) devices in a distributed read-out array (DROID; Fig. 5.17). It consisted of a number of subprojects characterising these DROID-STJ arrays, including a new theory of quasi-particle trapping in superconducting materials, new measurements

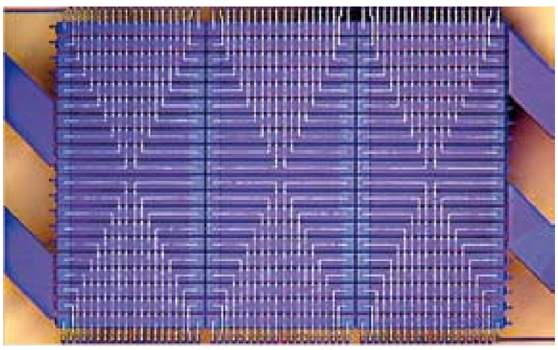


Figure 5.17: False color photograph of the STJ DROID array as assembled at ESTEC for use in the SCAM electronics. The dark purple areas are the Al absorber strips, the lighter blue squares the STJs at the end of each strip, the white lines the individual electronics leads and the dark orange the underlying substrate.

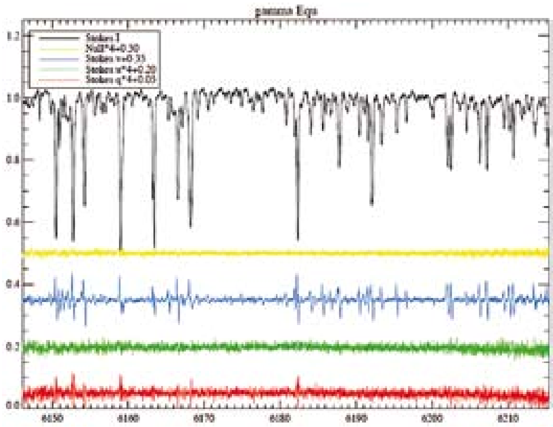


Figure 5.18: Part of the full Stokes spectrum of gamma Equ, observed with the HARPS polarimeter on May 31, 2009. Plotted are the intensity spectrum, the null spectrum (indicating the noise level), Stokes V, U and Q, all normalized by the continuum intensity. Abscissa: wavelength in Angstroms. Systematic effects are clearly absent in the null signal down to the ~0.3% level. Prominent Zeeman signatures in most spectral lines are observed in both circular and linear polarization.

methods for the spectral and spatial resolution of these materials and the demonstration of a new camera that can be used in astronomical applications.

5.13.2. New spectro-polarimeter HARPSpol

Snik (PhD), Keller, Rodenhuis (PhD), Jeffers (postdoc) together with Piskunov, Kochukhov (both Uppsala), Valenti (STScI) and Johns-Krull (Rice) designed, built, and commissioned a polarimeter that feeds the ultra-precise HARPS spectrograph on the ESO 3.6m. Circular polarimetry at high spectral resolution measures stellar magnetic geometry and net longitudinal field strength, providing clues about stellar dynamos, coronal heating, angular momentum evolution, etc. Linear polarimetry measures scattering by circumstellar material, providing clues about protoplanetary disks, asymmetric mass loss, etc. The GTO observations (Fig. 5.18) show that HARPSpol, the only general-purpose high-resolution spectro-polarimeter in the southern hemisphere, is comparable in performance to the very best instruments on the northern hemisphere.

Snik (PhD), Keller and Karalidi (MSc, now PhD) developed and tested a novel type of linear spectro-polarimeter that is now the core technology for Dutch involvement in planetary missions. Linear (spectro) polarimetry is usually performed using separate photon flux measurements after spatial or temporal polarization modulation. Such classical polarimeters are limited in sensitivity and accuracy by systematic effects and noise. The instrument makes use of a spectral modulation principle that is based on encoding the full linear polarization properties of light in its spectrum. Such spectral modulation is obtained with an optical train of an achromatic quarter-wave retarder, an athermal multiple-order retarder, and a polarizer. The emergent spectral modulation is sinusoidal with its amplitude scaling with the degree of linear polarization and its phase scaling with the angle of linear polarization. The large advantage of this passive setup is that all polarization information is, in principle, contained in a single spectral measurement, thereby eliminating all differential effects that potentially create spurious polarization signals. Since the polarization properties are obtained through curve fitting, the susceptibility to noise is relatively low. Currently, the setup in combination with a dedicated retrieval algorithm can be used to measure linear polarization signals with a relative accuracy of 5%.

5.14. Involvement in the instrumentation for the E-ELT

In 2008 NOVA signed up to participate in four Phase-A studies for instrument concepts for the E-ELT. All these studies are done in collaboration with partners in Europe. The typical lead time for each of the studies is 15-20 months. The studies on METIS and MICADO were completed in autumn 2009 and reviewed in November and December, respectively, by expert teams set up by ESO. Both studies received very good review reports. The Phase-A studies on EPICS and OPTIMOS-EVE will be completed in March 2010.

5.14.1. NOVA Optical-IR instrumentation group

From the 1st January 2008 onwards NOVA took over the Optical-IR instrumentation group of ASTRON. This development occurred after the decision by ASTRON and NWO to concentrate future ASTRON activities on radio astronomy. The group consists of ten experienced people with expertise ranging from optical, mechanical, and cryogenic design, system engineering, CNC and optical production capabilities, instrument integration, and verification. Over the last decade this group carried out the optical-IR instrumentation projects for which NOVA had final responsibility towards ESO, ESA, and international partners. Current arrangements between NOVA, ASTRON, and NWO concerning the Optical-IR instrumentation group are concluded in a contract that covers the period 2008-2011.

In the near term, the Optical-IR group will undertake the work packages on SPHERE-Zimpol and Matisse which are of major Dutch astronomical interest and for which NOVA has contractual obligations towards ESO and international partners. Furthermore, the group is involved in the hardware part of four Phase-A studies on E-ELT instruments, and carries out some technical R&D for future instrumentation. From 2011 onwards the group is expected to take

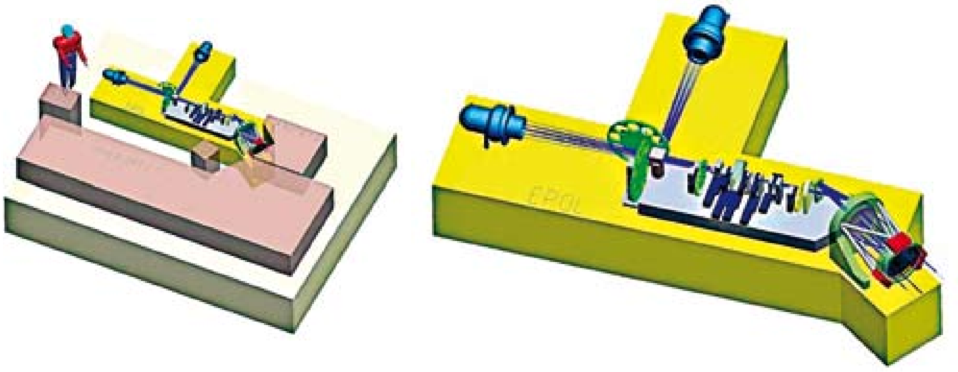


Figure 5.19: EPOL design as of December 2009. The figure on the left shows the overall EPICS instrument, and the figure on the right shows EPOL itself with the light from the telescope coming from the lower right, passing the 2-mirror coronagraph, the polarimetry components, and finally a polarizing cube beamsplitter and two cameras to simultaneously measure two orthogonal polarization states.

on the Phase-B work for one E-ELT instrument with ongoing R&D for a second E-ELT instrument. Head of the group is Navarro. ASTRON provides in-kind systems engineering support through Venema.

5.14.2. Program and funding

NOVA leads the national efforts on the E-ELT participation. The projects are undertaken in collaboration with ASTRON, SRON, technical universities, TNO, and several industrial partners.

In November 2008 the Ministry of OCW and NWO allocated a grant of 18.8 M€ to NOVA and its national partners for work on E-ELT instrumentation projects. The (instrumentation for the) E-ELT was one of the five projects that got national funding out of eight ESFRI projects that were identified as Dutch priorities by the national roadmap committee for large scale European research facilities. The grant includes 8.8 M€ for conceptual and preliminary design studies, Phase A and B, and technology development, and 10 M€ for participation in the final design and construction of one instrument. The latter part is conditional to ESO's decision to go ahead with the construction of the E-ELT and to select instruments in which NOVA has a leading-role. Payment is spread over the period 2009-2018.

5.14.3. EPICS

EPICS will directly image and characterize exoplanets at visible and near-infrared wavelengths by combining extreme adaptive optics with coronagraphic imaging, imaging spectroscopy and polarimetry. EPICS will characterize extrasolar gas giants that have been discovered by indirect methods, detect and characterize mature cold gas giants like Jupiter at orbital distances between ~5 and 15 AU in the solar neighborhood (< ~20 pc), young gas giants in star forming regions, and Neptune-like planets as well as massive rocky planets (super-Earths) around nearby stars (< ~10 pc). The ultimate goal of EPICS is to detect and characterize exoplanets with liquid water in the habitable zones around stars.
The EPICS Phase A (conceptual design) study started in 2007 and includes setting technical specifications for the telescope design and feedback to the science working group conducting the E-ELT Design Reference Missions. NOVA (co-PI Keller) and ETH Zurich (co-PI Schmid) are responsible for the investigation and conceptual design study of an imaging polarimeter, EPOL (EPICS POLarimeter), one of the two focal plane instruments fed by the common extreme adaptive optics system. Work packages carried out in the Netherlands include contributions to the science case (Keller, Snik, Waters and Stam), system engineering (Venema) and instrument design (NOVA optical-IR instrumentation group). A mid-term review was held by ESO in October 2008. The final report will be delivered to ESO at the end of January 2010 and reviewed in March 2010. Fig. 5.19 shows the current conceptual design.

EPOL will search for faint point-like polarization flux features on top of a much stronger, unpolarized halo due to the central star. The polarimetric sensitivity of EPOL of 10^{-5} combined with the extreme adaptive optics and coronagraph will provide contrast ratios of 10^{-9} and beyond. To achieve this contrast EPOL observations have to be carried out in such a way that systematic effects due to the telescope and adaptive optics can be compensated (subtracted) with differential techniques. These extremely sensitive polarization measurements are therefore accomplished with a cascade of differential techniques. Furthermore, the detected polarization signals must be calibrated absolutely in polarized intensity and direction on the sky, which requires additional instrument and telescope calibration procedures.

5.14.3.1. Technical progress in 2008 – 2009

Phase-A activities led to the optical EPOL concept, which was established together with the other EPICS consortium partners, and formed the basis of the optical and mechanical designs. The design is derived from the SPHERE/ZIMPOL instrument that is currently being assembled. Major advances in the design as compared to its VLT-based predecessor are a true dual-beam-exchange approach to the polarimetry, which reduces the systematic polarimetric errors by an order of magnitude, and a rotatable half-wave plate and a polarimetric calibration unit in the intermediate telescope focus that will dramatically improve the polarization accuracy.

The polarization concept consists of:
- Polarization-switching half-wave plate in the intermediate E-ELT focus;
- Half-wave plate after telescope fold mirror M5 to rotate the rotating telescope polarization into a fixed direction;
- Compensation of stabilized M5 polarization by a fold mirror or a tilted glass plate before the polarization modulator;
- Fast polarization modulator after the coronagraph;
- No other moving parts after the telescope except for the atmospheric dispersion compensator (ADC).

The rotatable half-wave plate in the intermediate focus can disentangle spurious instrumental signals from real signals by rotating polarization signals from the sky, while not affecting instrumental effects. Subtraction of images taken with two positions of this half-wave plate will cancel most instrumental effects. Active compensation of the instrument polarization to a low level with an active compensator plate within EPOL will provide a very high polarimetric sensitivity despite the fact that there are components that introduce instrument polarization that is orders of magnitude larger than the expected exoplanet signal.

Fast polarimetric modulation and demodulation is the basic measurement approach where a ferroelectric liquid crystal (FLC) retarder modulates the orientation of the linear polarization by 90 degrees and, together with a polarization analyzer, transfers the polarization signal into an intensity fluctuation. The optical paths and detector pixels of orthogonal polarization states are therefore identical, which minimizes differential aberrations and flatfield effects. Demodulation, or phase-locked detection, is achieved by charge transfer within the CCD detector. Every other exposure has the phase between modulation and demoduation reversed to subtract the differences in charge transfer efficiency.

By enforcing a strict optimization of the instrument for the primary science goal, the EPOL conceptual design achieves high system efficiency in terms of throughput, operation efficiency, and polarimetric efficiency.

5.14.4. METIS

METIS is a combined imager and spectrometer for the E-ELT, working in the mid-IR. METIS will provide:
- A diffraction-limited imager at L/M, and N band with an approximately 18″×18″ wide FOV. The imager also includes the following observing modes:
  - coronagraphy at L and N-band
  - low-resolution (R ≤ 5000) long slit spectroscopy at L/M and N band
  - polarimetry at N-band.
- An IFU fed, high resolution spectrograph at L/M (2.9 – 5.3 μm) band. The IFU field of view will be about 0.4″×1.5″, and the spectral resolution R ~ 100,000. An optional mode to cover also N-band in integral field spectroscopy mode is under consideration.

The METIS key science drivers are (1) proto-planetary disks and the formation of planets, (2) the physical and chemical properties of exoplanets, (3) the formation history of the Solar System, (4) the growth of super-massive black holes, and (5) the morphologies and stellar dynamics of high-z galaxies. Additional areas in which METIS promises breakthrough discoveries are: the Martian atmosphere, properties of low mass brown dwarfs, the formation of massive stars, the Galactic center, evolved stars and their circumstellar environments, IMF and disk survival studies in starburst clusters, and high-z Gamma-Ray Bursts as cosmological probes. Altogether, METIS on the E-ELT will provide an excellent synergy with JWST-MIRI and ALMA.

The METIS consortium is an international team, which consists of the PI Brandl (Leiden), the project manager Molster (NOVA), the project engineer Venema (ASTRON), and the consortium partners MPIA (co-I and instrument scientist Lenzen), CEA Saclay (Co-I Pantin), KU Leuven (Co-I Blommaert) and UK-ATC (co-I Glasse). This consortium comprises a large fraction of the relevant mid-IR expertise in Europe. It has vast experience in infrared instrumentation from projects like IRAS, ISO-SWS, TIMMI2, VISIR, Spitzer-IRS, HIFI, NAOS/CONICA, MICHELLE, HERSCHEL-PACS, MIDI and JWST-MIRI. The METIS technical team in the Netherlands consist of Kroes, ter Horst, Oudenhuijsen, Roelfsema, Navarro, Pragt, Elswijk, Kragt (all NOVA Op-IR instrumentation group), Stuik, Jolissaint, and Kendrew (all Leiden University). The science case was composed with significant help from van Dishoeck, van der Werf, Kaper, Wiersma, and Lahuis.

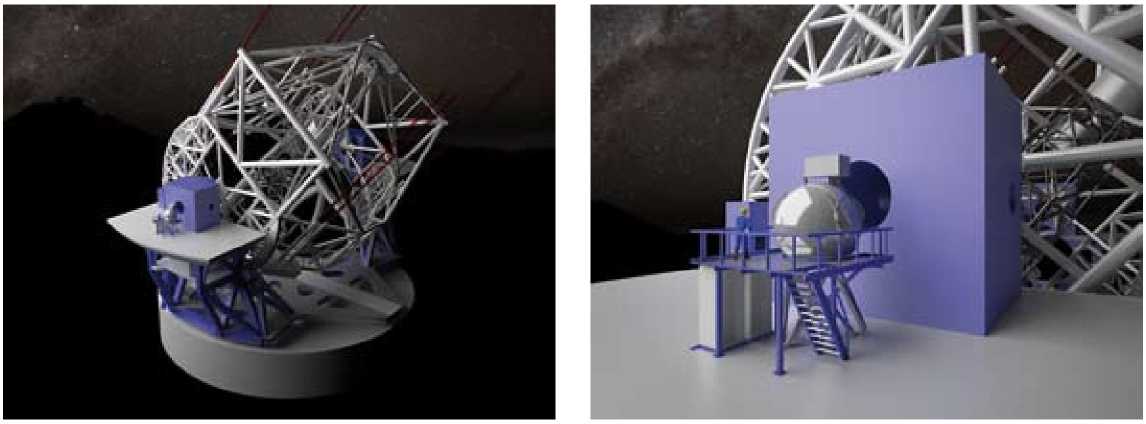


Figure 5.21: Left: the E-ELT with METIS on its Nasmyth platform A. Right: Zoom-in to show details of the cryostat support structure, the rig, and the location of the electronics racks. vertical structure. The imager is at the bottom and the IFU spectrograph to the center right. The big sphere is part of the calibration unit. Right: the same optical system, now integrated within the backbone structure.

5.14.4.1. Progress in 2008 - 2009

On 20 November 2007 ESO issued a call for proposals for the phase-A study of a mid-IR instrument for the E-ELT. The METIS consortium was selected, and performed the phase-A study from 7 May 2008 (kick-off) to the successful final review on 17/18 December 2009. The phase-A study led to the recommended instrument capabilities listed above. Furthermore, METIS will also provide its own calibration system and internal wavefront sensor module. Given its compact size (~2.5m in diameter) and low weight, METIS is considered a 'light instrument'. Together with the relatively low technology risks, METIS is a good candidate for an early E-ELT instrument (Fig. 5.20 and Fig. 5.21).

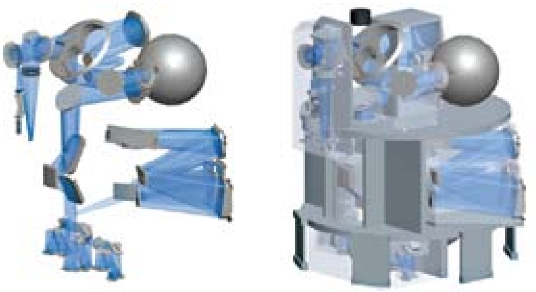


Figure 5.20: Outline of the optical system inside the METIS cryostat. Left: The telescope beam enters at the top left. The common fore-optics, including the chopper and derotator, is the central,

METIS has also been one of three instruments studies that were selected by the EU-FP6 ELT design study consortium for a so-called Point Design Study. This study – then called 'MIDIR' – started in November 2007 and was completed at the end of 2008, overlapping with the Phase A study. Duplication of efforts was avoided, and the two parallel studies enabled the METIS team to reach quite a detailed level in the science studies, instrument simulations and optical and opto-mechanical design. The METIS study profited in 2009 also significantly from the availability of funds from the ESFRI grant for E-ELT instrumentation. This enabled collaborations with industry on two critical technical developments and investigations (METIS chopper and thermal analysis).

5.14.5. MICADO

MICADO is also an instrument design study for the E-ELT, which ran for two years and was completed in December 2009, for a near-infrared (1-2.5 μm) imager for the E-ELT. It samples the focal plane at 1.5-3 milli-arcsecond pixels and so is suitable for diffraction limited imaging behind an MCAO module. In its basic operation it will cover a field of 53 arcsec with a 256 Mpixel array of HAWAII-4RG detectors. A second arm of the instrument enables higher resolution imaging of a smaller subfield, and R~3000 spectroscopy. Because of its relative simplicity and broad science case MICADO is a potential first-light instrument. A comparison of the image quality of existing instrumentations with what MICADO can deliver is given in Fig. 5.22.

High sensitivity imaging at this resolution is an enormous step in scientific capability compared to existing instrumentation. The science case is very diverse, and includes topics such as the environment of the central black hole in our own Galaxy, resolved stellar populations in Local Group galaxies and beyond, and high-redshift galaxies. We can highlight three science topics of special interest for the Netherlands, which all involve using the resolving power and sensitivity of MICADO to study galaxies and their formation, and hence to challenge current scenarios.

A prime capability of MICADO is the ability to image very distant galaxies, which are very faint and small, and whose light is redshifted to the infrared wavelengths. The synergy with longer-wavelength JWST images and spectra is very strong. Closer to home, MICADO allows studying the resolved stellar populations of nearby galaxies, affording a detailed view of the star formation history that cannot be attained from integrated light spectra. Finally, closer still, the astrometric capabilities of MICADO allow proper

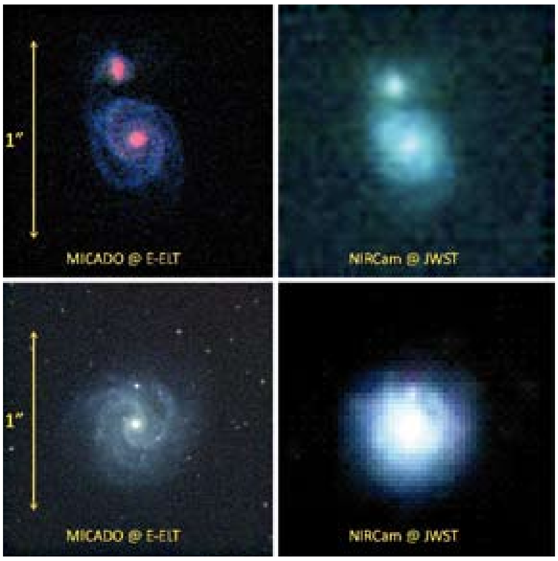


Figure 5.22: Comparison of the resolving power of MICADO with that of NIRCam at the JWST.

motion measurements of the internal kinematics of stars in Local Group galaxies: with this information it is possible to derive the orbit structure and hence the dark matter content of these galaxies.

5.14.5.1. Progress in 2008 - 2009

In 2008-2009 the design study was carried out by a consortium including NOVA, Padua, MPIA, and USM, and was led by Genzel and Davies (MPE). NOVA involvement centered on (I) the hardware design (cryogenic and opto-mechanical), done at the O-IR group in Dwingeloo (II) data handling aspects which built on the expertise developed at OmegaCEN in Groningen, and (III) many contributions to the science case. Co-PI for the Netherlands is Kuijken. The study consisted of two phases. During Phase 1, the science cases were developed specifically to identify scientific trade-offs necessary for selecting the appropriate opto-mechanical design. Two opto-mechanical designs were then worked out in parallel, addressing specifically technical/cost trade-offs. At the end of the first Phase, the consortium selected one design based on the scientific and technical trade-offs, and present their decision to ESO in a review meeting. During Phase 2, the selected design was developed further in a full Phase A study, addressing all technical issues. Phase 1 was completed in December 2008 and the final Phase A Conceptual Design review was held at ESO in December 2009.
NOVA was responsible for the Data Flow (Edwin Valentijn; RuG) and the cryo-mechanical design (Raymond van den Brink, Marco Drost, Hiddo Hanenburg, Niels Tromp).

5.14.6. Optimos-EVE

OPTIMOS-EVE is an optical to near-IR (310 - 1800 nm) spectrograph for the E-ELT at medium spectral resolutions of R=5000, 15000 & 30000 with high multiplexing capabilities of 240 fully-deployable single objects fibers (0.9'' diameter), 30 medium sized deployable IFU units (1.8''x3.0'', 52 fibers each) and one large fixed IFU (13.5''x7.8'', 1560 fibers). It reaches an instrument efficiency of 45% and works in natural seeing or with ground-layer adaptive optics. The field of view is 7'x7' (10'x10' with some vignetting). OPTIMOS-EVE will be the one-stop solution for all optical-near-infrared spectroscopy on the E-ELT. JWST will have no capability in this domain. The science case includes three key science drivers for the E-ELT: (I) the resolved stellar populations in the Local Universe, (II) the formation of the earliest galaxies and the end of the epoch of reionization and (III) the possibility to detect extra*galactic* planets. It is expected to be a workhorse instrument on the E-ELT and can be used to exploit the scientific potential of the E-ELT directly from the start.

Francois Hammer (PI, GEPI, France) and Lex Kaper (co-PI, API, Netherlands) are leading the phase A study. Other partners are RAL, Copenhagen and INAF Brera and INAF Trieste. The consortium is based on the successful VLT X-Shooter and FLAMES instrument projects with the addition of the UK-RAL group and their strong experience in fiber positioners and detectors.

5.14.6.1. Progress in 2008 - 2009

The kick-off of the phase A study was in November 2008 and the Phase A will be concluded at the end of February 2010 (review in late March 2010). The instrument has been designed to comply with the top-level requirements as derived from the Science Case. NOVA was responsible for the overall project management and the spectrometer design.

In addition, the science team (with NL members Groot, Kaper, Koopmans, Stam, and Tolstoy) has prepared science cases on galactic haloes at high redshift, lensed galaxies, IGM tomography, redshift surveys, transients, star formation, gaseous exoplanets, and trans-Neptunian objects, a testament to the highly versatile nature of OPTIMOS-EVE.

5.15. Astrophysical Multi-purpose Software Environment (AMUSE)

AMUSE is a software instrument for astrophysical multi-scale and multi-domain simulations. The project was started in May 2009. In the coming two years they will combine existing codes from four different domains (Gravitational Dynamics, Stellar Evolution, Hydrodynamics and Radiative Transfer) into one self-consistent software framework. Target applications are simulations of compound objects with widely differing length scales and physical regimes. The main aims of the project are:

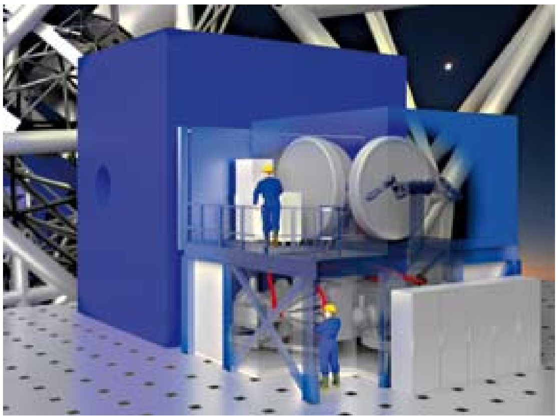


Figure 5.23: The multi-object optical to near-infrared spectrograph OPTIMOS-EVE at one of the focal stations of the European Extremely Large Telescope.

- A standard way of input and output of astrophysical data;
- Support for set-up and management of numerical experiments;
- A unique method to couple a wide variety of physical codes;
- A legacy set of standard, proven codes. These codes will be integrated into AMUSE as modules. Each module can be used stand-alone or in combination with other modules.
- A standard way for adding new modules to AMUSE;
- Examples to show the use of each module and possible couplings between the modules;
- Documentation containing introduction, how-to's and reference documents;

The AMUSE software is developed at the Leiden Observatory by a small core team of 4 scientists (post-doc, software engineer and scientific programmers) in collaboration with the Dutch computational-astrophysics community.

5.15.1. Technical Progress in 2009

In 2009, the AMUSE base framework was developed. Codes are included with a generic module communication strategy based on the standard MPI message passing. This strategy allows us to run different codes on different computers, distributing computational resources based on requirements of the different codes. Our choice for MPI also means that AMUSE will follow the parallel computing paradigm from the start. This strategy is also beneficial in alleviating concerns about memory contamination and control of the existing codes. Another notable inclusion in the base framework is the so called "unit handling module". With this module we can support arbitrary unit conversions. The module is used as an integral part of AMUSE. It has proven to be useful for stand-alone calculations. The framework includes an automatic software building and testing facility.

The project has released the software initially to a select community of national and international scientists (later releases will be fully public). These scientists have expressed their interest in using AMUSE and in integrating their existing codes into AMUSE. Two extra existing codes have been integrated as the result of this collaboration.

Currently, 6 existing physical codes have been included into AMUSE and 3 are in the prototype phase. The 6 included codes model Gravitational Dynamics or Stellar Evolution astrophysical domains. These are all proven codes and are used in production runs using the AMUSE framework.

6. NOVA funded research and instrumentation positions

The tables in the chapter list all research and instrumentation positions whose employment was – partially – funded through NOVA in 2008-2009.

Project	Title	Project leader	Univ	Researcher	Yrs	Start	End	Remark
Network #1								
10.1.2.01	Circumstellar dust in galaxies	Barthel	RuG	Drs. Guido van der Wolk	2,50	Jan 1, 2007	Jul 1, 2009	
10.1.2.03	2D spectroscopy of distant galaxies	Franx	UL	Drs. Maaike Damen (50%)	4,00	Sep 12, 2005	Sep 11, 2009	a
10.1.2.06	Sinfoni study starburst galaxies	Van der Werf	UL	Drs. Liesbeth Vermaas	2,00	Feb 1, 2008		a
10.1.2.07	3D astrophysical hydrodynamics	Icke	UL	Drs. Jan-Pieter Paardekooper	2,00	Sep 1, 2006	Aug 31, 2008	a
10.1.2.09.1	Network postdoc position	Franx	UL	Dr. Ryan Quadri	1,80	Nov 15, 2007	Sep 14, 2009	
10.1.2.10.1	The disk-mass project	Verheijen	RuG	Drs. Thomas Martinsson	1,90	Mar 1, 2007	Feb 1, 2009	
10.1.2.10.2	Resolving M32's main sequence	Trager	RuG	Drs. Antonella Monachesi	1,90	Oct 1, 2006	Sep 1, 2008	
10.1.3.2	Ly-α emission around galaxies	Schaye	UL	Drs. Alireza Rahmati	4,00	Sep 1, 2009		
10.1.3.3	Galaxy evolution at z=3	Franx	UL	Drs. Jesse van de Sande	4,00	Nov 1, 2009		
10.1.3.5	Warm interstellar medium	Van der Werf	UL	Dr. Edo Loenen	3,00	Dec 1, 2009		
10.1.3.10	Gaia in the galaxy	Helmi	RuG	Drs. Maarten Breddels	4,00	Feb 1, 2009		
10.1.3.11a	Modeling Herschel spectroscopy	Brandl	UL	Dr. Brent Groves	2,00	Nov 1, 2008	Apr 30, 2009	b
10.1.3.12	Network 1 postdoc	Franx	UL	Dr. Benjamin Oppenheimer	3,00	Aug 1, 2009		
Network #2								
10.2.2.2a	Spectra ions	Tielens	RuG	Drs. Nadine Wehres	1,00	Mar 1, 2008	Feb 28, 2009	
10.2.2.2b	Collisions	Tielens	RU	Drs. Hsin Yang Chung	1,00	Sep 1, 2008	Aug 31, 2009	
10.2.2.03	Gas-grain chemistry	Linnartz	UL	Drs. Sergio Ioppolo (40%)	4,00	Sep 1, 2006		
10.2.2.04	Massive young stars	de Koter	UvA	Drs. Lianne Muijres	4,00	May 1, 2006		
10.2.2.05	PDRs	Spaans	RuG	Drs. Juan Pablo Perez Beaupuits	2,50	Sep 1, 2006	Feb 28, 2009	
10.2.2.09	Mass loss during the AGB phase	Tielens	RuG	Drs. Christiaan Boersma	3,00	Feb 1, 2005	Jan 31, 2008	
10.2.2.10	AGB puls dust formation	Icke	UL	Drs. Chael Kruip	2,80	May 1, 2007		
10.2.2.12	3D astrophysical hydrodynamics	Icke	UL	Drs. Jan-Pieter Paardekooper	1,00	Sep 1, 2008	Aug 31, 2009	a
10.2.2.13	Methane photolytic processes	Linnartz	UL	Dr. Claire Romanzin	0,50	Nov 1, 2007	Mar 31, 2008	
10.2.3.3	Molecular complexity	Dominik	UvA	Drs. Gijs Mulders (50%)	4,00	Feb 1, 2009		c
10.2.3.4	HIFI, ALMA laboratory studies	Linnartz	UL	Drs. Edith Fayolle (50%)	4,00	Aug 1, 2009		
10.2.3.6	Disk surface layers	Waters	UvA	Drs. Gerrit van der Plas	1,00	Aug 1, 2009		
10.2.3.9	Disks around embedded YSOs	Hogerheijde	UL	Drs. Kuo-Song Wang	4,00	Oct 1, 2009		
10.2.3.14	ExPo disk modeling	Keller	UU	Dr. Michiel Min	3,00	Apr 1, 2009		
10.2.3.16	Modeling Herschel spectroscopy	Brandl	UL	Dr. Brent Groves	0,50	May 1, 2009	Oct 31, 2009	b
Network #3								
10.3.2.01	X-rays from accreting compact objects	Langer	UU	Drs. Laurens Keek (50%)	4,00	Nov 15, 2004	Nov 14, 2008	a
10.3.2.02	GRB light curves and environment	Wijers	UvA	Drs. Hendrik van Eerten	4,00	Oct 1, 2005	Sep 30, 2009	
10.3.2.03	Emission radio pulsars	Van der Klis	UvA	Drs. Eduardo Rubio Herrera	4,00	Oct 1, 2005	Sep 30, 2009	
10.3.2.05.1	X-ray spectroscopy	Verbunt	UU	Dr. Elisa Constantini	2,00	Mar 1, 2006	Feb 29, 2008	
10.3.2.07	GRB progenitors	Langer	UU	Drs. Matteo Cantiello	2,00	Jan 1, 2007	Dec 31, 2008	
10.3.2.09	HE CR detection with LOFAR	Hörandel	RU	Drs. Sarka Jiraskova	2,00	Aug 15, 2008		
10.3.2.11	OmegaWhite	Groot	RU	Dr. Niall Deacon	1,00	Oct 1, 2008	Sep 30, 2009	
10.3.3.2	Neutron stars and transients with LOFAR	Van der Klis	UvA	Drs. Thijs Coenen	2,00	Apr 1, 2009		
10.3.3.5	X-ray timing of stellar mass black holes	Van der Klis	UvA	Drs. Maithili Kalamkar	4,00	Aug 1, 2009		
10.3.3.6	Accretion in neutron-star X-ray binaries	Mendez	RuG	Drs. Andrea Sana	2,00	Jul 1, 2009		
10.3.3.8	Burst oscillations in Type-I X-ray bursts	Levin	UL	Drs.Yuri Cavecchi	2,00	Jul 1, 2009		
10.3.3.9	X-ray binaries with ultra-short periods	Verbunt	UU	Drs. Oliwia Madej	4,00	Sep 1, 2009		c
10.3.3.10	X-ray sources in the Galactic Bulge Survey	Wijnands	UvA	Dr. Alessandro Patruno	1,92	Apr 1, 2009		
10.3.3.20	Progenitors of Type Ia supernovae	Vink	UU	Drs. Joke Claeys	4,00	Sep 1, 2009		

Project	Title	Project leader	Univ	Researcher	Yrs	Start	End	Remark
Cross Network								
10.CN.3.5	Modeling Herschel spectroscopy	Brandl	UL	Dr. Brent Groves	1,00	Nov 1, 2009		
Science Support								
10.SS.3.3	PuMa pulsar data recorder LOFAR	Van der Klis	UvA	Dr. Anastasia Alexov	3,00	May 15, 2009		
10.SS.3.4	The Herschel harvest	Barthel	RuG	Dr. Max Avruch	2,50	Dec 1, 2009		
10.SS.3.5	OmegaCEN, calibration software scientist	Van der Hulst	RuG	Prof.dr. Edwin Valentijn	Pw	Apr 1, 1999	Dec 31, 2009	
10.SS.3.5	OmegaCEN, database	Valentijn	RuG	Dr. Danny Boxhoorn	Pw	Apr 1, 1999		
10.SS.3.5	OmegaCEN, surveys	Valentijn	RuG	Dr. John McFarland	4,90	May 1, 2005		
10.SS.3.5	OmegaCEN, photometry	Valentijn	RuG	Dr. Gijs Verdoes Kleijn (0.8)	5,75	Dec 1, 2006		
10.SS.3.5	OmegaCEN, commissioning support	Valentijn	RuG	Drs. Ewout Helmich	3,75	Jun 1, 2006		
Overlap appointments								
10.OA.2/3.1	Proto planetary disks	van der Klis	UvA	Prof.dr. Carsten Dominik	8,50	Jan 1, 2006		
10.OA.2.1	Computational astrophysics	van der Klis	UvA	Dr. Simon Portegies Zwart (0.5)	1,14	Jan 1, 2007	Feb, 2009	
10.OA.2.2	Evolution of galaxies	van der Hulst	RuG	Dr. Amina Helmi	5,30	Sep 1, 2003	Nov 30, 2009	
10.OA.2.2	Black holes and neuton stars	van der Hulst	RuG	Dr. Mariano Méndez	5,42	Sep 1, 2007		
10.OA.2.2	Star formation	van der Hulst	RuG	Dr. Inga Kamp	1,75	Jan 1 , 2008	Sep 30, 2009	
10.OA.2.3	Laboratory astrophysics	van Dishoeck	UL	Dr. Harold Linnartz (0.5)	3,66	Sep 1, 2005	Jul 1, 2008	
10.OA.2.3	Optical-infrared instrumentation	Miley	UL	Dr. Bernhard Brandl	5,00	Jul 1, 2003	Jun 30, 2008	
10.OA.3.3	Dark matter, dark energy	Kuijken	UL	Dr. Henk Hoekstra	2,67	Jan 1, 2009		
10.OA.2.4	Numerical solar physics	Keller	UU	Dr. Alexander Vögler	2,83	Jan 1, 2007	Oct 31, 2009	
10.OA.2.4	Extragalactic star clusters	Langer	UU	Dr. Søren Larsen	1,83	Apr 1, 2006	Jan 31, 2008	
10.OA.3.5	Astroparticle physics	Groot	RU	Dr. Jörg Hörandel	3,00	Jul 1, 2009		
Remarks								
a	Additional funding up to 4 year in total is covered by the university							
b	Position jointly funded by networks #1, #2 and cross network							
c	Co-funded by SRON with 2 PhD years							
Pw	Permanent contract with warning							

Instrumentation Program

Project / job description	Project leader	Inst	Researcher	Yrs	Start	End	Remark
Allegro							
Technical astronomer	Hogerheijde	UL	Dr. Tracy Hill	1,50	Sep 1, 2006	Feb 29, 2008	
Technical astronomer	Hogerheijde	SRON	Dr. Floris van der Tak	0,42	Nov 1, 2007	Mar 31, 2008	
Technical astronomer	Hogerheijde	RuG	Dr. Wilfred Frieswijk	2,40	Jan 1, 2009		
ALMA Band-9, CHAMP+, technical R&D							
Project manager	Boland	SRON	Dr. Brian Jackson	P	Oct 1, 2003	Dec 31, 2009	
Deputy project manager	Jackson	SRON	Rieks Jager (0.3)	P	Jan 1, 2009		
Manager industry contracts	Jackson	RuG	Drs. Joost Adema	Pw	Mar 1, 2003		
Instrument scientist	Jackson	RuG	Dr. Andrey Baryshev	Pw	Nov 15, 1999	May 1, 2008	
Front-end scientist	Jackson	RuG	Dr. Ronald Hesper	Pw	Sep 1, 2000		
Receiver scientist	Jackson	RuG	Jan Barkhof	7,79	Mar 16, 2004		
Front-end technician	Jackson	RuG	Gerrit Gerlofsma	Pw	Oct 10, 2001		
Test engineer	Jackson	RuG	M. van den Bemt	3,90	Oct 1, 2008		
Test engineer	Jackson	RuG	L.H.R. de Haan - Stijkel	3,93	Nov 1, 2009		
Documentalist	Jackson	RuG	Albert Koops	Pw	Dec 1, 2004		
Assembly technician	Jackson	SRON	Klaas Keizer	1,80	Mar 1, 2005		
Assembly technician	Jackson	RuG	Marielle Bekema (0.4)	7,00	Jan 1, 2005		
Test engineer	Jackson	RuG	J. Koops van het Jagt	4,93	Nov 1, 2009		
Receiver scientist	Jackson	RuG	Dr. Patricio Mena	3,50	Sep 1, 2004	Feb 29, 2008	
SIS junction design and production	Klapwijk	TUD					
Astronomical support Champ+	Hogerheijde	SRON	Dr. Floris van der Tak	3,00	Sep 1, 2005	Sep 1, 2008	
AMUSE							
Project manager	Portegies Zwart	UL	Dr. Arjen van Elteren	2,00	May 1, 2009		
Technical postdoc	Portegies Zwart	UL	Dr. Inti Pelupessy	2,00	May 1, 2009		
Programmer	Portegies Zwart	UL	Drs. Marcel Marosvölgyi	2,00	Oct 1, 2009		
Programmer	Portegies Zwart	UL	Dr. Nathan de Vries	2,00	Dec 1, 2009		
Gaia							
Software design	Brown	UL	Dr. Giorgia Busso	3,75	Jan 1, 2009		
Software design	Brown	UL	Dr. Paola Marrese	2,08	Jan 1, 2009		
LOFAR							
Postdoc Reionization 1	de Bruyn	RuG	Dr. Sarod Yatawatta	5,00	July 1, 2005		
Postdoc Reionization 2	de Bruyn	RuG	Dr. Vishambar Pandey	2,50	Oct 1, 2008		
PhD student Transient sources 1	Wijers	UvA	Drs. Hanno Spreeuw (50%)	4,00	Sept 1, 2005	May 31, 2009	
PhD student Transient sources 2	Wijers	UvA	Drs. Bart Scheers (50%)	4,00	Sept 1, 2005	May 31, 2009	
Postdoc Surveys+ array enhanc	Röttgering	UL	Dr. Niruj Mohan Ramanujam	3,50	July 1, 2005		
TRA-08a data analist	Wijers	UvA	Dr. Kenneth Anderson	2,25	Jan 19, 2009		
Postdoc Cosmic Rays 1	Falcke	RU	Drs. Satyendra Thoudam	2,00	Apr 1, 2009		
Postdoc Cosmic Rays 2	Falcke	RU	Dr. Clancy James	2,25	Jun 15, 2009		
Matri2ces							
Surfreside	Linnartz	UL	Drs. Sergio Ioppolo	2,40	Sep 1, 2006		
PhD student	Linnartz	UL	Drs. Karoliina Isokoski	2,40	Jan 1, 2009		a
MIRI							
NL project manager	van Dishoeck	SRON	Rieks Jager	P	Jun 1, 2003		
PhD student instrument calibration	Brandl	UL	Drs. Juan Rafael Martinez Galarza (0.5)	2,00		Dec 1, 2007	a
Several ASTRON staff	Jager	ASTRON					
MUSE; MUSE-ASSIST							
Project manager	Schaye	UL	Dr. Remko Stuik	3,50	Jan 1, 2008		

Project / job description	Project leader	Inst	Researcher	Yrs	Start	End	Remark
Postdoc calibration software	Schaye	UL	Dr. Denis Serre	2,00	May 1, 2008		
Optical designer	Stuik	UL	Dr. Pascal Hallibert	3,50	April 1, 2005	Sep 30, 2008	
Postdoc ASSIST hardware	Stuik	UL	Dr. Atul Deep	3,25	April 1, 2007		b
Postdoc AO control	Stuik	UL	Dr. Laurent Jolissant	2,00	March 1, 2007	Feb 28, 2009	
Optical-IR instrumentation group							
Groups manager: Ramon Navarro	Boland	NOVA	Ramon Navarro				
System engineer/cryogenic engineer	Navarro	NOVA	Ronald Roelfsema				
Optical designer	Navarro	NOVA	Rik ter Horst (0.8)				
Optical designer	Navarro	NOVA	Florance Rigal (0.8)				
Senior mechanical designer	Navarro	NOVA	Gabby Kroes (0.8)				
Mechanical designer	Navarro	NOVA	Jan Kragt				
Mechanical design	Navarro	NOVA	Johan Pragt (0.5)				
Construction/test	Navarro	NOVA	Eddy Elswijk				
Construction/test	Navarro	NOVA	Menno Schuil				
Construction/test	Navarro	NOVA	Menno de Haan				
Sphere Zimpol							
Optical engineer	Waters	UL	Charlotte Groothuis	2,00	Mar 1, 2009		
SINFONI							
PhD student	Van der Werf	UL	Drs. Liesbeth Vermaas	2,00	Feb 1, 2006	Jan 31, 2008	a
S5T							
Technical PhD student	Keller	UU	Drs. Helena Becher	4,00	Mar 1, 2008		
X-Shooter							
Postdoc calibration software	Kaper	UvA	Matthew Horrobin (0.5)	1,00	Jan 1, 2008	Dec 31, 2008	
E-ELT Phase-A studies							
METIS, conceptual design study	Brandl	UL	Dr. Sarah Kendrew	1,00	Jan 1, 2009	Dec 31, 2009	
Postdoc AO trade-off studies	Brandl	UL	Dr. Laurant Jolissaint	0,67	March 1, 2009	Oct 31, 2009	
EPICS - ESFRI R&D							
Postdoc polarimetry systems	Keller	UL	Dr. Frans Snik	4,00	Jul 1, 2009		

a	Additional funding up to 4 year in total is covered by the university
b	Additional funding from Groningen, VICI grant Tolstoy
P	Permanent contract
Pw	Permanent contract with warning

7. Workshops & Visitors

The NOVA workshops & visitors program enables researchers to invite foreign experts to the Netherlands for collaborative projects.

7.1. Workshops in 2008-2009

The table below lists the workshops which received financial support from NOVA. The table is followed by a description of each meeting. In addition the university astronomical departments in Amsterdam, Groningen, Leiden, Nijmegen and Utrecht received NOVA funding up to 3400 € per institute per year to strengthen the local colloquia program by inviting more foreign speakers. A common approach is to coordinate the colloquium programs in various places in such a way that foreign speakers visit two or more institutes during their stay in the Netherlands.

Nr	Date	Applicant	Event	University	Duration (days)
W-118	28-01-2008	M. Franx	Galaxy evolution from mass-selected samples	UL/LC	5
W-119	06-10-2008	H. Cuppen	Interstellar surfaces; from laboratory to models	UL/LC	5
W-120	29-09-2008	K. Groen	400 years of astronomical telescopes	ESTEC	4
W-121	14-04-2008	R. Wijnands	A decade of accreting millisecond X-ray pulsars	UvA	5
W-122	15-09-2008	J. Schaye	Galaxies in real life and simulations	UL/LC	5
W-123	23-06-2008	E.v.d. Heuvel	KNAW symposium telescopisch perspectief	KNAW	1
W-124	04-06-2008	S. Markhoff	Mini-workshop on MHD/jets	UvA	1
W-125	04-10-2008	H. Olthof	KNVWS symposium 2008	Middelburg	1
W-126	23-06-2008	R. Strom	Low-frequency pulsar science	UL/LC	5
W-127	01-09-2008	S. Harfst	Modeling dense stellar systems	UvA	5
W-128	28-07-2008	R. McDermid	Central mass concentrations in galaxy nuclei	UL/LC	5
W-129	17-11-2008	B. Groves	Fitting the spectral energy distributions of galaxies	UL/LC	5
W-130	15-12-2008	C. Law/Wijnands	LOFAR and the transient radio sky	UvA	3
W-131	19-08-2008	A. Johansen	Pencil code meeting 2008	UL	4
W-132	31-10-2008	P. Barthel	Symposium in honor of Bob Sanders: Galaxies from inside to out	RuG	1
W-133	24-04-2009	R. v.d. Weijgaert	Fysica 2009	RuG	1
W-134	20-11-2008	S. Portegies Zwart	Cosmogrid workshop	UvA	3
W-135	19-08-2009	P. Mulders	Intern. summer school on astroparticle physics 'Nijmegen '09'	RU	9
W-136	16-03-2009	D.Salter/I.Oliveira	2009 EARA workshop 'from disks to planets: learning from starlight'	UL/LC	5
W-137	06-04-2009	Hoekstra/Zhao	Interactions in the dark: making physics of dark energy - dark matter interactions testable	UL/LC	4
W-138	02-02-2009	Franx	Deep IR studies of the distant Universe	UL/LC	5
W-139	01-12-2008	H. Rottgering	First science with LOFAR	UL	
W-139	13-07-2009	A. Brown	Distribution of mass in the Milky Way galaxy	UL/LC	5
W-140	21-09-2009	Pols	Stellar mergers	UU/LC	14
W-142	26-06-2009	R. Waters	Interaction of cosmic grains with light: recent developments	UL	1
W-143	12-10-2009	P. Barthel	Symposium in honor of Piet van der Kruit: Challenges	RuG	1
W-144	09-11-2009	M. Franx	Evolution of galaxies form mass selected samples	UL/LC	5
W-146	02-11-2009	H. Linnartz	Cavity enhanced spectroscopy	UL/LC	5

W-118: Galaxy evolution from mass-selected samples

The workshop "Galaxy evolution from mass-selected samples" was organized in the Lorentz Center, during the week of January 28 - February 1 2008. We had 24 participants. The workshop consisted of presentations (in the morning), and free time for discussions and work in the afternoon. Overall, the workshop was a great success. We initiated several papers, heard about new exciting results, and used it also to have several meetings with small collaborations on specific projects. These kind of meetings are essential to stay productive.

W-119: Interstellar surfaces; from laboratory to models

The aim of this workshop was to bring together experimental and theoretical solid state physicists, chemists and astronomers to discuss how laboratory results and astrochemical models should interact in order to interpret or guide astronomical observations. The workshop was held in the Lorentz Center in Leiden from 6-10 October 2008 and its program included more than 20 talks following four topics along with special discussion sessions. With nearly 50 registered participants the meeting gathered the majority of the leading scientists in the field. It was a successful meeting, addressing the big questions we are facing and a high degree of interaction between the participants.

W-120: 400 years of astronomical telescopes: a review of history, science and technology

This very successful conference was held from 29 September to 2 October at ESTEC/ESA, Noordwijk. It honored the 400th anniversary of Hans Lipperhey's patent application on 25 September 1608 for the "spy glasses", the optical system that became the basis for optical astronomical telescopes. More than 130 participants, including the present and four former DGs of ESO, listened to talks about the history of the telescope making and usage, key technologies that drove the development of telescopes, and political as well as sociological aspects. The program covered all types of telescopes across (and even beyond) the entire electromagnetic spectrum. The 3.5 day program consisted exclusively of review talks given by invited speakers who have been working in or even shaped the field. In the evening there was a well attended social program, which included an opening reception, dinner cruise and a special session at the Boerhaave museum where an exhibition of historical telescopes had just been opened.

W-121: A decade of accreting millisecond X-ray pulsars

The workshop 'A decade of accreting millisecond X-ray pulsars' was held at the Astronomical Institute 'Anton Pannekoek' of the University of Amsterdam, from April 14th until April 18th, 2008. The purpose of the workshop was to celebrate the 10th anniversary of the discovery of the first accreting millisecond pulsar, to discuss the most important discoveries in this field in the last 10 years, and to discuss the progress which has been made in our understanding of these systems.

For this workshop, we were able to obtain an impressive list of invited speakers, which consisted of almost all astronomers who have made important contributions in the field of accreting millisecond X-ray pulsars. In total there were 55 participants with 20 invited presentations and 23 contributed ones. The workshop was very successful. All important, related topics were discussed and progress has been made in obtaining a unified interpretation of the observational results.

W-122: Galaxies in real life and simulations

The workshop "Galaxies in Real Life and Simulations" took place on September 15-19 at the Lorentz Center in Leiden. The aim of the workshop was to bring together researchers from the observational and theoretical communities to discuss the origin and evolution of massive galaxies. The workshop was attended by 44 invited international participants and about 10 interested people from the astronomical community in the Netherlands. The program consisted of 20 keynote and 16 highlight talks of 15 and 25 minutes respectively, and a total of 10 hours of discussion (divided over the different sessions). In particular the discussion sessions were a great success. We addressed many outstanding issues concerning build-up of massive galaxies, and discussed ways to solve these issues.

W-123: KNAW symposium telescopic perspective

This one-day symposium on June 23 2008 was organized by the Royal Netherlands Academy of Arts and Sciences in Amsterdam to celebrate the 400th anniversary of the invention of the telescope, by Middelburg optician Hans Lippershey. The aims of the symposium were presenting a historic overview of the invention and early developments of the telescope and giving a perspective of how future telescopes for all electromagnetic wavelength regions - from gamma rays to radio waves, as well as for neutrinos - are expected to improve our understanding of the origin and evolution of the Universe and its constituents. Following a beautiful historical overview by Utrecht Professor Albert van Helden, international experts for each wavelength/particle region presented their views on the future developments in their respective fields. Accompanying the symposium was an exhibition of some beautiful specimens from the Louwman Collection of Historic Telescopes. The symposium was attended by over 100 participants and was a great success.

W-124: Miniworkshop on MHD and jets

Prof. P. Chris Fragile, Dr. David Meier and Dr. Masa Nakamura and Sera Markoff have a collaboration, funded by the NASA Astrophysical Theory Program, to simulate and better understand the inner accretion disk, jet launching, jet acceleration and jet formation in general in accreting black holes. In order to make progress on one of the most difficult topics in astrophysics, and to increase the exchange between "pure" theorists and observers, a single day workshop was organized on the topic of (magneto) hydromagnetic modeling of astrophysical flows. The Mini-Workshop on (M)HD was held at June 4th at the University of Amsterdam, and was attended by more than 20 people. It also allowed some scientific collaborators to come over for a research visit, as well as then maximize the scientific interaction between these visitors and the local Dutch community. The talks spanned the range from inner accretion disk theory to outer jet collimation. The meeting was a success, running from early in the morning until late in the evening.

W-125: KNVWS symposium 2008

On 4 Oktober 2008 the KNVWS organised the symposium: "The Telescope-past, present and future" in collaboration with the public observatory "Philippus Lansbergen" and the Flemish Society for Astronomy (VVS). To honor the invention of the telescope 400 years ago this symposium took place in Middelburg. The program was opened by the President of the Royal Academy of Sciences in the Netherlands, Professor Robbert Dijkgraaf, and covered the impact in the 17th century of the invention of the telescope on the understanding of the Solar System, the development of new telescopes in the optical, infrared and high energy astrophysics domains as well as the development of new telescopes for amateur astronomers. The symposium was attended by 320 participants, mostly amateur astronomers and included a strong representation of the Flemish amateur astronomy society in Belgium.

W-126: Low-frequency pulsar science

The workshop (23 to 27 June 2008) on exploring the science and technical details of the new low-frequency arrays attracted 53 scientists from 11 countries, including 10 people from the Netherlands. Although many senior scientists attended as well, the median age was about 30. The workshop started with a discussion of techniques, instrumentation, and the numerous large-scale surveys that will be undertaken with the new instruments. Computational constraints and promise were a recurrent theme throughout these discussions. Items that were discussed were: (1) the advances that these instruments will bring to our understanding of how pulsars produce their radio beams, (2) transients, one of the LOFAR key science projects, and a scientific driver for many of these areas since they have the potential to instantaneously scan large portions of the sky, (3) single pulse studies and magnetospheric physics, (4) Interstellar medium and (5) the prospects of the "killer applications" of the low-frequency arrays and eventual scientific connections with the Square Kilometer Array. All topics were well covered in both reviews and in depth discussions. On Thursday the group visited Exloo, site of the first LOFAR station, for two informative talks and a tour of the labs.

W-127: Modelling dense stellar systems

We have organized a 5-day workshop from September 14th to 19th in Amsterdam for a group of international computer scientists, astronomers and computational astrophysicists where we continued the development and discussed the future of the Multi-scale Multi-physics Software Environment (MUSE). MUSE is designed to realistically model dense stellar systems, such as young star clusters and galactic nuclei and it is a project resulting from the MODEST collaboration. Our meeting was well attended by a total of 19, mostly young, researchers in computer science and astrophysics. About half of the participants had been involved in the MUSE project before, either by attending one of the previous meetings or by contributing their own software packages. We also welcomed many scientists who only recently got interested in MUSE and attended the meeting to learn more. Thus, the workshop was a success and we were able to make another step towards realistic modelling of dense stellar systems.

W-128: Central mass concentrations in galaxies

This workshop (28 July to 1 August 2008) brought together an international group of active researchers in the distinct fields of nuclear star clusters and super-massive black holes. The well-known scaling relations between black holes and galaxy properties are constantly being refined with high-quality observations and modelling, which are helping to reduce uncertainties in the individual measurements. The conclusion from this workshop is that a more homogeneous approach to this problem, both from modelling and observational sides, is needed for a large sample of objects. Nuclear star clusters often, and perhaps always, co-exist with a super-massive black hole, although this is still limited by current observational limits. Models were presented to show how nuclear star formation could be self-regulating, with the same physical mechanisms as those thought to regulate black hole growth. This hints towards the beginning of a holistic formation scenario of both the black hole and the coincident nuclear star cluster, although full consideration of co-evolving clusters and black holes seems to be largely unexplored. From this workshop, it became clear that the communities of nuclear star clusters and super-massive black holes can clearly benefit from their overlapping expertise, and thanks to this workshop, will interact more in the future.

W-129: Fitting the spectral energy densities of galaxies

The aim of this workshop (17 to 21 November 2008) was to bring together the main players in the fields of modelling, multi-wavelength observations and SED fitting techniques, to provide an overview of the current limitations in the field and to define where improvements need to be made. We achieved this through a programme arranged to have formal talks in the morning and open discussion sessions in the late afternoon, with time set aside after lunch for smaller discussion groups and networking. With 46 attendees, covering a broad range of topics, from SED modelling, empirical SEDs, multi-wavelength observations and SED Fitting, including photometric redshifts, the talks were very informative, and lead to active discussions in the afternoon. The breakaway sessions were also well utilized with many discussions.

W-130: LOFAR and the transient radio sky

The workshop was held from December 15-17, 2008 at the Astronomical Institute of the University of Amsterdam. The total number of attendees was 59, including 10 invited speakers. The workshop focused on developing ideas and collaborations for the first observations of radio transients with LOFAR. Regular LOFAR observations will begin next year, so many from the international community are excited to participate. The final day of the workshop was dedicated to presentations from other astronomical observatories. These talks emphasized the emergence of "multi-messenger astronomy" (sometimes known as "astro-particle physics"), a focus of future EU research.

W-131: Pencil code meeting 2008

The Pencil Code Meeting 2008 was held August 19-22 2008 at Leiden Observatory in Leiden in the Netherlands. The Pencil Code Meeting is an annual meeting dedicated to the Pencil Code. The purpose of the meeting is to bring regular users and core developers together to discuss scientific and technical progress since the last meeting, to instigate collaborative projects and to allow new users to learn more about the code and to interact with other users and developers. This year's meeting in Leiden had 19 participants. We discussed the transition from CVS to SVN version control systems and had several scientific talks about dynamo theory, planet formation and the new chemistry modules.

W-132: Galaxies from inside to out

On October 31, 2008, the Kapteyn Astronomical Institute organized a symposium "Galaxies from inside to out" at Groningen University, honoring Prof. R.H. (Bob) Sanders, on the occasion of his retirement. The theme of the symposium was centralized on the career of Prof. Sanders, and various aspects of it were highlighted by the speakers. Liszt (NRAO, Charlottesville) discussed studies of the Galactic Center, thereby including the contributions of Sanders, early in his career. van Gorkum (Columbia University, New York) spoke about her work as one-time Groningen student, together with Sanders, on the issue of Gas in Elliptical Galaxies. Milgrom (Jerusalem) discussed the work of himself, Sanders and others, dealing with alternative gravity theories. That same topic was also addressed by van Albada (emeritus Groningen). Following personal Concluding Reflections by Sanders himself, the well-attended symposium was concluded with a reception.

W-133: Fysica 2009

On April 24, 2009, the annual national physics conference Fysica2009 was organized in the Martiniplaza in Groningen. Within the organization prof. dr. P. Barthel and prof. dr. R. van de Weijgaert represented astronomy. Within the context of the Year of Astronomy, the symposium contained 2 parallel sessions. The Year of Astronomy was the most popular session, with more than 150 attendants, and had 3 lectures on new instrumental developments in Dutch astronomy (optical: Tolstoy; IR/mm: van Dishoeck; radio: Verheijen), while the session ``From LHC to Planck', included lectures on inflation and an update of the Planck CMB project by Jaffe (Imperial College). Overall, the conference was a big success, with a participation level exceeding 400.

W-134: CosmoGrid workshop

We have organized a three-day workshop (20-22 November 2008) dedicated to two large-scale cosmological projects, the CosmoGrid and the Gravitational Billion Body Problem (GBBP). In these projects, we run very large cosmological N-body simulations using several supercomputers across the globe in parallel. The workshop was attended by 12 participants of the CosmoGrid project, which consists of astrophysicists, computer scientists and network specialists, as well as experts in the fields of high-performance computing and cosmology. During the workshop we have discussed the initial conditions, supercomputer time scheduling and exchanged information about the data analysis. The workshop was planned at a crucial moment in the project, as we have now started production.

W-135: International summer school on astroparticle physics 'Nijmegen '09'

The 3rd International Summer School on Astroparticle Physics was held from 19-28 August 2009 in hotel Val Monte, Berg en Dal, Nijmegen. The lecture program of the school listed many distinguished international speakers on a wide range of topics in astroparticle physics at a state-of-the-art level. The 43 students, all studying for their PhD, were from 14 different countries on four continents. Five excellent students were granted free access to the school. About half of the time was spent by the students in working groups preparing either a defense or a review of a new astroparticle physics experiment, resulting in presentations towards the end of the school.

W-136: EARA workshop 'from disks to planets: learning from starlight'

Astronomers from three different fields of expertise (stellar astrophysics, circumstellar disks and exoplanets) were brought together to connect the different stages of evolution of these systems and discuss the challenges and next steps in the understanding of planet formation. 47 registered participants, plus many local attendees from Leiden were present in this PhD student organized workshop. Students represented just over one third of the registered participants, counting 17 in total. The mornings were saved for presentations, while the afternoons were more flexible, allowing plenty of discussion between participants, mixing observers, modellers and theoreticians. The important constructive part of the workshop was to create communication between experts on different fields. The inter-field discussions were plenty and fruitful, indicating the success of the workshop. The workshop was finished with a discussion on the forthcoming facilities that will move these fields, what can be expected and what need to be prepared for a bright future.

W-137: Interactions in the dark

With the amazing precision of observational data on the largest scales of the universe, "dark energy" has established itself firmly in our thinking of fundamental theoretical physics. The current paradigm, the ΛCDM cosmology, provides an excellent model to describe the universe, but we lack a convincing theoretical framework to accommodate the extreme fine-tuning of the dark energy density parameter to 10^{+120}. To explore alternative models and to examine how these can be efficiently tested using state-of-the-art observational data, a unique combination of researchers from three communities (theoretical physics, observational cosmology and experts on numerical simulations) convened at the Lorentz Center April 6-9 2009. The workshop was a great success and was attended by ~45 participants who actively participated in the discussions. A clear outcome from the meeting is that there is no shortage of theoretical ideas, but that it is much more difficult to put these to the test, due to the lack of appropriate tools to make predictions. As such the workshop has provided ideas for new research directions, with a particular focus on developing better tools to compare observations to predictions.

W-138: Deep IR studies of the distant Universe

We organized the workshop titled "Deep IR studies of the distant Universe". The location was the Lorentz Center, and the meeting took place on Feb 2-6, 2009. The meeting focused on the evolution of galaxies from z=5 to z=0. Various collaborative efforts brought the group together, and the meeting was crucial to obtain an overall view of the status of the field, but also of the specific projects that the participants worked on. The meeting was structured to have most presentations in the morning, with ample time for discussion in the afternoon. The Lorentz Center is the perfect location for such workshops, as it provides ample office space and discussion rooms for the participants, crucial to the success of this meeting.

W-139: Distribution of mass in the Milky Way Galaxy

The workshop (13 to 17 July 2009) was attended by about 50 participants, with a good mix of experts from Dutch institutes (Leiden, Groningen) and international speakers. We are pleased that we managed to bring together a good combination of junior and senior astronomers, theorists and observers to update each other on the latest developments in the research into the structure and formation of the Milky Way galaxy. There was a wide range of talks and posters were also presented. Many participants felt that the workshop helped them to build new collaborations.

W-140: Stellar mergers

The merger of two stars is a process that touches many branches of modern astrophysics and is responsible for some of the most spectacular astronomical phenomena, from Type Ia supernovae to the formation of helium subdwarfs. This workshop, held from 21 September - 2 October 2009 at the Lorentz Center in Leiden, brought together 47 scientists including many of the world's leading experts in this fast-moving field in order to compare progress, especially at the interfaces between different methodologies, and to plan the next steps in developing a coherent science. Amongst new insights, the discussion of how a common envelope evolves was of particular value. The physics of this process, how to model it numerically and under what circumstances it leads to a merger, is far from obvious. Other highlights included the presentation of B[e] and other exotic stars as likely candidates of massive star mergers, and the extreme conditions close to the Galactic center that create an environment in which stellar collisions are significantly more likely than even the dense cores of globular clusters.

W-142: Interaction of cosmic grains with light: recent developments

The one day (26 June 2009) workshop, in honor of the Oort professor Bruce Draine, covered a rich variety of dusty environments, providing ideas and inspiration on practically every step in the dust cycle and was attended by 15 people. A good example in this respect was given by F. Kemper using astromineralogy in extragalactic sources as a clock tracing star formation rate and history. Two talks covering the theory of optical properties of dust grains (by M. Min and M. Yurkin) provided an overview of the current capabilities of computational methods and how these connect to laboratory measurements. The interstellar dust and how to probe its characteristics was covered by C. de Vries and B.T. Draine. Finally, there were several presentations on the evolution of dust from protoplanetary disks (C. Keller) to comets (A-C. Levasseur-Regourd) and planetary atmospheres and rings (D. Stam). It was an inspiring workshop full of interesting ideas, with a lot of interaction and discussion.

W-143: Symposium in honor of Piet van der Kruit: Challenges

At the occasion of Piet van der Kruit's 65th birthday, a symposium "Challenges" was held in Groningen, on October 12, 2009. Ten of Piet's colleagues and friends discussed challenges, from various aspect angles. Academia is full of challenges, in research, in teaching and in administration. Scientific research is challenging in itself; there is the permanent adaption of insight to new observations, new ideas, new techniques and a permanent shift of paradigms. There is also the challenge to communicate the new developments to a broad audience and policy makers and to incorporate it in the academic curriculum and lectures. Finally there is the challenge to develop and realise new facilities, scientifically as well as technically, financially and politically. Piet's final address summarized his personal views on all of these challenges, which he all met during his career.

The symposium was held under the joint auspices of the Kapteyn Astronomical Institute and the Koninklijk Natuurkundig Genootschap. Given that "Challenges" drew close to 200 attendants, it can be considered a great success.

W-144: Evolution of galaxies from mass selected samples

The 5 day (9-13 November 2009) workshop brought together 23 people from several groups working on galaxy evolution and galaxy formation. This is a topic which is developing very rapidly with the new observational capabilities and new theoretical insights. On the observational side, the workshop was focussed on near-ir selected samples. These samples are the only samples which can lead to proper mass selected samples. Many presentations were given highlighting the newest results in the field, especially those using medium band filters to determine accurate photometric redshifts and spectral energy distribution of the galaxies. In addition, "hot" results from the WF3 camera, recently installed on the Hubble Space Telescope, were reported. Theoretical and interpretative results were reported which help us to understand these results. Ample time was left open for work and discussion (about half the time).

W-145: The first science with LOFAR

An important goal of LOFAR, the Low Frequency Array, is to explore the low-frequency radio sky by means of a series of unique surveys. During the first day of the workshop an overview was given of the exciting science that will be carried out with LOFAR. Most of the second day was devoted to parallel session for each of the 9 science working groups. The final day was comprised of a long plenary session where the groups reported on their discussions. The very positive outcome was that there was general agreement on how the survey definition should be modified to optimize the science that the groups would like to pursue.

W-146: Cavity enhanced spectroscopy Lorentz Center meeting

The Cavity Enhanced Spectroscopy Lorentz Center meeting (November 2-6, 2009) consisted of two parts: a two-day winter school (6 lecturers, 50 participants) and a three-day workshop (6 invited talks, 13 contributed talks, a poster session and industrial exhibition, 70 participants). During the meeting the newest book on cavity ring down spectroscopy (Wiley, 2009) was presented. Applications of cavity enhanced techniques are currently found in many different directions ranging from trace-gas and breath analysis to analytical chemistry, plasma and laboratory astrophysics. Both gas phase, fluids and the solid state samples are studied with more and more advanced cavity enhanced setups, allowing to obtain both spectroscopic and dynamical information. The workshop provided a complete cross-view through recent techniques and applications.

7.2. Visitors in 2008 – 2009

The table in this section lists the foreign visitors who received financial support from NOVA to visit the Netherlands for collaborative projects with NOVA researchers. The table is followed by a description of each activity.

Nr	Date	Applicant	Visitor/Event	University	Duration (days)
V-146/1	09-02-2007	L. Kaper	Colloquium	UvA	
V-146/4	2007	S. Larsen	Colloquium	UU	
V-155	19-11-2007	E. v.d. Heuvel	Prof.dr. Pranab Ghosh	UvA	7
V-157	Mrt '08-'09	H. Linnartz	Dr. Lou Allamandola	UL	2x30
V-158/1		S. Markoff	Colloquium	UvA	
V-158/2		T. v.d. Hulst	Colloquium	RuG	
V-158/2		T. v.d. Hulst	Colloquium	RuG	
V-158/3		J. Lub	Colloquium	UL	
V-158/4		S. Larsen	Colloquium	UU	
V-158/5		P. Groot	Colloquium	RU	
V-159	April/May '08	S. Portegies Zwart	Michiko Fujii	UvA	42
V-160	April/May '08	S. Portegies Zwart	Tomoaki Ishiyama/Keigo Nitadori	UvA	35
V-161	21-04-2008	R. Waters	Dr. Sacha Hony (IAS Paris)	UvA	1
V-162	01-06-2008	O. Pols	Dr. Amanda I. Karakas	UU	60
V-163	July 2008	J. Hörandel	Satyendra Thoudam	RU	
V-165a	25-07-2008	R. v.d. Weijgaert	Prof. dr. B. Chaboyer	RuG	5
V-165b	01-07-2008	R. v.d. Weijgaert	P. Araya-Melo	RuG	14
V-166	08-09-2008	G. Nelemans	Dr. Lev Yungelson	RU	88
V-167	12-10-2008	Zaroubi	Prof. Joe Silk & Prof. Naoshi Sugiyama	RuG	7
V-168	10-11-2008	R. v.d. Weijgaert	Dr. G. Mellema	RuG	10
V-169	03-11-2008	L. Kaper	Dr. Arjan Bik	UvA	5
V-170	18-11-2008	H. Henrichs	Dr. K. Kolenberg	UvA	2
V-173	09-03-2009	R. v.d. Weijgaert	Dr. M. Aragon-Calvo	RuG	4
V-174	May-Nov 2009	H. Rottgering	Dr. C. Ferrari	UL	15
V-176	01-05-2009	Hammerschlag-Hensberge	Dr. Julie McEnery (NASA, GSFC) NAC 2009	UvA	1
V-177	10-05-2009	S. Portegies Zwart	Tomoaki Ishiyama (Univer. Of Tokyo)	UL	14
V-178/1		S. Markoff	Colloquium	UvA	
V-178/2		J. Lub	Colloquium	UL	
V-178/3		S. Larsen	Colloquium	UU	
V-178/4		P. Groot	Colloquium	RU	
V-178/5		T. v.d. Hulst	Colloquium	RuG	
V-179	June/July '09	M. Franx	Prof.dr. P. van Dokkum	UL	30
V-180	01-06-2009	M. Mendez	Dr. Tomaso Belloni, INAF-Osserv Italy	RuG	30
V-181	19-07-2009	E. v.d. Heuvel	Prof. Verma	UvA	3
V-182	13-07-2009	R. v.d. Weijgaert	Prof. dr. R. Juszkiewicz	RuG	7
V-183	08-07-2009	R. v.d. Weijgaert	Drs. Wojciech Hellwing	RuG	10

V-155: Visit of Prof. Dr. P. Ghosh

Prof. P. Ghosh from the Tata Institute of Fundamental Research in Mumbai visited the "Anton Pannekoek" Institute from November 19 to 25 2007. During his visit he had several scientific meetings with van der Klis, Wijnands, van den Heuvel, PhD student Altamirano, and PD Casella, especially about the physics of the millisecond X-ray and Radio pulsars and the formation of these objects. Ghosh also gave a colloquium about this topic on Thursday 25th. Furthermore, Altamirano, van den Heuvel and Ghosh discussed plans for the observation of X-ray sources with the Indian X-ray satellite "Astrosat" which will be launched in the end of 2008. Overall the visit was very successful.

V-157: Visit of Dr. L. Allamandola

Dr. Lou Allamandola (NASA AMES) visited the Sackler Laboratory for Astrophysics at Leiden Observatory three times for periods of two months during March 2008 - June 2009. He has been working with Harold Linnartz, postdoc Herma Cuppen and PhD student Jordy Bouwman on the UV photo chemistry of PAHs in inter- and circumstellar ice analogues under astronomical conditions using an UV/VIS detection scheme. This allows real time and in situ studies of the processes that dominate PAH ice chemistry. In addition, the solid state laboratory spectra offer a new approach to search for PAHs in space. VLT measurements are under analysis.

V-159: Visit of M. Fujii

Michiko Fujii visited the Astronomical Institute 'Anton Pannekoek' for a period of 6 weeks in April/May 2008. The objective of her visit was to continue the development an N-body code which can handle the long-term dynamical evolution of star clusters in its parent galaxy. In our code, both a star cluster and its parent galaxy are modeled by N-body systems. During Michiko's visit we used this code to investigate the orbital evolution of two star cluster that spiral-in subsequently to the Galactic center. Our emphasis was to understand the young and dense star cluster IRS13E, which may host a black hole of intermediate mass, but also towards the possibility of stars in libration points orbiting the supermassive black hole in the galactic center. If the spiral-in timescale of the star cluster is significantly short, clusters like IRS13E may be responsible for transporting the S-stars from relatively large distance to the sphere of influence of the supermassive black hole in the Galactic center, where they are currently observed. Michiko has successfully incorporated her method in MUSE, the Multi Scale software environment for modeling dense stellar systems.

V-160: Visit of T. Ishiyama/K. Nitadori

Tomoaki Ishiyama visited the astronomical institute "Anton Pannekoek" from from April 20 to May 24, 2008 and Keigo Nitadori visit was from May 5 to May 11, 2008. During their stay they have worked together with the group of Simon Portegies Zwart on the parallelization and optimization of the TreePM code which they plan on using for our 10 billion particle cold dark matter cosmological simulations. In addition they have worked on the optimization of the assembler code to run on two different architectures (Intel and IBM). The final simulation has 10^4 times higher resolution than any simulation done before and is carried out in close collaboration with the University of Tokyo, Drexel University and the University of Amsterdam. The first test simulations were very successful and a paper is in preparation where we report the results of this test run. During his visit, Keigo has improved the assembler code that will run on the two supercomputers to amazing speed. During his visit Tomoaki has been working on the parallelization and network aspects of two (and later four) supercomputers. He designed the main code which will run on both computers.

V-161: Visit of Dr. S. Hony

Dr. Sacha Hony visited the Netherlands in April 2008 to present an invited talk at the April 21 meeting of the NOVA network 2 meeting, held at the Astronomical Institute of the University of Amsterdam. The topic of Dr. Hony's contribution was entitled: "Agents of galaxy evolution in the Magellanic Clouds", focusing on new results obtained with the Spitzer space telescope on the interstellar medium in the Magellanic clouds.

V-162: Visit of Dr. A.I. Karakas

Amanda Karakas (Australian National University) visited the Astronomical Institute in Utrecht from 2 June - 18 July 2008, where she collaborated with members of the stellar evolution group on modelling nucleosynthesis in asymptotic giant branch stars. In particular, she worked with Maria Lugaro (VENI fellow) and Mark van Raai (MSc student) on the comparison of detailed nucleosynthesis models of massive AGB stars to abundance observations of type-I planetary nebulae, and to assess the role of these models in producing short-lived radioactive nuclei in the early solar system. This work has led to the submission of two refereed publications (in ApJ, see arXiv:0809.1456; and in Meteoritic and Planetary Science)

V-163: Visit of Sateyendra Thoudam

Sateyendra Thoudam (Mumbai, India) visited the Department of Astrophysics at the Radboud University Nijmegen from July 7th to 11th, 2008. Thoudam gave a colloquium on the propagation of cosmic rays in the Galaxy. He worked with Hörandel on the same subject. This effort encourages work at RU in the frame of the LOFAR project and the Pierre Auger Observatory. It is expected that this initial work will stimulate upcoming scientific publications.

V-165a: Visit of Prof. Dr. B. Chaboyer

Prof. B. Chaboyer of Dartmouth College visited the Kapteyn Institute from July 25-30, 2008. During this time he presented a seminar on the HST Treasury Program of Galactic Globular Clusters. His visit was very successful.

V-165b: Visit of Dr. P. Araya-Melo

Dr. P. Araya-Melo visited the Kapteyn Institute from July 1-Aug 10, 2008. During the visit we concentrated on finishing two papers: one on the future evolution of clusters in a Lambda-dominated Universe and the second on the systematics of scaling relations of clusters as a function of cosmology. Both papers have been published.

V-166: Visit of Dr. L. Yungelson

The visit of Lev Yungelson to the Astrophysics department was a great success. In the three months of his visit he was a very active member of our community and interacted with many people, including some PhD students that just started and benefitted greatly from his knowledge. Most of the time has been spent on a project to determine if and how the chemical composition (abundance) of the donor stars in ultra-compact binaries, as measured in the spectra of the accretion, can be used to trace the formation history of the observed systems. This work does not only apply to AM CVns (systems with a white dwarf accretor) but also for ultra-compact X-ray binaries (systems with a neutron star accretor) for which Lev worked together with the PhD student Lennart van Haaften. This work already resulted in a paper. Furthermore a start has been made with a population study of subdwarf B stars, the thesis topic of PhD student Haili Hu and a literature study of newly discovered embedded X-ray sources has been made, as a first step for a project together with Ed van den Heuvel.

V-167: Visit of Prof. Joe Silk and Prof. Naoshi Sugiyama

The purpose of the visit was to continue an existing collaboration that focuses on an attempt to explain some puzzling features that have been reported over the last few years by various large scale structure and cosmological probes. For example, the Wilkinson Microwave Anisotropy Probe (WMAP) has been reporting a number of anomalies in its results, especially, the detection of large scale cold and hot spots that could not be explained by the normal Gaussian initial conditions. In order to explain these results one has to appeal to unusual models, which is very hard to do given the large set of high quality data available that constrain such models. The idea that we began pursuing during this visit is to explore the possibility of having initial density fluctuations models with kurtosis that has a little bit of excess power. The three of us spent a couple of days discussing the possible models. The initial stage of the project was to devise such a model and discuss how to calculate its implications on the observable large scale structure quantities. During the last three days of the visit (after Prof. Silk had already left) we started working on the detailed calculations required for the project and have progressed significantly. In 2009 the three of us met again in Japan to finish the project.

V-168: Visit of Dr. G. Mellema

Dr. G. Mellema visited the Kapteyn Institute from Nov. 10-21, 2008. The intention of his visit was twofold. He and Rien van de Weygaert share a common PhD student, Drs. Jakob van Bethlehem who is based in Groningen. He is working on the development and implementation of a 3D radiative transfer code to model the reionization process of the universe. During the second week prof. Mellema introduced and guided Jakob to his C2Ray code. They also used the time to improve the coordination of the project. Prof. Mellema is also member of the LOFAR-EoR key science project. He continued working on a couple of current projects with Prof. Zaroubi and his student focused on creating an end-to-end simulation (from signal to instrument) of the LOFAR-EoR data. During the first week Prof. Mellema also gave a presentation at the LOFAR-EoR meeting.

V-169: Visit of Dr. A. Bik

The visit of Arjan Bik to Amsterdam in November 2008 has been very successful. He has been busy with two ongoing projects. The first project consisted of a near-IR imaging survey of 45 Ultra compact HII regions, the birth places of high-mass stars. They finalized the discussion section of the paper and made it almost ready for submission. The second project consisted of an integral-field spectroscopic survey using ESO's instrument SINFONI of several high-mass star clusters. This project will provide them with a near-IR classification of all the brighter cluster members, allowing them to obtain a full census and understanding of these young high-mass star clusters. They have discussed the progress of this project and defined the content of the first paper on this data set.

V-170: Visit of Dr. K. Kolenberg

The primary purpose of the visit of Dr. K. Kolenberg (Vienna) was to work on a collaborative paper on the early B star sigma Lupi, for which discovery magnetic measurements had been collected by her during the last year, including those taken by her coworkers at the AAT on the days of her visit. These magnetic data have been further analysed in Amsterdam and incorporated in the paper. We predicted the existence of such a magnetic field from an analysis of specific stellar wind variations. It happens to be the third B star for which the magnetic field was found because of such wind modulations. This star is thought to evolve into a magnetar, which underlines its uniqueness and importance. From our data we were not able to confirm the expected 3 days rotation period, and new observations were planned.

V-173: Visit of Dr. M. Aragon-Calvo

During the visit of Dr. M. Aragon-Calvo they concentrated on finishing as far as possible the paper "Spin alignment of SDSS galaxies in filaments", in which they seek to demonstrate the existence of significant shape and spin alignment of late-type spiral galaxies with respect to the filamentary structures in which they are embedded. Besides statistical analysis they have finished the draft. In addition to this project, M. Aragon-Calvo has started two projects with Platen, to be finished during the work visit of the latter to Baltimore.

V-174: Visit of Dr. C. Ferrara

Chiara Ferrara visited the University Leiden from May 5-8, 2009, to work on a number of collaborative projects. These projects are all related to the preparation of LOFAR observations of nearby and distant clusters. With Huib Intema, she worked on reducing low frequency radio data, with a particular emphasis on the ionospheric calibration. With Mohan she worked on a shapelet decomposition of the radio morphology of clusters with the aim of investigating up to what distances LOFAR can detect such objects. Finally, with Röttgering she worked on radio halo luminosity functions and discussed a project to observe a sample of clusters with the GMRT.

V-176: Visit of Dr. J. McEnery

Dr. Julie McEnery, project scientist of the Fermi Gamma-ray Space Telescope (formerly GLAST) at NASA, GSFC, was invited as NOVA keynote speaker at the Netherlands Astronomy Conference (NAC). The 64th NAC took place at the Conference Center Rolduc, Kerkrade from 13 to 15 May 2009 and was attended by 176 participants. . In her talk, McEnery described the current status of the Fermi observatory and reviewed the science highlights from the first year of observations. Fermi, launched in June 2008, is a high energy gamma-ray observatory that has opened a new and important window on a wide variety of phenomena, including pulsars, black holes and active galactic nuclei, gamma-ray bursts, supernova remnants and the origin of cosmic rays, and also searches for hypothetical new phenomena such as super symmetric dark matter annihilations. Of course, there was ample time for scientific discussions and an exchange of ideas with McEnery during the 3 days of the conference.

V-177: Visit of Tomoaki Ishiyama

Dr. Tomoaki Ishiyama visited the Sterrewacht Leiden from Sunday 10 May until Sunday 24 May, 2009. During his visit the progress of CosmoGrid was discussed. CosmoGrid is a large project with Japanese, European and American researchers to perform the largest cosmological N-body simulation ever on a distributed supercomputer. Dr. Ishiyama had been studying the formation and evolution of the cold dark matter halo using large cosmological N-body simulations during his PhD. He is the only project member who is familiar with the data reduction and analysis of the output of large cosmological N-body simulations. His presence in the Netherlands was crucial for the progress of the CosmoGrid project. During his stay he participated at the NAC by presenting a unique demonstration of the CosmoGrid project. The CosmoGrid project started at April 2008. We have now reached z=4.4, where we started at z~70, and we plan on continuing the run to z=0.

V-179: Visit of Prof.dr. P. van Dokkum

Prof.dr. P. van Dokkum visited the Leiden Observatory from June 22 to July 15 to work with staff members, postdocs, and PhD students. He worked closely together with Marijn Franx about their ongoing and future projects, and talked with many other staff members. He supervised Ned Taylor and Maaike Damen. In addition he worked on the paper which has been submitted after the visit to ApJ. This work benefited enormously from the discussions they had during the visit.

V-180: Visit of Dr. T. Belloni

In June 2009 Belloni (INAF, Brera, Italy) visited the Kapteyn Astronomical Institute for a month. There he collaborated with Mendez, Hiemstra, Zhang, Sanna and Avellar, members of the high-energy group. Belloni and Mendez started a large-scope project for the systematic analysis of high-frequency oscillations in bright neutron-star low-mass X-ray binaries. They implemented automatic procedures for the production of power-density spectra and the detection of quasi-periodic signals therein. As part of this project, Belloni installed proprietary software for high-energy timing analysis, which is now being tested and used by Mendez and some of his students for joint projects. Belloni also taught a 5-hour course on timing methods in X-ray astronomy and a 7.5-hour course on black-hole binaries to Master and PhD students in Groningen.

V-181: Visit of Prof. dr. M. Verma

Prof. dr. M. Verma visited the Astronomical Institute of the University of Amsterdam from the 19th to the 21st of July 2009. During his visit he discussed with E.P.J. van den Heuvel and several other staff members about the possible causes of Dark Energy in the Universe. On July 20 he gave a colloquium at the institute entitled "Dark Energy and the Cosmological Constant". The visit of Verma was very useful for the understanding of the possible alternative causes of Dark Energy.

V-182: Visit of Prof. dr. R. Juszkiewicz

Prof. dr. Roman Juszkiewicz visited the Kapteyn Institute in Groningen from July 14-22, 2009. The visit concentrated on two mutually related projects, involving also drs. W. Hellwig (Copernicus Institute, Warsaw). One project concerns the study of voids and underdense regions in N-body simulations of structure formation in cosmologies involving a scalar field long-range attractive force in addition to conventional gravity. Together with the masters student, Patrick Bos, they explored the resulting N-body simulations with the Watershed Void Finder. A second project concerned the so called void probability function. They have been working on a better (analytical) understanding of the VPF, given various assumptions about the clustering of galaxies. The intention is to see how many orders of the clustering hierarchy is needed to include before the VPF converges to its final value. In July they found some encouraging approximations, although a later check with simulations did not confirm these.

V-183: Visit of drs. W. Hellwing

Drs. Wojciech Hellwing visited the Kapteyn Institute in Groningen from July 14-22, 2009. The visit concentrated on two mutually related projects, involving also his supervisor professor Roman Juszkiewicz (Copernicus Institute, Warsaw). The projects are described in the report above (V182). Wojciech Hellwing has been instrumental in including an extension of the GADGET2 N-body simulation code with a module for an extra scalar field term to the gravity term. He has been teaching Patrick Bos and Rien van de Weygaert in the use of this code.

8. Public outreach and Education

8.1. NOVA Information Center (NIC)

8.1.1. NOVA Information Center (NIC)

The NOVA Information Center (NIC) has been established to popularize astronomy and astrophysics in the Netherlands. NOVA feels a strong responsibility to report its frontline research in the widest sense. Popularization of astronomy is also an excellent vehicle for stimulating interest in the natural sciences in general, which is of great importance at a time when the interest in university studies in some of these disciplines is declining. The NIC has different target groups for its outreach efforts: I) the press; II) students and teachers, III) policy makers, and IV) the general public.

The NIC is managed by Marieke Baan (0.6 fte, 1.0 fte from July 2009). Jaap Vreeling (0.5 fte) is responsible for developing and managing educational programs and Annemiek Lenssen (0.2 fte) is the web-editor. From November 2009 onwards Frederiek Westra van Holthe (1.0 fte) jointed as the national coordinator of Universe Awareness. The NIC is located at the University of Amsterdam. The NOVA outreach program is monitored by the Minnaert Committee, chaired by de Koter.

Figure 8.1: More than 7500 people visited the "Weekend van de Sterren" at the NEMO Science Center on April 3 and 4, as part of the International Year of Astronomy 2009. The NIC was the National Node for this global celebration, initiated by the International Astronomical Union and the United Nations, marking the 400th anniversary of the first use of an astronomical telescope by Galileo Galilei.

8.1.2. Astronomie.nl in the Year of the Telescope 2008

To celebrate the 400th anniversary of the invention of the telescope, for which the Dutch lensmaker Hans Lippershey applied for a patent in the year 1608, the NIC, in part in collaboration with the Stichting Volkssterrenwacht Philippus Lansbergen in Middelburg, initiated and organized multiple events throughout the year. During the closing symposium on November 22, 2008, organized by the KNVWS, the first copy of the book 'Astronomie.nl. Een Hollandse kijk op het heelal' was offered to KNAW-president Robbert Dijkgraaf. The book, written by Govert Schilling, was realized thanks to practical and financial support by NOVA. In twenth chapters it provides a view of the past, present and future of astronomy in the Netherlands.

8.1.3. International Year of Astronomy 2009

The United Nations proclaimed 2009 to be the International Year of Astronomy in recognition of the fact that Galileo Galilei for the first time 400 years ago used a telescope to study the universe. The IYA2009, initiated by the International Astronomical Union and UNESCO, was a global celebration of astronomy and its contributions to society and culture and aimed at establishing collaborations between professionals and amateur astronomers, science centers, educators and science communicators. The NIC was the national node for the Netherlands and took the lead role in initiating and organizing the Dutch activities for this celebrational year. Activities included the 'Weekend van de Sterren', the gala evening 'Avond van de Sterren', the issuing of stamps, the naming of an asteroid after prof. mr. Pieter van Vollenhoven and 'Missie Maan' (see Sect. 8.1.6). The NIC launched the special website jaarvandesterrenkunde.nl, announcing events and providing news and materials.

8.1.4. Educational program 'Bringing Astronomy into Classrooms'

The NOVA project 'Bringing Astronomy into Classrooms' by de Koter, Barthel and Baan addresses the problem of the transfer of astronomical knowledge in schools. Vreeling is organizing and executing this project. Through different media, the NIC actively approaches both primary and secondary schools to inform and enthuse students and teachers about astronomy. The NIC has set up NOVA-Lab, which develops booklets with astronomy projects and exercises. Currently, three booklets are in the production phase introducing the analysis of star light (two booklets) and planets.

In the context of the IYA2009, the NIC is involved in the promotion and distribution of the galileoscope, a high quality low-cost telescope kit developed for the IYA2009. To further enlarge the interest in astronomy the NIC has acquired a mobile planetarium with which it will visit schools nationwide starting early 2010.

8.1.5. Astronomie.nl

The NIC reports news and provides information on astronomy and NOVA in particular, as well as educational material, on its website astronomie.nl. News is presented on a daily basis through collaboration with the site www.allesoversterrenkunde.nl by Govert Schilling, and on a more or less biweekly basis, through press releases on NOVA activities and news on astronomy in general. In 2008 the site attracted 220,000 unique visitors, which increased to 270,000 in 2009. In addition to news, the site includes a news archive, information on NOVA, an overview of astronomical facilities, an interactive sky chart, games, a picture library, a FAQ section, a quiz module, an astronomy encyclopedia, educational material and information for teachers and (prospective) students.

8.1.6. Astronomical press service and astro-newsletter

Press releases to the media via the NIC electronic news service 'Astronomische Persdienst' produced a steady stream of information about national highlights of new astronomical discoveries to journalists. Through this channel NIC informed the media in the Netherlands 99 times in 2008 and 112 times in 2009. Press releases were issued in close collaboration with outreach officers at ESO, ESA, SRON, and ASTRON, when appropriate. In many cases the press releases got prime media attention. The 'astronieuwsbrief', targeting the general public, though specifically teachers of primary and secondary schools, was issued 17 times in 2008 and 15 times in 2009 and currently has 1400 subscribers.

8.1.7. Highlights of special events or projects

The NIC, in collaboration with the Nederlandse Astronomen Club (NAC), NWO Physical Sciences, the KNVWS and NEMO, organized the 'Weekend van de Sterren' in the national science museum NEMO in Amsterdam on April 3 and 4, 2009. A total of 7500 people visited the science museum (see also Fig 8.1) and participated in the event 'Laat je verleiden door de sterren'. NOVA astronomers gave lectures and explained the workings of the spectrograph and pulsar timing. Children could participate in workshops and telescopes on the roof showed the image of the solar disk.

In collaboration with TNT Post, the NIC initiated the issuing of two official stamps which have astronomy as a theme. At the 'Avond van de Sterren' on April 4, 2009, Minister Ronald Plasterk of OCW received the first sheet of the Dutch edition of Europa stamps 2009, portraying the lens Christiaan Huygens used to discover Titan and the new Dutch radio telescope LOFAR.
The NIC organized the official ceremony of the naming of an asteroid after prof. mr. Pieter van Vollenhoven by the International Astronomical Union, on the recommendation of mevr. Ingrid van Houten-Groeneveld. The asteroid is henceforth known as Vanvollenhoven 12170.

The NIC, in collaboration with NEMO and the public astronomical observatories, organized the project 'Missie Maan' for primary school students in December 2009. At 140 schools over all of the Netherlands thousands of children observed the moon before sunrise, using telescopes operated by amateur astronomers and astronomers from university institutes.

The NIC presented the IYA2009 and NOVA at the 50PlusBeurs in de Jaarbeurs in Utrecht, from 16 to 20 September 2009. Over 100,000 people visited this fair. At the NOVA stand visitors were presented lectures, movies, a photo exhibition and information about Dutch and European astronomy.

8.2. Astronomy Olympiad

In 2007 the first Nederlandse Sterrenkunde Olympiade (NeSO; Dutch Astronomy Olympiad) was organized. It consisted of two rounds. The Olympiad starts with a selection round on the internet. High school students could download a test on astronomy, answer the questions and send in their solutions. Based on the answers a selection is made and the best students are invited for a week long master class on astronomy. At the end of the week

Figure 8.2: Dejan Gajic wins the Dutch Astronomy Olympiad 2008 (credit: Edwin Mathlener, Zenit)

Figure 8.3: The participants of the master class week in 2009, during the excursion to the Westerbork Synthesis Radio Telescope.

the participants make a test and the winner wins a trip to La Palma to observe with the Mercator telescope.
In 2008 the second NeSO was organized by the Astronomical Institute of Utrecht University. The 20 best students were invited for the master class astronomy. For one week they followed lectures on several subjects. On Saturday morning de final test was taken in Museum and Sterrenwacht Sonnenborgh in Utrecht. Dejan Gajic (18, 't Atrium, Amersfoort) won the Olympiad (Fig. 8.2) just before Bakx (18, Reynaertcollege, Hulst) and Matthijs Vákár (17, Stedelijk Gymnasium Johan van Oldebarnevelt, Amersfoort). As a bonus Dejan was also invited for the official opening of the Year of Astronomy 2009 at UNESCO in Paris.

In 2009 the NeSO was organized by the Kapteyn Institute of the University of Groningen. Thanks to the large publicity given, the questions on the internet have been downloaded 600 times. Students from all over the Netherlands participated, and the eight best were invited for a master class in astronomy at the RuG. After four days of lectures ranging from star formation, exo-planets, galaxies, black holes, the Big Bang and cosmology they had to do the test on the fifth day. Daniël Verschueren passed the test best and became the winner of NeSO2009. The second prize went to Léon Houben. Apart from the trip to La Palma, which due to problems with the dates was donated by Daniël to Léon, both winners also received one year of free study at the university.

8.3. Education

8.3.1. NOVA MSc education

The five universities participating in NOVA are the only ones that offer Astronomy MSc studies in the Netherlands. These MSc studies are being monitored by the Dutch National Astronomy Education Committee (Sect. 8.3.2), overseeing both the MSc and the PhD education. Whereas the quality of the MSc studies in The Netherlands is uniformly excellent, there are obviously differences of a programmatic nature.
The 'Interacademy Course' is taught every year in Utrecht for Master students of all Dutch universities. Each year the topic for next year's school is selected by the National Astronomy Education Committee, which subsequently appoints a national coordinator for the course. Dutch MSc students quite frequently 'shop around', that is to say take advanced courses at other institutes than the home university. In this way highly individual MSc programs can be realized, optimized to the interests and skills of the MSc student. The same can be said about the final research projects. These are uniformly of very high quality, and specifically tailored projects can be realized at technically oriented research groups in, for example space research, soft- or hardware development, or instrument- or telescope-development groups (inside and outside the universities). Most NOVA institutes also provide the opportunity to carry out a short observing program at the local observatory and/or at a professional observatory (e.g. La Palma, Spain).

The topics of the 'Interacademy Course' were 'Astroparticle Physics' in 2008 and 'Physics of Gamma-Ray Bursts and the nature of their host galaxies' in 2009.

8.3.2 National astronomy education committee

The two national education committees for undergraduate and for graduate education are merged into the National Astronomy Education Committee, overseeing the total of university astronomy education (BSc, MSc, PhD). Membership of the Committee (Section 9.6) consists of staff members of the five NOVA institutes, a staff member of ASTRON or JIVE, and five students (graduate and undergraduate) from the NOVA institutes. The Committee, chaired by Kaper, usually meets twice per year. The committee chair is invited as an observer at the NOVA Board meetings when educational matters are on the agenda. The National astronomy education committee also takes responsibility for educational matters to be discussed in the Kamer Sterrenkunde of the VSNU (Association of universities in the Netherlands).

8.3.3. Graduate education

Broadening of the astronomical knowledge of young graduate students is necessary, because several topics that are essential for graduate students are not always part of the undergraduate curriculum. Furthermore, there are differences between the undergraduate curricula in the different astronomy institutions, which are related to historical differences between areas of research carried out at the different institutions. Nowadays a significant fraction of the graduate students come from abroad; several of these students have a physics rather than an astronomy background. NOVA fills these gaps by organizing an annual 'NOVA School' for graduate students, with courses on the required topics. All graduate students are required to attend this NOVA School at least once (during their first year) and are recommended to attend the school twice. Another motivation to organize the NOVA School is to stimulate interaction between graduate students hosted at different institutes.

Monitoring of the education in the graduate program and of the actual graduate research and career prospects is carried out on behalf of NOVA by the so-called 'Graduate Student Review Committee', at the NOVA institutes. Every institute has its own review committee, consisting of three to four persons (without the advisor) of which one is from a sister institute, or from NWO. The members of these committees serve 2 to 3 years to guarantee a smooth continuation of the supervision. Every year the graduate students present their progress, problems and future prospects with the review committee. The findings are discussed with the thesis-advisor. Institute directors report orally on progress of the PhD students at the NOVA Board.

Graduate students also receive training in reporting scientific results in papers, in oral presentations and as posters. The annual Dutch Astronomers Conference provides an excellent opportunity for undergraduate and graduate students to present their work to a professional audience. The minimum requirements, which are being monitored by the graduate student review committee, are:

- A short presentation of the planned research at the NOVA School;
- A seminar at the home institution;
- A seminar at another institute or an oral presentation at the annual Dutch Astronomers Conference;
- A poster presentation at an international conference.

Finally, at the time of completion of his/her PhD research, every PhD student is urged to provide the NIC with a Dutch summary of the thesis work/ results, to be used in a NIC press release.

8.3.4. NOVA fall school

The NOVA fall school is meant to broaden the knowledge of astronomy graduate students. Every graduate student in The Netherlands must participate in a NOVA Fall school at least once; participation in two schools is recommended. The school is offered annually, at the ASTRON premises in Dwingeloo, during 5 days in the fall.

NOVA fall schools generally consist of two parallel course streams, which rotate between three topics (1) galaxies, (2) interstellar medium and star- and planet formation, and (3) compact objects and the late stages of stellar evolution. The streams are targeted at students who did not have the topic in their undergraduate studies, to broaden their general background in astronomy. PhD students should choose the stream after consultation with their thesis supervisor. All courses are taught in English, and often include practical exercises. The school also includes a workshop on scientific presentation. All participating students are required to make a short oral presentation about their planned thesis research project for their fellow students and the lecturers.

In the reporting period the NOVA schools were organized by Barthel and Peletier in 2008 and by Peletier in 2009 and held at ASTRON, with local support from Moller. The lecturers in 2008 were Spaans (on star and galaxy formation) and Levin (on compact objects and gravitational waves). In 2009 the lectures were given by Hoekstra (on gravitational lensing) and Snellen (on exoplanets).

9. Organization

9.1. Board

Prof.dr. M. van der Klis (chair)	UvA
Prof.dr. P. Groot	RU
Prof.dr. J.M. van der Hulst	RuG
Prof.dr. K.H. Kuijken	UL
Prof.dr. N. Langer	UU, until Dec 2008
Prof.dr. C.U. Keller	UU, since Jan 2009

9.2. International Review Committee

Prof.dr. F.H. Shu (chair)	University of California, San Diego, USA Academia Sinica Institute of Astronomy and Astrophysics, Taiwan
Prof.dr. R.D. Blandford	Stanford University, California, USA
Prof.dr. R.C. Kennicutt	University of Cambridge, UK
Prof.dr. H-W. Rix	MPIA, Heidelberg, Germany
Prof.dr. A. Sargent	Caltech, Pasadena, California, USA
Prof.dr. R.A. Sunyaev	MPA, Garching, Germany

9.3. Key Researchers

Prof.dr. A. Achterberg	UU
Prof.dr. P.D. Barthel	RuG
Prof.dr. E.F. van Dishoeck*	UL
Prof.dr. H. Falcke	RU
Prof.dr. M. Franx	UL
Prof.dr. P. Groot*	RU
Prof.dr. A. Helmi	RuG, since Jul 2009
Dr. M. Hogerheijde	UL
Prof.dr. J.M. van der Hulst*	RuG
Prof.dr. C.U. Keller*	UU
Prof.dr. M. van der Klis*	UvA
Prof.dr. L.V.E. Koopmans	RuG
Prof.dr. A. de Koter	UvA/UU
Prof.dr. K.H. Kuijken*	UL
Prof.dr. N. Langer*	UU, until Dec 2008
Dr. S.S. Larsen	UU
Prof.dr. R.F. Peletier	RuG
Prof.dr. S.F. Portegies Zwart	UvA/UL
Prof.dr. H.J.A. Röttgering	UL
Dr. J. Schaye	UL
Prof.dr. M.C. Spaans	RuG
Prof.dr. A.G.G.M. Tielens	UL, since Jan 2009
Prof.dr. E. Tolstoy	RuG
Prof.dr. F. Verbunt	UU
Prof.dr. L.B.F.M. Waters	UvA
Prof.dr. R.A.M.J. Wijers	UvA
Dr. R.A.D. Wijnands	UvA

* The members of the NOVA Board and the NOVA scientific director are key researchers at large.

9.4. Coordinators research networks

Prof.dr. M. Franx	UL	Network 1
Prof.dr. L.B.F.M. Waters	UvA	Network 2
Prof.dr. H. Falcke	RU	Network 3

9.5. Instrument Steering Committee

Dr. R.G.M. Rutten (chair)	ING, La Palma, until Oct 2008
Prof.dr. P. Roche (chair)	Oxford, since Oct 2008
Prof.dr. R. Bacon	Univ. Lyon
Ing. F. Bettonvil	UU, since Mar 2009
Dr. B. Brandl	UL
Dr. M. Casali	ESO
Dr. H.J. van Langevelde	JIVE
Prof.dr. L. Kaper	UvA
Prof.dr. C.U. Keller	UU, until Dec 2008
Dr. G. Nelemans	RU
Prof.dr. M. Verheijen	RuG
Dr. M. de Vos	ASTRON
Prof.dr. W. Wild	ESO

9.6. Education Committee

Prof.dr. J. Kuijpers (chair)	RU, until Feb 2008
Prof.dr. L. Kaper (chair)	UvA/VU, since Feb 2008
Prof.dr. P. Barthel	RuG
Dr. M. Brentjens	ASTRON, since Sep 2008
Dr. J. Hörandel	RU, since Feb 2008
Prof.dr. F.P. Israel	UL
Prof.dr. L. Kaper	UvA/VU, member until Feb 2008
Prof.dr. R. Peletier	RuG (NOVA school)
Prof.dr. F. Verbunt	UU
P. Bos (student)	RuG, since Sep 2008
Drs. N. Degenaar (PhD student)	UvA, until Sep 2008
L. Einarsen (student)	UU, since Sep 2008
Drs. H. Hu (PhD student)	RU, until Sep 2008
Drs. S. Jiraskova (PhD student)	RU, since Feb 2009
E. Kuiper (student)	UL, since Feb 2009
T. van der Laan (student)	RuG, until Sep 2008
S. Rieder (student)	UU, until Feb 2008
Drs. A.M. Weijmans (PhD student)	UL, until Feb 2009

9.7. Minnaert Committee

Prof.dr. A. de Koter (chair)	UvA/UU
Prof.dr. P.D. Barthel	RuG
Prof.dr. V. Icke	UL
Dr. G. Nelemans	RU
Dr. J. Vink	UU
Dr. W. Boland (observer)	NOVA

9.8. Principal Investigators of NOVA instrumentation projects

Dr. B. Brandl	UL	METIS Phase-A study
Dr. A.G.A. Brown	UL	Gaia
Prof.dr. E.F. van Dishoeck	UL	MIRI
Prof.dr. H. Falcke	RU	AUGER-radio
Dr. M. Hogerheijde	UL	ALLEGRO
Prof.dr. J.M. van der Hulst	RuG	ESKAC
Prof.dr. W. Jaffe	UL	MATISSE
Prof.dr. L. Kaper	UvA	X-Shooter
Prof.dr. L. Kaper, Prof.dr. P. Groot	UvA, RU	OPTIMOS-EVE Phase-A study
Prof.dr. C.U. Keller	UU	EPICS Phase-A study

Prof.dr. C.U. Keller, Dr. F. Snik	UU	S^5T
Prof.dr. K.H. Kuijken	UL	OmegaCAM
Prof.dr. K.H. Kuijken	UL	MICADO Phase-A study
Prof.dr. H.V.J. Linnartz	UL	Sackler Laboratory for Astrophysics
Dr. S.B. Markoff, Dr. J. Vink	UvA, UU	CTA pilot
Prof.dr. S.F. Portegies Zwart	UL	AMUSE
Prof.dr. R. Röttgering	UL	LOFAR-DCLA
Dr. J. Schaye, Prof.dr. M. Franx	UL	MUSE / ASSIST
Prof.dr. E.A. Valentijn	RuG	OmegaCEN
Prof.dr. L.B.F.M. Waters	UvA	SPHERE-Zimpol
Prof.dr. W. Wild	RuG/SRON	ALMA receiver technical R&D, until Dec 2008
Prof.dr. M. Spaans	RuG	ALMA receiver technical R&D, since Jan 2009

9.9. NOVA Information Center (NIC)

Drs. M. Baan	UvA
Drs. A. Lenssen	UvA
Dhr. J Vreeling	UvA, since Oct 2008
Mw. F. Westra van Holthe	contract, since Nov 2009

9.10. Office

Prof.dr. E.F. van Dishoeck (scientific director)	UL
Dr. W. Boland (executive director)	NOVA
Mw. C.W.M. Groen (finance and control)	NOVA, since Sep 2009
Mw. C.W.M. Groen (management assistant)	NOVA, until Sep 2009
Mw. J.T. Quist (management assistent)	NOVA, since Sep 2009

10. Financial report 2008 - 2009

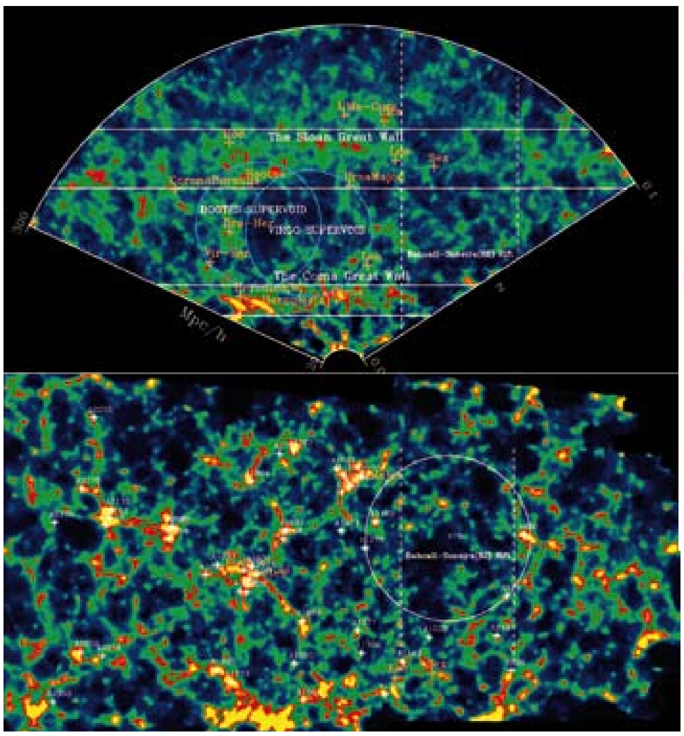
in k€	2008	2009
ASTRONOMICAL RESEARCH		
Overlap Appointments	**600**	**576**
Research Networks		
Network 1: formation and evolution of galaxies	290	255
Network 2: formation of stars and planetary systems	261	376
Network 3: astrophysics of black holes, neutron stars and white dwarfs	214	359
Miscelleneous research activities	47	7
Cross network research projects	0	13
Science support	0	380
Workshops and visitors	57	47
Total research funding	**869**	**1,437**
TOTAL ASTRONOMICAL RESEARCH	**1,469**	**2,013**
INSTRUMENTATION (NOVA administrated projects)		
ALMA ALLEGRO and technical R&D	123	129
ALMA Band-9 prototype cartridges	127	
ALMA Band-9 production cartridges	2,201	2,023
AMUSE	0	109
CHAMP+	192	0
EU funded projects	322	255
Fringe Tracker	0	20
Gaia	0	141
LOFAR - DCLA	134	361
Laboratory Astrophysics / MATRI2CES	116	162
MIRI	926	491
MUSE, incl ASSIST	279	365
OmegaCAM/CEN	347	0
Optical-IR instrumentation group	453	1,119
S5T	0	110
Seed funding / miscelleneous projects	0	73
Contingency / new Initiatives	361	0
Sinfoni	3	0
X-shooter	188	0
TOTAL INSTRUMENTATION	**5,772**	**5,358**
OVERHEAD		
NOVA office	229	245
Outreach – NIC	125	119
TOTAL OVERHEAD	**354**	**364**
TOTAL EXPENDITURE	**7,595**	**7,735**

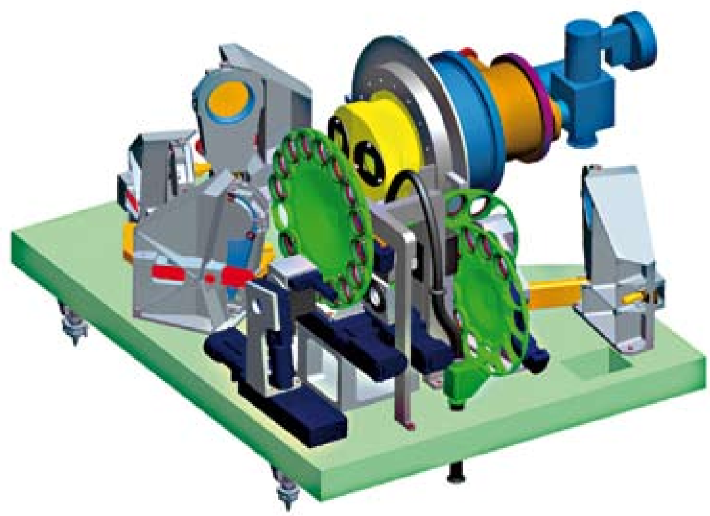
11. List of abbreviations

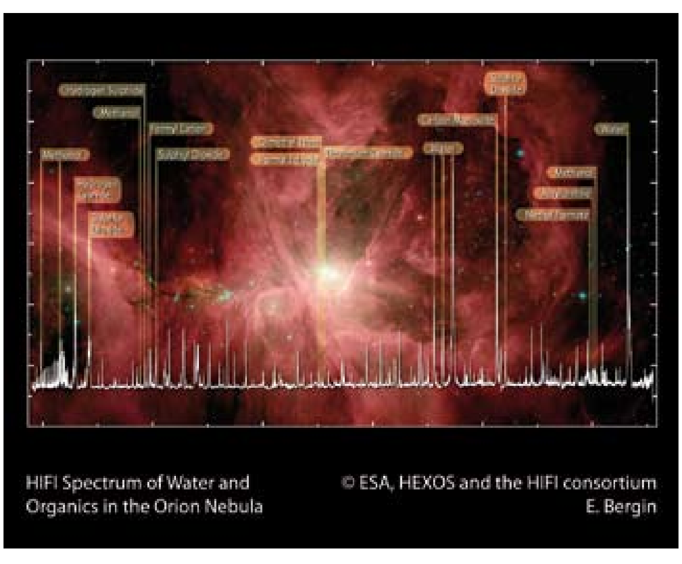
2SB	Sideband Separating
A&A	Astronomy & Astrophysics
AAS	American Astronomical Society
ACS	Advanced Camera for Surveys (instrument on HST)
AGN	Active Galactic Nuclei
AIO	Assistant-in-onderzoek - PhD student
AIP	Astrophysical Institute Postdam (Germany)
AJ	Astronomical Journal
ALLEGRO	ALMA Local Expertise GROup
ALMA	Atacama Large Millimeter/submillimeter Array
AMBER	Astronomical Multiple Beam Recombiner (instrument on VLTI)
AMUSE	Astrophysical Multipurpose Software Environment (NOVA project)
ANTARES	Neutrino telescope in Mediterranean Sea; prototype of KM3NeT
AO	Adaptive Optics
AOF	Adaptive Optics Facility
APERTIF	APERture Tile in Focus (Multi-beam receiver for WSRT)
APEX	ALMA Pathfinder Experiment
API	Astronomical Institute Anton Pannekoek (UvA)
ApJ	Astrophysical Journal
ARC	ALMA Regional Center
ASSIST	Adaptive Secondary Setup and Instrument Simulator (NOVA project)
ASTRON	ASTRON-Netherlands Institute for Radio Astronomy (NWO institute)
ASTRO-WISE	Astronomical Wide-field Imaging System for Europe (EU-funded network involving NOVA-RuG)
AU	Astronomical Unit
Auger	see PAO
Band-9	ALMA receiver for the atmospheric window between 610 and 720 GHz
Beppo-SAX	Italian-Dutch satellite for X-ray astronomy
Caltech	California Institute of Technology
CCD	Charge-Coupled Device
CDF	Chandra Deep Field
CDM	Cold Drak Matter
CEA Saclay	Commissariat à l' Energie Atomique (institute at Saclay, France)
CERN	European Organization for Nuclear Research
CESSS	Cavity Enchanced Solid State Spectometer (laboratory set-up at Sackler Laboratory at Leiden Observatory)
CfA	Center for Astrophysics (Harvard, USA)
CFHT	Canada France Hawaii Telescope
CFHTLS	CFHT Legacy Survey
CHAMP+	CHAMP+ is a dual-frequency heterodyne submillimeter array receiver built by MPIfR and NOVA/SRON/TuD for APEX
Chandra	NASA's X-ray space observatory
CMB	Cosmic Microwave Background
COROT	French led astronomical space observatory to search for extrasolar planets and stellar seismology
COSMOGrid	Worldwide super-computer collaboration for astrophysical simulations
CRAL	Centre de Recherche Astronomique de Lyon (Fr)
CRIRES	Cryogenic high-Resolution InfraRed Echelle Spectrograph (instrument on VLT)
CRs	Cosmic Rays
CRYOPAD	CRYOgenic Photoproduct Analysis Device (set-up at Sackler Laboratory at Leiden Obdervatory)
CSO	Caltech Submillimeter Observatory
CTA	Cherenkov Telescope Array
DAS-4	Distributed ASCI Supercomputer-4 (High performance computer network, see http://wiki.cs.vu.nl/das-4/index.php/Main_Page)
DCLA	Development and Commissioning of LOFAR for Astronomy
DTFE	Delaunay Tessellation Field Estimator
DPAC	Data Processing and Analysis Consortium (on development data processing software for Gaia)
DSM	Deformable Secondary Mirror (for one of the VLT telescopes)
DTFE	Delaunay Tessellation Field Estimator
DUEL	Dark Universe through Extragalactic Lensing (EU Network)
E-ELT	European Extremely Large Telescope
ECDFS	Extended Chandra Deep Field-South
EoR	Epoch of Reionization
EPICS	Exo-Planet Imaging Camera and Spectrograph (Instrument in study for the E-ELT)
EPOL	EPICS Polarometer
ESA	European Space Agency
ESFRI	European Strategy Forum on Research Infrastructures
eSMA	extended SMA
ESO	European Southern Observatory
ETH	Eidgenössische Technische Hochschule (Zürich)
EU	European Union
EU FP7	EU Framework Program 7
EUCLID	Possible ESA Cosmic Vision mission to map the geometry of the dark universe
EUV	Extreme Ultra Violet
eV	electron Volt
EVN	European VLBI Network
ExPo	Exoplanet Polarimeter (instrument on WHT)
Fermi	Fermi Space Telescope for gamma ray wavelengths (NASA)
FIR	Far InfraRed
FIRES	Faint Infrared Survey (large program at the VLT)
FLAMES	Fibre Large Array Multi Element Spectrograph (instrument on VLT)
FOM	Fundamenteel Onderzoek der Materie (NWO institute for physics)
FP	"Framework Program (EU) Fundamental Plane"
Gaia	Gaia - ESA's astrometric cornerstone mission
GALACSI	Ground Atmospheric Layer Adaptive Corrector for Spectroscopic Imaging (for MUSE)
GALEX	Galaxy Evolution Explorer (NASA satellite for UV wavelengths)
GEPI	Galaxies Etoiles Physique et Instrumentation (Division of Observatoire de Paris, France)
GHz	Giga Herz
GMRT	Giant Meterwave Radio Telescope
GRAAL	Ground layer Adaptive optics Assisted by Lasers (ESO facility for instrument tests)
GRAPPA	Astroparticle physics and gravitation initiative (at UvA)
GRB	Gamma Ray Burst
GTC	Gran Telescopio CANARIAS
GTO	Guaranteed Time Observations
GZK	Greisen-Zatsepin-Kuzmin limit (energy cut-off for cosmic rays)
HAWK-I	High Acuity Wide field K-band Imager (instrument on VLT)
HerCULES	Herschel Comprehensive ULIRG Emission Survey
Herschel	Herschel - Far infrared space observatory (ESA)
HI	Hydrogen 21 cm line
HIFI	Heterodyne Instrument for the Far-Infrared for Herschel
HST	Hubble Space Telescope
HV-setup	High Vacuum setup (at Sackler Laboratory at Leiden Observatory)
HzRGs	High-redshift Radio Galaxies
IAP	Institut d'Astrophysique de Paris
IAU	International Astronomical Union
IceCube	Neutrino telescope at South Pole
ICM	Inter-Cluster Medium
IFS	near-IR integral Field unit (part of SPHERE)
IFU	Integral Field Unit
IGM	Inter-Galactic Medium
IMF	Initial Mass Function
INAF	Instituto Nazionale di Astro-Fisica (Italy)
ING	Isaac Newton Group of the Roque de los Muchachos Observatory on La Palma
INSU/CNRS	Institut National des Sciences de l'Universe du Centre National de la Recherche Scientifique (funding agency, Fr)
INT	Isaac Newton Telescope (part of ING)
IR	Infra-Red
IRAM(-PdBI)	Institut de Radio Astronomie Millimétrique (Grenoble, Fr) - Plateau de Bure Interferometer
IRAS	InfraRed Astronomical Satellite
IRDIS	InfraRed Dual Imaging Spectrograph (part of SPHERE)

IRS	InfraRed Spectrometer (instrument on Spitzer Space Telescope)
ISAAC	Infrared Spectrometer And Array Camera (instrument on VLT)
ISC	Instrument Steering Committee (NOVA)
ISM	InterStellar Medium
ISO	Infrared Space Observatory (ESA)
IXO	International X-ray Observatory (under consideration, ESA, NASA, JAXA)
IYA2009	International Year of Astronomy 2009
JAXA	Japan Aerospace Exploration Agency
JCMT	James Clerk Maxwell Telescope (on Mauna Kea, Hawaii)
JIVE	Joint Institute for VLBI in Europe
JPL	Jet Propulsion Laboratory, Pasadena, USA
JWST	James Webb Space Telescope (successor of Hubble Space Telescope)
KiDS	Kilo-Degree Survey (planned for VST/OmegaCAM)
KIPAC	Kavli Institute for Particle Astrophysics and Cosmology
KM3NeT	Neutrino telescope in Mediterranean Sea; successor of ANTARES
KNAW	Koninklijke Nederlandse Akademie van Wetenschappen (Royal Academy of Arts and Sciences)
KRP	Key Research Project
KRs	Key Researchers (leaders of the NOVA research networks)
LABOCA	Large APEX Bolometer Camera
LAM	L'Observatoire Astronomique de Marseille-Provence (Fr)
LAOG	Laboratoire d'Astrophysique de l'Observatoire de Grenoble (France)
LAOMP	Laboratoire d'Astrophysique Observatoire Midi-Pyrénées (Fr)
LASSIE	Laboratory Astrophysics Surface Science In Europe (EU-funded network)
LERMA	Laboratoire d'Etude du Rayonnement et de la Matière en Astropysique (part of Observatoire de Paris)
LESIA	Laboratoire d'études spatiales et d'instrumentation en astrophysique (part of Observatoire de Paris)
LESS	LABOCA ECDFS Submillimetre Survey
LEXUS	Laser EXcitation setup for Unstable Species (setup at Sackler Laboratory at Leiden Observatory)
LGS	Laser Guide Star
LIGO	Laser Interferometer Gravitational-Wave Observatory (USA)
LIRG	Luminous InfraRed Galaxy
LISA	Laser Interferometer Space Antenna (possible ESA mission to detect gravitational waves)
LLAGN	Low Luminosity Active Galactic Nucleus
LMC	Large Magellanic Cloud
LOFAR	LOw Frequency ARray - new radio observatory managed by ASTRON in collaboration with European partners
LOPES	LOFAR PrototypE Station (at Karlsruhe, Germany)
LRIS	Low Resolution Imaging Spectrometer (Keck Instrument)
LSS	Large Scale Structure Survey (by XMM)
LUAN	Laboratoire Univeritaire d'Astrophysique de Nice (Fr)
M2-unit	Secundary mirror in telescope
MATISSE	Multi AperTure Mid-Infrared Spectroscopic Experiment (2nd generation VLTI instrument)
MATRI2CES	Mass Analytical Tool of Reactions in Interstellar ICES (set-up at Sackler laboratory at Leiden Observatory)
METIS	Mid-infrared ELT Imager and Spectrograph (possible E-ELT instrument)
MICADO	Near-infrared wide-field imager (possible E-ELT instrument)
MICHELLE	Mid-Infrared imager and spectrometer (instrument on Gemini-north)
MIDI	MID-Infrared instrument (instrument on VLTI)
Mid-IR	Mid-InfraRed
MIRI	Mid Infra-Red Instrument (under construction for JWST)
MIT	Massachusetts Institute of Technology
MNRAS	Monthly Notices of the Royal Astronomical Society
MODEST	MOdeling DEnse STellar systems (international consortium, see www.manybody.org)
MPE	Max-Planck-Institut für Extraterrestrische Physik (Garching, Germany)
MPIA	Max-Planck-Institut für Astronomie (Heidelberg, Germany)
MPIfR	Max-Planck Institut für Radioastronomie (Bonn, Germanny)
MUSE	Multi Unit Spectroscopic Explorer (instrument under construction for VLT)
NAC	Nederlandse Astronomen Club
NASA	National Aeronautics and Space Administration (USA)
NIC	NOVA Information Center
NICMOS	Near Infrared Camera and Multi-Object Spectrometer
NIKHEF	Nationaal Instituut voor Kernfysica en Hoge-Energiefysica (institute of FOM)
NL	Netherlands
nm	nanometer
NOVA	Nederlandse Onderzoekschool Voor Astronomie (Netherlands Research School for Astronomy)
NRAO	National Radio Astronomical Observatory (USA)
NRL	Naval Research Laboratory (USA)
NSF	National Science Foundation (USA)
NSO	National Solar Observatory (USA)
NW	NOVA research network
NWO	Nederlandse organisatie voor Wetenschappelijk Onderzoek (Netherlands Organization for Scientific Research)
OCW	Dutch ministry for Education, Culture and Science
OmegaCAM	Wide-field camera for the VLT Survey Telescope
OmegaCEN	OmegaCAM data center (at RuG)
ONERA	Office National d'Etudes et de Recherches Aérospatiales (Fr)
OP/IR	Optical to InfraRed
OPTIMOS	OPTical to Infrared Multi-Object Spectrograph (possible instrument for E-ELT)
OPTIMOS-EVE	Fr-UK-NL consortium for Phase-A study for OPTIMOS
OSIRIS	Optical System for Imaging and low Resolution Integrated Spectroscopy
OSO	Onsala Space Observatory (in Sweden)
OWLS	OverWhelmingly Large Simulations
PACS	Photodetector Array Camera and Spectrometer (instrument on Herschel)
PAH	Polycyclic Aromatic Hydrocarbon molecule
PAO	Pierre Auger Observatory (international cosmic ray observatory in Argentina)
pc	parsec
PD	Postdoc
PDF	Probability Density Function
Ph	Phase
PhD	Philosophiæ Doctor
PI	Principal Investigator
PLATO	PLAnetary Transits and Oscillations of stars (ESA mission in preparation)
PN.S	Planetary Nebula Spectrograph.
PSF	Point Spread Function
PuMa	Pulsar Machine (instrument on WSRT)
R&D	Research and Development
RadioNet	EU-funded network for radio astronomy
RAIRS	Reflection Absorption InfraRed Spectroscopy
RAL	Rutherford Appleton Laboratory (Didcot, UK)
RCSx	Red-sequence Cluster Survey x
RM	Rotation Measure
RU	Radboud Universiteit, Nijmegen
RuG	Rijksuniversiteit Groningen
RXTE Rossi	X-ray Timing Explorer (NASA satellite)
S5T	Small Synoptic Second Solar Spectrum Telescope (NOVA project)
SAFARI	SpicA FAR-infrared Instrument (instrument on Japanese-European SPICA mission)
SAURON	Spectroscopic Areal Unit for Research on Optical Nebulae (instrument on WHT)
SCUBA-2	Submillimetre Common-User Bolometer Array (instrument on JCMT)
SDSS (DRx)	Sloan Digital Sky Survey (Data Release x)

SINFONI	Spectrograph for INtegral Field Observations in the Near Infrared (instrument on VLT)
SIS	Superconductor Insulator Superconductor; detector technology for (sub)-mm and far-IR
SKA	Square Kilometer Array
SLACS	Sloan Lens ACS Survey
SMA	SubMillimeter Array (on Mauna Kea, Hawaii)
SMC	Small Magellanic Cloud
SMG	SubMillimeter Galaxies
SMO	Spectrometer Main Optics
SNN	Samenwerkingsverband Noord Nederland
SOLIS	Synoptic Optical Long-term Investigations of the Sun (facility at NSO)
SPHERE	Spectro-Polarimetric High-contrast Exoplanet Research (instrument under construction for VLT)
SPICA	SPace Infrared telescope for Cosmology and Astrophysics (likely Japanese mission with European participation)
SPIRAS	Supersonic Plasma InfraRed Absorption Spectrometer (set-up for Sackler Laboratory at Leiden Observatory)
Spitzer	NASA's infrared space observatory
SRON	SRON - Netherlands Institute for Space Research
SURFRESIDE	SURFace Reactions Simulation Device (setup for Sackler Laboratory at Leiden Observatory)
SWS	Short Wavelength Spectrometer (instrument on ISO)
TNO	Research Institute for applied physics in the Netherlands
TPD	Temperature Programmed Desorption
TUD	Technical University Delft
UCSB	University of California Santa Barbara
UCSC	University of California Santa Cruz
UD	Assistant professor
UHD	Associate professor
UHE	Ultra-High Energy
UHECR	Ultra-High Energy Cosmic Rays
UK	United Kingdom
UKIDSS	UKIRT Infrared Deep Sky Survey
UKIRT	United Kingdom Infrared Telescope
UL	Universiteit Leiden
ULIRG	Ultra Luminous Infra-Red Galaxy
UltraVISTA	Ultra deep near-IR imaging program with VISTA
ULX	Ultra-luminous X-Rays
UNAWE	Universe Awareness (international outreach activity aimed at kids of 4-10 years)
UNESCO	United Nations Educational, Scientific and Cultural Organization
univ	university
USM	Universität-Sternwarte München (Germany)
UU	Universiteit Utrecht
UV	ultra violet
UvA	Universiteit van Amsterdam
VIKING	Vista Kilo-degree Infrared Galaxy survey
VIMOS	Visible Multi-Object Spectrograph (VLT instrument)
VISIR	VLT-Imager and Spectrometer for mid InfraRed (instrument on VLT)
VISTA	Visible and Infrared Survey Telescope for Astronomy (ESO)
VLA	Very Large Array
VLBI	Very Long Baseline Interferometry
VLT	Very Large Telescope (ESO)
VLTI	Very Large Telescope Interferometer (ESO)
VO	Virtual Observatory
VST	VLT Survey Telescope
WFI	Wide-Field Imager (ESO 2.2m instrument)
WFPC	Wide-Field Planetary Camera (instrument on HST)
WHT	William Herschel Telescope (part of ING)
WMAPx	Wilkinson Microwave Anisotropy Probe release x
WSRT	Westerbork Synthesis Radio Telescope
XMM-Newton	X-Ray Multiple Mirror (ESA's X-ray observatory)
XRB	X-Ray Binary
X-Shooter	Single target optical and near-IR spectrometer (instrument on VLT)
YSO	Young Stellar Object
ZIMPOL	Zurich IMaging POLarimeter - part of SPHERE






HIFI Spectrum of Water and
Organics in the Orion Nebula
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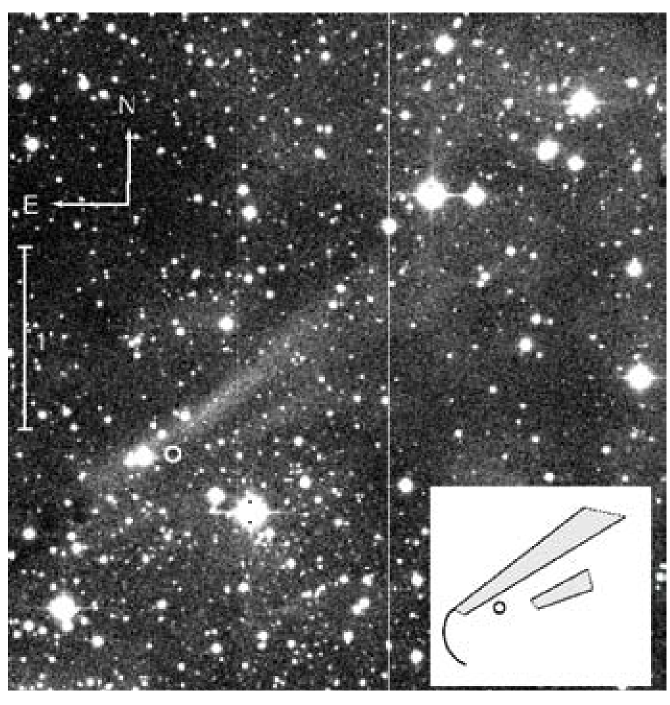
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