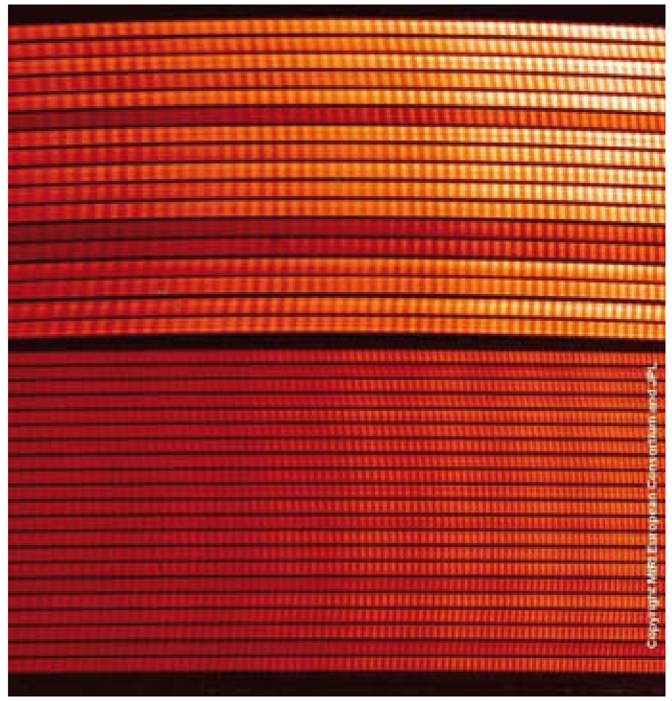
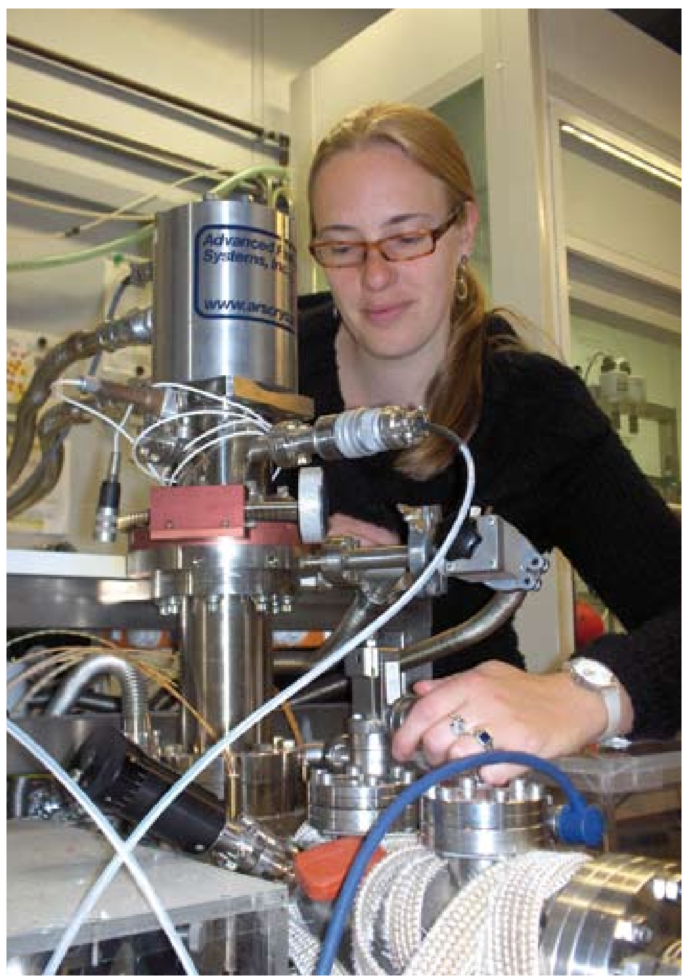
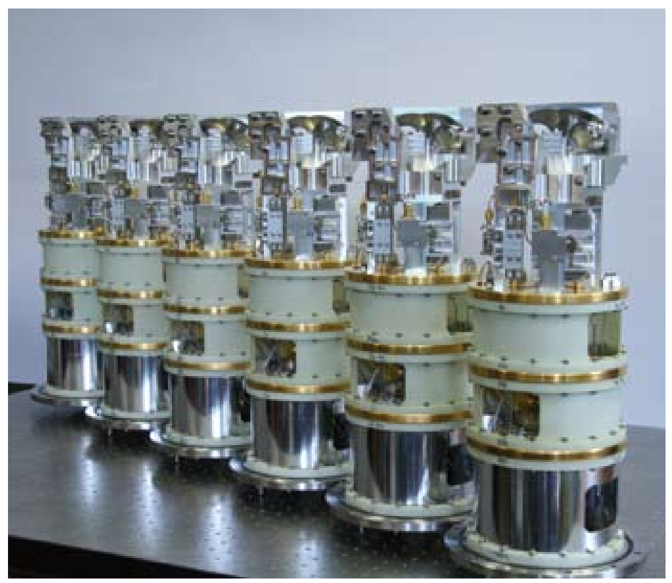
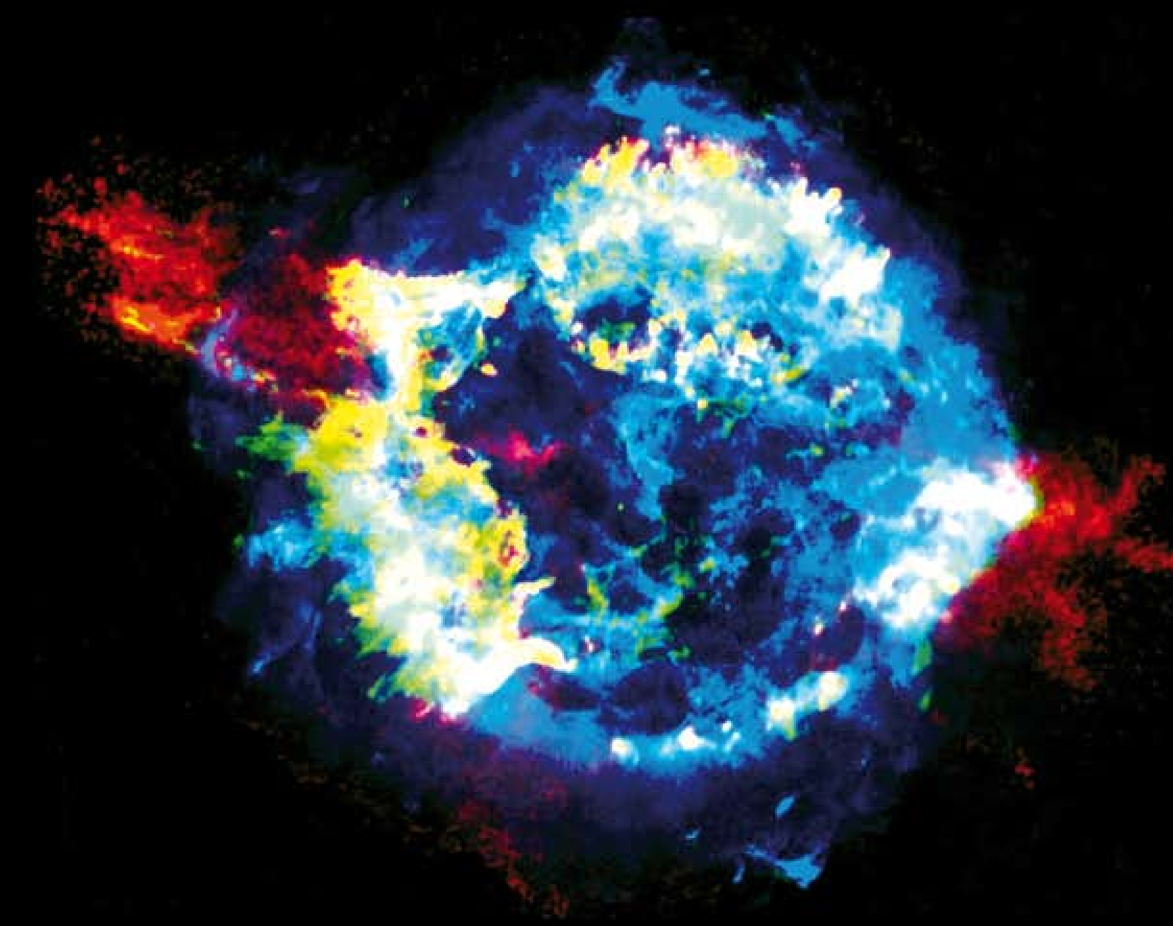






NOVA REPORT 2006 - 2007



NOVA REPORT 2006-2007

Illustration on the front cover

The cover image shows a composite image of the supernova remnant Cassiopeia A (Cas A). This object is the brightest radio source in the sky, and has been created by a supernova explosion about 330 year ago. The star itself had a mass of around 20 times the mass of the sun, but by the time it exploded it must have lost most of the outer layers.
The red and green colors in the image are obtained from a million second observation of Cas A with the Chandra X-ray Observatory. The blue image is obtained with the Very Large Array at a wavelength of 21.7 cm. The emission is caused by very high energy electrons swirling around in a magnetic field.
The red image is based on the ratio of line emission of Si XIII over Mg XI, which brings out the bi-polar, jet-like, structure. The green image is the Si XIII line emission itself, showing that most X-ray emission comes from a shell of stellar debris. Faintly visible in green in the center is a point-like source, which is presumably the neutron star, created just prior to the supernova explosion.
Image credits: Creation/compilation: Jacco Vink.
The data were obtained from: NASA Chandra X-ray observatory and Very Large Array (downloaded from Astronomy Digital Image Library http://adil.ncsa.uiuc.edu). Related scientific publications: Hwang, Vink, et al., 2004, Astrophys. J. 615, L117; Helder and Vink, 2008, Astrophys. J. in press.

Illustrations on the back cover

Clockwise starting at upper left.

1. First light of the near-infrared arm of X-shooter in December 2007. A Th-Ar spectrum with wavelength running from below left (1000 nm) to top right (2500 nm) showing that the spectrograph is working properly (photo credit: Matthew Horrobin).

2. First MIRI verification model test results obtained in the cryo-vacuum chamber at RAL on 19 December 2007. The individual image slices are clearly seen. The strong fringing in the spectral (vertical) direction is well characterized and is being investigated by Lahuis and Martinez.

3. ALMA Band-9 receiver cartridges #3-8 tested and awaiting acceptance in August2007 (photo credit Ronald Hesper).

4. Suzanne Bisschop at work on SURFRESIDE, a NOVA funded laboratory project at the Raymond and Beverly Sackler Laboratory for Astrophysics, to study the formation of complex molecules in space, including the first production of alcohol ice under simulated interstellar conditions.

NOVA Report

2006 - 2007

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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 the University of Groningen until 31 August 2007 and by the University of Utrecht from 1st September 2007.

Table of contents

1. Introduction

The ultimate goal of astronomical research is to understand the Universe and the objects within it in terms of the laws of physics. Questions concerning the nature and evolution of the Universe are profound and appeal to a deep human desire to understand our place in the Universe. They relate directly to such questions as the geometry of space time, the nature of dark matter and dark energy which constitute over 95% of the matter and energy in the universe but leave no direct trace, the formation of the elements, and ultimately, the origin of stars, planets, such as the Earth, and life itself. Furthermore, the Universe provides a unique laboratory for investigating the laws of physics and chemistry under conditions far more extreme than can be reached in a laboratory on Earth. Astrophysicists study phenomena involving enormous scales of time, length and mass (the entire Universe), huge densities (e.g., neutron stars, black holes), extreme vacua (interstellar and circumstellar media), immense energies (explosive phenomena such as supernovae, quasars) and intense fluxes of particles and radiation (neutrinos, gamma ray bursts).

The Netherlands Research School for Astronomy, NOVA, is one of the six national focus points of excellent research. They were selected by the Netherlands Organization for Scientific Research (NWO) from 34 proposals covering all academic disciplines. Funding started in 1999 under the so-called 'In-Depth Strategy' program initiated by the Ministry of Education, Culture and Science. In 2006 the minister decided to continue the funding for the six 'top-research schools' for the period 2009 – 2013 and to initiate a major program review in 2009- 2010 which could result in continuation of funding beyond 2013 if the 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'. This requires full knowledge of many aspects of astronomy and astrophysics (see Chapter 3 for examples), and access to state-of-the-art observations. 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 270 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, 40 fte postdoctoral fellows, 130 fte PhD students, and ~40 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 year 2007 saw the departure of Tim de Zeeuw, who had served as the founding Director of NOVA since 1992. He helped shape Dutch astronomy over many years, and had a key role in the development of the entire NOVA program. He accepted the challenging position of Director-General of ESO starting September 1 2007. A one day national symposium highlighting NOVA science over the last decade was held in his honor on August 27 2007.

A number of other changes in the NOVA organization also occurred on September 1 2007: (1) transfer of the legal representation of NOVA from the University of Groningen, who had this task for five years, to the University of Utrecht; (2) van der Kruit stepped down as chair of the NOVA Board after holding this position for four years. He was succeeded by van der Klis; (3) van Dishoeck started as NOVA Scientific Director and Boland was promoted to Executive Director.

The period 2006-2007 saw once again a rich variety of new astrophysical results which are summarized in Chapter 3. Highlights include discoveries of massive red galaxies in the early universe that stopped forming stars at a surprisingly young age (Kriek, Franx et al.), of a new class of transitional protoplanetary disks with large inner dust holes still containing gases and PAHs (Geers, van Dishoeck et al.) and of the first transient Z-type low-mass X-ray binary (Homan, van der Klis, Wijnands et al.). Also, strong indications were found that our Milky Way did not form by a merger of dwarf satellite galaxies, contrary to popular formation theories (Helmi, Tolstoy, et al.), that the SNR RCW 86 was formed in the 185 AD supernova recorded in China (Vink et al.), and that the enigmatic supernova 2006gy resulted from a merger of two massive stars (Portegies Zwart & van den Heuvel). Ormel, Dominik and collaborators improved our understanding of grain growth and dust aggregation as the first steps toward planet formation; Mokiem, de Koter, Langer et al. determined the initial rotation rates of the most massive stars and subsequent evolutionary consequences; and Falcke and his group participated in the first Pierre Auger Observatory results showing a correlation between high energy cosmic rays and Active Galactic Nuclei, and pursued complementary radio experiments.

A total of 51 PhD degrees in astronomy were awarded at the five NOVA institutions (Chapter 4), with cum laude for Battaglia (RuG, 2007), Kriek (UL, 2007), Leenaarts (UU, 2007), Mokiem (UvA, 2006) and Weltevrede (UvA, 2007). Many NOVA researchers received awards and honors, including:

- Election to the Royal Dutch Academy of Sciences (KNAW) for de Zeeuw (2006) and Butcher (2007)
- Election to the Young Academy of the KNAW for Helmi (2006)
- Bruno Rossi prize of the American Astronomical Society for Wijnands and two colleagues (2006)
- Honorary doctorate University of Chicago for de Zeeuw (2007)
- R.M. Petrie award of the Canadian Astronomical Society for van Dishoeck (2007)
- Akademiepreis der Berlin-Brandenburgischen Akademie der Wissenschaften for Falcke (2006)
- Pastoor Schmeits prize: Tolstoy and Portegies-Zwart (both 2007)

NWO awarded research innovation grants to the following persons: VICI grant for Tolstoy (2006), VIDI grants for Larsen (2006), Levin (2006), Schaye (2006), Stam (2006), Jonker (2007) and Markov (2007), and VENI grants for Cuppen (2006), Hopman (2006), Baryshev (2007), Cazaux (2007), Costantini (2007) and Rea (2007).

The NOVA instrumentation program (Chapter 5) saw the completion of the CRYOPAD and SURFRESIDE instruments for the Sackler Laboratory for Astrophysics in 2006 which started to produce a steady stream of science results (see Chapter 3.2). Furthermore the CHAMP+ instrument on the Atacama Pathfinder Telescope (APEX) was completed and commissioned in 2007, - the first heterodyne array receiver at 650/850 GHz worldwide to which NOVA contributed the detectors -, demonstrating the robustness of the detector design of the ALMA Band-9 receiver cartridge, and completion of the eight prototype ALMA Band-9 receiver cartridges.

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. The University of Groningen was penvoerder from September 1, 2002 until August 31, 2007. Since September 1, 2007, NOVA is legally represented by the Utrecht University (UU) for a term of five years.

2.1. NOVA's mission

NOVA's mission is to carry out frontline astronomical research in the Netherlands, and to train young astronomers at the highest international level. All graduate astronomy education in the Netherlands is concentrated in NOVA.

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

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 form. 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. Recent technological advances make it possible to observe this evolution all the way back to epochs when the Universe was less than 5% of its present age. The theme of the NOVA Program is to unravel the history of the universe and to further develop the understanding of the life cycle of stars and galaxies.

The NOVA research program concentrates on the following three interconnected areas:

• *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: Final stages of stellar evolution: physics of neutron stars and black holes*
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 research is carried out in three interuniversity networks, each led by 5-6 key researchers with strong international reputations. The list of NOVA Key Researchers is given in section 9.3.

The NOVA instrumentation program is carried out in collaboration with the NWO institutes ASTRON and SRON, and institutions abroad. The aim is to strengthen the technical expertise at the universities, and to develop and construct new instrumentation and high-level software for world-class observatories, with a focus on instrumentation for the European Southern Observatory (ESO). At the moment these include 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.

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

This chapter summarizes the research highlights of the three research networks. More information can be found in the annual reports of the five university astronomical institutes.

3.1. Formation and Evolution of Galaxies: from high redshift to the present

The aim of the research of Network 1 is to study the formation and evolution of galaxies from our local neighborhood at redshift 0 to the first observable objects in the Universe at redshifts more than 7 (a look back time of more than 95% of the history of the universe). The most prominent research focuses on probing the evolutionary state of extremely distant and luminous galaxies, and unraveling the formation history of nearby galaxies through studying their dynamical state and their stellar content and chemical evolution history.

3.1.1. The Galaxy and resolved stars in external galaxies

3.1.1.1. Bulge dynamics

Kuijken, together with Soto (PhD) and Rich (UCLA), is constructing 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 Integral Field Unit (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. Repeated HST images separated by 3-5 years 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.

3.1.1.2. Substructures in the Galaxy

Li (PhD) and Helmi analyzed the substructure properties in the new Milky Way-sized dark matter simulations carried out by Stoehr (IAP). Clustering of subhalos at the accretion epoch has been found indicating group infall. The present-day angular momentum still preserves the clustering infall signals up to z ~ 1. This work also showed that group infall is a plausible mechanism to account for both the Ghostly streams and the highly anisotropic satellite disk traced by the eleven classical Milky Way satellites.

Li and White (MPA) calibrated the classical "Timing Argument (TA)" to estimate the masses for the Local Group and the Milky Way. Combining modern observational data, the Local Group mass is estimated $\sim 5.27\times10^{12}\ M_\odot$, and the Milky Way mass to be $\sim 2.43\times10^{12}\ M_\odot$, with 95% confidence level lower limits of $1.81\times10^{12}\ M_\odot$ and $0.80\times10^{12}\ M_\odot$ respectively. The relative transverse velocity of the M31 is predicted to be about 86 km/s.

3.1.1.3. The Radial Velocity Experiment (RAVE)

The RAVE collaboration (PI: Steinmetz (AIP); NL-PI: Helmi) has now measured spectra for over 200,000 stars (see Fig. 3.1). A subset of the data has been used to constrain the presence of infalling stellar streams through the local Galactic disk. Seabroke (Cambridge) and collaborators have found that there are no vertical streams in the RAVE sample with stellar densities $>1.5\times10^3$ stars kpc^{-3}. This is sufficiently sensitive to allow our RAVE sample to rule out the passing of the tidal stream of the disrupting Sagittarius dwarf galaxy through the solar neighbourhood, supporting models in which the halo potential is prolate as proposed by Helmi in 2004.

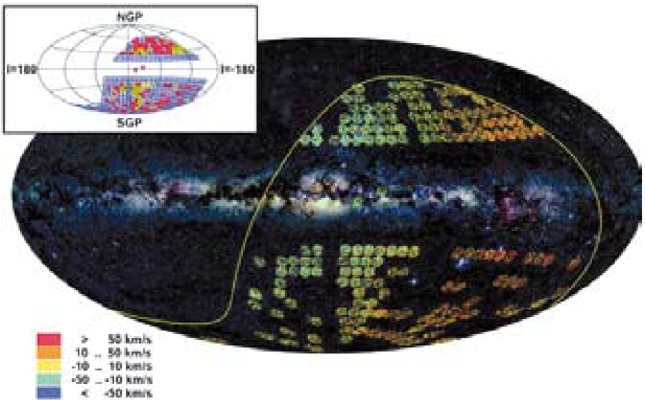

Figure 3.1: Projection in Galactic coordinates of the RAVE first data release fields. All field centers are located at |b| ≥ 25''. The heliocentric radial velocity gradient around the sky, traced by the colors, reflects Solar motion and the projection of the different components of the velocity along the line of sight. The inset shows the location of the RAVE fields, color coded according to the number of times they have been visited: red is for one pointing, yellow two, green three and light brown four (from: Mellinger, based on: Steinmetz et al. 2006, Astron. J. 132, 1645).

Veltz (Strasbourg) and the RAVE team have analyzed the distribution of G and K type stars towards the Galactic poles using RAVE and ELODIE radial velocities, 2MASS photometric star counts, and the 2nd US Naval Observatories CCD Astrograph Catalog proper motions. The combination of photometric and 3D kinematic data has allowed the identification of discontinuities in the kinematics and magnitude counts that separate the thin disk, thick disk and a hotter component. In particular, the existence of a kinematic gap between the thin and thick disk constrains formation models for these components, and rules out those in which the thick disk forms by a continuous process, such as scattering of stars by spiral arms or molecular clouds in the thin disk.

3.1.1.4. Various other galactic projects

Smith (postdoc), Wozniak (LANL) and collaborators, continued his Monte Carlo simulations to better understand the effect of stellar crowding on microlensing results. He was also involved in a project together with Kozlowski (Manchester) to measure proper motions in the Galactic bulge by combining archival HST data with new ACS observations, obtaining accuracies as good as ~0.1 mas/yr. The resulting proper motion dispersions and anisotropy were investigated.

In collaboration with the Spaghetti survey (PI: Morrison, CWRU), Helmi and Kepley (Wisconsin) assembled a sample of halo stars in the solar neighborhood to look for halo substructure in velocity and angular momentum space. This data set confirms the existence of the streams found by Helmi. New tests for substructure show that detecting these streams with radial velocities alone would require a large sample (e.g., approximately 150 stars within 2 kpc of the Sun within 20 degrees of the Galactic poles). In angular momentum space a new substructure has been discovered, whose stars move on retrograde orbits. The fraction of stream stars in the sample is between 6% and 13%.

3.1.1.5. Nearby dwarf galaxies

Tolstoy continued her work on galaxy formation and evolution with particular interest in the resolved stellar populations of nearby dwarf galaxies. Together with Battaglia (PhD) she used the VLT to gather stellar spectroscopy of individual stars in nearby dwarf spheroidal galaxies, predominantly following up on the DART (Dwarf Abundances and Radial velocities Team) program. With Parisi (Msc student Bologna) the kinematic and metallicity properties of the Sextans dwarf spheroidal were studied.

Tolstoy, Cole (NOVA postdoc, now at Minnesota/ Tasmania) and collaborators analyzed Color-Magnitude diagrams using deep HST(-ACS) data of the nearby dwarf galaxy Leo A to determine the star formation history back to the earliest times based on main sequence turnoff photometry, allowing speculation on the relationship to large-scale processes occurring in the early Universe, including the Epoch of Reionisation. Possibly the effects of reionisation on the star formation of these small systems are seen: after a very early start it seems that star formation stops, perhaps due to increased ionizing radiation, only resuming again when radiation levels fall sufficiently 6–8 Gyr ago.

3.1.1.6. Local group dwarf galaxies

Tolstoy worked with Mapelli (Zurich), Ripamonti, and Irwin (Cambridge) on a study of blue stragglers in dwarf spheroidal galaxies, using INT/WFC imaging for two dwarf spheroidals, Draco and Ursa Minor. The goal was to determine if the presence of small numbers of blue stars above the oldest main sequence turnoffs are bonifide blue stragglers or whether they 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 a younger population. Tolstoy, together with Fiorentino and others, including the ELT project office at ESO, has started to develop techniques and methods to observe resolved stellar populations in the infrared with Adaptive Optics.

3.1.1.7. Chemistry and kinematics of stars in Local Group galaxies

Battaglia, Tolstoy, Helmi, and the DART team focused on two Milky Way satellites, the Sculptor and Fornax dSph, with the aim of understanding their properties in terms of their metallicity distribution, kinematic status and dark matter content. Low-resolution Ca-II triplet spectroscopic estimates of the overall metallicity ([Fe/H]) of individual red giant branch (RGB) stars agree to ± 0.1–0.2 dex with detailed high-resolution spectroscopic determinations over the range $-2.5 < [Fe/H] < -0.5$. This has implications on the efficiency for deriving metallicity distribution functions for nearby resolved galaxies, since Ca-II metallicities for ~120 stars observed at low spectral resolution can be obtained in just one hour observing time at VLT/FLAMES, compared with ~6 nights at high-resolution.

Battaglia and collaborators found no obvious sign of tidal disruption in the kinematics of the Sculptor dSph, but for the first time a statistically significant velocity gradient was detected in a dSph, likely due to actual rotation of this galaxy. This discovery has been possible thanks to the large spatial coverage of the galaxy, large number statistics and high accuracy of the velocity measurements. Battaglia et al. also carried out accurate mass modeling of the Sculptor dSph, finding that the best-fitting dark matter profile is a cored profile with core radius of 0.5 kpc and a mass within 1.8 kpc of 3.4×10^8 $M_\odot$.

3.1.1.8. Metallicity distribution in dwarf spheroidal galaxies

The metallicity properties of dSph, and their spa-

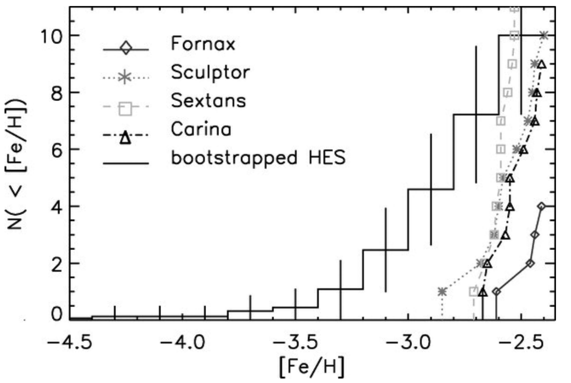

Figure 3.2: Comparison of the metal-poor tail of the [Fe/H] distribution for stars in four dSph and the Galactic halo (solid line, indicated as HES). The lack of very metal-poor stars in the dSph, which is in stark contrast with the Galactic halo, implies that any merging, even very early on, of the progenitors of the nearby dwarf galaxies as a mechanism for building up the Galactic halo is ruled out (from: Helmi et al. 2006, Astrophys. J. Letters 651, L121).

tial variations, give important insights in the processes of star formation and chemical enrichment at the low mass galaxy end. Using the Ca-II triplet as metallicity estimator Tolstoy and collaborators have measured the metallicities of a large sample of RGB stars in Sculptor, Sextans, Fornax and Carina. Helmi and collaborators found a significant lack of stars with metallicities below [Fe/H] ~ –3 in all four systems. This suggests that the gas that made up the stars in these systems had been uniformly enriched prior to their formation. Furthermore, the metal-poor tail of the dSph metallicity distribution is significantly different from that of the Galactic halo (Fig. 3.2). These findings show that the progenitors of nearby dSph appear to have been fundamentally different from the building blocks of the Milky Way, even at the earliest epochs.

3.1.1.9. Dust and gas in the Small Magellanic Cloud

As part of a large international team (PI: Bolatto), Israel studied infrared emission from the Small Magellanic Cloud (SMC) observed with Spitzer Space Observatory. PAH abundances are found to have large spatial variations probably representing the effects of photodestruction. They also cataloged about 400,000 mid- and far-infrared point sources in the SMC. The sources detected at the longest wavelengths fall into four main categories: (1) Young stellar objects bright at 5.8 μm but having very faint optical counterparts and very red mid-infrared colors; (2) Carbon stars bright in the mid-infrared with mildly red colors; (3) Oxygen-rich evolved stars, bright in both the optical and the mid-infrared, with neutral colors; and (4) Unreddened early B stars (B3-O9) with a large 24 μm excess, reminiscent of disks and detected in only a small fraction of these stars (<~5%). The majority of the brightest infrared point sources in the SMC fall into the first three categories. Israel and collaborators found a total dust mass of $M_{dust} = 3x10^5\ M_\odot$ from the far-infrared data, implying a dust-to-total-hydrogen ratio of about 1:700. Assuming the dust to trace the total gas column, they used a method pioneered by Israel to derive H_2 surface densities across the SMC, and found a total H_2 mass $M(H_2) = 3.2\times10^7$ $M_\odot$ with a distribution similar to that of the CO, but more extended by a factor of about 1.3. The implied CO-to-H_2 conversion factor over the whole SMC is $X(CO) = 13\times10^{21}$ cm^{-2} (K km/s)$^{-1}$. Over the volume occupied by CO the conversion factor is lower, $X(CO) = 6\times10^{21}$ cm^{-2} (K km/s)$^{-1}$, but still a few times larger than that found using virial mass methods. For a given hydrostatic gas pressure, the SMC has a 2-3 times lower ratio of molecular to atomic gas than spiral galaxies. Combined with lower mean densities, this results in this galaxy having only 10% of its gas in the molecular phase.

3.1.1.10. Neutral hydrogen in the Local Group

Oosterloo and collaborators obtained HI WSRT observations of the recently discovered Local Group dwarf galaxy Leo T. This is a particularly interesting galaxy because it is the smallest known galaxy (absolute magnitude in V is –7) where continuous star formation has taken place, at a low rate, over the Hubble time. In such small galaxies there are many processes that slow down star formation. For example as soon as a few stars form, supernovae and stellar winds will expel the gas. The WSRT observations actually show that Leo T is very gas rich (M(HI)/L = 5) and the HI distribution is very regular (Fig. 3.3). No signs of any gas outflows are observed, despite the recent star formation. Leo T appears to have a normal ISM with both cold (<500 K) and warm (≈6000 K) HI, very similar to larger galaxies. One scenario is that the ISM in Leo T cools in the same way as in larger galaxies, but as soon as a few stars form, their radiation prevents further cooling and star formation halts temporarily, leading to a small trickle of periodic star formation. Leo T is also found to be the most dark matter dominated, gas-rich dwarf in the Local Group.

3.1.1.11. Star clusters in external galaxies

Several theoretical and observational studies of young star clusters in the Milky Way and beyond have been carried out by Larsen (NOVA overlap), Lamers, Scheepmaker (NOVA PhD) and collaborators. The overall aim is to understand the formation, evolution and eventual disruption of star clusters,

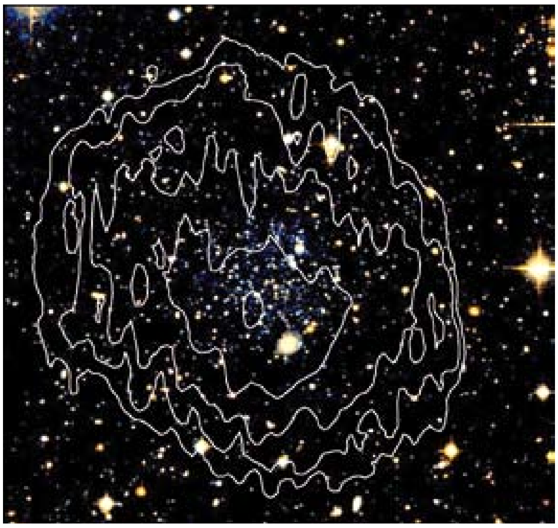

Figure 3.3: HI observations of the Local Group dwarf galaxy Leo T superposed on an optical image (from: Ryan-Weber et al. 2008, MNRAS 384, 535).

so that they may be effectively employed as tracers of the star formation histories in external galaxies. HST/ACS observations of the rich cluster system in the nearby interacting spiral M51 have provided important information about the early size evolution of star clusters and the spatial correlation of star/cluster formation. Lamers, Gieles (NOVA PhD) and collaborators concluded that the dominant disruption mechanism of open clusters in the Solar neighborhood is encounters with Giant Molecular Clouds (GMCs). This may explain why the disruption time scales appear to be different in other galaxies, where the GMC density is different than in the Solar neighborhood.

Mora, Larsen and Kissler-Patig (ESO) published a study of star clusters in the nearby spiral galaxy NGC 45, based on observations with the HST-ACS. NGC 45 is a relatively low luminosity galaxy in the Sculptor group, and from comparison with Local Group galaxies of similar luminosity (SMC, LMC) one might expect a handful of globular clusters. Instead, the HST data revealed 19 old globular clusters. Spectroscopic follow-up observations with the ESO-VLT were obtained and confirm that the clusters are old and relatively metal-poor. Surprisingly, they appear to have sub-solar alpha-elements-to-Fe abundance ratios, unlike globular clusters in major galaxies, suggesting that chemical enrichment may have proceeded at a slower rate in NGC 45.

Larsen, in collaboration with Richtler (Concepcion) studied planetary nebulae identified as an excess of [O III] emission in the spectra of three extragalactic star clusters. Since star clusters can be age-dated (from photometry or spectroscopy), this provides unique constraints on the progenitor star masses of the PNe and hence on the initial-final mass relation if the PN central star masses can be determined. For two of the PNe the central star masses were found to be close to 0.60 $M_\odot$, while the cluster ages indicated an initial mass of 3 and 6 $M_\odot$. The central star masses are lower than expected from standard initial-final mass relations, according to which a 6 $M_\odot$ AGB star should produce a 1 $M_\odot$ remnant.

Efforts to carry out abundance analyses from integrated spectra of extragalactic star clusters are on-going by Larsen and collaborators. Keck/NIRSPEC data yielded abundances of several individual elements in the massive, young star cluster NGC 1569-B. VLT/UVES spectra have been obtained for three of the globular clusters in the Fornax dSph. An unexpected byproduct of this study was the discovery of a planetary nebula in one of the clusters (Fornax 5). This PN is peculiar in showing no Balmer line emission, possibly indicating an extreme degree of H depletion. This would make it the second such case identified in a globular cluster, the first being a planetary nebula in the galactic globular cluster M22.

3.1.2. Nearby Galaxies

3.1.2.1. The PN.S project

Douglas, Kuijken, Coccato and collaborators continued their study of elliptical galaxy halos using the Planetary Nebula Spectrograph (PN.S) on the WHT which finds and measures velocities of a large number of planetary nebulae (PNe) in external galaxies from a single observation. The ongoing survey typically yields 100-200 PNe per galaxy, mostly at large radii from the center where their motions are dominated by the dark matter halo potential. A dozen galaxies now have good datasets. A recent highlight is NGC 3379, an elliptical galaxy with a curiously falling velocity dispersion, implying a rather light-weight dark matter halo around this galaxy. A novel 'made-to-measure N-body code', NMAGIC, developed in the group of Gerhard (MPE) has been applied to the data in order to explore what modeling freedom the data still allow. As a side-project kinematic maps of S0 galaxies are produced, with which the rotation and dispersion properties of the outermost stars are being investigated.

Work also continued on the $H\alpha$ camera, an add-on facility to the PN.S, which will provide a direct image to complement the two dispersed images in [OIII]. This will provide redundancy in the position/velocity solution and will help in calibration as well as in the elimination of unresolved background objects. Finally, the extra camera will also provide valuable photometry of all galaxies studied. The first observational run was in December 2007.

3.1.2.2. **The SAURON Project**

De Zeeuw, Peletier, Falcón-Barroso, McDermid (both NOVA postdoc), van den Bosch, Ganda and Weijmans (all three PhD) are members or associates of the SAURON team that has built a panoramic integral-field spectrograph for the WHT, in a collaboration with Lyon (Bacon) and Oxford (Davies). SAURON was used to map 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), as well as for several follow-up projects on specific objects. The team has also developed a number of tools that are key to analyze all the resulting maps. The survey results are summarized in a series of papers, 8 of which were published in the reporting period.

The survey data were used to analyze the fundamental plane of early-type galaxies. This established that the scatter in the mass-to-light ratio versus galaxy mass relation is extremely small, and that ellipticals have almost no dark matter in their central regions. SAURON also revealed that early-type galaxies contain large amounts of ionized gas, in many cases in regular, stable orbits, but in other cases showing signs of infall. The two-dimensional maps of the absorption line strength indices for the elliptical and S0 galaxies allow the derivation of the age and metallicity of the stellar populations. Measurements with OASIS, an integral field spectrograph with a much higher spatial resolution and a smaller field of view on the WHT, resulted in the discovery of small kinematically distinct cores in many systems.

Further analysis of the kinematic maps showed that early-type galaxies appear in two broad flavors, depending on whether they exhibit clear large-scale rotation or not. Slow and fast rotators were shown to be physically distinct classes of galaxies, a result which cannot simply be the consequence of a biased viewing orientation. Fast rotators tend to be relatively low-luminosity galaxies with $M_B < -20.5$. Slow rotators tend to be brighter and more massive galaxies, but are still spread over a wide range of absolute magnitude. The fast rotators have a simple orbital distribution, with a velocity ellipsoid that is flattened in the direction perpendicular to the equatorial plane. The velocity and velocity dispersion fields for gas and stars in the 24 early-type spirals of the SAURON survey show that many of these objects have central stellar disks which dominate the light distribution. The absorption-line maps show that many galaxies contain younger populations (<1 Gyr), distributed in small or large inner discs, or in circumnuclear star-forming rings. The observations can be understood if the central regions of Sa galaxies contain at least two components: a thin, disc-like component, often containing recent star formation, and another, elliptical-like component, consisting of old stars and rotating more slowly, dominating the light above the plane. These components together form the photometrically defined bulge, in the same way as the thin and the thick disc co-exist in the Solar neighborhood.

Ganda, together with Peletier, Falcón-Barroso and McDermid, used SAURON to investigate 18 late-type spiral galaxies (type Sb-Sd). In many cases the stellar kinematics suggest the presence of a cold inner region, as visible from a central drop in the stellar velocity dispersion. The ionized gas is ubiquitous and behaves in a complicated fashion: the gas velocity fields often display more features than the stellar ones, including wiggles in the zero-velocity lines, irregular distributions, and ring-like structures. The line ratio [OIII]/Hβ often takes on low values over most of the field, probably indicating wide-spread star formation. The absorption line measurements confirm that late-type spirals are in general younger and more metal-poor than ellipticals and lenticulars, and that they cover a narrower parameter range than early-type spiral galaxies, possibly indicating more quiescent star formation processes. The larger galaxies tend to have experienced a single short starburst, while star formation in smaller galaxies, with lower dispersion continued for longer times. Ganda also performed bulge-disc decomposition on the basis of archival NIR images. The bulges are in most cases very tiny (with effective radii smaller than 10 arcsec) and can be fitted with Sersic profiles with n in the range 1–3.

De Zeeuw, McDermid, Cappellari and Weijmans contributed to a follow-up survey lead by Morganti to study the HI content of a subset of SAURON galaxies using the WSRT. Neutral hydrogen was detected in 70 % of these (field) galaxies, showing a clear connection to the ionized gas observed in the central regions with SAURON. A variety of HI morphologies was found, but surprisingly little correlation with other galaxy properties, such as stellar populations and dynamical structure. The occurrence and morphology of the gas suggests, however, that early-type galaxies continue to build up their mass to the present day.

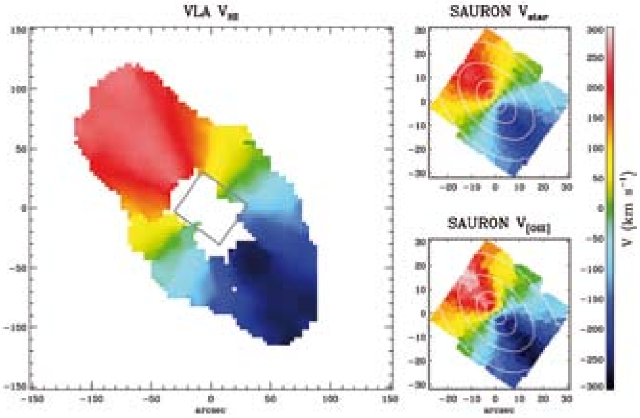

Figure 3.4: Velocity maps of the neutral hydrogen (VLA) and ionized gas and stars (SAURON) in early-type galaxy NGC 2974. The grey box in the VLA map encloses the SAURON fields shown at the right. The neutral and ionized gas are well aligned, indicating that they form a single disc. Analysis of the rotation curves leads to the conclusion that at least 55% of the matter in this galaxy is dark (from: Weijmans et al. 2008, MNRAS 383, 1343).

Weijmans and van de Ven (Princeton) combined the kinematics of ionized gas (observed with SAURON) in the early-type galaxy NGC 2974 with those of HI gas (observed with VLA) by applying an asymmetric drift correction to the ionized gas. They were able to separate the random motions caused by gravitational interaction from those caused by turbulence in the ionized gas. A dark matter halo is needed to reproduce the flat rotation curve. A pseudo-isothermal sphere provides the best model (Fig. 3.4).

Van den Bosch and de Zeeuw, together with van de Ven (Princeton), continued the development of the Schwarzschild orbit superposition software for triaxial galaxies. This technique uses orbital families to describe a galaxy, and can be used to fit the observed light and kinematics of stellar systems in order to derive the dynamical structure, mass-to-light ratio, viewing angle and mass of the central black hole. This code is the only one that can model galaxies with triaxial geometries, allowing features such as photometric position angle twists and kinematically decoupled components to be modeled with minimal assumptions. By using analytic models developed previously by van de Ven, van den Bosch fully tested the triaxial Schwarzschild code, and demonstrated it can reproduce the input distribution function. He used the code to model the complex elliptical galaxy, NGC 4365. This galaxy is well known for its central kinematically decoupled component, and its apparently prolate outer body. Modeling of NGC 4365 revealed the surprising result that the galaxy is not (as may be assumed from the observed kinematics) simply an oblate core rotating in a prolate system, but in fact has a significant fraction of stars orbiting in extended,

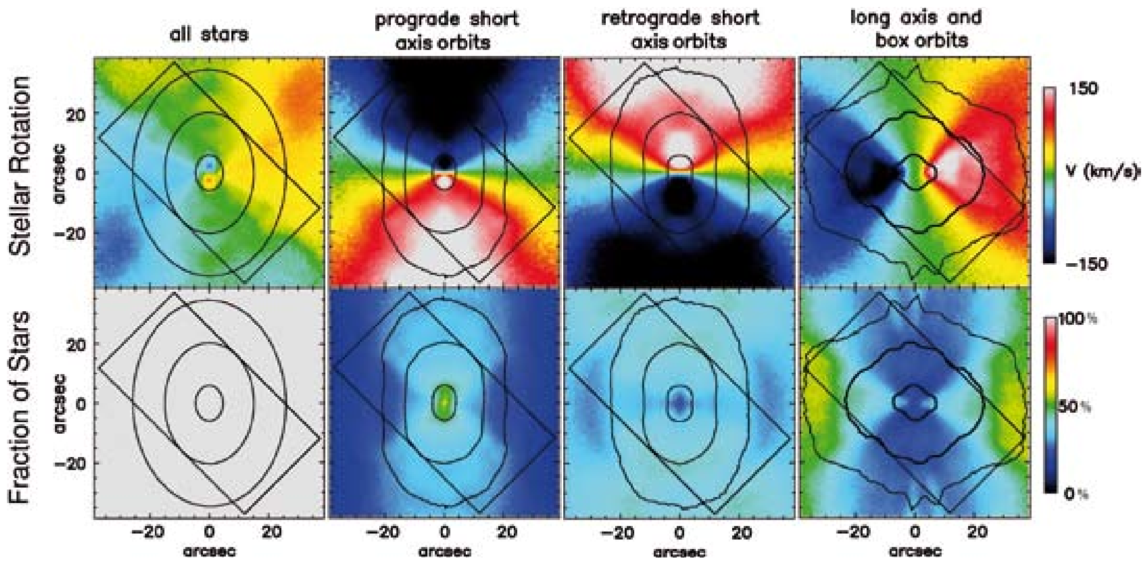

Figure 3.5: The top row shows stellar rotation velocity. The bottom row shows the fraction of the total number of stars contributing to the model at a given position. Contours indicate the projected surface brightness of the component associated to the velocity field, and the rectangular box indicates the region covered by the fitted SAURON observations. The left column shows the complete triaxial Schwarzschild model fitted to SAURON data of NGC 4365. This model reproduces well the central decoupled component and overall velocity structure of the galaxy. The next three columns show the major orbital components populated in the model, indicating also to which orbital family they belong. All three orbital components are extended across the whole galaxy, and surprisingly the short axis orbits contribute 60% of the mass (split almost equally between prograde and retrograde orbits), showing that the galaxy is more complex than simply a prolate main body harboring a small decoupled core (from: van den Bosch et al. 2008, MNRAS 385, 647).

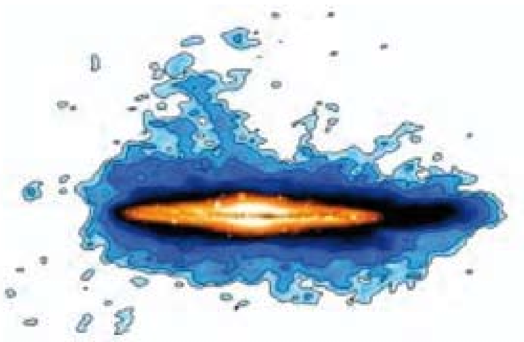

Figure 3.6: Very deep WSRT HI observations of the edge-on galaxy NGC 891 showing a huge extended gaseous halo (from: Oosterloo, Fraternali and Sancisi 2007, Astron. J. 134, 1019).

disk-like components, which, when viewed in projection, appear as a compact core embedded inside a prolate galaxy (Figure 3.5).

3.1.2.3. The Atlas 3D project

The Atlas 3D Survey (PIs: McDermid, Emsellem (Lyon), Cappellari and Krajnović (Oxford), and including de Zeeuw, Verdoes Kleijn, Falcón-Barroso, Weijmans and van den Bosch), of a complete, volume-limited sample of early-type galaxies using SAURON on the WHT, continues to gather momentum. The project also launched an observational campaign to measure molecular and neutral gas components of these galaxies using the IRAM 30m (PI Combes, Paris) and the WSRT (PI Morganti). Together with complementary imaging data from the SDSS and INT, and archival data from Chandra, GALEX and Spitzer, this project aims to provide a broad but detailed view of the local early-type galaxy population, creating a local benchmark for studies of galaxy formation and evolution.

3.1.2.4. Neutral hydrogen tracing accretion and mapping the dark matter in nearby galaxies

Spiral galaxies contain large amounts of gas in their extra-planar regions (i.e., outside the star-forming disk). Oosterloo, in collaboration with Sancisi and Fraternali (both Bologna) published very deep WSRT HI observations of the edge-on galaxy NGC 891 (Fig. 3.6), revealing a huge gaseous halo that is much more extended than seen previously, and which contains almost 30% of the HI of this galaxy. This HI halo shows structures on various scales. On one side, there is a filament extending (in projection) up to 22 kpc vertically from the disk. Moreover, small halo clouds (with a gas mass of about 10^6 $M_\odot$), some with forbidden (i.e. apparently counter-rotating) velocities, are also detected. The overall kinematics of the halo gas are characterized by differential rotation lagging with respect to that of the disk. The lag, more pronounced at small radii, increases with height from the plane. There is evidence that a significant fraction of the halo is due to a galactic fountain. However, accretion from intergalactic space must also play a role in building up the halo and providing the low angular momentum material needed to account for the observed rotation lag. The long HI filament, and the counter rotating clouds, may be direct evidence of such accretion.

3.1.2.5. Star-forming nuclear rings

Falcón-Barroso, together with Böker (ESTEC), Schinnerer (Heidelberg) and others completed the study of star-forming nuclear rings based on integral-field near-IR SINFONI observations in a sample of 5 galaxies. Maps of various emission lines that reveal the individual star forming regions (”hot spots”) delineating the rings were constructed and the morphological parameters of the rings, velocity fields of the stars and the emission line gas were derived. A qualitative but robust diagnostic for relative hot spot ages based on the intensity ratios of the emission lines Brγ, He I, and [Fe II] was proposed. Application of this diagnostic to the data provided tentative support for a scenario in which star formation in the rings is triggered predominantly at two well-defined regions close to and downstream from the intersection of dust lanes along the bar with the inner Lindblad resonance.

3.1.2.6. The Disk Mass project

Verheijen, Martinsson (NOVA PhD), Bershady and Westfall (both Wisconsin), Swaters (Maryland) and Andersen (Victoria) measured the vertical velocity dispersions of stars in the disks of 40 nearly face-on spiral galaxies using two custom-built fiber-based IFU’s (Fig. 3.7). From this kinematic information, the mass surface densities and mass-to-light ratios of the galaxy disks can be derived and the disk-halo degeneracy in the decomposition of galaxy rotation curves can be broken. Hα velocity fields of some 135 nearly face-on galaxies were obtained and analyzed. Observations of the stellar velocity dispersions in the MgIb region of the spectrum of 40 galaxies have been completed. Imaging with Spitzer at 4.5, 8, 24, and 70 μm is also completed while HI imaging of these 40 galaxies with WSRT and GMRT is still in progress. Initial results indicate that local mass surface density follows local surface brightness regardless of the disk central surface brightness of the galaxy, with high surface brightness galaxies being close to a maximum disk situation and low surface brightness galaxies being significantly sub-maximum. Dependencies on global properties like total mass, color, morphology, disk scale length etc are being explored.

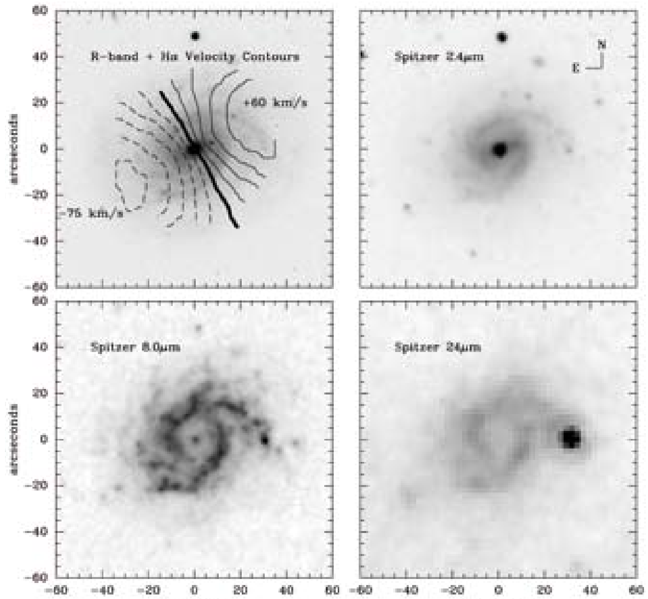

Figure 3.7: Results of Spitzer imaging of UGC 74 taken for the Disk Mass Project. Upper left: R-band image with Hα iso-velocity contours overlayed. Upper right and lower panels: Spitzer images at 4.5, 8.0 and 24 μm (from Verheijen et al. 2007, in Island Universes, Astrophysics and Space Science Proceedings, eds. de Jong and van der Kruit).

3.1.2.7. Study of the stellar line-strength indices and kinematics along bars

Pérez (Veni), Sanchez-Blazquez (Lancashire) and Zurita (Granada) studied the stellar content of the bar region in spiral galaxies to constrain its formation and evolution. This has been done using stellar line-strength indices in the bar region of a sample of 20 barred galaxies to derive age and metallicity gradients along the bars using stellar population models. Some galaxies show a positive radial bar metallicity gradient, implying that there has been a chemical enrichment and that star formation has lasted for a long time. This fact indicates that some bars are long lived. The radial negative metallicity gradient found along the bar of some of the galaxies possibly reflects the original disk gradient. The metallicity gradient seems to be correlated with the central stellar velocity dispersion, with a positive metallicity gradient found in galaxies with higher central velocity dispersion.

3.1.2.8. Comparison between 2D and 3D codes in dynamical simulations of gas flow in barred galaxies

Pérez and collaborators analyzed the effect of using 2D and 3D codes in calculating the gas flow in barred galaxies and to what extent the results are affected by the code by deriving the velocity field and density maps for the mass model of NGC 4123 using a 3D N-body/SPH code and comparing the results to the previous 2D Eulerian grid code results. The global velocity field and the gas distribution are very similar in both models. The study shows that the position and strength of the shocks developed in the SPH simulations do not vary significantly compared to the results derived from the 2D FS2 code. The largest velocity difference across the shock is 20 km/s between the 2D and 3D fluid dynamical models. The results for deriving the dark matter content of barred galaxies using the bar-streaming motions and strength and position of shocks are robust to the fluid dynamical model used.

3.1.2.9. Where are the massive stars of the bar of NGC 1530 forming?

Pérez and Zurita (Granada) have obtained BVRKs and Hα photometry of the HII regions of the bar of NGC 1530 (Fig. 3.8) in order to constrain the content of dust and age of the HII regions as a function of their position with respect to the dust lanes of the bar of NGC 1530. Differences in the Hα equivalent widths of the HII regions were found located in the trailing and leading zones of the bar, indicating that HII regions located in the leading part are older than those located on the trailing part by 3-4 Myr. This indicates that massive stars are forming in the trailing side of the bar dust lane and not in the shocked areas and/or in the leading side of the bar dust lane as is usually derived from the models.

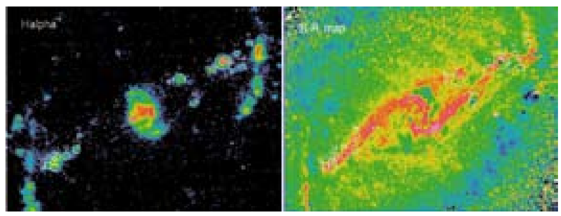

Figure 3.8: Hα (figure on the left) and B-R map (figure on the right) of the bar region in NGC 1530, the circles indicate the HII regions classified and analyzed for this project. The Hα image is characterized by the HII region location and the B-R map features the position of the dust lane. Notice the position of the HII regions with respect to the dust lane. The HII regions located on the leading part of the bar dust lane are older than those located on the trailing part by 3-4 Myr. The length of the bar is 24 kpc (from Pérez and Zurita 2008, Astron. Astrophys).

3.1.2.10. Warps and truncations in edge-on galaxies

Edge-on spiral galaxies often have stellar disks with relatively sharp truncations and there is extensive observational material of warped HI-layers in the outer parts. Van der Kruit made a comparative study of warps and truncations in edge-on galax-

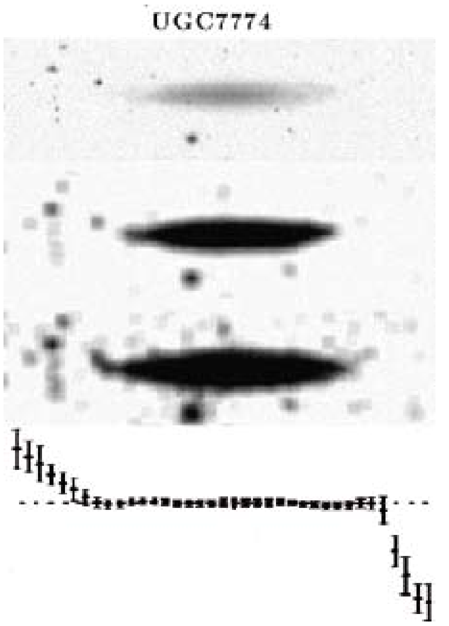

Figure 3.9: UGC 7774 has a truncation and a warped HI-layer that sets in (projected onto the sky) at about the truncation radius of the optical image. The total radial size of the image is 10' or 25 kpc. The HI is more extended than the optical disk. Top: the three images from the SDSS; the top one is unprocessed and the lower two are clipped and smoothed at a shallow and a deep level. The lower panel shows the vertical position of the centroid of the gas-layer as determined from the distribution of the HI by García-Ruiz et al., on the same radial scale and with the aspect ratio restored to the real sky (from: van der Kruit 2007, Astron. Astrophys. 466, 883).

ies. Samples with detailed surface photometry or HI-mapping have little overlap. The WSRT HI sample by Garcia-Ruiz (PhD) and collaborators was complemented with luminosity distribution from the SDSS (and in a few cases the STScI Digital Sky Survey). Shallow and deep clipped and smoothed images have been tested using the sample of edge-on galaxies of van der Kruit and Searle. Results are: (1) the majority (17 out of 23) of the galaxies show evidence for truncations in optical images, consistent with previous findings in other samples; (2) when an HI-warp is present it starts at 1.1 truncation radii (statistically allowing all possible geometries) (see example in Fig. 3.9); (3) the truncation radius and the onset of the warps coincide radially sometimes with features in the rotation curve and often with steep declines in the HI-surface density. The latter is also true for less inclined systems; (4) the definition and derivation of the Holmberg radius is discussed.
These findings suggest that the inner flat disk and the outer warped disk are distinct components with quite different formation histories, probably involving quite different epochs. The inner disk forms initially and the warped outer disk as a result of much later infall of gas with a higher angular momentum in a different orientation. The results are also consistent with an origin of the disk truncations that is related to the maximum specific angular momentum available during its formation.

Pohlen (postdoc), Zaroubi, Peletier, and Dettmar (Bochum) employed a simple algorithm to de-project the two dimensional images of a pilot sample of 12 high-quality images of edge-on disk galaxies and studied their intrinsic 3D stellar distribution. Radial profiles of the stars as functions of height above the plane show a general trend of an increasing radial scale length with height outside of dust lane. This could be explained by the widespread presence of a thick disk component in disk galaxies. In addition, the 3D view allows them to study the vertical distribution of the outer disk, beyond the break region, where they detect a significant increase in scale length with vertical distance from the major axis for the truncated disks. This could be regarded as a weakening of the "truncation" with increasing distance from the plane. Furthermore, they conclude that the recently revised classification of the radial surface brightness profiles found for face-on galaxies is indeed independent of geometry. In particular, they find at least one example of each of the three main profile classes as defined in complete samples of intermediate to face-on galaxies: not-truncated, truncated and anti-truncated.

3.1.2.11. Distribution of gas and dust in radio-loud Active Galactic Nuclei

Merger events are often invoked as triggers of the activity in galaxies. The presence of large amounts of HI distributed over large radii can be used to reconstruct the formation history of galaxies and to trace whether mergers have occurred, as studied by Morganti, Emonts (Columbia), Oosterloo and Tadhunter (Sheffield). The main goal was to search for evidence of gas-rich galaxy mergers or interactions (tails, bridges, disks, etc.) that could be related to the triggering of the radio source in these systems. Remarkably, enormous disks and rings of HI gas are detected around several nearby radio galaxies. These HI disks/rings appear to be in regular rotation and reach diameters up to 190 kpc and masses up to 4 times the HI mass of the Milky Way. One case, B2 0648+27, has been studied in great detail and was found to be a product of a major merger. The HI ring formed from tidally expelled debris that fell back and settled around the host galaxy. A multi-wavelength analysis was performed, including synthesis modeling of the stellar population throughout the galaxy, and deep optical imaging of the stellar counterpart to the HI ring. Evidence was found for a young stellar population of 0.3 Gyr. All the observations suggest that B2 0648+27 is a direct link between (Ultra-) Luminous Infra-Red Galaxies and Radio Galaxies.

Van der Wolk (PhD) studied the mid- and far-infrared properties of the centers of galaxies in collaboration with Barthel and Peletier. A mid-infrared survey of the nuclei of radio galaxies using VLT-VISIR was completed. In total a sample of 27 radio galaxies, including broad line radio galaxies, low and high excitation galaxies and low-luminosity FR1-galaxies, are under study. The data indicate that high-excitation objects and broad line galaxies have active nuclei obscured by dust tori, while FR1-galaxies are not obscured and low-excitation galaxies do not have currently active nuclei.

3.1.2.12. Shell galaxies

Sikkema (PhD), in collaboration with Peletier, Carter (Liverpool), Valentijn, and Balcells (IAC) found that HST-ACS observations of 6 shell galaxies reveal shells well within the effective radius in some cases (at 0.24, r_{eff} = 1.7 kpc in the case of NGC 5982). In other cases, strong nuclear dust patches prevent detection of inner shells. Most shells have colors which are similar to the under lying galaxy. All six shell galaxies show out of dynamical equilibrium dust features, like lanes or patches, in their central regions. The merger model better describes the shell distributions and morphologies than the interaction model. Red shell colors are most likely due to the presence of dust and older stellar populations. The high prevalence and out of dynamical equilibrium morphologies of the central dust features point toward external influences being responsible for the visible dust features in early type shell galaxies. Inner shells are able to manifest themselves in relatively old shell systems.

3.1.2.13. HI at anomalous velocities in nearby galaxies

The properties of the gas in halos of galaxies constrain global models of the ISM. Kinematical information is of particular interest since it is a clue to the origin of the gas. Kamphuis (PhD), Peletier, Dettmar (Bochum), van der Hulst, van der Kruit, and Allen (STScI) obtained observations of the kinematics of the thick layer of the diffuse ionized gas in NGC 891 in order to determine the rotation curve of the halo gas. From a Fabry-Pérot data cube in Hα obtained at the WHT the kinematics of the halo gas were measured with an angular resolution much higher than obtained from HI observations. The best fit model has a dust scale length of 8.1 kpc and an ionized gas scale length of 5.0 kpc. Above the plane the rotation curve lags with a vertical gradient of -18.8 km s^{-1} kpc^{-1}. The scale length of the Hα must be between 2.5 and 6.5 kpc. Furthermore evidence was found that the rotation curve above the plane rises less steeply than in the plane. This is all in agreement with the velocities measured in HI.

Boomsma (PhD) completed his study on the vertical structure and kinematics of HI gas in spiral galaxies with Van der Hulst, Oosterloo, Sancisi and Fraternali. Two galaxies were studied in detail, NGC 6946 and NGC 253. In NGC 6946 large complexes of kinematically anomalous HI have been detected as well as a large number of HI holes. Most of the anomalous HI seems to be located in the halo and rotates more slowly than the HI in the disk. In addition, vertical flows of HI have been detected in the direction of star forming regions. The HI halo, the massive star formation in the disk and the HI holes seem intimately linked. Furthermore, a plume of HI is seen at the edge of the disk which can be interpreted as the aftermath of accretion of an HI cloud or small companion. The high-velocity HI complexes in NGC 6946 may be analogous to the High-Velocity Clouds in the Milky Way.

Sancisi, van der Hulst, Oosterloo and Fraternali finished a comprehensive review of HI accretion phenomena in nearby galaxies. They described how HI observations of galaxies and their environment have brought to light new facts and phenomena which are evidence of ongoing or recent accretion: 1) a large number of galaxies are accompanied by gas-rich dwarfs or are surrounded by HI cloud complexes, tails and filaments. This suggests ongoing minor mergers and recent arrival of external gas and may be regarded as direct evidence of cold gas accretion in the local universe. It is probably the same kind of phenomenon of material infall as the stellar streams observed in the halos of our galaxy and M31; 2) considerable amounts of extra-planar HI have been found in nearby spiral galaxies. While a large fraction of this gas is undoubtedly produced by galactic fountains, it is likely that a part of it is of extragalactic origin. Also the Milky Way has extra-planar gas complexes: the Intermediate- and High-Velocity Clouds; 3) spirals are known to have extended and warped outer layers of HI. It is not clear how these have formed, and how and for how long the warps can be sustained. Gas infall has been proposed as the origin; 4) the majority of galactic disks are lopsided in their morphology as well as in their kinematics. Also here recent accretion has been advocated as a possible cause. Accretion takes place both through the arrival and merging of gas-rich satellites and through gas infall from the intergalactic medium. The new gas could be added to the halo or be deposited in the outer parts of galaxies and form reservoirs for replenishing the inner parts and feeding star formation. The infall may have observable effects on the disk such as bursts of star formation and lopsidedness. A mean "visible" accretion rate of cold gas in galaxies of at least 0.2 $M_\odot\ yr^{-1}$ can be inferred. In order to reach the accretion rates needed to sustain the observed star formation (~1 $M_\odot\ yr^{-1}$), additional infall of large amounts of gas seems to be required.

3.1.2.14. **Stellar populations in galaxies**

Peletier, in collaboration with Sánchez-Blázquez (Lancashire) and others, published the first paper of the MILES-library, a new stellar library for stellar population synthesis modeling. The library consists of 985 stars spanning a large range in atmospheric parameters. The spectra were obtained at the INT and cover 3525–7500 Å at 2.3 Å (full width at half-maximum) spectral resolution. The spectral resolution, spectral-type coverage, flux-calibration accuracy and number of stars represent a substantial improvement over previous libraries used in population-synthesis models. A second paper contains a homogeneous set of stellar parameters T_{eff}, log g and [Fe/H]. This study also contains a number of cluster stars, the parameters of which were revised and updated according to recent metallicity scales, color-temperature relations, and an improved set of isochrones.

Trager studied the stellar populations of early-type galaxies in the Coma cluster in collaboration with Faber (Santa Cruz) and Dressler (Carnegie). Strong evidence was found for galaxies that are "too young" in the cluster, suggesting very recent star formation. Serra and Trager have examined in detail the impact of composite (multiple) stellar populations in the spectra of galaxies on their interpretation. They also collaborated with van der Hulst, Oosterloo and Morganti, van Gorkom (Columbia), and Sadler (Sydney) to probe the stellar populations, ionized gas properties, and HI content and kinematics in elliptical and lenticular galaxies selected to be gas-rich to understand the formation of these galaxies. An analysis of a sample of roughly 20 gas-rich and 20 gas-poor galaxies with similar data has been completed to understand the formation and evolution of local spheroidal galaxies. The absence of HI gas in low-mass galaxies is often accompanied by age gradients, such that their centres are younger than their outer parts. This finding suggests that these galaxies have been rejuvenated by the accretion of gas, likely in a merger.

3.1.2.15. **Structure of early-type galaxies**

Peletier, together with Jesseit, Naab and Burkert (all Munich), did a 2-dimensional kinematic analysis of a sample of simulated binary disk merger remnants with mass ratios 1:1 and 3:1. A multitude of phenomena also observed in real galaxies was found in the simulations. These include misaligned rotation, embedded disks, gas rings, counter-rotating cores and kinematically misaligned disks. The effects of including gas in the merger are shown as well. It is found that kinematically peculiar subsystems are preferably formed in equal-mass mergers. The inclusion of gas makes the remnants appear more round (1:1) and axisymmetric (3:1). Counter-rotating cores are almost exclusively formed in equal-mass mergers with a dissipational component. The simulations were compared with real observations from SAURON using kinemetry, as developed by Krajnović et al.

Peletier, with Balcells (IAC) and Graham (Swinburne) studied in detail near-IR surface brightness profiles of a sample of nearby early-to intermediate-type galactic bulges, obtained with HST and ground-based telescopes. Central star clusters were found in 58% of the sample, with luminosities that scale with the bulge luminosity of the host galaxy. Together with the relation between central black hole and bulge luminosity this implies a relation between the luminosity of the nuclear cluster and the mass of the central object. Another 32% of the galaxies show evidence for resolved nuclear components such as nuclear disks. Global photometric properties of both bulges and disk correlate with bulge luminosity and central velocity dispersion, and not with, e.g., Hubble type. The lack of significant correlations between bulge parameters such as size, luminosity and density, with disk luminosity remains a serious challenge for secular evolution models of disk growth.

3.1.2.16. **Molecules in galaxy nuclei**

Israel and collaborators continued their systematic studies of the massive concentrations of dense molecular gas frequently found in the central regions of late-type galaxies. Before their evolution (black hole infall, jet expulsion, starburst consumption etc) can be studied, fundamental properties such as excitation and mass need to be determined. Such information is provided by extensive observing programs of molecular line emission from a range of species in various transitions, and their interpretation in terms of physical parameters. Together with Meijerink and Spaans, Israel constructed numerical models of the thermal and chemical balance of molecular gas exposed to X-rays (XDR) and far-UV

(PDR) radiation as a function of cloud depth (see also section 3.2). A grid of XDR and PDR models spanning a range in volume density, irradiation and column density has been run, and various line intensity ratios and combinations thereof have been identified as diagnostic tools to differentiate between (volume) excitation by X-rays and (surface) excitation by UV photons. Useful as such are the [SiII]/[CII] fine structure line ratio, and the HCN/HCO^+, HNC/HCN, and CN/HCN ratios, as well as the higher CO rotational line ratios observable with the future HIFI instrument on-board of the Herschel Space Observatory. Column density ratios indicate that CH, CH^+, NO, HOC^+ and HCO may also be good PDR/XDR discriminators.

In order to gauge the potential effect of cosmic rays on molecular gas excitation in active galaxy centers, Meijerink, Spaans and Israel also constructed PDR (UV-excitation) models with both 'normal' and highly elevated cosmic-ray intensities, and compare these to those obtained for XDRs. They obtain larger high J (J>10) CO ratios in PDRs in the presence of highly elevated cosmic ray emission, but these ratios are always exceeded by the corresponding XDR ratios. Neutral carbon to ^{13}CO line ratios are a reasonable tracer of enhanced cosmic ray fluxes in relatively low-density PDRs (~1000 cm^{-3}), whereas the HCN/CO and HCN/HCO^+ ratios, when combined with high J CO emission lines, continue to distinguish PDRs and XDRs under both low and high cosmic ray irradiation conditions.

3.1.2.17. Mid-infrared interferometry of AGN's

Jaffe finalized the large VLTI-MIDI observing program on NGC 1068 with the 8m VLTI UTs and showed that the warm dust disk is tilted with respect to the radio axis, an unexpected result. Shorter baseline AT observations are planned to map the cooler dust at larger radii, and see the transition from the "obscuring torus" to the wind driven Narrow Line regions.

The first interpretations of the Circinus galaxy and Cen A have been published by Meisenheimer and Tristriam (Heidelberg), in collaboration with Jaffe, Raban and Israel. Circinus seems quite similar to NGC 1068, whereas Cen A is clearly different, with the mid-infrared dominated by synchrotron emission rather than thermal dust. There appears to be a weak dust disk however. Further MIDI observations are planned to characterize the dust better, and a VISIR, VLBI, X-ray campaign is being planned to map the dust structures by infrared reverberation mapping.

3.1.2.18. Hot gas near black holes in active galactic nuclei

Costantini (Veni), together with Arav (Colorado), Kaastra and Verbunt, analyzed the X-ray data of the AGN Mkn 279 obtained with the low-energy transmission grating of Chandra, combined with HST-STIS and FUSE to study the hottest gas closest to the central object. The ultraviolet data were compared with a model for the broad line region in which the emission of the photoionized plasma was computed as a function of distance to the central source and of gas density. Costantini and co-workers showed that the best fit to the ultraviolet lines correctly describes the broad X-ray lines as well, and that the X-ray emission arises from down to 10 light-days from the central black hole, a factor of 10 closer to the black hole than the ultraviolet lines.

The analysis of the narrow X-ray absorption lines was based on the ionization parameter. A model with two discrete components, one with ionization parameter 100 times higher that the other, gives an acceptable fit, as does a model with a continuous distribution of the column density as a function of ionization parameter. The best fit ionization gives the combination $n\ r^2$, which can only be disentangled with extra information. A tentative detection of the O V* absorption feature near 22.5 Å (in the source rest frame) provides a density $>3 \times 10^{12}$ cm^{-3}, and hence a distance to the central source $<3 \times 10^{15}$ cm, i.e. the distance of the broad line region. The low column density and line widths of the absorption lines, compared to the high column density and widths of the broad emission lines, indicate that the absorption occurs in a relatively narrow sheet of gas outflow.

Costantini, Arav and Kaastra compared the HST-STIS and FUSE data with a detailed model in which the covering factor and column density were fitted as a function of velocity for lines with excellent signal to noise. The presence of hydrogen lines in the ultraviolet spectra (as opposed to their absence in X-ray spectra) allowed the determination of the abundances of carbon, nitrogen and oxygen with respect to hydrogen: they are found to be 2.2±0.7, 3.5±1.1 and 1.6±0.8 times the solar abundance. This is the first time that such reliable abundances could be obtained, and showed conclusively that the hot gas flowing from the active nucleus is highly processed, and thus that accretion onto the central black hole and evolution of the interstellar medium are strongly coupled.

3.1.2.19. Starbursts near super-massive black holes

Levin proposed a scenario in which massive stars form in a self-gravitating gaseous disk around a super-

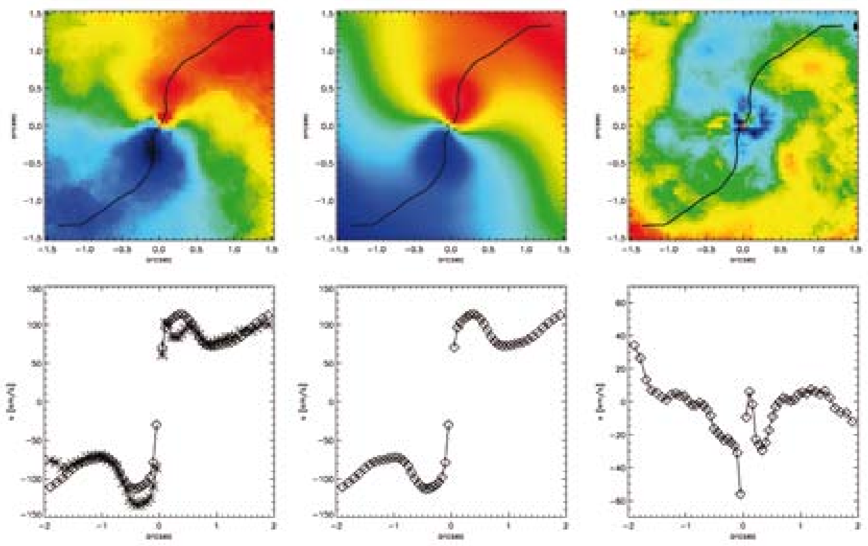

Figure 3.10: Velocity field of the 2.12 µm H_2 line in the nuclear region of Cen A obtained with SINFONI. The left panel shows the observed velocity field, the central panel a model with a black hole of 4.5x10^7 $M_\odot$ and the right panel shows the difference between these. The black line shows the line of modes of the warped disk, along which rotation curves have been extracted, which are shown in the bottom panels (diamonds: model; crosses: data). From: Neumayer et al., 2007, Astrophys. J. 671, 1329).

massive black hole. The main driver for this model is the observed young stellar disks near the SgrA* black hole in the Galactic Center, but the theory is more generally applicable. Angular momentum in the forming disk is transported by turbulence induced by the disk's self-gravity. Once the surface density of the disk exceeds a critical value, it fragments into dense clumps which accrete material from the remaining disk and merge into larger clumps; the upper mass of a merged clump is a few tens to a few hundreds of solar mass. While this scenario fits well the masses and spatial distribution of the young stars near SgrA*, it cannot explain the origin of several young stars closest to the black hole (the S-stars): their orbits are compact, eccentric, and have random orientation. It is proposed that the S-stars were born in a previous starburst(s), and then migrated through their parent disk via type-I or runaway migration. Their orbits were then randomized by the Rauch-Tremaine resonant relaxation.

Levin also explored the consequences of the star formation scenario for AGN disks, which are continuously resupplied with gas. Some compact remnants (stellar-mass black holes) generated by the starburst will get embedded in the massive disk, will interact gravitationally with it and be dragged towards the central black hole. Mergers of a disk-born black hole with the central black hole will produce a burst of gravitational waves, which should be observable by the Laser Interferometer Space Antenna (LISA).

3.1.2.20. **Nearby starburst galaxies**

Van der Werf, Snijders (PhD) and Vermaas (NOVA PhD) studied a number of nearby starburst galaxies with the ESO/VLT using SINFONI (in NOVA GT) and VISIR. A highlight is the development of a "ground-based-only" set of mid-infrared diagnostics, in collaboration with Kewley (Hawaii). This restricted set of lines ([NeII], [ArIII], [SIII] and [SIV]) has the advantage of vastly superior resolution on the ground (~0.3" diffraction limit) compared with space (~3" Spitzer). VISIR observations of super star clusters in the Antennae (NGC4038/4039) demonstrated significant spectral differences with Spitzer data, leading to quantitatively different results, underlining the need for high angular resolution. The most important results are the diffuse nature of the PAH emission, which is therefore not directly related to the most recent (i.e., current) star formation, and the high densities and ionization parameters derived for the superstar-clusters, made possible by the VISIR data.

Van der Werf, Reunanen (NOVA postdoc) and De Zeeuw completed their analysis of SINFONI data of the circumnuclear region of the nearby radio galaxy Cen A in a project led by Neumayer (Heidelberg). With adaptive optics, the resolution was 0.12", so that the region of influence of the black hole could easily be resolved. The key results are that atomic lines of higher excitation are more and more affected by non-gravitational motions, thus compromising earlier estimates of the black hole mass. In contrast, the H_2 emission displays pure rotation in a warped but otherwise regular disk (Fig. 3.10). The black hole mass is determined to be 4.5×10^7 $M_\odot$, which brings Cen A in full agreement with the relation between black hole mass and velocity dispersion for galaxies. The warped molecular disk displays a number of ridges and peaks which can be interpreted as shocks or spiral arms, but which have no corresponding features in the velocity field. The disk must play a central role in feeding the nuclear black hole.

In collaboration with Papadopoulos (ETH) and Isaak (Cardiff), van der Werf completed his study of the warm and dense molecular gas in Mrk231. The first detections of CO (4-3) and (6-5) of a ULIRG were obtained, resulting in a fascinating new picture of the star-forming ISM in this object. While in lower luminosity objects such as the Milky Way, cooling is totally dominated by the 158 μm [C II] line, in Mrk231 the total cooling by CO emission (integrated over the rotational ladder) is comparable to that by [C II]. This effect becomes clear only when CO (4-3) and higher lines are observed, since the warm dense gas component producing the CO cooling totally dominates the high-J lines, while the lower-J lines are produced by a more diffuse gas component. Physically, these results point toward dense PDRs where the ionized carbon layer is thin and the warm dense gas dominates the mass budget. Given that mid-J CO lines and [CII] lines will be fundamental probes of high-z galaxies with ALMA, these results have important consequences for the interpretation of future ALMA measurements of high-z galaxies.

Beirao (PhD) and Brandl analyzed Spitzer-IRS spectra of the nearby, low-metallicity starburst galaxy NGC 5253, in particular the properties of the interstellar radiation field with distance from the ionizing super star cluster out to 250 parsec. Over that distance, the radiation hardness drops by a factor four while the relative strength of the PAH feature increases with distance, demonstrating the counterbalance between radiation field and the presence of molecules in the ISM. These results also demonstrate the importance of spatially resolved mid-IR spectroscopy.

Groves (postdoc), together with the IR group at MPE, examined the shape of the silicate emission feature and the possible contribution from the narrow line region to AGN and starburst galaxy spectra. A series of model templates for starbursting galaxies were created with Dopita (ANU), which can be used to determine fundamental physical parameters of these galaxies, such as star formation rate and ISM pressure.

3.1.2.21. Nearby clusters of galaxies

Katgert and Thomas (Enschede) used a large subset of the galaxies in clusters from the ESO Nearby Abell Cluster Survey to study the relation between the morphological classification (according to the standard procedures of expert visual classifiers) and the results of a bulge-disk decomposition (using GIM2D) based on CCD-imaging data obtained for the same galaxies. The expected correlation between morphological type and bulge fraction is recovered, but the distributions of bulge fraction for the different types show considerable overlap. For example, a sizable fraction of ellipticals shows an exponential disk component, while the early spirals can have sizeable bulges. A comparison has been made of the properties of the disks of spirals in and outside of clusters, and a discussion of the exponential components in elliptical galaxies is given.

Katgert and Biviano (Trieste) have studied the evidence for kinematical and dynamical substructure in the clusters in the ESO Nearby Abell Cluster Survey. A new method was devised to quantify the probability that a given galaxy finds itself in a cold and/or moving group within its cluster. The results of this analysis are very promising and the identification of substructures appears quite convincing.

3.1.2.22. Abundances in low-metallicity dwarf galaxies

Brandl, together with collaborators at Cornell, continued the work on blue compact dwarf (BCD) galaxies. Deep Spitzer observations of I Zw 18, which has the second lowest metallicity measured in a star-forming object, yielded no emission from PAHs. However, in contrast to other very low-metallicity galaxies, the 15 - 70 μm continuum emission of I Zw 18 has a much steeper slope, more characteristic of a typical starburst galaxy of solar abundance. They also extended the study to include 13 of the most metal-deficient BCDs known, and found that the mid-IR abundance measurements of neon and sulfur are consistent with the oxygen abundance derived from optical lines. The main result is that either the metallicities of dust-enshrouded regions in BCDs are similar to the optically accessible regions, or that – if they are different – they do not contribute substantially to the total infrared emission of the host galaxy.

3.1.3. The high redshift Universe

3.1.3.1. HI in distant galaxy clusters

Verheijen, together with Deshev, van Gorkom (Columbia), Szomura and others continued his WSRT large program to image the cold HI in and around two galaxy clusters at z~0.2 (Fig. 3.11). Abell 963 is a massive Butcher-Oemler cluster at z=0.206 with a large blue fraction of 19% while Abell 2192 at

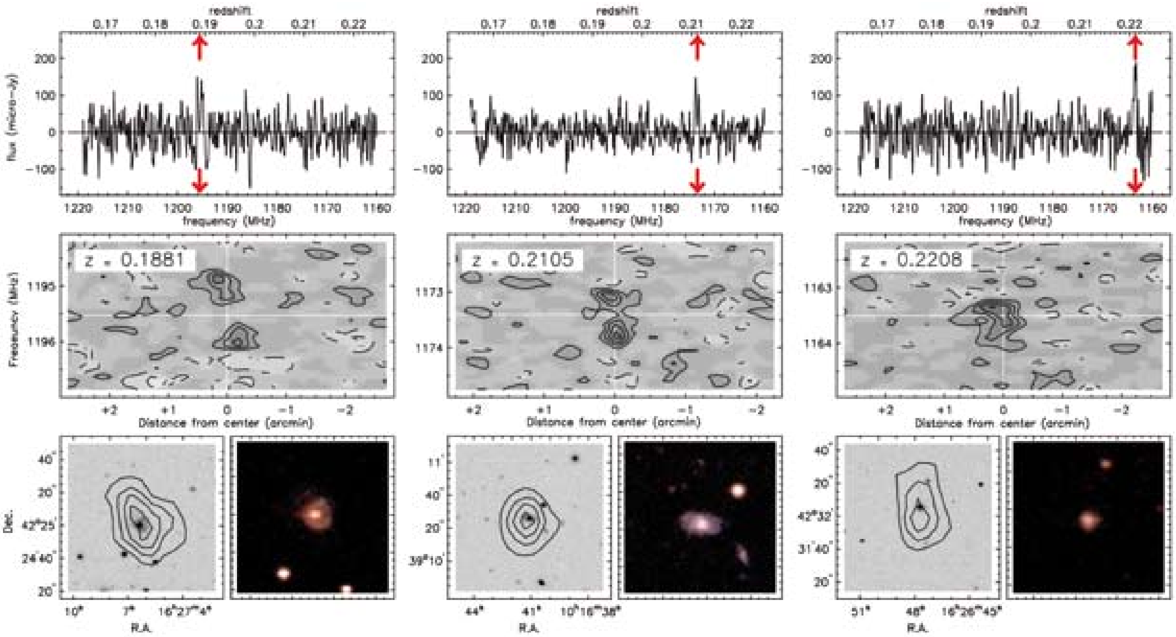

Figure 3.11: Examples of HI detections at z=0.2. Upper panels: HI spectrum over the full velocity range. Arrows indicate the redshift (top) and observed frequency (bottom) of the detected HI emission. Middle panels: position-velocity diagram extracted from the HI data cube, taken along the kinematic major axes of the galaxy. The horizontal white line indicates the systemic velocity. The vertical white line coincides with the spatial center of the galaxy. Bottom left panels: integrated H I map in contours overlayed on an R-band image in grey scales. Bottom right panels: blow-up of the optical images. (from: Verheijen et al. 2007, Astrophys. J, 668, 9).

z=0.188 is a more diffuse and less massive cluster. The large field-of-view of the WSRT and the broad bandwidth of the new back-end allow a study of the clusters proper as well as the large scale structure in which they are embedded, with a total surveyed volume of 7×10^4 Mpc^{-3}. Pilot observations have re vealed 39 detections of HI emission, 19 in A 963 and 20 in A 2192. The HI detected galaxies in A 963 are mainly located to the NE of the cluster core, with the bulk of the HI rich galaxies at slightly larger redshifts. None of the individual blue galaxies in the core of A 963 has been detected in HI. Stacking the HI spectra also yields a statistical non-detection while galaxies of similar luminosity and color in the surrounding field have been detected. This leads to the preliminary conclusion that the blue galaxies in the core of A 963, responsible for the Butcher-Oemler effect, are relatively gas-poor compared to similar galaxies in the field. Further data will allow a detailed study of the amount of cold gas of galaxies in relation to their global and local environments and the evolutionary state of their stellar populations.

3.1.3.2. Faint submillimeter galaxies

A key result by Knudsen (PhD, now at MPIA) and van der Werf was the discovery of a triply-lensed submillimeter galaxy at z=2.516, behind the cluster A 2218. This galaxy is lensed by a factor of about 45, and would be too faint to detect without lensing. With its low intrinsic flux, its properties are of interest since it is characteristic of the galaxies that make up the bulk of the submillimeter background. Follow-up radio observations with the WSRT and the VLA in collaboration with Garrett detect all three images, with an implied star formation rate of about 500 $M_\odot$ yr^{-1} and no evolution in the infrared-radio relation out to z=2.5. The object was also observed in the CO(3–2) and CO(7–6) lines with the IRAM PdBI in collaboration with Kneib (Marseille). The velocity profile of the CO(3–2) line displays a double-peak profile which is well fit by two Gaussians with FWHM of 220 km/s and separated by 280 km/s. The implied dynamical mass is ~ 1.5×10^{10} $M_\odot$ and an H_2 gas mass of 4.5×10^9 $M_\odot$. This system is much less luminous and massive than other high-redshift submillimeter galaxies studied to date, but it bears a close similarity to similarly luminous, dusty starburst galaxies resulting from lower-mass mergers in the local Universe.

3.1.3.3. Distant radio galaxies

Distant luminous radio galaxies are among the brightest known galaxies in the early Universe and the likely progenitors of dominant cluster galaxies. Miley, Röttgering, Overzier (PhD), Intema (NOVA PhD) and collaborators used these objects as probes of the early Universe. Following a VLT Large Program on the environment of distant radio galaxies, Overzier provided a detailed study of the protocluster environments of several z > 2 radio galaxies with HST-ACS, including objects at redshifts z = 4.1 and z = 5.2. The overdensities are consistent with the presence of protoclusters around all the radio galaxies studied. The results are related to general scenarios for the formation and evolution of galaxy clusters.

A second highlight was a spectacular deep image of the dominant galaxy in a protocluster at z ~ 2.2 taken with HST-ACS. This showed more than 10 clumpy features, apparently star-forming satellite galaxies in the process of merging with the progenitor of a dominant cluster galaxy, 11 Gyr ago (Fig. 3.12). The new image is the best demonstration so far that massive galaxies assemble by merging of smaller objects in a hierarchical process. A striking feature of the newly named "Spiderweb Galaxy" is the presence of several faint linear galaxies within the merging structure. The dense environments and fast galaxy motions at the centers of protoclusters may stimulate the formation of these structures, which dominate the faint resolved galaxy populations in the Hubble Ultra Deep Field. The new image provides a unique testbed for simulations of forming dominant cluster galaxies.

Intema and collaborators presented broad-band imaging with the Subaru Telescope of a 25' × 25' field surrounding the radio galaxy TN J1338-1942 at redshift z = 4.1. The field contains excesses of Lyman-α emitters and Lyman break galaxies (LBGs) identified with a protocluster surrounding the radio galaxy. There are 874 candidate LBGs within this field, having redshifts in the range z = 3.5-4.5. An examination of the brightest of these (with i' < 25.0) shows that the most prominent concentration coincides with the previously discovered protocluster.

Venemans (now at Cambridge), Röttgering, Miley and collaborators presented the results of a large program conducted with the VLT and Keck to search for forming clusters of galaxies near powerful radio galaxies at 2.0 < z < 5.2. Narrow band imaging was used to select candidate Lyα emitting galaxies in 3×3 Mpc^2 areas near the radio galaxies. A total of 300 candidate emitters were found and follow-up spectroscopy was performed on 152 candidates in seven of the radio galaxy fields. Of these, 139 were confirmed to be Lyα emitters, four were low redshift interlopers and nine were non-detections. At least six of the eight fields are overdense in Lyα emitters by a factor of 3-5 as compared to the field density of Lyα emitters at similar redshifts, although the statistics in the highest redshift field (z = 5.2) are poor. The protoclusters have sizes of at least 1.75 Mpc, and have masses in the range $2\text{-}9\times10^{14}\,M_\odot$. The velocity dispersion of the emitters increases with cosmic time, in agreement with the dark matter velocity dispersion in numerical simulations of forming massive clusters.

Reuland (PhD), Röttgering and Miley performed optical and near-IR spectroscopy of giant nebular emission-line halos associated with three z>3 radio galaxies, 4C 41.17, 4C 60.07, and B2 0902+34. The outer regions of these halos show quiescent kinematics with typical velocity dispersions of a few hundred km/s and velocity shears that can mostly be interpreted as being due to rotation. The inner regions show shocked cocoons of gas closely associated with the radio lobes. The dynamical structures traced in the Lyα line are, in most cases, closely echoed in the carbon and oxygen lines. This shows that the Lyα line is produced in a highly clumped medium of small filling factor and can therefore be used as a tracer of the dynamics of high-redshift radio galaxies. It is concluded that these galaxies are undergoing a final jet-induced phase of star formation with ejection of most of their interstellar medium before becoming 'red and dead' elliptical galaxies.

Snellen, together with de Vries (PhD) and Schilizzi, studied very young radio galaxies which shed new light on why certain galaxies become active and how the central activity influences the surrounding galaxy. Together with Rigby and Best (both Edinburgh) the high redshift space density and cosmological evolution has been measured of Fanaroff and Riley Class I radio galaxies, indicating modest density enhancements at redshifts of >1.0.

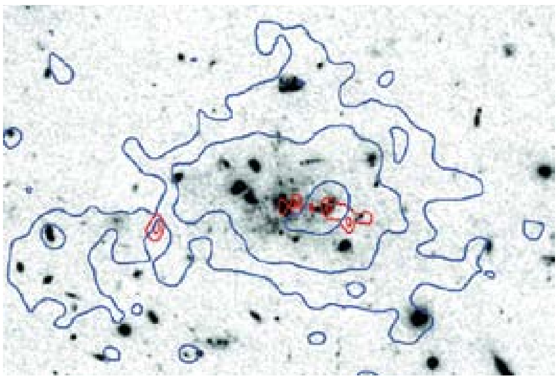

Figure 3.12: The Spiderweb Galaxy - a forming massive galaxy at the centre of a protocluster at z = 2.2. This ultra-deep image made with 19 orbits using HST-ACS demonstrates the importance of hierarchical merging processes in the formation and evolution of massive galaxies. The black clumps are satellite galaxies that are merging with the massive host galaxy – "flies" being captured by the spiderweb. Contours of radio emission are shown in red and Lyα emission in blue. The Lyα ionized gas halo extends over a size of ~ 200 kpc and is one of the largest known objects in the Universe. The image shows a 33" x 23" region rotated 10° from north (from: Miley et al. 2006, Astrophys. J. 650, L29).

Binette (Mexico), Röttgering and others presented photoionization calculations for the spatially-extended absorbers observed in front of the extended emission-line spectrum of two high-redshift radio galaxies, 0943-242 (z=2.922) and 0200+015 (z=2.230), with the aim of reproducing the absorber column ratio, N_{CIV}/N_{HI}. They found that hot stars from a powerful starburst, or a metagalactic background radiation in which stars dominate quasars, are equally successful in reproducing the observed N_{CIV}/N_{HI} ratio, assuming subsolar gas metallicities for each absorber.

Dannerbaumer (Heidelberg), Daddi (Tucson), Röttgering and others carried out MAMBO 1.2 mm observations of five vigorous starburst galaxies at z~2 and detected two. They advocate a scenario in which z~2 galaxies, after their rapid (sub)millimeter-bright phase that is opaque to optical/UV light, evolve into a longer lasting phase of K-band-bright and massive objects.

Tasse (PhD), Röttgering and others carried out low frequency radio surveys of the XMM-Large Scale Structure 10 square degree field using the VLA at 74 and 325 MHz, and the GMRT at 230 and 610 MHz. Photometric redshifts, stellar masses, and specific star formation rates were determined for $\sim 3 \times 10^6$ galaxies with CFHT, using the ZPEG photometric redshift code. The combined data set allowed constraints on the small (~ 75 kpc) and large (~ 450 kpc) scale environments of radio sources independently from their stellar mass estimates. Subsequent analysis showed that there are two distinct types of radio sources, whose radio source activity seems to be triggered by two different mechanisms. The first population, which dominates at high stellar masses ($M > 10^{10.5}$–$10^{10.8}$ $M_\odot$) is that of massive elliptical galaxies, lying in galaxy groups or clusters, where the radio source is triggered by the cooling of the hot gas in their atmosphere. At these stellar masses, the fraction of galaxies that host radio-loud sources is essentially the same as that in the local Universe. The second population of radio sources has lower stellar masses, lie in large scale underdensities, and show excess mid-IR emission consistent with a hidden active nucleus. The radio-loud fraction at these masses is increased relative to the local Universe. The observed environmental dichotomy suggests that the activity in low stellar mass systems is driven by galaxy interactions or mergers while for the massive galaxies the activity is driven by hot gas cooling from an X-ray emitting atmosphere.

3.1.3.4. Galaxy evolution at high redshift

Franx and collaborators continued their comprehensive program on the evolution of galaxies from z=7 to z=0, based on a variety of search techniques, but focusing mostly on the properties of massive galaxies at z=1.5-4 selected by near-IR imaging. This technique enables the construction of mass selected samples in this redshift range, thereby providing a good census of the mass distribution of galaxies. Together with van Dokkum (Yale), the properties of a mass selected sample at z=2-3 based on the MUSYC and FIRES surveys were studied. Intrinsically red galaxies, previously dubbed 'DRGs' for Distant Red Galaxies, are found to dominate the mass in galaxies at the massive end. Galaxies found as Lyman Break galaxies are abundant, but contribute less. Massive galaxies at z=2-3 have a wide range in properties. Kriek (PhD), van Dokkum, Franx, and collaborators presented spectroscopic data of massive galaxies at z ~ 2.3, showing that a considerable fraction (45 %) has no emission lines and hence no evidence for (strong) star formation. The sample is considered to be typical for high redshift, massive galaxies, and the results indicate that the star formation rate is very low for a considerable fraction of massive galaxies. The mechanism responsible for the down turn in star formation still needs to be identified. These quiescent galaxies are only part of the population, however: Webb (postdoc), Franx, and collaborators studied the 24 μm fluxes of massive galaxies at z=2-3, as measured by Spitzer. Many of the DRGs identified in the field have strong fluxes, indicating high star formation rates and contributing significantly to the overall star formation rate at redshifts z=2-3.

Bouwens, Illingworth (both Santa Cruz), Franx, and Blakeslee (Washington) analyzed the luminosity function of z=6 i-dropout galaxies in the fields with the deepest available HST-ACS imaging. 506 candidates were found, and the corresponding luminosity function showed significant evolution at the bright end, between z=3 and z=6, indicating that the star formation rate density increases significantly between z=6 and z=3.

Labbé (Carnegie), Franx, and collaborators studied the mid-IR emission of z=7 galaxies, identified as z-dropout galaxies in the UDF. Two of the four candidates were unambiguously detected with Spitzer, and hence their reality was confirmed. Masses and ages were derived for these two galaxies.

Franx, van der Wel, Wuyts (both PhD), and collaborators compared dynamical masses of early-type galaxies out to z=1, with those obtained by fitting stellar population models to photometry. Stellar population models are found to work well when fitted to the rest-frame optical photometry, but not when fitted to rest-frame near-IR photometry. This probably results from uncertainties in the modeling of the late stages of stellar evolution. In collaboration with Quadri (postdoc), van Dokkum and colleagues, the correlation function of massive red galaxies at z=2-3 was determined. The galaxies are very strongly correlated, a result which is very difficult to model in current theories. Further confirmation using different fields is required.

Toft, Zirm (postdoc), Franx and collaborators studied the sizes and star formation rates of galaxies at redshifts around 2.5. Deep HST imaging in the H-band was used to determine sizes, and Spitzer to measure star formation rates. In both fields studied (Hubble Deep Field South and the field of MS1054-03) there was a good correlation between size and specific star formation rate: galaxies with low specific star formation rate had small sizes, galaxies with high specific star formation rate had large sizes for their mass. This shows the strong variety of galaxies at high redshift, analogous to the variety seen in the local universe.

In collaboration with Holden (Santa Cruz) and others, Franx studied the evolution of the morphologies in clusters. The galaxies were selected by stellar mass, estimated from the rest frame luminosities and colors. This newly defined sample shows no evolution of the morphological mix of galaxies in clusters as a function of redshift. This is very different from luminosity selected samples which do show a strong evolution. The evolution in the latter samples is caused by luminosity evolution of very low mass galaxies. Van der Wel, Franx, and colleagues also studied the evolution of morphologies of massive galaxies in the field. Similar to the result described above, no evolution in the morphologies is found between z=1 and 0, if the galaxies are selected by stellar mass. Apparently, galaxies evolve along the morphology-density relation, which remains rather constant with redshift.

3.1.3.5. Detecting cosmic strings?

Together with Vachaspati (Case Western) and Siemens (Caltech), Kuijken studied the effect and observability of a cosmic string when it passes in front of a distant quasar. Cosmic strings induce double images of distant sources, and boost the total detected flux even when the individual images are too close to be resolved. For sufficiently compact sources the flux increases a factor of two. A signature of such 'microlensing' by cosmic strings is therefore a temporary doubling of the brightness of a source (Fig. 3.13). In practice, this phenomenon will be very difficult to detect, in view of (i) limits on the number and mass density of cosmic strings from the CMB fluctuation spectrum (ii) the finite size of bright quasar cores, and (iii) the attention span of even the most tenacious astronomer.

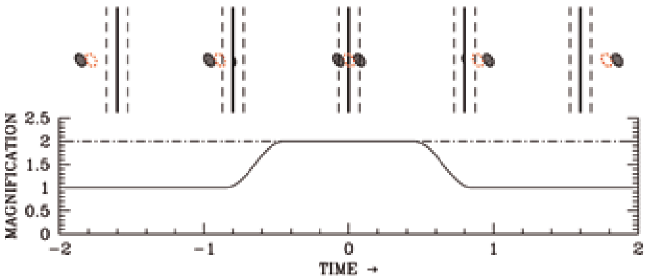

Figure 3.13: Microlensing by a cosmic string that passes in front of a distant, compact source. The dotted outline shows the source as it would appear without the string; the shaded images show what would be observed on the sky. The plotted light curve shows how the total flux detected from the source temporarily doubles as the string passes between us and the source (from: Kuijken et al. 2008, MNRAS 384, 161).

3.1.3.6. Theory of galaxy formation

Dalla Vecchia (postdoc), Duffy, Haas (PhD), Schaye, van de Voort (master student) and Wiersma (PhD), working with Springel (MPA), Theuns (Durham) and others, used the LOFAR correlator, an IBM Bluegene/L computer, to run large-scale cosmological hydrodynamical simulations. The simulations were run with the code Gadget III, augmented with new modules for star formation, galactic winds, chemodynamics, and cooling. Software for the analysis of the simulations was written, including programs to do population synthesis and visualization as well as codes for the creation of halo catalogues and absorption spectra. The simulations will be used to study the formation of galaxies and the evolution of the intergalactic medium.

Pawlik (PhD) and Schaye have worked on the development of a module for the transfer of ionizing radiation in the Smoothed Particle Hydrodynamics code Gadget. The method takes advantage of Gadget's parallelization scheme and runs on distributed memory systems. It is spatially adaptive and well-suited for problems with a large number of sources. Rakic (master student), Schaye, Steidel (Caltech), and Aguirre (Santa Cruz) searched for correlations between the distance to Lyman-break galaxies and absorption by the intergalactic medium in the spectra of background quasars. Using pixel optical depth techniques the absorption by HI, CIV, and OVI was found to be significantly enhanced within a few co-moving Mpc of the galaxies.

Schaye, Carswell (Cambridge) and Kim (Potsdam) carried out a survey for high-metallicity CIV absorbers at $z \approx 2.3$ in 9 high-quality quasar spectra. Using a novel analysis technique, based on detections of CIV lines and automatically determined upper limits on the column densities of HI, CIII, NV, and OVI, they found a large ($dN/dz > 7$) population of photo-ionized, compact ($R \sim 10^2$ pc), metal-rich ($Z \gtrsim Z_\odot$) CIV clouds with moderate densities ($n_H \sim 10^{-3.5}$ cm^{-3}), with properties that are robust with respect to uncertainties in the ionization model. In particular, local sources of ionizing radiation, overabundance of oxygen, departures from ionization equilibrium, and collisional ionization all imply more compact clouds. The clouds are too small to be self-gravitating and pressure confinement is only consistent under special conditions. These clouds are likely to be short-lived, implying that the clouds could easily have been responsible for the transport of all metals that end up in the intergalactic medium (IGM). When metal-rich clouds reach pressure equilibrium with the general, photo-ionized IGM, the heavy elements will still be concentrated in small high-metallicity patches, but they will look like ordinary, low-metallicity absorbers. It is concluded that intergalactic metals are poorly mixed on small scales and that nearly all of the IGM, and thus the Universe, may therefore be of primordial composition.

Schaye developed an analytic model for high column density quasar absorption line systems. Assuming that they arise in the halos of galaxies, the model can be used to predict the distribution of impact parameters, luminosities and flux from the central sources. Local radiation, which is usually ignored, likely dominates over the ionizing background radiation for systems rarer than Lyman limit systems. For damped Lyman-alpha systems, the local radiation field has actually been measured and is in excellent agreement with the model. The consistency between observations of the UV background, the UV luminosity density from galaxies, and the number density of Lyman limit systems requires escape fractions of order 10 percent.

Spaans and Silk (Oxford) have investigated the formation of black holes in the early universe. Massive, more than a million solar mass, black holes are found in most galaxy centers (also the Milky Way). This is interesting in its own right, but it has also been established observationally that the masses of these black holes are roughly 1/1000th of the stellar bulge mass. This constant fraction hints at a deep relationship between the formation of black holes and stars in primordial galaxies. It is found that in halos of more than $10^7\ M_\odot$ at redshifts of 10-20, resonant scattering of HI and HeII Lyman-α photons is so dominant that a line photon cannot escape the halo within a free-fall time. These photons normally cool the gas down to 10^4 K. If cooling radiation is trapped, the halo becomes adiabatic and the temperature rises fast enough to keep the Jeans mass constant. The halo then suffers a singular collapse into a central object without fragmentation. The fraction, by mass, of the halo that experiences this adiabatic condition is about 0.001, suggestively close to the observed black hole/stellar bulge ratio. As a consequence, pre-galactic black holes are formed with typical masses of 10^4-$10^6\ M_\odot$. These can act as seeds for the current population of super massive black holes.

3.1.3.7. Gravitational lensing

Koopmans and collaborators studied the structure, formation and evolution of massive early-type galaxies out to z=1, using gravitational lensing and stellar dynamics. With data from the largest galaxy-scale lens survey to date, the Sloan Lens ACS Survey (SLACS), and several powerful analysis codes, they have been able to measure the mass-density profiles of these galaxies between 0.1 and 100 effective radii. More recently, IFU stellar kinematics obtained with VLT-VIMOS combined with HST-ACS imaging allow dissecting the internal phase-space structure of a comparatively distant early type galaxy. Based on a large sample of new lens systems it is shown that the tilt in the fundamental plane is almost certainly due to an increasing dark-matter fraction in the inner regions of more massive galaxies. More recent work includes the use of lensing to assess the level of mass-substructure in galaxies, for which a new grid-based adaptive modelling code has been developed.

Barnabè (PhD) and Koopmans designed a very general method to carry out the joint and fully self-consistent analysis of gravitational lensing and stellar kinematics with the purpose of studying the mass distribution of E/s0 galaxies up to a redshift $z \sim 1$. Within this unifying framework a gravitational potential which is a function of some non-linear parameters is assumed and consistently used for both the lensed image reconstruction and the dynamical modeling. The most plausible values for the non-linear parameters of the potential are found by means of a series of iterative optimization loops based on the maximization of the Bayesian evidence. Barnabè has developed a fast implementation of this methodology which applies specifically to two-integral axisymmetric systems; it is possible to recover the non-linear parameters of a reference model within a few percent even when starting from a very implausible initial guess. Moreover, it was demonstrated that, when the constraints given by the stellar dynamics are considered, the joint analysis can break the degeneracies between different lens models.

Together with Berciano-Alba (PhD), Garrett and Wucknitz, Koopmans has continued working on cluster lensing of sub-mm sources and has more recently started on the pipe-line development for the analysis of a large multi-frequency VLA monitoring data-set on a CLASS lens system.

Weak gravitational lensing can be used to study the mass distribution around galaxies, as well as on larger scales. With this in mind the 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 with OmegaCAM on the VST at Paranal. Unfortunately the telescope construction has been long delayed, with start of operations in early 2009. Preparations for KiDS continued in algorithm development for multi-color photometry and for weak lensing measurement. The KiDS project, now including Schrabback (postdoc), Hildebrandt (postdoc), van Uitert (PhD) and Welander, benefits from participation in a European training network, 'DUEL', built around the scientific challenges in determining the cosmological model with weak lensing measurements.

Van de Ven (former NOVA PhD, now at Princeton), together with Falcón-Barroso, McDermid, de Zeeuw and Cappellari (Oxford), used Gemini data to study the famous Einstein Cross gravitational lens system. Using a combination of lensing and stellar dynamics, it was shown that dark matter does not dominate the central regions of galaxies, but seems to be distributed in a similar way to the luminous component, at least on kilo parsec scales.

3.1.3.8. The Epoch of Reionization of the Universe

The Epoch of Reionization (EoR) is a term used to describe the period during which the gas in the Universe went from being almost completely neutral to a state in which it became almost completely ionized. This watershed event – which occurred when the Universe was a few hundred million years old (about a twentieth of its current age) and the first radiating objects formed – is intimately linked to many fundamental questions in cosmology and structure formation and evolution. LOFAR has the EoR as one of its key projects, by measuring the neutral gas fraction in the Universe as a function of redshift and angular position through the HI 21 cm line. Zaroubi, together with de Bruyn and Koopmans, is developing the necessary data-analysis and theoretical tools to, initially, prepare the ground and, subsequently, fully exploit the LOFAR-EoR data set.

Thomas (PhD) and Zaroubi developed a spherically symmetric radiative transfer code to track the evolution of the ionization and heating structures around individual objects in the early Universe, especially first stars and mini quasars. The code follows HI, HII, HeI, HeII, HeIII, and free electrons and is suited to deal with a general source radiation spectrum (e.g., thermal or power-law). The results will be implemented in large scale simulation in order to predict the reionization history of the Universe, which in turn will be used in order to simulate LOFAR EoR data cubes.

Valdés and Ferrara (both Trieste), Ciardi (Munich), Johnston-Hollitt (Hobart) and Röttgering used independent numerical simulations of cosmic reionization and radiative processes related to the HI emission line to produce synthetic radio maps for LOFAR and other upcoming facilities. Two different scenarios, in which the end of reionization occurs early ($z\sim13$) or late ($z\sim 8$) depending on the initial mass function (IMF) of the first stars and ionizing photon escape fraction, have been explored. HI maps are produced by convolving the simulation outputs with the provisional LOFAR sampling function in the frequency range 76-140 MHz. If reionization occurs late, LOFAR will be able to detect individual HI structures on arcmin scales, emitting at a brightness temperature of ~35 mK as a 3σ signal in about 1000 hours of observing time.

Zaroubi, with Tashiro, Aghanim, Langer and Douspis (Paris), cross-correlated the CMB polarization and the HI line fluctuations from cosmic reionization. Since the E-mode polarization reflects the amplitude of the quadrupole component of the CMB temperature fluctuations, the angular power spectrum of the cross-correlation exhibits oscillations at all multipoles. The first peak of the power spectrum appears at the scale corresponding to the quadrupole at the redshift that is probed by the HI line fluctuations. The peak reaches its maximum value at the redshift when the average ionization fraction of the universe is about half. On the other hand, on small scales, there is a damping that depends on the duration of reionization. Thus, the cross-correlation between the CMB polarization and the HI line fluctuations has the potential to constrain accurately the epoch and the duration of reionization.

Ripamonti, Mapelli (Zurich), and Zaroubi studied the effects of radiation from early black holes on the neutral IGM. In the pre-reionization Universe,the regions of the IGM which are far from luminous sources are the last to undergo reionization. Until then, they should be scarcely affected by stellar radiation; instead, the X-ray emission from an early black hole population can have much larger influence. The effects of such emission have been investigated for a number of black hole model populations (differing for the cosmological density evolution of black holes, the black hole properties, and the spectral energy distribution of the black hole emission). Black hole radiation can easily heat the IGM up to 10^3-10^4 K, while achieving partial ionization. The most interesting consequence is that black holes are expected to induce a HI signal (with differential brightness temperature 20-30 mK at $z < 12$) which should be observable with forthcoming experiments (e.g. LOFAR). They also find that at $z < 10$ black hole emission strongly increases the critical mass separating star-forming and non-star-forming halos.

3.1.3.9. Large scale structure

Van de Weygaert and Schaap (PhD) developed and implemented the Delaunay Tessellation Field Estimator (DTFE), a natural parameter-free method for translating discrete particle or galaxy distributions into continuous density fields which retain the topological characteristics of the matter distribution. Three publications specifying the details of the method and including tests on their ability to measure anisotropy, substructure and voids have been written. An additional study analyzes the (non-Gaussian) noise and error properties of the technique. Finally, it has been applied to the 2dF galaxy redshift survey for testing its ability to trace the cosmic web in realistic observational circumstances.

The first stage of the project dealing with the identification of voids concerned a study of the evolution of the void population in large N-body simulations of cosmic structure formation. Platen (PhD) developed an algorithm to identify voids within the mass distribution along the lines of the watershed algorithm. The underlying density distribution is the one inferred on the basis of the DTFE method of Schaap & van de Weygaert. It was found that the population of small collapsing voids should mainly be identified with that of anisotropically sheared voids near the transition regions between voids and the surrounding medium-density filaments and walls. Even though the absolute sizes differ, the inferred void size distribution resembles the peaked void size distribution implied by the work of Sheth and van de Weygaert. The distribution indeed includes a small void cutoff.

Aragón, in collaboration with van de Weygaert, Jones and van der Hulst, developed a cosmic web/ filament detection and identification algorithm based on the Scale Space formalism applied to the identification of elongated or blob like features in medical images. The first implementation is based on the use of Gaussian filters and the DTFE density field of the underlying N-body (or galaxy) distribution. The MMF has been tested on a range of Voronoi clustering models in order to allow the calibration of its final step, the thresholding step meant to select significant features amongst those resulting from the noisy particle/ galaxy sample. An application of the method was a study of spin and shape alignments of dark halos with filaments and walls in the cosmic web. The shape orientation is such that the halo minor axes tend to lie perpendicular to the host structure, be it a wall or a filament. The orientation of the halo spin vector is mass dependent. Low mass halos in walls and filaments have their spins aligned with the parent structure, while higher mass halos in filaments have spins that tend to lie perpendicular to the parent structure. In addition they studied galaxy alignments in the Cosmic Web traced by SDSS. A marginal alignment effect of galaxy shape with embedding filaments has been detected for galaxies with a blue magnitude MB ≈ -20.

Araya (PhD), van de Weygaert and Reisenegger studied future supercluster evolution in λ-CDM model of structure formation, in particular the halo mass function, as well as the density profile and shape evolution and the development of supercluster multiplicity from a=1 to a=100. While the supercluster mass function quickly reaches its final form, the internal nonlinear evolution of superclusters continues for many expansion factors. This results in a continuous change of shape, density profile and multiplicity.

Araya and Jones examined cluster evolution in a set of 12 different cosmological models. The study attempts to evaluate the influence of dark matter, dark energy and cosmic curvature on the evolution of clusters, including specific properties such as the halo mass distribution and the virialization of dark matter haloes and the resulting scaling relations (the fundamental plane). The simulations show the large influence of Ω_m in determining the outcome of this evolution. The influence of dark energy is more subtle. Its main effect is that of setting the cosmological timescales. Also its influence on the primordial power spectrum (in particular its amplitude) is noticeable. The local dynamical influence is nearly negligible.

3.2. Formation and Evolution of Stars and Planetary Systems

The aim of the research of Network 2 is to study the origin and evolution of stars and planetary systems, using spectral features from gases and dust as the main tracers. The projects range from studies of the most deeply embedded protostars to dying stars which are in the process of returning a significant fraction of their material to the diffuse interstellar medium. They involve a combination of observations, mostly at infrared and submillimeter wavelengths, theoretical modeling and laboratory astrophysics. In the following sections a brief summary of scientific highlights is given. The work connects with Network 1 in projects on the interstellar medium in galaxies, and with Network 3 on stellar evolution and minerals in meteorites. Regular network meetings were held every six months (see http://www.strw.leidenuniv.nl/~dave/ISM-CSM-meetings/index.htm for programs).

3.2.1. Interstellar medium

3.2.1.1. DIBs in the LMC and SMC

Cox (NOVA PhD), Cordiner, Kaper, Ehrenfreund and collaborators studied the properties of the Diffuse Interstellar Bands (DIBs) in a large sample of galactic and extragalactic regions. The carriers of these bands – detected more than 80 years ago – are still a mystery. The Large and Small Magellanic Clouds offer a unique laboratory to study the DIBs under conditions and 'metallicities' (carbon abundance) that are profoundly different from those in the Galaxy. For the LMC, Cox and collaborators present measurements of twelve DIBs in five lines of sight to early-type stars, including the 30 Doradus region. From the high resolution spectra obtained with VLT-UVES environmental parameters were derived that characterize the local interstellar medium in the probed LMC clouds. The behavior of DIBs in the LMC was compared to that of DIBs in in the Milky Way. A key result is that in most cases the diffuse band strengths are weak (up to a factor of 5) with respect to Galactic lines of sight of comparable reddening, E(B-V). The most significant parameter that governs the behavior of the DIB carrier is the strength of the UV field. Similar conclusions were found for the SMC.

3.2.1.2. Interstellar silicates

Min (Veni) and collaborators have studied the composition of the interstellar silicate component in detail using advanced models of particle shapes and structures. Contrary to previous studies it was found that the silicates in interstellar space are highly magnesium rich. Also, a small amount of the exotic material silicon carbide, only formed around carbon-rich stars, is reported. This material may provide a unique tracer of processing of material in interstellar space and during the star formation process.

3.2.1.3. H_2D^+: from primoridal clouds to pre-stellar cores

Dominik and Ceccarelli (Grenoble) have studied the possibility that H_2D^+ may be an abundant molecule in primordial gas clouds with very low or zero metallicity, low temperatures (< 10 K) and high densities (>10^7 cm^{-3}). Such clouds with radii of order 1 AU and masses of order 10^{-2} $M_\odot$ have been proposed as possible carriers of the baryonic dark matter in galaxies, because they would be undetectable with conventional tracers. It was shown that it may be possible to

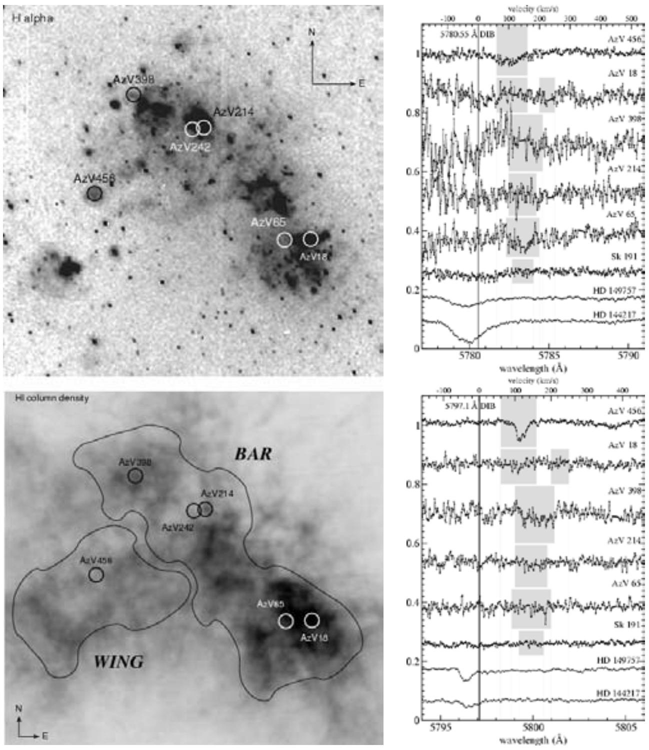

Figure 3.14: (Left:) The observed OB stars are plotted as black and white circles on two maps of the SMC at different wavelengths. The top map shows Hα. The bottom panel shows the map of the HI column density. For N(HI) the scale is from 0 to 1.03x10^{22} atoms cm^{-2}. The maps are aligned in the world coordinate system (North is up, East is to the right), and have the same size (about three degrees squared). The SMC wing and bar region are indicated schematically in the bottom panel. (Right:) Normalized spectra of the 5780 Å (top) and 5797 Å (bottom) DIBs observed in the lines-of-sight toward AzV 456, AzV 18, AzV 398, AzV 214, AzV 65 and Sk 191 (from top to bottom). For comparison the corresponding observed DIB spectra of Galactic lines of sight toward HD 144217 (sigma-type) and HD 149757 (zeta-type) are shown (from Cox et al. 2007, Astron. Astrophys. 470, 941).

detect the ground transition of ortho-H_2D^+ at 372 GHz under favorable conditions.

Hogerheijde and collaborators reported the detection of the molecular ion H_2D^+ in the prestellar core Barnard 68 with the newly commissioned APEX telescope. In dense and cold clouds, the deuterium fractionation of molecules is enhanced through the reaction of H_3^+ with HD producing H_2D^+, which can further react to form many different species. Because the density and temperature of Barnard 68 have been very well established in the literature, Hogerheijde et al. could directly infer the abundance of H_2D^+ from the strength of the emission line, which was found to agree well with theoreticalpredictions.

3.2.1.4. Structure and composition of star-forming clouds

Martinez-Galarza (MSc), together with Hogerheijde, analyzed the structure and composition of a dense ridge in the Ophiuchus star forming region. HCO^+ and HCN line observations were obtained with the BIMA interferometer, and augmented with ARO 12-m maps to fill in the missing 'zero-spacing'. The resulting data cubes were found to be well explained by a simple theoretical model of a collapsing magnetized cylinder, producing the same almost-periodic spacing of the condensations.

Hogerheijde, together with Hatchell (Exeter), Ward-Thompson (Cardiff), and Di Francesco (Herzberg Institute), coordinated the JCMT Legacy Survey of the Gould Belt. This program aims to map most star forming regions within 0.5 kpc from the Sun in 850 and 450 μm continuum emission with SCUBA2 and selected regions in ^{12}CO, ^{13}CO and $C^{18}O$ line emission with HARP-B. The latter instrument was successfully commissioned at the telescope, and the first survey data were taken of the Serpens, Taurus, and Ophiuchus regions.

Van Dishoeck and collaborators continued harvesting the scientific fruits of the Spitzer Space Telescope `Cores to Disks' (c2d) legacy project, led by Evans (Texas). Many papers were completed, including presentation of the IRAC and MIPS maps of the nearby Chamaeleon, Lupus, Ophiuchus, Perseus and Serpens molecular clouds. Together with complementary 2MASS and millimeter data a full inventory of young stellar objects (YSOs) was presented. All reduced IRS spectra were delivered to the Spitzer Science Center with extensive documentation provided by Lahuis and Kessler-Silacci (Texas).

3.2.1.5. Massive molecular cloud cores

A search for candidate (quiescent) massive molecular cores in the outer Galaxy (similar to Inner Galaxy Infrared Dark Clouds) was carried out by Frieswijk (PhD), Spaans and Shipman. The near infrared colors of stars, available from the 2MASS Catalog were used, but a direct conversion of the average color excess to extinction was found to be questionable. Instead, a statistical analysis (U-test) has been performed to derive the probability that the color distribution in adjacent nearby regions is different compared to the local surroundings. For a number of objects a morphology comparison with existing CO data is used to derive a kinematic distance which allows a more detailed analysis of the appearance in 2MASS. Follow-up observations of the object G111.8+0.5 using Spitzer unambiguously allowed the identification of the first Infrared Dark Cloud observed as such in the Outer Galaxy. Moreover, star forming activity is presumably present in some of the dense cores, indicated by the IRAC 4.5 μm 'green fuzzy' emission (shock-indicator) and the clustering of Young Stellar Objects.

3.2.1.6. Models for interpreting water line observations

Water is one of most important molecules in the universe. It has great diagnostic merit and strongly influences the thermal balance, and hence evolution, of star-forming molecular clouds. Poelman (PhD), Spaans and Tielens have developed a state-of-the-art 3D radiative transfer code to analyze and interpret existing observations of H_2O in different environments, and to make predictions for the intensities of submillimeter lines to be observed with the HIFI instrument on board the Herschel Space Observatory. The ground-state transition 1_{10}-1_{01} of ortho-H_2O at 557 GHz can be used to measure the water column density throughout an interstellar cloud for low water abundances, i.e., low optical depth. However, for line optical depths larger than 10, collisional de-excitation breaks the linear relation between emerging intensity and H_2O column because a line photon is scattered many times on its way to the surface of the cloud, thus lowering the effective critical density. Therefore, with increasing abundance multiple line measurements of optically thin transitions are needed to disentangle radiative transfer and local excitation effects.

3.2.1.7. Water ice formation in molecular clouds

Cuppen (Veni) finalized a project with Herbst (Ohio State) on simulations of the growth of icy mantles in molecular clouds using the continuous-time random-walk Monte Carlo technique developed by Cuppen and co-workers. The rate of production of water-ice-dominated mantles through surface reactions was calculated for different physical conditions ranging from diffuse to dense clouds, roughly reproducing the observed onset of water ice mantles

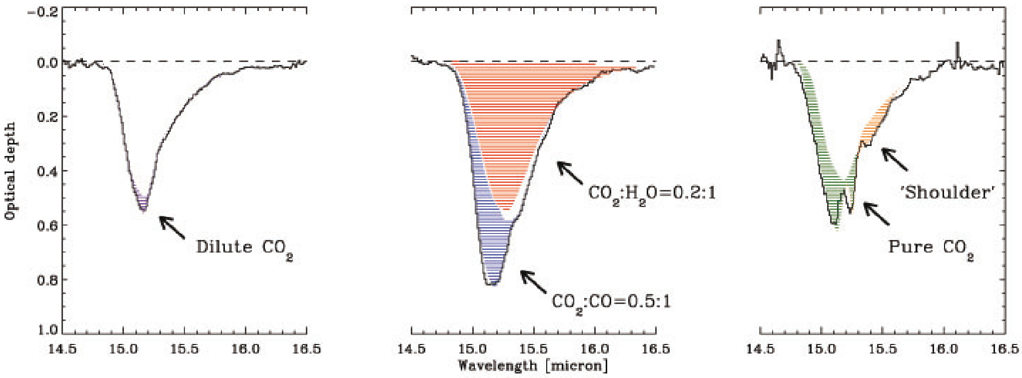

Figure 3.15: Illustration of the five different components of the solid CO_2 band. The Spitzer spectra of Oph IRS 51 (left), Serpens SVS 4-5 (middle) and Oph RNO 91 (right) are shown. The identifications are based on laboratory spectra taken in the Raymond & Beverly Sackler laboratory (from: Pontoppidan et al. 2008, Astrophys. J. 678, 1005).

around A_V~3 mag. For the first time images of the morphology of interstellar ices are presented. Cuppen and collaborators also continued their studies of H_2 formation on silicate and carbonaceous grains, including surface roughness and stochastic heating of the smallest grains.

3.2.1.8. A PDR-code comparison study

Van Dishoeck, Jonkheid (PhD), Kamp (postdoc), Meijerink (PhD) and Spaans initiated and participated in a comparison between independent computer codes modeling the physics and chemistry of interstellar photon dominated regions (PDRs), led by Rollig (Cologne). Such models are widely used in astrophysics in the interpretation of data ranging from diffuse and dense molecular clouds to planetary nebulae, protoplanetary disks, galactic nuclei and starburst galaxies. A number of benchmark models were created, covering low and high gas densities and radiation fields. One set of models assumed constant temperatures, thus testing the consistency of the chemical network and photoprocesses, and a second set determined the temperature self consistently by solving the thermal balance, thus testing the modeling of the heating and cooling mechanisms. A number of key processes governing the chemical network were identified which have been treated differently in the various codes and a proper common treatment was defined. The remaining spread in the computed observables such as the atomic fine-structure line intensities serves as a warning that there is still a considerable uncertainty when interpreting astronomical data with PDR models.

3.2.2. Star formation and early disk evolution

3.2.2.1. Ice survey toward low-mass protostars

Boogert (NOAO/IPAC), Pontoppidan (former NOVA PhD, now at Caltech), van Dishoeck, Lahuis (PhD) and the c2d-IRS team finished their Spitzer and ground-based 3-38 μm spectral survey of ices toward a sample of 41 low luminosity YSOs down to proto-brown dwarfs (<0.1 $L_\odot$); previous mid-infrared ice spectra had been largely limited to high-mass protostars (>10^4 $L_\odot$). An important first conclusion is that all features observed toward massive YSOs are also seen toward low mass YSOs, indicating that processing of ices by internal UV fields is a minor factor in the early chemical evolution of ices. The long-known 6.0 and 6.85 μm bands are detected toward all sources, with the most deeply embedded Class 0 YSOs showing the deepest bands ever observed.

The solid CO_2 15.2 μm bending mode, studied by Pontoppidan, Boogert, van Dishoeck and the c2d-IRS team for the same low-mass YSO sample, indicates a CO_2/H_2O ice abundance ratio of 0.32±0.02, significantly higher than that found in quiescent clouds and massive YSOs. Decomposition of all the observed CO_2 profiles requires a minimum of five unique components (Fig. 3.15). Roughly 2/3 of the CO_2 ice is found in a water-rich environment, while most of the remaining 1/3 is in a CO-rich environment, from comparison with Leiden laboratory data. As for high-mass YSOs, the solid CO_2 15.2 μm profile is an excellent diagnostic of thermal processing.

Solid CH_4 is proposed to be the starting point of a rich organic chemistry. Öberg (PhD), Boogert, van Dishoeck and the c2d-IRS team detected CH_4 ice at 7.7 μm in 25 out of 52 ice sources in the c2d survey. Toward ice-rich sources, the CH_4 abundances are nearly constant at 4.7±1.6 %. Correlation plots reveal a closer relationship of solid CH_4 with CO_2 and H_2O than with solid CO and CH_3OH. The inferred solid

CH_4 abundances are consistent with models where CH_4 is formed through sequential hydrogenation of C on grain surfaces. The equal or higher abundances toward low mass YSOs compared with high mass sources and the correlation studies support this formation pathway as well, but not the two competing theories: formation from CH_3OH and formation in gas phase with subsequent freeze-out.

3.2.2.2. Deeply embedded protostars

Jørgensen (former NOVA PhD, now at CfA/Bonn), Bourke, Myers (both CfA), van Dishoeck and collaborators presented the first results from a large spectral line and continuum survey of eight deeply embedded (Class 0) low-mass protostellar cores using the SubMillimeter Array (SMA). High-excitation line emission from 11 molecular species originating in warm and dense gas has been imaged at 1''-3'' (typically 200-600 AU). Compact continuum emission at 0.8 and 1.3 mm is observed for all sources, which likely originates in marginally optically thick circumstellar disks, with typical lower limits to their masses of 0.1 $M_\odot$ (1% -10% of the masses of their envelopes) and a dust opacity law with $\beta \sim 1$. Prominent collimated outflows are seen in CO J=2-1 line observations in all sources. The most diffuse (i.e., least collimated) outflows are found in the sources with the lowest ratios of disk to envelope mass, suggesting that these sources are in a phase where accretion of matter from the envelope has almost finished and the remainder of the envelope material is being dispersed by the outflows. CH_3OH and H_2CO emission are often found to be associated with the shocks caused by the protostellar outflows. Only one source, NGC 1333 IRAS 2A, has evidence for hot compact CH_3OH emission coincident with the embedded protostar, consistent with the `hot corino' interpretation.

Van Kempen (PhD), in collaboration with van Dishoeck, Hogerheijde, Doty (Denison, NOVA visitor) and Jørgensen, has modeled the water emission from low-mass protostars in preparation of HIFI and PACS observations with Herschel. The rotational water line emission from Class 0 and Class I protostars has been calculated for a large model grid, using physical parameters constrained by observations. Results are presented for various abundance structures, which include ice formation and freeze-out at low temperatures and evaporation above 90 K. Expected line fluxes are presented convolved with the Herschel beam size. It is clear that the optically thin $H_2{}^{18}O$ lines are best suited to probe the water abundance structure, whereas highly excited optically thin main isotope lines are good diagnostics of the warm inner regions. Line profiles provide important additional information and depend on the dust continuum. The results for low-mass YSOs agree well with those for massive protostars found by Poelman and van der Tak (see section 3.2.7.4).

3.2.2.3. Early disk formation

A particularly interesting evolutionary YSO phase is the Class I stage, in which the disks are still young but the envelopes are largely dispersed so that they no longer overwhelm the disk emission. Lommen (NOVA PhD), van Dishoeck, Crapsi (postdoc) and Jørgensen used the SMA to determine the physical and chemical characteristics of young disks for a set of low-mass Class I sources. Results for the first two sources, IRS 63 and Elias 29 in Ophiuchus, reveal a large range in disk properties, with disk masses from <0.006 to 0.05 $M_\odot$ and M_{env}/M_{disk} from 1 to 6. The latter values are clearly in between those of the Class 0 (>10) and Class II (<1) stages. HCO^+ 3-2 is detected, with position-velocity diagrams indicative of Keplerian rotation. This allows an estimate of the stellar masses at this early stage for the first time.

The object L1489 IRS presents an intriguing possibility to study the formation of a protoplanetary disk and the transition from an envelope dominated by infall to a disk dominated by rotation. Using archival OVRO, BIMA, and JCMT molecular-line data, and newly obtained SMA and Spitzer observations (Fig.3.16), Brinch (PhD), Hogerheijde, Crapsi, and

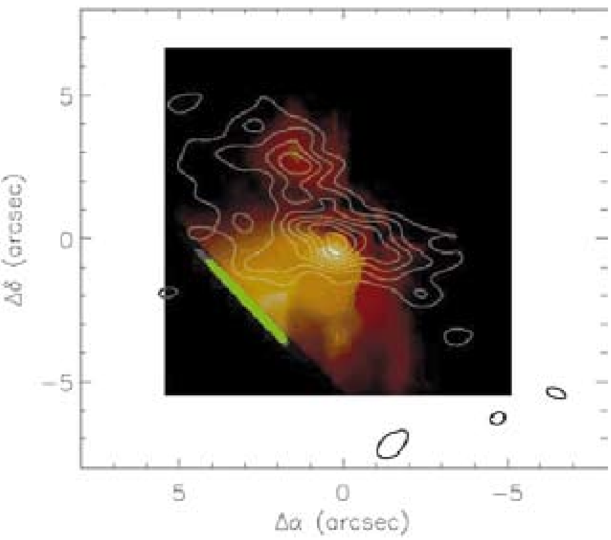

Figure 3.16: Integrated HCO^+ 3-2 emission observed with the SMA (contours) superposed on the scattered near-infrared light observed with HST/NICMOS (colors; from Padgett et al. 1999). The former traces the rotating and collapsing envelope, while the latter outlines the lower density cavities above and below the disk midplane (from: Brinch et al. 2007, Astron. Astrophys. 475, 915).

Jørgensen, derived a detailed model for the object. Inside a flattened envelope extending out to 2000 AU, a 300 AU accretion disk surrounds the star. In the envelope, material is spiralling inward, while in the disk gas is probably entirely in Keplerian motion. Most interestingly, the disk is inclined by 30 degrees with respect to the envelope. This suggests that, as star/disk systems form from the collapse of a turbulent cloud medium, the orientation of the angular momentum axis is not constant. Instead, it simply reflects the average angular momentum accreted so far, which can differ from material which is still to accrete.

Another object where the effects of infall, rotation, and outflow are apparent is Barnard-1c in Perseus, studied by Matthews (Victoria), Hogerheijde, and Bergin (Michigan). Interferometric and single-dish molecular line observations of $C^{18}O$, HCO^+, and N_2H^+ reveal the detailed structure of these three components. The N_2H^+ emission traces a 2400 AU radius rotating and infalling envelope, but entirely disappears in the inner 600 AU. Most likely, the rising gas temperature in the inner envelopes causes CO to evaporate and subsequently react with N_2H^+. The changing dust properties in this region also explain the unusual polarization signature detected from B1c.

Brinch, Hogerheijde, Richling (IAP), and van Weeren (MSc) used the outcome of a hydrodynamical simulation of cloud-core collapse, and fitted the resulting synthetic spectra with a simple parametrized velocity-field model, in order to understand molecular line spectra. They conclude that a combination of optically thin and optically thick lines, and a combination of single-dish and interferometric observations offers best constraints on the velocity field. The effects of the time-dependent molecular chemistry, and most noticeably the freeze-out of species like CO, was modeled using a novel method developed by van Weeren. In this method, infinitesimal parcels of gas float with the material in the hydrodynamical simulation, and their chemical content is updated for each time step.

3.2.3. Protoplanetary disks around pre-main sequence stars

3.2.3.1. Evolution of protoplanetary disks

Brown, Blake (both Caltech), Merín (postdoc), van Dishoeck, Geers, Lahuis (both PhD) and the c2d-IRS team have discovered four circumstellar disks with a deficit of dust emission from their inner 15-50 AU. All four stars have F-G spectral type and were uncovered as part of the c2d-IRS survey. Modeling of their SEDs indicates a reduction in dust density by factors of 100-1000 from disk radii between ~0.4 and 15-50 AU but with massive gas-rich disks at larger radii. This large contrast between the inner and outer disk has led to the term 'cold disks' to distinguish these unusual systems. A very small amount of hot dust (0.02-0.2 Moon masses) is still present close to the central star (<0.8 AU). Although rare, cold disks are likely in transition from an optically thick to an optically thin state and thus offer excellent laboratories for the study of planet formation.

The T Tauri class of pre-main-sequence stars is divided in two categories: classical and weak-line objects. The latter do not show signs of accretion, and are usually thought to have lost most of their disk. Recent Spitzer measurements show that few weak-line T Tauri stars indeed show emission from cold dust particles, and that many are truly 'diskless'. Whether this is an evolutionary effect remains to be seen, because the presence of a close companion may also have prevented the formation of a disk. To test this hypothesis, Kockx (MSc), Hogerheijde, and Ménard (Grenoble), analyzed AO observations of a sample weak-line T Tauri stars in Lupus to search for any previously undetected companions. Twelve multiple objects were positively identified, with a further four as candidates. The multiplicity factors of weak-line and classical T Tauri stars in Lupus are found to be indistinguishable, and both are smaller than the multiplicity factor derived for the Taurus region. This suggests that weak-line T Tauri stars are more evolved than classical objects, and that binarity is a function of cloud environment.

3.2.3.2. The gas content of protoplanetary disks

Panić and Salter (both PhD), together with Hogerheijde, Blake (Caltech), Wilner (CfA) and Qi (CfA) have started a detailed investigation using literature SEDs and newly obtained molecular-line interferometric measurements from SMA and CARMA. The disk around HD169142 shows very similar structure in both the dust and the gas, and the line observations are well matched by model predictions based on the SED-derived disk structure. In contrast, the disk around IM Lup appears significantly larger and thicker in molecular gas than inferred from continuum measurements. Spatially resolved continuum measurements from SMA show that its surface density follows closely the radial power-law with index -1 predicted by accretion-disk theory. The nature of the molecular gas outside 400 AU from the star is currently under investigation (Fig. 3.17).

Complementary to the work by Panić, Salter and Hogerheijde are using the same SED-based molec-

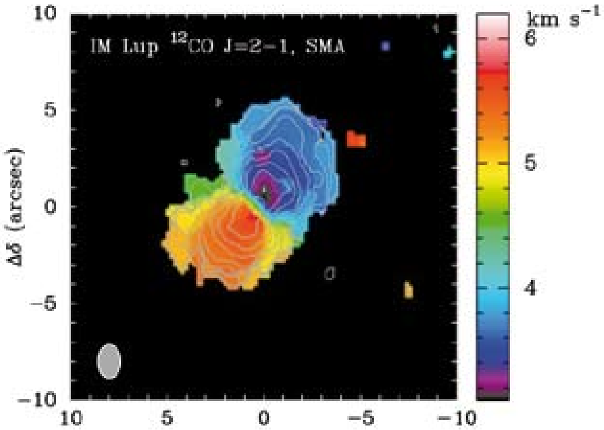

Figure 3.17: CO J=2-1 line emission from the disk around the T Tauri star IM Lup observed with the SMA (contours). The velocity centroid of the emission lines (color scale) indicates Keplerian rotation in this 700 AU radius disk. (From: Panić et al. in prep.)

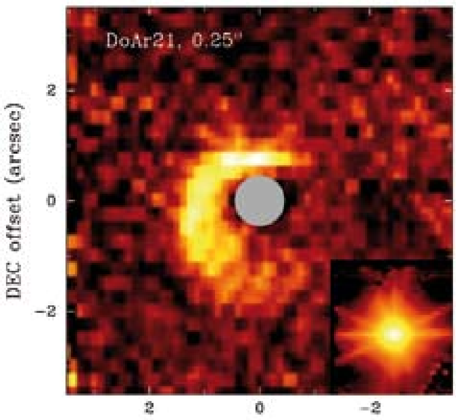

Figure 3.18: Continuum-subtracted image of the H_2 fluorescent line emission surrounding the T Tauri star DoAr21. The inset in the lower right shows the full stellar image over the same 4"x4" region. The grey circle denotes the area where no good continuum subtraction could be obtained. (From: Hogerheijde et al. in prep.).

ular-line modeling to study a sample of disks that show a variety of crystallinity and grain-growth signatures. Here the leading question is whether the gas evolves together with the dust, or independently. Together with Wilner, Qi, and Hughes (all three CfA), Hogerheijde used similar modeling approaches to study the disk around TW Hya, showing resolved imaging of the central clearing; to investigate the tenuous disk around 49 Ceti (together with Kamp, STScI), tracing a disk in gas-clearing stage; and to show that the apparent discrepancy in disk outer radii derived from dust and molecular line measurements can in fact be reconciled if one assumes a radial power-law surface density with an exponential taper. The latter is expected for a viscous accretion disk.

Some T Tauri stars show narrow and compact H_2 line emission at 2.12 μm, attributed to fluorescently excited gas in the inner disk. Schouten (MSc), in collaboration with Hogerheijde, Panić, and Merín, imaged one of these objects, DoAr21, using SINFONI on VLT (Fig. 3.18). This powerful AO-assisted integral field unit allows the stellar continuum to be subtracted with great accuracy, because of the simultaneous PSF obtained at either side of the emission line. The H_2 emission was found to originate from a partial ring, surrounding the star at a distance of 100-200 AU. This radial separation is consistent with its SED, which shows that the disk has cleared its dust from the inner 100 AU. The SINFONI observations show that this region must also be free of any (molecular) gas. Why the emission is confined to a partial ring is unclear.

Lahuis, van Dishoeck and the c2d-IRS team surveyed mid-infrared gas-phase lines toward a sample of 76 circumstellar disks. [Ne II] and [Fe I] are detected for the first time toward classical T Tauri stars in ~20% respectively ~9% of the c2d sources (Fig. 3.19). The observed [Ne II] line fluxes are consistent with X-ray irradiated disks around stars with $L_X=10^{29}$ - 10^{31} erg s^{-1}. [Fe I] is detected, but not [S I] or [Fe II]. The [Fe I] detections indicate the presence of gas-rich disks with masses of >0.1 M_{Jup}. No compact H_2 0-0 S(0) and S(1) disk emission is found, except for S(1) toward one source. These data give upper limits on the warm (T~100-200 K) gas mass of a few Jovian masses, consistent with recent T Tauri disk models which include gas heating by stellar radiation. Compact disk emission of hot (T>500 K) gas is detected through the H_2 0-0 S(2) and/or S(3) lines toward ~8% of the sources. These line fluxes are higher by more than an order of magnitude than those predicted by recent disk models, even when X-ray and excess UV radiation are included. Oblique shocks of stellar winds interacting with the disk can explain many aspects of the hot gas emission, but are inconsistent with the non-detection of [S I] and [Fe II] lines.

Van Kempen (PhD), van Dishoeck, Brinch and Hogerheijde performed a JCMT CO J=3-2 survey of 21 T Tauri stars with disks in Lupus, all of them part of the Spitzer c2d legacy survey. One new large gas-rich disk was found, IM Lup, which is an excellent target for future SMA and ALMA studies (Fig. 3.17). For all other targets, the single-dish data are dominated by extended cloud emission, illustrating the need for high-resolution interferometry in the southern sky.

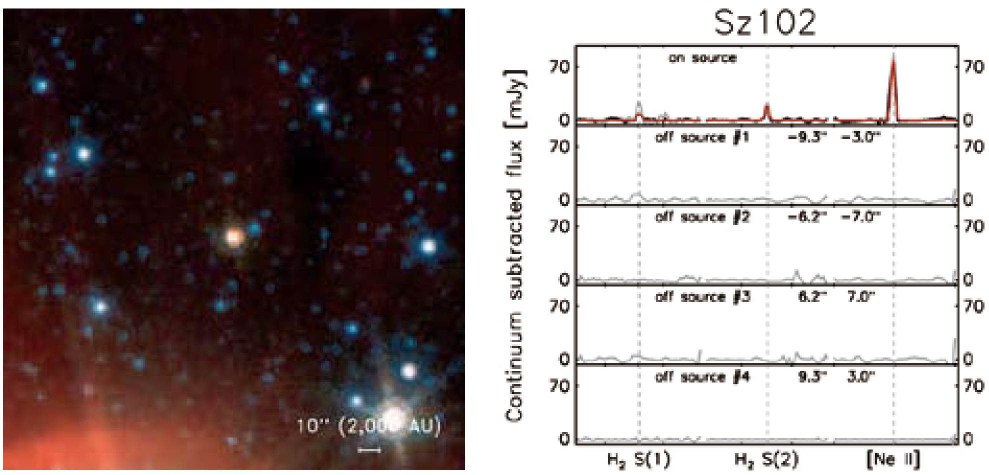

Figure 3.19: Observations of H_2 v=0 S(1) 17.0 µm, S(2) 12.2 µm and [Ne II] 12.8 µm emission observed on and off source toward the isolated T Tauri star Sz 102. The image shows the Spitzer composite of IRAC1 3.6 µm (blue), IRAC2 4.5 µm (green) and IRAC4 8.0 µm (red), centered on the source. Note that the [Ne II] emission is limited to the source whereas the H_2 is somewhat extended (Lahuis et al. 2007, Astrophys. J.665, 492).

Jonkheid (PhD), van Dishoeck, Hogerheijde and Dullemond (Heidelberg) explored the chemistry and gas temperature of evolving protoplanetary disks around Herbig Ae stars with decreasing mass or dust settling, testing the sensitivity of various gas-phase tracers. The chemistry and gas temperature were computed self-consistently following 2D UV radiative transfer. The chemistry shows a strong correlation with disk mass. Molecules that are easily photodissociated, like HCN, require high densities and large extinctions before they become abundant. The products of photodissociation, like CN and C_2H, become abundant in models with lower masses. Dust settling mainly affects the gas temperature, and thus the emission of high temperature tracers like the O and C^+ fine structure lines. The carbon chemistry is found to be very sensitive to the adopted PAH abundance.

3.2.3.3. **PAHs in protoplanetary disks**

Polycyclic Aromatic Hydrocarbons (PAHs) are also an important diagnostic for disks: due to the non-thermal excitation process, these molecules can be tracers to large distances, where they can be used as diagnostics for the radiation field and densities in the disk surface. Geers (PhD), van Dishoeck, Merín, Pontoppidan (Caltech), Oliveira (MSc) and Pel obtained spatially resolved VLT-VISIR mid-IR images of the disk surrounding the young star IRS 48 in Ophiuchus (Fig. 3.20). The disk exhibits a ring-like structure at 18.7 µm, and is dominated by very strong emission from PAHs at shorter wavelengths. The 18.7 µm ring peaks at a diameter of 110 AU, with a gap of ~60 AU. In contrast, the PAH emission bands are centered on the source and appear to fill the gap within the ring. The measured PAH line strengths are 10-100× stronger than those typically measured for young stars and can only be explained with a high PAH abundance and/or strong excess optical/UV emission. The morphology of the images, combined with the absence of a silicate emission feature, imply that the inner disk has been cleared of micron-sized dust but with a significant population of PAHs remaining.

Geers, van Dishoeck, Visser, Augereau (Grenoble) and co-workers used VLT-VISIR, VLT-ISAAC and VLT-NACO spectra of 29 disks around T Tauri and Herbig Ae stars to determine the presence and location of the emission from PAHs. Spatial-extent profiles of the 3.3, 8.6, 11.2, and 12.6 µm PAH features and the continuum emission have been derived. For 6 sources, the PAH spatial extent is confined to scales typically smaller than 0.12-0.34'', corresponding to radii of 12-60 AU, definitively associating the PAHs with the disks. For HD 100546, the 3.3 µm emission is confined to 12 ± 3 AU, most likely associated with the outer rim of the dust gap in this disk.

The PAH chemistry and emission from protoplanetary disks has been modelled by Visser (PhD), Geers, Dullemond (Heidelberg), van Dishoeck and co-workers. PAHs can exist in different charge states and they can bear different numbers of hydrogen atoms. Destruction of PAHs by UV photons, possibly in multi-photon absorption events, is taken explicitly into account. The chemistry model is coupled to a radiative transfer code to provide the PAH emission together with the spectral energy distribution (SED) from the star+disk system. Normally hydrogenated PAHs account for most of the observed PAH emission, with neutral and positively ionized

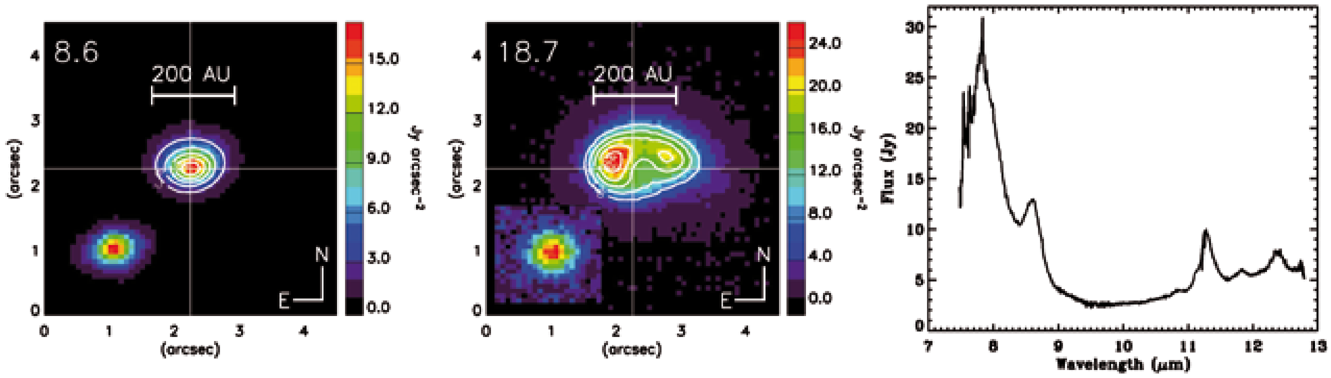

Figure 3.20: VLT-VISIR mid-infrared images of the disk around the young T Tauri star IRS 48, showing strong centrally peaked PAH emission at 11.3 μm as well as a 60 AU diameter gap devoid of large grains emitting at 19 μm. The inserts show the PSF of a standard star. The 8-13 μm VISIR spectrum with the strong PAH features is included (from: Geers et al. 2007, Astron. Astrophys 469, L35).

species contributing in roughly equal amounts for disks around Herbig Ae stars. Large PAHs of about 100 carbon atoms or more are needed to explain the observations of the 8.6 and 11.2 μm extent measured by Geers et al. The PAH emission from T Tauri disks is much weaker and concentrated more toward the central star. Positively ionized PAHs are largely absent there because of the weaker radiation field.

The effects of dust sedimentation have also been investigated in a study led by Dullemond. For high turbulence, the PAH emission is barely affected, but for low levels of turbulence the PAH features are boosted relative to the continuum because PAHs stay well mixed in the disk's surface layer while the 0.1 μm size grains sediment deep into the disk. This trend is opposite to that observed for Herbig Ae stars, suggesting that coagulation may also be at work.

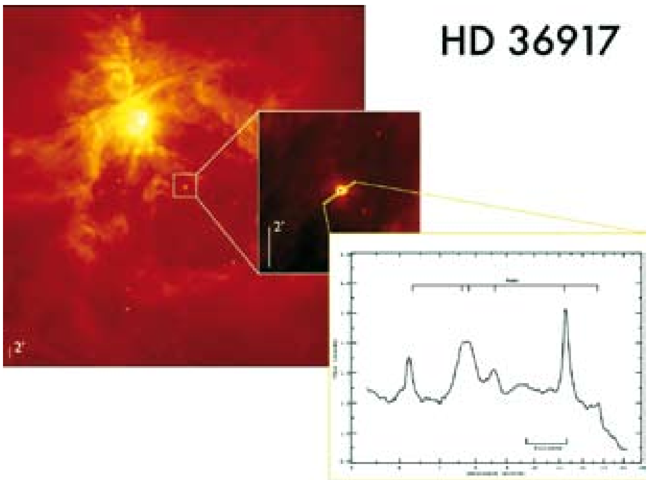

Figure 3.21: 8 μm mosaic of part of the OB1c association (Orion) as obtained by the IRAC instrument onboard Spitzer (credit: NASA/ Harvard-Smithsonian Center for Astrophysics). The mosaic displays the overall structure of the region. The box (3.5'x3.5') is centered on the position of the Herbig Ae star HD 36917. The blow-up of the box reveals an extended diffuse envelope surrounding the young stellar object on a scale of about 30,000 AU (at 510 parsec).The displayed IRS slit (136x3.65 arcsec) clearly covers this envelope (from: Boersma et al., in preparation).

Boersma (NOVA PhD) has developed together with Allamandola and Tielens (NASA/Ames) a theoretical description of the cooling mechanism of PAHs and has implemented it into a state-of-the art PAH fitting procedure capable of, in conjunction with the Ames PAH spectral database, identifying the individual carriers (families). Synthetic PAH spectra have been constructed using quantum-chemical calculations and used to link molecular properties of the PAHs to specific emission characteristics. The constructed spectra have been compared to interstellar PAH spectra in order to trace the composition of the interstellar PAH population and infer from it for example the degree of ionization and the strength of the interstellar radiation field.

Boersma is also collaborating with Tielens, Waters, Bouwman and Henning (both Heidelberg) on the analysis of observations of PAHs in disks around Herbig Ae stars using Spitzer-IRS. The spectrum shown in Figure 3.21 of one such source, HD 36917, illustrates the spectral richness of the region. The structure in the 7-8 μm region due to PAHs is made up of two components which can be traced back to two spatially separated PAH families. None of the detected PAH emission can in this case be ascribed to the unresolved circumstellar disk, indicating that the onset of chemical processing already occurs in an earlier evolutionary phase, in the envelope.

3.2.3.4. Dust in protoplanetary disks: crystallization and grain growth

Meijer (NOVA PhD), Dominik, de Koter, van Boekel, and Waters investigated the nature of the two empiricially identified groups of proto-planetary disks surrounding Herbig stars, i.e., intermediate-mass pre-main-sequence A and B stars, by performing self-consistent model calculations of such disks. They find that the parameter of overriding importance in this group classification is the total mass in small dust grains, confirming earlier results by Dullemond and Dominik. It appears that moderate grain growth leads to spectra with weak or no 10 μm feature, both for flaring (Group I) and non-flaring (Group II) sources. The fact that sources with weak features have mostly been found in Group I sources is therefore surprising and must be due to observational biases or evolutionary effects.

Meijer and collaborators also investigated whether direct imaging at near- and mid-IR wavelengths allows to discriminate between a flaring or non-flaring disk geometry. Simulating direct imaging of these disks and fitting their sizes by following a procedure commonly used in observational studies – i.e. by fitting the extended emission by a Gaussian distribution – they find that the two cases actually have very similar sizes at 10-25 μm (around 20-25 AU at 18.8 μm) so that imaging cannot distinguish them.

The effect of mixing of crystalline grains, grain growth and disk geometry on the spectral signature of the 10 μm silicate feature in disks around Herbig Ae and Be stars has been studied by Meijer, de Koter, Min, van Boekel, Dominik, and Waters (Fig. 3.22). The mass fraction of crystals as derived from a standard analysis of the 10 μm feature is found to be a complex quantity that is sensitive to the characteristic size of the dust particles (the larger the grains, the more pronounced the signature of crystals) and geometrical shape (for flat disks a higher crystallinity is derived because the warm zone producing the 10 μm feature is geometrically smaller so that the fully crystalline inner disks have a larger relative contribution). It is shown that Herbig disks with less than 10% crystalline material have a radial distribution of crystalline silicates consistent with thermal annealing in the innermost disk region (up to 0.5 AU), without the need for radial mixing or other crystallization processes. So these disks are crystalline where they must be, and are amorphous where they can be. Herbig disks showing crystallinities in the range 15-30% in spatially unresolved spectra appear to require in situ crystallization in the passive phase. These crystalline disks are all dominated by large dust grains, therefore they appear to be more evolved.

Kessler-Silacci (Texas), Dullemond (Heidelberg), Geers (PhD), van Dishoeck and co-workers analyzed the c2d-IRS and Spitzer results of lower-mass T Tauri and brown dwarf disks in comparison with the Herbig disks, which indicate that the grain size and crystallinity may be correlated with the spectral type of the central star and/or disk geometry. Using a simple two-layer disk model it is found that the radius of the 10 μm silicate emission zone goes as $(L_*/L_\odot)^{0.56}$. The observed correlations, together with simulated spectra of olivine and pyroxene mixtures, imply a dependence of grain size on luminosity. Combined with the fact that the emission radius is smaller for less luminous stars, this implies that the apparent grain size of the emitting dust is larger for low-luminosity sources. In contrast, the models suggest that the crystallinity is only marginally affected, because for increasing luminosity, the zone for thermal annealing (assumed to be at T>800 K) is enlarged by roughly the same factor as the silicate emission zone. The observed crystallinity is affected by disk geometry, however, with increased crystallinity in flat disks, consistent with the Meijer et al. results.

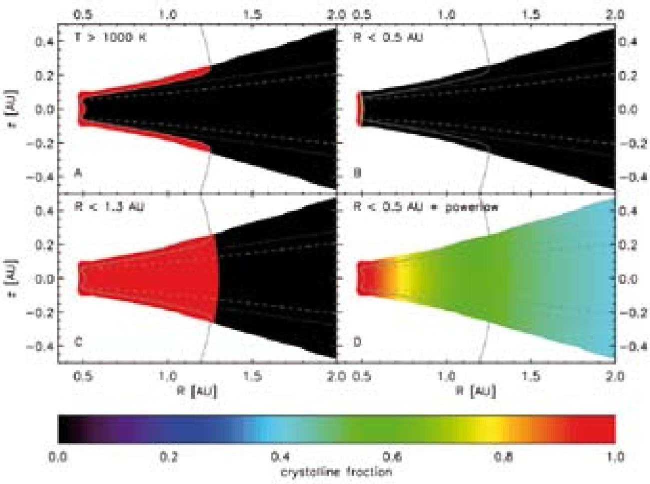

Figure 3.22: Four scenarios for the spatial distribution of crystalline grains in passive proto-planetary disks around Herbig A stars. Scenario A is a non-mixing scenario, in which grains are only crystalline if the local medium has a temperature in excess of 1000 K. Scenario B, not intended to be physically, assumes that the disk is fully crystalline only in the region where the mid-plane temperature is above 1000 K. Scenario C implies efficient vertical mixing, continuing for a long time. Vertical mixing has transported crystals formed in the chromospheric surface layer down throughout the entire vertical slice of the disk. Scenario D assumes a radial profile of the crystallinity. The value for the power law index (-0.65) is predicted by detailed mixing/annealing models. Herbig disks with less than 10% crystals favor scenarios with very limited mixing (A and C); disks showing crystallinities in the range 15-30% are more consistent with scenario D (from: Meijer, PhD thesis).

The full 5-35 μm IRS spectrum of the disk around SST-Lup3-1, a very low mass star close to the brown dwarf boundary in Lupus III, was quantitatively analyzed by Merín, van Dishoeck, Augereau (Grenoble) and the c2d-IRS team. The dust in the disk upper layer has a crystalline silicate grain fraction between 15% and 33%, depending on the assumed dust continuum. The hot (~300 K) dust responsible for the 10 μm feature consists of a roughly equal mix of small (~0.1 μm) and large (~1.5 μm) grains, whereas the cold (~70 K) dust responsible for the longer wavelength silicate features contains primarily large grains (>1 μm). Together, these results provide evidence for combined grain growth and settling in the disk. Since only the inner 0.02 AU of the disk is warm enough to anneal the amorphous silicates, even the lowest fraction of 15% of crystalline material requires either very efficient mixing or other crystallization mechanisms.

Pontoppidan, Blake (both Caltech), Stapelfeldt (JPL), Dullemond (Heidelberg) and van Dishoeck used Spitzer IRS spectroscopy and 2D radiative transfer modeling of the 'Flying Saucer' disk in Ophiuchus to study the grain size distribution. Its SED exhibits the characteristic two-peak shape predicted for a disk viewed very close to edge-on (Fig. 3.23). The short-wavelength peak is entirely due to photons scattered off the surface of the disk, while the long-wavelength peak beyond 15 μm is due to thermal emission from the disk itself. The depth and the wavelength of the mid-infrared SED 'valley' constrain the large grains in the disk to have sizes of 5-10 μm at radii of 50-300 AU. The detection of relatively large grains in the upper layers implies that vertical mixing is effective, since grain growth models by Dominik and collaborators predict that such large grains would otherwise settle deep in the disk on short timescales.

Pontoppidan, Dullemond and co-workers, including van Dishoeck, also modeled the IRS spectra of the UX Orionis star VV Ser, combined with interferometric and spectroscopic observations from the literature covering UV to submm wavelengths. The complete data set is modeled with an axisymmetric Monte Carlo radiative transfer code and the results are fully consistent with the prediction of Dullemond and Dominik that disks around UX Ori stars are self-shadowed and seen nearly edge-on. The grains in the upper layers of the puffed-up inner rim must be small (0.01-0.4 μm) to reproduce the colors of the optical light curve, while the silicate emission features indicate that grains in the outer disk (>1-2 AU) are somewhat larger (0.3-3.0 μm). The location of the puffed-up inner rim is estimated to be at 0.7-0.8 AU, almost twice the rim radius estimated from near-IR interferometry. Since larger (more gray) grains are able to penetrate closer to the star for the same dust sublimation temperature, a model is proposed in which large grains in the disk midplane reach to within 0.25 AU of the star, while small grains in the disk surface create a puffed-up rim at ~0.7-0.8 AU.

3.2.4. Planet formation

3.2.4.1. Dust aggregation in protoplanetary disks

Paszun (PhD) and Dominik studied the formation of dust aggregates in a gaseous environment, to understand the first microscopic steps on the path from

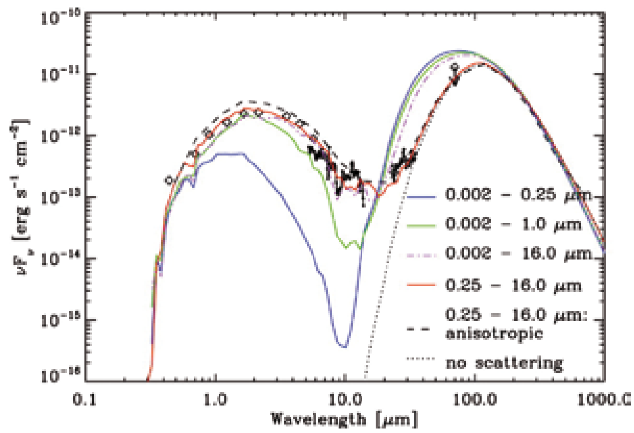

Figure 3.23: Left: spectral energy distribution including the Spitzer-IRS spectrum and model fit of the edge-on 'Flying Saucer' disk. Right: VLT near-IR image from Grosso et al. showing the disk as a dark lane. Grain size distributions weighted toward increasing grain sizes move the mid-IR minimum to longer wavelengths. The best-fit model (red curve) contains grains larger than 10 μm at radii larger than 50 AU (from: Pontoppidan et al. 2007, Astrophys. J. 658, L111).

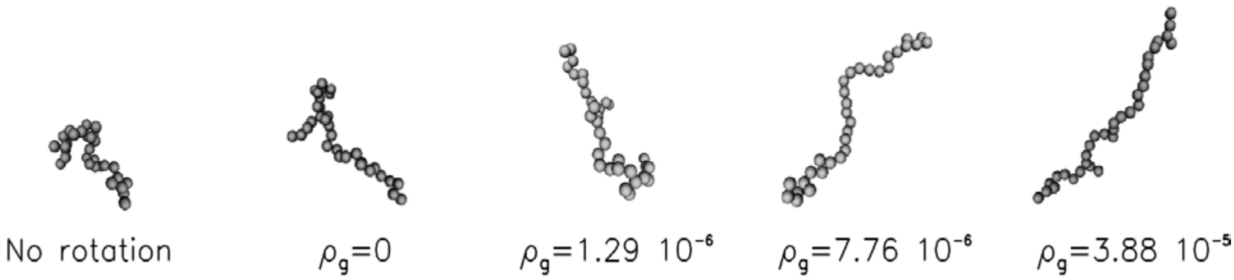

Figure 3.24: The typical shape of an aggregate formed by Brownian motion aggregation without rotation (left panel), and with rotation, at different gas densities. The grains are composed of silicate spheres with radius of 1.05 µm. The labels below the plots provide the density in gr cm^{-3} (from: Paszun and Dominik 2006, Icarus, 182, 274).

dust to planets in protoplanetary disks. There has been a puzzling effect in the literature: aggregates from experiments in zero-gravity have very elongated shapes, while same-size aggregates constructed in theoretical models are more compact. It was shown that this is an effect of the thermal rotation of aggregates during a collision (Fig. 3.24), a feature neglected so far in model calculations. This effect is strongly enhanced when the aggregation process takes place in high density gas, so that the mean path length for Brownian motion of the aggregates is smaller than the aggregates themselves. The new models predict that at even higher densities, almost entirely linear chains of grains should result. This still has to be verified by experiments.

Ormel (NOVA PhD), in collaboration with Spaans and Tielens, finished a theoretical and numerical study on the role of the internal structure of dust aggregates in the growth process in protoplanetary disks. Obtaining an adequate prescription for the internal structure is important: it determines the surface-area to mass ratio and therefore the velocity structure between dust particles. They found that, compared to compact particles, 'realistic', i.e., fluffy aggregates, stay longer entrenched in the upper layers of the protoplanetary disks and grow to larger sizes before compacting and settling to the disk midplane.

Paszun, Ormel, Tielens and Dominik initiated a project to include collisions that result in fragmentation. Disk observations almost always show the presence of small dust grains, which signifies the importance of replenishment of small dust particles (e.g., through fragmentation). The outcomes of the detailed numerical collisions will then be used as input in the form of easily applicable recipes for the Monte Carlo collision model developed by Ormel. Cuzzi (NASA Ames) and Ormel also generalized earlier findings by Cuzzi to provide an analytical expression for the relative velocities between particles in a turbulent environment.

Ormel, in cooperation with Cuzzi and Tielens (NASA Ames), studied the topic of dust rimming and sticking of chondrules in disks. It was found that chondrules (~mm-sized stony spherules) could stick to each other if they were enshrouded by a porous rim of micron-sized dust particles - just as is observed in pristine chondritic meteorites. It was then investigated for which combination of physical parameters growth could be maximized: in particular, is growth to planetesimals possible? It was found, however, that the presence of radial drift motions, caused by the friction particles experience with the gas moving at sub-Keplerian velocities moving prevented growth beyond decimeter or m-sizes.

Together with Spaans, Ormel improved the ability of Monte-Carlo methods for dust aggregation computations to handle cases where the particle distribution spans orders-of-magnitude in size. An approximation was introduced - the grouping method – in which the less important (small) particles are considered as one unit, sharing the same structural parameters. The new method was tested against analytical coagulation formalisms and good correspondence was obtained even for orders-of-magnitude growth. The new method is particularly suited to tackle runaway coagulation models or population balance models including fragmentation (Fig. 3.25).

Together with Blum and Heisselmann (both Braunschweig), Fraser (Strathclyde), Reissaus (Kayser-Thred), Chapparo, Salter and Van der Wolk (all three MSc) designed and performed an experiment to study low-velocity collisions of millimetre-sized dust, dust-ice and ice aggregates and participated in ESA's 45th Parabolic Flight Campaign. During all three flights, which provided thirty minutes of

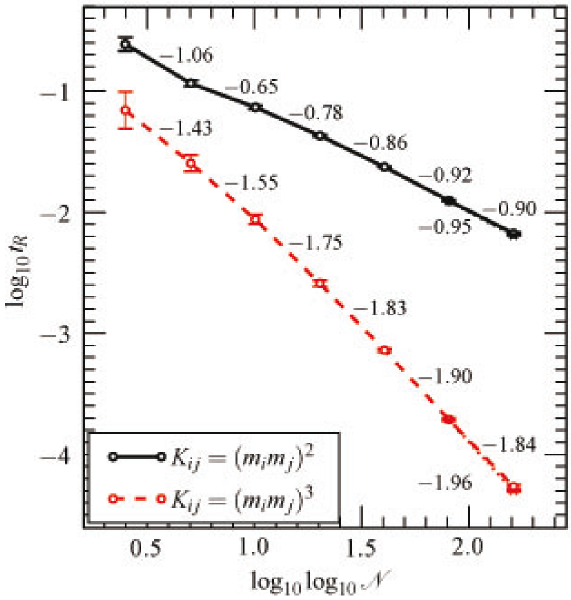

Figure 3.25: The runaway coagulation time tR (essentially the time in which all the mass is transferred to the runaway particle) versus the number of particles N for the coagulation kernels (or collision probabilities) $(m_i\, m_j)^v$ with v=2 (solid line) and v=3 (dashed line). These are highly runaway kernels, meaning that if N approaches infinity the runaway timescale goes to zero (instantaneous gelation). However, in any physical system N is always finite and t_R is expected to decrease with increasing N. The predicted power-law dependence on the logarithm of N with exponent ~ (1 – v) has been verified by the new Monte Carlo grouping method until N = 10160 (from: Ormel and Spaans 2008, Astrophys. J. in press).

weightlessness in total, the apparatus worked flawlessly and more than a hundred collision events of dusty aggregates at ambient temperature were observed.The majority of both particle-particle collisions and particles colliding with a dusty target showed a quasi-elastic rebounding behavior.

3.2.5. Solar system

3.2.5.1. Comets

The volatile content of comets provides a record of the composition of the early Solar System and the disk from which the planets formed. Hogerheijde and collaborators have developed a method to infer molecular production rates from millimeter interferometric line observations, taking into account the effects of non-LTE excitation and radiation. This has been applied to simultaneous observations with the BIMA and OVRO arrays of the comet C/2002 T7 (LINEAR), and recently to SMA observations of the comet 17P/Holmes.

3.2.6. Extrasolar planets

Snellen and Covino (Naples) have made the first high precision near-infrared observation of a transiting extrasolar planet. Measurements of planet OGLE-TR-113 in K-band using SOFI on the ESO NTT resulted in unprecedented photometric precisions of 1 millimag per 10 minutes. The observations of the transit showed a flat-bottomed light-curve indicative of a significantly lower stellar limb darkening at near-infrared than at optical wavelengths. The observations of the secondary eclipse result in a 3σ detection of emission from the exoplanet at 0.17±0.05%. If true, these would constitute the first detection of direct emission from an extrasolar planet from the ground, however, residual systematic errors make this detection rather tentative.

The undergraduate students van der Burg, de Hoon, and Vuijsje (Fig. 3.26) discovered a possible transiting extrasolar planet during their bachelor research project, under supervision of Snellen. They selected data for 15,000 stars from the public OGLE-II database, and found 13 candidates which exhibit transits with such depth and duration that they are caused by an object with a radius less than twice that of Jupiter. One of them, OGLE2-TR-L9, turned out to be an excellent planet candidate.

Most planets are surrounded by a nearly spherical atmosphere filled with various gases and liquid or solid particles. Incident light from the Sun or (in the case of exoplanets) from a star is often scattered many times in the atmosphere before it emerges and can be observed. For the interpretation of such observations in terms of particle properties rather complicated model computations are necessary. Usually this is only possible by dividing the atmosphere in a large number of horizontal regions, each of which is assumed to be plane-parallel. Hovenier and Stam, however, discovered a peculiar discontinuity in the intensity of light reflected by a plane-parallel atmosphere when the directions of incidence and reflection become both horizontal. Such a situation occurs, for instance, when an observer at the top of a mountain peak above a cloud deck looks at the horizon at sunset.

Exoplanets are so far away that no distinct regions of their atmospheres can be observed. The observed light is that from all regions together. This means that in model computations the reflected light for each region must first be calculated separately and then integrated over the part of the atmosphere that at a certain moment is both illuminated and visible. For a long time this was a very time-consuming calculation and hardly possible for polarized light. This long standing problem was re-investigated by Stam, Hovenier and collaborators and an efficient numerical method was found.

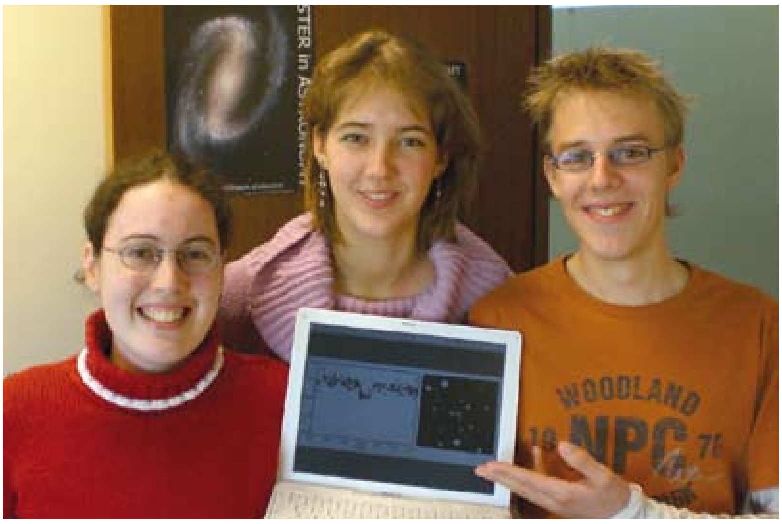

Figure 3.26: The proud astronomy Bachelor students with their discovered transiting extrasolar planet. From left to right, Francis Vuijsje, Meta de Hoon and Remco van der Burg.

3.2.7. Formation and evolution of massive stars

3.2.7.1. Massive star formation and methanol masers

Van Langevelde, together with Torstensson (PhD) and Bartkiewicz (Torun), studied a sample of methanol masers to investigate the earliest evolutionary tracers of high-mass stars. Data from the European VLBI Network were used to pinpoint the location where methanol is abundantly present and special excitation conditions prevail. A common result is that in sources where the central source can be identified, the methanol maser is typically found on 500 - 1000 AU scales. In one case, a unique ring-shaped methanol maser was discovered, which is being followed up with proper motion observations and attempts to detect the central source. Toward Cep A, the masers lie in the equatorial region around the well-known outflow source. Although the appearance is disk-like, the kinematic structure rules out masers in a rotating accretion disk.

3.2.7.2. Testing grain surface chemistry in massive hot cores

Bisschop (NOVA PhD), van Dishoeck, de Wachter and Jørgensen (CfA) published their JCMT submillimeter line survey toward 7 high-mass YSOs to search for H_2CO, CH_3OH, CH_2CO, CH_3CHO, C_2H_5OH, HCOOH, HNCO and NH_2CHO (Fig. 3.27). The aim was to establish the chemical origin of this set of complex organic molecules which are thought to be produced by grain surface chemistry based on schemes developed by Tielens. Based on their rotation diagrams, these molecules can be classified as either cold (<100 K) or hot (>100 K), implying that complex organics are present in at least two distinct regions. Furthermore, the abundances of the hot oxygen-bearing species are correlated, as are those of HNCO and NH_2CHO. This is suggestive of chemical relationships within, but not between, those two groups of molecules.

3.2.7.3. How much X-ray and UV radiation do protostars emit?

Stäuber, Benz (both ETH), Jørgensen (CfA), van Dishoeck and co-workers published their JCMT survey of ions and radicals toward low- and high-mass protostars, with the aim to probe any high energy radiation emitted by these sources which is not directly observable owing to their large extinctions. The species were selected to be particularly sensitive to either X-rays or UV radiation based on chemical models by Stäuber et al. For high-mass sources, the CN, SO^+ and CO^+ abundances are best explained by an enhanced UV field impacting gas at temperatures of a few hundred K. For low-mass YSOs, an X-ray enhanced region close to the protostar (<500 AU) is more plausible. The observed abundances imply X-ray fluxes for the deeply embedded Class 0 objects of $L_X \sim 10^{29}$-10^{31} erg s^{-1}, comparable to those observed from less deeply embedded YSOs.

The chemical models have been tested in more detail through SMA interferometric observations at 0.6" (600 AU) resolution of the high-mass YSO AFGL 2591 in lines of CS, SO and HCN. The CS and SO main peaks are extended at the FWHM level, as predicted in the model assuming protostellar X-rays. Broad pedestals in the CS and HCN emis-

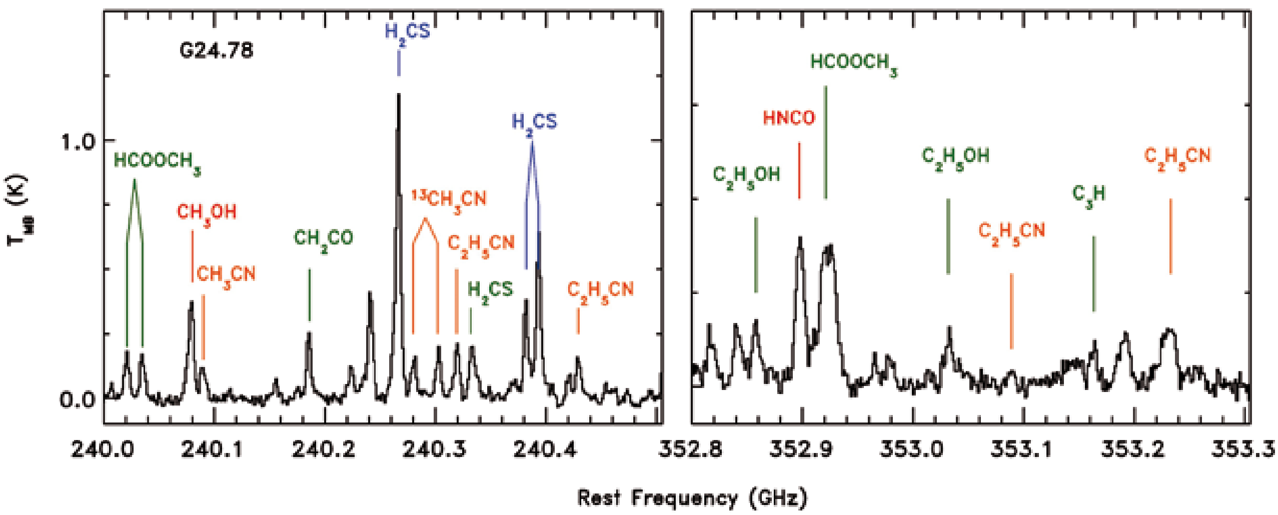

Figure 3.27: JCMT spectra of the high mass protostar G24.78 showing a wealth of complex organic molecules. From the relative strengths of the lines, excitation temperatures can be determined. Most molecules have high temperatures, except for CH^2CO, CH^3CHO and HCOOH (based on Bisschop et al. 2007, Astron. Astrophys. 465, 913).

sion can be interpreted by far-UV irradiation in a non-spherical geometry, possibly comprising outflow walls on scales of 3500-7000 AU. The extended CS and SO main peaks suggest sulfur evaporation near the 100 K temperature radius.

3.2.7.4. Water as a probe of high-mass YSO evolution

Doty (Denison), van Dishoeck and Tan (Florida) modeled the water abundance in high-mass YSO envelopes, taking infall and a realistic source evolution into account for the first time. Both ad/desorption of ices using recent laboratory measurements are included. It is found that the observed water abundance jump near 100 K is reproduced by an evaporation front which moves outward as the source luminosity increases. The age of the well-studied AFGL 2591 source is constrained to 8± 4 × 10^4 yr since collapse. More generally, it is shown that the chemical age-dating of hot cores at a few ×10^3-10^4 yr and the disappearance of hot cores on a timescale of ~10^5 yr is a natural consequence of infall in a dynamic envelope and protostellar evolution. Dynamically stable structures of ~350 AU size such as disks should contain most of the complex second generation species, given the chemical timescales of hot core, second generation chemistry.

Poelman (PhD) and van der Tak investigated the diagnostic value of specific water transitions in the high-mass star-forming region AFGL 2591. For this, 2D models are run by means of a multi-zone escape probability method developed by Poelman and Spaans. It is found that the low-lying transitions are more sensitive to outflow features and represent the excitation conditions in the outer regions. High-lying transitions are more sensitive to the adopted density and temperature distribution which probe the inner excitation conditions. The Herschel mission will thus be very helpful to constrain the physical and chemical structure of high-mass star-forming regions such as AFGL 2591.

3.2.7.5. The formation and evolution of massive stars

With VLT-ISAAC, Bik (NOVA PhD, now at ESO), Kaper and Waters obtained high-quality K-band spectra of strongly reddened point sources, deeply embedded in (ultra-)compact H II regions revealing a population of 20 young massive stars showing no photospheric absorption lines, but sometimes strong Brγ emission. The K-band spectra (Fig. 3.28) exhibit one or more features commonly associated with massive YSOs surrounded by circumstellar material: a very red color (J-K > 2), CO bandhead emission, hydrogen emission lines (sometimes doubly peaked), and Fe II and/or Mg II emission lines. The YSO properties mostly resemble those of Herbig Be stars, but some of them are young O stars. The spectral properties of the observed objects are consistent with an origin in a dense and neutral circumstellar disk causing the CO bandhead emission, and an ionized upper layer where the hydrogen lines are produced.

3.2.7.6. Formation and evolution of massive stars and binaries

Using near-infrared spectra obtained with VLT-ISAAC, Apai (Tucson), Bik, Kaper and collaborators performed the first multi-epoch radial velocity study of embedded young massive stars, with the aim of detecting massive binaries. Two stars were identified with about 90 km/s velocity differences between two epochs, indicating that these systems are close massive binaries. At least 20% of, but pos-

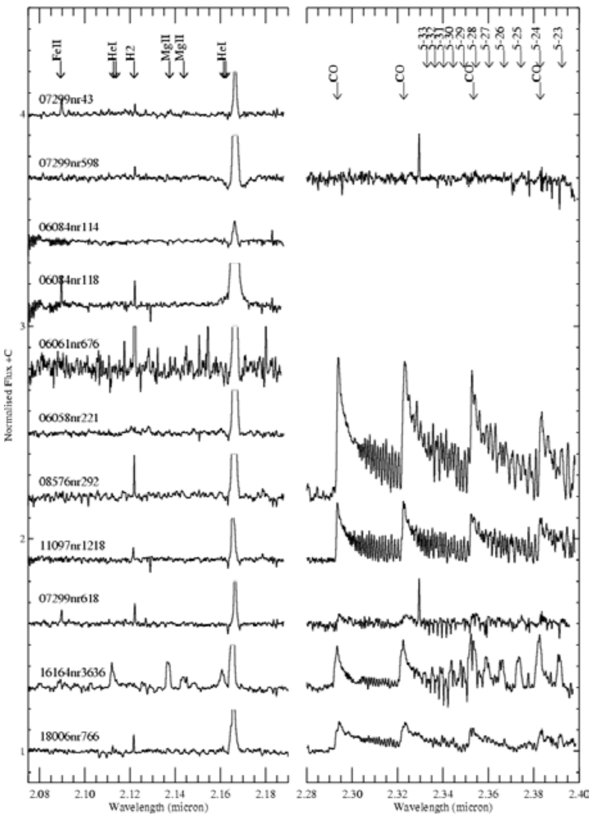

Figure 3.28: Normalized VLT-ISAAC K-band spectra of candidate massive YSOs. CO first-overtone emission, likely produced by the remnant accretion disk, is detected in 5 objects with pronounced difference in line shape.16164nr3636 and 18006nr766 show both CO and Pfund emission lines (from: Bik, Kaper and Waters 2006, Astron. Astrophys. 455, 561).

sibly all, young massive stars are formed in close multiple systems. The radial velocity dispersion of the full sample is about 35 km/s, significantly larger than our estimated uncertainty (25 km/s). This finding is consistent with similar measurements of the young massive cluster 30 Dor, which might have a high intrinsic binary rate.

Kouwenhoven (PhD), Kaper, Portegies Zwart and Brown performed an observational and computational study to find the primordial binary population, which is the population of binaries as established just after the expulsion of gas from the forming system. This study was done on the Scorpius-Centaurus OB association (Sco OB2) which is young and dynamically relatively inactive and therefore an ideal place to look for study. The recovery of the binary population includes detailed modelling of the observational selection effects, and indicates that virtually all stars of spectral types O-A in this association are part of a binary or multiple system. The components of the binary systems are not randomly paired, but a well-defined power-law mass ratio distribution is present instead.

The study of Kouwenhoven and co-workers further indicated a very small number of brown dwarf companions among intermediate mass (spectral types B and A) stars in Sco OB2, a property which is often referred to as the brown dwarf desert. However, this small number is consistent with an extrapolation of the observed stellar mass ratio distribution into the brown dwarf regime. This indicates that the physical mechanism for the formation of brown dwarf companions around intermediate mass stars is similar to that of stellar companions, and that the embryo ejection mechanism does not need to be invoked in order to explain the small number of brown dwarf companions among intermediate mass stars in Sco OB2.

3.2.7.7. The VLT-FLAMES survey of massive stars

Smartt (Belfast), Evans (Edinburgh), de Koter, Mokiem (PhD), Langer, Yoon and co-workers obtained spectra of an unprecedented sample of 800 massive stars in open cluster fields in the Magellanic Clouds and Milky Way, primarily with the multi-fibre FLAMES instrument on the VLT. Mokiem, de Koter and collaborators studied the optical spectra

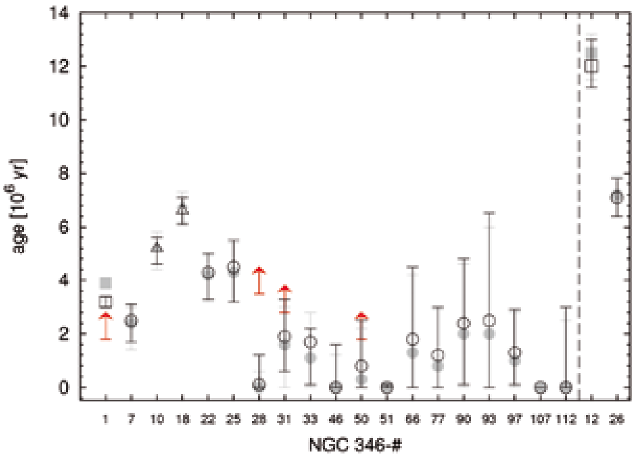

Figure 3.29: Age determination of the target stars in NGC 346 in the Small Magellanic Cloud using non-rotating models (open symbols) and those including rotation (closed symbols).Circles, triangles, and squares denote dwarfs, giants, and supergiants, respectively. The horizontal axis gives an identifier number of the star; the vertical axis the age in Myr. The lower limits (upward pointing arrows) provide age estimates from tracks of chemically homogeneous evolution. Most stars are best represented by an age of 1-3 Myr (from: Mokiem et al. 2006, Astron. Astrophys. 456, 1131).

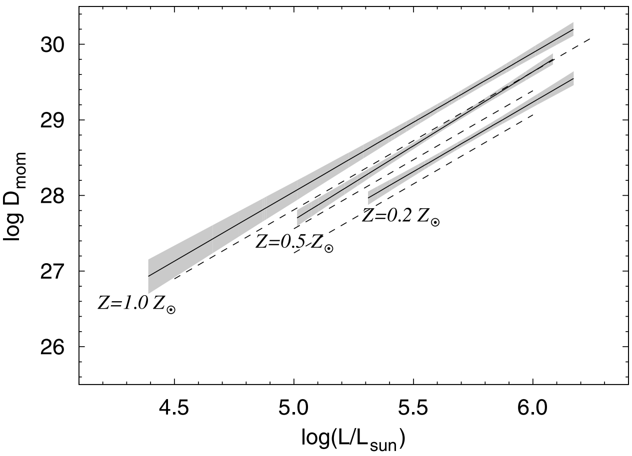

Figure 3.30: Comparison of the observed wind momentum – luminosity relation (solid lines) with the predicted relations of Vink et al. (dotted lines). Top, middle and bottom lines of each style, respectively, correspond to Galactic, LMC and SMC observed and predicted wind momenta. The offset between the lines is within the error bars the same for observations and theory, implying the same scaling of mass loss with metal content. The offset between observations and theory, for each galaxy, is likely due to inhomogeneities in the stellar winds (from: Mokiem et al. 2007, Astron. Astrophys. 473, 603).

of a sample of 31 O-and early B-type stars in the SMC, 21 of which are associated with the young massive cluster NGC 346. An age between 1-3 Myr (Fig. 3.29) was derived, and also the rotational velocity distribution. The young age of the cluster suggests that this rotational velocity distribution is representative for the initial distribution. Stars with helium enrichment can be understood when rotation is included in stellar evolutionary calculations. The mass loss rates of the SMC objects having luminosities in excess of 250,000 times the solar luminosity are in excellent agreement with predictions. However, for lower luminosity stars the winds are too weak to determine the mass loss rate accurately from the optical spectrum.

Mokiem, de Koter and Langer also derived the observational dependence of the mass-loss rate in stationary stellar winds of hot massive stars on the metal content of their atmospheres. Assuming a power-law dependence the mass loss is found to scale with metal content with a power-law index of 0.83 ± 0.16. Within the errors this agrees well with predictions (Fig. 3.30). Absolute empirical values of the mass loss, based on Hα and ultraviolet wind lines, are found to be a factor of two higher than predictions for stars having a brightness at least 160,000 times the sun. Most likely this discrepancy can be attributed to the presence of inhomogeneities in the stellar wind, implying clumping factors of about a factor of four.

3.2.8. Late stages of stellar evolution

3.2.8.1. Evolved low-mass stars

Mass loss plays a dominant role in the evolution of low mass stars while they are on the Asymptotic Giant Branch (AGB). By modelling the full line profile of low excitation CO lines emitted in the circumstellar envelope, Decin, de Koter, Waters and colleagues studied the mass-loss history of VY CMa. It is shown that both the observed integrated line strengths as well as the structure present in the observed line profiles, unambiguously demonstrate that this source underwent a phase of high mass loss some 1000 yr ago. This phase took place for some 100 yr, and was preceded by a low mass-loss phase taking some 800 yr. The current mass-loss rate is estimated to be in the order of 8×10^{-5} $M_\odot$ per year.

Together with Dijkstra (PhD) and Bouwman (Heidelberg), Dominik and de Koter have studied the formation of water ice mantles on grains in the outflow from red giants using model calculations of ice condensation in the flow. The water ice features probe the evolution of the star and its wind. Both crystalline and amorphous water ice form. The 43 and 62 μm crystalline water ice features are most prominent during the post-AGB phase, and only modestly or not present during the AGB and PN phase, in agreement with observations. The total amount of ice predicted (a few percent of the total dust mass) agrees with observations, but the crystalline ice mass fraction is consistently underpredicted. This is mainly due to efficient amorphization by interstellar UV photons, and leads to weaker 43 and 62 μm crystalline water ice features than observed.

Gielen, van Winckel (both Leuven), Dominik, Waters, and Min studied the grain processing in circumbinary disks around evolved binaries, focussing on the spectra of the RV Tauri twins RU Centauri and AC Herculis. The mineralogy and grain sizes indicate that the dust is highly processed, both in crystallinity and grain size. The cool crystals show that either radial mixing is very efficient and/or that the thermal history of grain formation has been very different from that in outflows. The physical processes governing the structure of these discs are very similar to those observed in protoplanetary disks around YSOs.

Together with Deroo, Acke, Verhoelst and Van Winckel (all Leuven) and Tatulli (Florence), Dominik studied the structure of the circumbinary disk around the post-AGB star IRAS 08544-4431, using interferometric observations with VLTI-AMBER and MIDI. Stable dust reservoirs around these stars have been postulated and studied for a number of years. The observations resolve the object both in the K 2.2 μm and in the N 10 μm band. The K band observations show a large asymmetry. The high spatial resolution measurements are used in conjunction with the broad band spectral characteristics to determine the dust geometry, based on self consistent 2D radiative transfer models. The dust around this evolved binary star is locked in a circumbinary disk with a significant scale height. Grain growth, settling, radial mixing and crystallization are efficient in such an environment.

3.2.8.2. Abundance determinations in planetary nebulae

Pottasch, together with Bernard-Salas (Cornell), compared the results of abundance studies of planetary nebulae and H II regions obtained over the past 5 years using ISO spectra with evolutionary models. This resulted in a consistent picture in how the evolution of different nebulae affects the abundances. It was furthermore found that the planetary nebulae evolve from stars of a chemical composition similar to the sun and to HII regions. A preliminary study of abundances of planetary nebulae in the Magellanic Clouds using mid-infrared observations from Spitzer was also performed. The ISO spectrum of the nebula Hb5 was studied in detail together with Surendiranath (Bangalore) and a model has been built which predicts both the ionic lines of many elements and those of H_2. This required inclusion of a photoexcitation region around the ionized nebula.

3.2.9. Molecular clouds in galaxies

3.2.9.1. The IMF in starburst environments

Spaans, in collaboration with Klessen (Heidelberg) and Jappsen (Potsdam) have finialized their investigations of the initial mass function (IMF) in interstellar environments that are exposed to intense radiation and exhibit large densities. Such extreme environments include the nuclei of starburst galaxies and the center of our Milky Way. It is found that the equation of state in such environments is very stiff and causes interstellar gas to heat up under compression. This prevents gas clouds to fragment significantly. Detailed hydrodynamical simulations of gravo-turbulent fragmentation then lead to the result that the IMF in starburst nuclei deviates from the typical Salpeter shape and exhibits a deficit of stars below 5 $M_\odot$. Such a top-heavy IMF is likely to persist for only a brief time and is the consequence of radiative (O and B stars, AGN) and mechanical (supernovae, AGN jets) feedback.

3.2.9.2. XDRs and infrared pumping in AGN

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 energy balance of interstellar gas and their study allows one to determine how the ISM survives the accretion of gas by a central black hole. X-ray photons from near-by sources heat through photo-ionization and dissociate the gas by UV emission from interactions of H and H_2 with secondary electrons. Fine-structure lines of [O I] and [C II] as well as molecular emission of, e.g., CO and H_2O provide cooling. Spaans and Meijerink (PhD, now at Berkeley) finished their investigation of XDRs and have developed a set of models that allow the modelling of the HCN, HNC, HCO^+, CO, ^{13}CO, CS and other emission lines of active galaxies. It turns out that the presence of very high J (>15) CO line emission is an excellent indicator for the presence of an embedded AGN. These lines are observable with Herschel-HIFI.

Meijerink and Spaans further added models on the formation of the transient molecule CO^+ that turns out to be very sensitive to even modest amounts of X-ray irradiation. As such, it provides a good probe of the onset of black hole accretion or for systems that radiate at sub-Eddington rates. Furthermore, Aalto (Onsala) and Spaans, together with Wiedner (Cologne) and Hüttemeister (Bochum), have investigated the formation and excitation of HNC in the active galaxies Arp 220, NGC 4418 and Mrk 231. It was found that X-ray or FUV irradiation is not sufficient to explain the bright HNC emissions of these systems. Instead, pumping of the molecule by infrared emission from dust grains, at temperatures above 50 K, is necessary.

3.2.9.3. Ultra Luminous Infra Red Galaxies

Together with Baan (ASTRON) and Spaans, Loenen (PhD) continued his investigation of the physical conditions in the cores of active galaxies (both starburst and AGN). The goal is to develop a method to infer physical properties from IR and mm observations like the (column) density and temperature of the gas and dust and the type and strength of the impinging radiation field. The first part of this project, which focused on the IR emission of dust surrounding a region of active star formation, was completed. In order to study the evolution of these dust enshrouded star-forming regions, a model was created using available stellar evolution and radiative transfer codes and was calibrated using IRAS data. The second part of the project focuses on the emission lines from molecules. A database was created containing observations of molecular emission lines (e.g. rotation lines of CO, HCN, HNC, HCO+, CN, CS) from own observations and literature.

3.2.10. Laboratory astrophysics

The experiments in the Raymond and Beverly Sackler Laboratory for Astrophysics at Leiden Observatory simulate inter- and circumstellar processes under laboratory controlled conditions, led by Linnartz. The focus is on gas phase studies of molecular transients of astrophysical interest and on solid state studies of inter- and circumstellar ice analogues (see section 5.5.4. for details). Together with Cuppen, van Dishoeck and co-workers, the results are interpreted in terms of unambiguous physical-chemical models to understand and to guide astronomical observations, and are used as input in astrochemical models.

The light scattering laboratory in Amsterdam has a setup to measure the intensity and polarization of light scattered by small dust particles, with complementary theoretical studies by Min, Hovenier and co-workers.

3.2.10.1. Interstellar and circumstellar ice analogues

Infrared spectroscopy towards dense molecular clouds and young stellar objects using ISO, Spitzer and VLT often reveals prominent bands that can be attributed to H_2O ice. It has been a long standing problem in the astronomical community that the observed intensity ratio of the 3 μm H_2O stretching mode and the 6 μm H_2O bending mode differs as much as a factor two compared to laboratory spectra recorded for pure water ice. It has been suggested that this discrepancy may be due to substantial amounts of other species mixed into the H_2O ice matrix. Two likely pollutants are CO_2 and CO. Systematic spectroscopy and band strength measurements have been performed at the HV setup for H_2O:CO_2 ices by Öberg (PhD) et al. and H_2O:CO-ices by Bouwman (PhD) et al. using Fourier transform transmission spectroscopy. To guide the interpretation of Spitzer data, HCOOH containing ices, mixed with CH_3OH, HCOOH and H_2O, have been measured by Bisschop (NOVA PhD) et al.

Öberg, Bisschop, Fuchs (NOVA PD), Acharyya (Greenberg fellow) and co-workers have studied the desorption of oxygen-bearing ices using CRYOPAD. The reason is that a substantial amount of interstellar oxygen may well freeze out onto grains in the form of molecular oxygen, potentially explaining the very low gaseous O_2 abundances observed in space. It is interesting to ask to what extent O_2 differs from CO, since CO is readily observed in the gas phase and in solid form, and how O_2 compares to N_2 which is observed to be present even in the coldest gas through the detection of N_2H^+ (see section 3.2.2.3). For this reason pure CO, N_2 and O_2 ices have been studied, as well as layered and mixed CO/N_2 and CO/O_2 ices. O_2 is found to be less volatile than CO and CO does not co-desorb with O_2, leading to the conclusion that in cold clouds with T_d < 18 K, O_2 can be frozen out onto grains. However, the relative difference in desorption between CO (and N_2) and O_2 is so small that this is unlikely to be the explanation for the missing gaseous O_2 in those interstellar clouds that show significant amounts of gaseous CO.

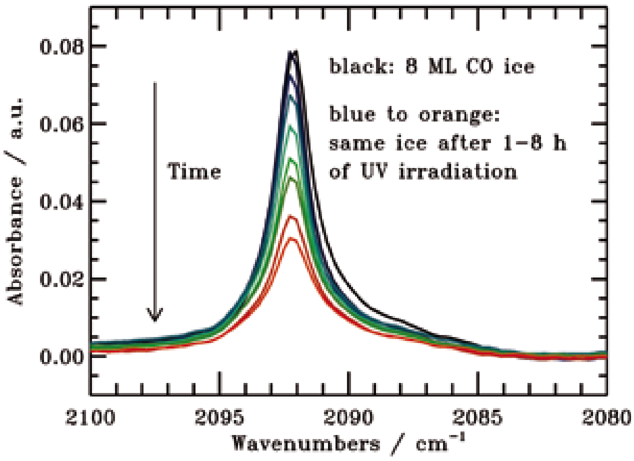

Figure 3.31: Reflection-absorption infrared spectra of the $C^{18}O$ v=1-0 vibrational band at 2093 cm^{-1} (2140 cm^{-1} for $C^{16}O$) acquired before irradiation of 8 ML of CO ice and then after every hour of irradiation during 8 hr. The drop in integrated absorbance is due to photodesorption and is linear with UV fluence, giving a yield per incident photon of ~3x10^{-3} (from: Öberg et al. 2007, Astrophys. J. 662, L23).

Photodesorption has been proposed in the past as a potential desorption pathway of CO in regions with excess UV photons but dismissed because of low estimated desorption yields. Öberg and co-workers have used the new ultra high vacuum experiment CRYOPAD in which CO-ice is exposed to UV radiation simulating the cosmic-ray induced radiation field inside dense clouds using a H_2 microwave discharge lamp (roughly 1000-2000 Å). In this experiment RAIRS (reflection absorption infrared spectroscopy) is used to monitor the CO absorption signal that is directly proportional to the amount of available CO ice. Upon irradiation the RAIRS signal linearly decreases with time (Fig. 3.31) and as the UV flux is known at the ice surface, it is straight forward to derive a value for the photodesorption rate: 3×10^{-3} CO molecules / per incident UV photon.

This is orders of magnitude higher than assumed previously. Incorporation in an astronomical model shows that the value is sufficiently high to explain the observed CO gas phase abundances in dark clouds and the coldest parts of disks.

Hydrogenation of atoms and molecules in ices is one of the key processes leading to more complex molecules in star-forming clouds. This has been proposed by Tielens and co-workers decades ago, but has never been tested in the laboratory. Bisschop and collaborators demonstrated for the first time that ethanol can form in interstellar ice upon H-atom bombardment of solid acetaldehyde, one of the steps in the proposed network.

Fuchs and co-workers studied the physical dependencies that may affect CO-ice hydrogenation, in particular: temperature, H-atom flux, layer thickness and ice morphology. Both the formation of H_2CO and CH_3OH are readily observed down to 12 K in CO-ice upon H-atom bombardment using RAIRS and temperature programmed desorption (TPD) as detection techniques. The previously observed discrepancy by other groups is likely due to the different H-atom fluxes used. The reaction rates show a maximum for both H_2CO and CH_3OH around a surface temperature of 13-15 K.

Al-Halabi and van Dishoeck performed classical trajectory calculations on the adsorption of H atoms to water ice at surface temperatures of 10 K. The adsorption probability as function of incident H-atom energy can be fitted to a simple decay function, with probabilities close to unity at 10 K. The average binding energy of the trapped H atoms for amorphous ice is significantly higher than that found for crystalline ice, affecting the residence times and consistent with laboratory experiments. The 'hot-diffusion' distance traveled by the impinging atom over the surface before being thermalized is found to be large, about 30 Å at incident energies of 100 K. The diffusion coefficient of thermally trapped H atoms is calculated for the first time. These data are important ingredients for models to describe the formation of H_2 on interstellar ices and reactions of H atoms with other species at the ice surface as performed by Cuppen.

3.2.10.2. Light scattering on dust

Volten, Munoz (both postdoc), Hovenier, Waters and co-workers have measured the intensity and degree of linear polarization of scattered light, for incident unpolarized light, for seven different samples of aggregates in random orientation. The aggregates are fluffy with cosmic dust analog compositions and diameters up to several micrometers. The measurements were performed at a wavelength of 6328 Å in the scattering angle range of 5-174 degrees. The results show extremely high values for the degree of linear polarization with maxima between about 60% to almost 100%. The phase functions appear to be determined by the overall shape of the aggregates and are similar to those of compact micron-sized particles. The results can be used to constrain the different physical properties of dust in e.g. circumstellar clouds and in comet ejecta. Similar measurements, but for the entire scattering matrix, were presented for large Saharan dust particles.

The effects of absorption on multiple scattering by random particulate media such as surfaces of planets, asteroids and moons was studied by Mishchenko, Liu and Hovenier. The numerically exact superposition T-matrix method was used to perform extensive computations. The results demonstrate the heuristic value of the concept of multiple scattering even in application to densely packed particulate media.

Usually, dust grains are frozen inside a matrix material that is mostly transparent to the radiation at which the dust is studied. However, effects of the matrix are not negligible. Mutschke, Min and co-workers have performed measurements of free-flying dust grains of various compositions and show that the optical properties derived in this way significantly deviate from those obtained using the matrix technique. These measurements provide crucial information for the studies of infrared spectra of dusty astronomical objects.

Min, Hovenier, Dominik, de Koter et al. have provided an analytic basis for the statistical approach to simulate the optical properties of complex, irregularly shaped particles by showing that, for very small particles, the optical properties of arbitrary distributions of arbitrarily shaped particles can be exactly represented by the optical properties of a distribution of very simple shapes. They also provided a way to compute this shape distribution for arbitrarily shaped particles.

Min, Dominik, Hovenier, de Koter and Waters have conducted research on the optical properties of agglomerates of particles. They found that the optical properties of very open, so-called 'fluffy', aggregates still very much resemble the optical properties of the constituents of the aggregate. This implies that estimates of the sizes of the grains from their optical properties very much depend on the assumed structure of the aggregates. Furthermore, Min contributed to a review of various methods for computing these optical properties for aggregated particles and Min and Hovenier started developing a method to efficiently perform computations for in-homogeneous aggregates of irregularly shaped constituents.

Hovenier and Stam proved that the intensity and the three other Stokes parameters of light reflected by a plane-parallel atmosphere are discontinuous if the directions of incidence and reflection are both horizontal. An exact expression describing these discontinuities was derived. It was shown that the discontinuities are only due to first order scattering at the top of the atmosphere. The exact expression may be applied , for example, to clarify the results of photo-polarimetric observations of regions near the intensity poles of a planet. Extension of this work to (bidirectional) reflection functions has been started by Hovenier and Stam.

Guirado, Hovenier and Moreno investigated how much circular polarization can be produced by scattering of unpolarized light by randomly oriented asymmetrical particles, i.e. particles without a plane of symmetry. They presented results of calculations of the degree of circular polarization considering aggregates of homogeneous spheres and analyzed the effects of changing the refractive index and size of the monomers. The values of the computed degree of circular polarization are generally in the range of the observed ones for light scattered by dust particles in several comets, the interplanetary medium and the interstellar medium.

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

The aim of NOVA 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. 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

Gamma-ray bursts (GRBs) are among the most violent explosions in the Universe. The study to understand them continues to generate considerable excitement.

3.3.1.1. The link between SNe and GRBs

With international colleagues, Wijers and co-workers made significant progress in elucidating the link between supernovae and gamma-ray bursts. In a major study with HST in which locations of GRBs in their host galaxies were compared with the locations of supernovae in their hosts, it was found that GRBs are strongly concentrated towards the brightest parts and do not follow the distribution of blue light. Supernovae, on the other hand, do follow the distribution of blue light in their hosts, indicating that the progenitors of the two classes of explosion are not the same. Strikingly, however, Type Ic supernovae, which were already suspected to be closely related to gamma-ray bursts, have the same concentrated distribution in galaxies. A further specific example of such an association was discovered and studied in a collaboration led by Pian (Trieste): supernova 2006aj coincided with GRB/XRF060218. It was a less luminous supernova than those associated with earlier GRBs, suggesting perhaps a slightly less massive progenitor star, or possibly even a neutron star central engine rather than a black hole. In a study led by Fynbo (Copenhagen), it was found that there are, however, some GRBs that do not appear to be associated with any supernova. In two cases, any presence of a supernova could be excluded to a luminosity at least 100 times less than the very bright Type Ic's found in, e.g., GRB 980425 and GRB 030329.

Van der Horst (PhD, now at NASA-Huntsville), Strom, and Wijers participated in an extensive study led by Kaneko (NASA-Huntsville) to compare the energetics and light curves of all gamma-ray bursts in which there was good evidence of an accompanying supernova, which used among others the results from the WSRT GRB follow up program. They also studied the properties and energetics of the supernova itself and showed that those of the relativistic part of the explosion (the GRB) span a much wider range than those of the non-relativistic part (the supernova). This latter component also carries most of the energy, indicating that overall the energy release accompanying the formation of a GRB is roughly standard, but the ultra-relativistic part of the explosion varies dramatically from case to case.

3.3.1.2. GRB observations

In a series of studies of the physics of afterglows of short GRBs, including Wijers and co-workers, it was reported that the degree of collimation of the outflow varies significantly between bursts: in GRB051221A, there is clear evidence of a collimated explosion, whereas in GRB050724 the outflow shows no collimation at all, implying at least a very large flow opening angle.

The study of extinction at high redshift in GRB afterglows also received considerable attention. The redshift record of z=6.3 of any GRB afterglow was established using photometric techniques by Wijers and collaborators, and later confirmed spectroscopically by a team from Subaru. The afterglow of GRB 060206 was probed with the WHT and other La Palma telescopes and found to have a very low-metallicity host, in which H_2 was tentatively detected. Some GRBs have extraordinarily large amounts of material around them: GRB 030115 is extremely red, and so is its host galaxy, indicating copious internal extinction and obscured star formation. However, no millimeter emission was detected from GRB hosts in a study led by Priddey (Hertfordshire), indicating perhaps hotter dust than in 'normal' submm galaxies. A systematic study of H column densities led by Jacobson (Hertfordshire) showed that they are generally consistent with the origin of GRBs in large molecular clouds. In the very rich line of sight towards GRB 060418, 3 foreground absorbers were seen, none of which are found with NTT spectroscopy after the GRB has faded; thus, all these intervening absorbers must correspond with fairly faint galaxies.

Wiersema (NOVA PhD; now in Leicester), Curran, Van der Horst, and Wijers studied the impact of a GRB on its ambient medium, and derived properties of that medium and the GRB host from spectroscopy of the afterglow. X-ray and optical absorption properties are found to be very poorly correlated, indicating that the two wavelengths may probe different media. The absorbing gas is more consistent with material from the general host ISM than with the star-forming cloud in the immediate vicinity of the burst. In a very rapid series of UVES spectra of GRB 060814 within the first hour after the burst, lines from metastable levels of FeII and NiII are found, which indicate that the gas is again far (~2 kpc) from the GRB and the levels are pumped by the UV flux of the explosion. A detailed VLT (UVES and FORS) spectral study of the dwarf galaxy that hosted GRB 060218/SN2006aj showed that it is extremely metal poor ($Z=0.07\ Z_{\odot}$). It has a very low star formation rate, but given its small mass its starburst can still be no older than 200 Myr.

Figure 3.32: The host of the highly extincted GRB 051022 in optical; the blueish color shows that the galaxy is only locally strongly extincted, suggesting that the GRB took place in a small, locally obscured star forming area. The size of the image is 9.2 x 5.7 arcmin (adapted from: Rol et al. 2007, Astrophys. J. 669, 1098).

In a study of broad-band X-ray to optical SEDs of a complete sample of pre-Swift afterglows, previous extinction estimates were improved by simultaneously fitting the data from optical to X-rays. It was found that the extinction law best representing the data is SMC-like, i.e., again metal poor. The absorption spectrum of the second-most distant GRB to date (060927, at z=5.47) was found to have a huge hydrogen column density as measured in the Ly-α line, indicating a very gas-rich host, which nonetheless is quite faint. This demonstrates that GRBs provide a way of pinpointing high-redshift star formation that is hard to find by other techniques.

Curran, Van der Horst, Wiersema, Strom and Wijers studied the physical properties of GRB blast waves by comparing their light curves at different wavelengths and constructing broadband SEDs. In a combined radio and X-ray study of GRB 051022 - a so-called 'dark burst' because it was undetected in optical and near-IR despite deep observations - physical parameters could be determined even without the optical data. Despite the high obscuration, the density immediately around the burst is not unusually high (Fig. 3.32); the afterglow blast wave energy appears less than that of the prompt gamma-rays, indicating very efficient gamma-ray emission. A study of the X-ray to optical emission of GRB 060210 (Fig. 3.33) indicated that the central energy source was long-lived, powering the afterglow up to 7 hours after the burst. Its total energy, corrected for jet beaming, is on the high side, at 2×10^{52} erg. A similar study of GRB 060206 suggests an answer to the riddle why Swift bursts show evidence of a jetted nature of the explosion much less

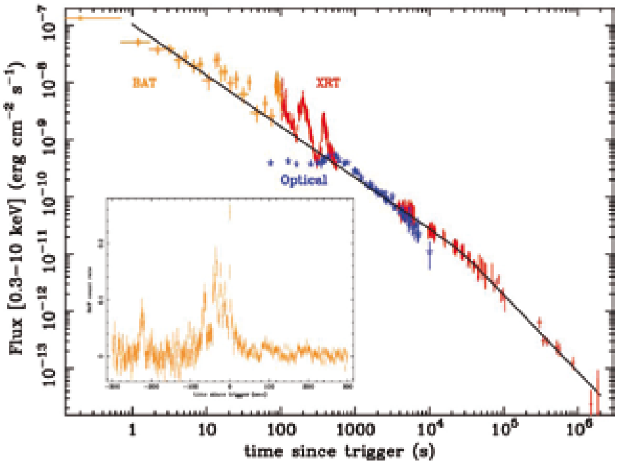

Figure 3.33: The multi-wavelength (gamma-ray to optical) light curve of GRB 060210. The sharp flares late in the light curve are evidence that the central engine can output significant power up to seven hours after the prime outburst causing the GRB (from: Curran et al. 2007, Astron. Astrophys. 467 1049).

often than pre-Swift bursts. The reason may well be that a jet break is much harder to find in X-ray data than in optical, whereas Swift bursts very often only have X-ray data for the afterglow (and pre-Swift bursts usually had the reverse: better optical than X-ray data).

3.3.1.3. GRB modeling

Peér (PhD, now at StScI), Wijers, and collaborators examined a novel way of measuring the Lorentz factor of the gamma-ray emitting ejecta in GRBs. This makes use of a thermal component seen in the first few seconds of the burst and provides the first fairly model-independent values of the initial Lorentz factor. Application to the data showed a value of around 300, with 10% accuracy. They also measured the initial size of the fireball for the first time, finding it to be about 10^7 cm.

Peér, Wijers, and colleagues concluded that the early emission of GRBs, and even the start of the afterglow, can have contributions from a quasi-thermal component. They also studied in detail the effect of a GRB blast wave reaching the termination shock of the stellar wind of the GRB progenitor, and predicted that this event should be visible in the light curve of the afterglow, allowing one to estimate the progenitor's properties. Peér also studied how the emission of a GRB changes if only a thin layer of material just behind the shock has a significant magnetic field.

Koers (PhD; now at Brussels) and Giannios (MPA) studied the consequence of the presence of neutrons in different models of the outflows of GRBs. They found a very strong difference between thermal fireballs on the one hand and magnetic-dominated outflows on the other, which is due to the much slower acceleration in the magnetically powered case. Specifically, only the fireballs produce significant GeV gamma-ray emission, making GLAST a promising instrument to diagnose the nature of the jet-powering mechanism.

3.3.1.4. GRB/SN progenitor models

Yoon (Veni), Langer and Norman (Baltimore) investigated the effects of rotation on the stellar structure and the transport of angular momentum and chemical elements through the Spruit-Tayler dynamo and rotationally induced instabilities in low metallicity massive star evolution models. The final fate of massive stars as a function of initial mass and spin rate is considered for a range of metallicities. In particular, the initial conditions for which long GRBs are expected to be produced in the frame of the collapsar model are explored. Using an empirical spin distribution of young massive metal-poor stars and a specified metallicity-dependent history of star-formation, the expected GRB rate as function of metallicity and redshift is subsequently produced based on Langer's stellar evolution models. The GRB production in these models is limited to metallicities of $Z < 0.004$, with the consequence that about 50% of all GRBs are predicted to be found at redshifts above $z = 4$, with most supernovae occurring at redshifts below $z < 2.2$. The average GRB/SN ratio predicted is about 1/200 globally, and 1/1250 at low redshift (Fig. 3.34).

The collapsar model for long gamma-ray bursts requires a rapidly rotating Wolf-Rayet star as progenitor. Cantiello (NOVA PhD), Yoon, Langer and Livio (STScI) tested the idea of producing rapidly rotating Wolf-Rayet stars in massive close binaries through mass accretion and consecutive quasi-chemically homogeneous evolution. They use a 1D hydrodynamic binary evolution code to simulate the evolution of a 16+15 $M_\odot$ binary model with an initial orbital period of 5 days and SMC metallicity (Z=0.004). The considered binary system undergoes early Case B mass transfer. The mass donor becomes a helium star and dies as a Type Ib/c supernova. The mass gainer is spun-up, and internal magnetic fields efficiently transport accreted angular momentum into the stellar core. The orbital widening prevents subsequent tidal synchronization, and the mass gainer rejuvenates and evolves quasi-chemically homogeneously thereafter. The mass donor explodes 7 Myr before the collapse of the mass gainer. Assuming the binary to be broken-up

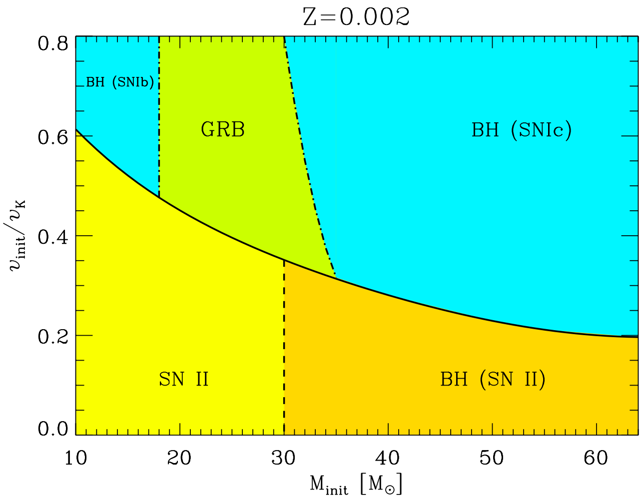

Figure 3.34: Final fate of rotating massive star models at a metallicity of Z=0.002, in the plane of initial mass and initial fraction of the Keplerian value of the equatorial rotational velocity. The solid line divides the plane into two parts, where stars evolve quasi-chemically homogeneous above the line, while they evolve into the classical core-envelope structure below the line. The dotted-dashed lines bracket the region of quasi-homogeneous evolution where the core mass, core spin and stellar radius are compatible with the collapsar model for GRB production. The dashed line in the region of non-homogeneous evolution separates type II supernovae (SN II; left) and black hole (BH; right) formation, where the minimum mass for BH formation is simply assumed to be 30 $M_\odot$ (from: Yoon, Langer & Norman 2006, Astron. Astrophys. 460, 199).

by the supernova kick, the potential GRB progenitor would become a runaway star with a space velocity of 27 km/s, traveling about 200 pc during its remaining lifetime. While the binary channel does not provide a new physical model for collapsar production, it may provide a means for massive stars to obtain the required high rotation rates. Moreover, it suggests that a possibly large fraction of long gamma-ray bursts occurs in runaway stars.

Pair creation supernovae (PCSN) are thought to be produced from very massive low metallicity stars. The spectacularly bright SN 2006gy does show several signatures expected from PCSNe. Langer, Yoon, de Koter, Cantiello, with Norman (Baltimore) and Vink (Belfast) investigated the metallicity threshold through stellar evolution calculations for stars of 150 $M_\odot$ and 250 $M_\odot$ of 0.2×$Z_\odot$ and 0.05×$Z_\odot$. The bifurcation between quasi-chemically homogeneous evolution for fast rotation and conventional evolution for slower rotation, which has been found for massive low metallicity stars, persists in the mass range considered here. Consequently, there are two separate PCSN progenitor types: (1) fast rotators produce PCSNe from very massive Wolf-Rayet stars, and (2) slower rotators that generate PCSNe in hydrogen-rich massive yellow hypergiants. Hydrogen-rich PCSNe are found to be possible at metallicities as high as 0.3×$Z_\odot$, which – assuming standard IMFs to estimate their birth rates – results in a rate of about one PCSN per 1000 supernovae in the local universe, and one PCSN per 100 supernovae at a redshift of z = 5. PCSNe from WC-type Wolf-Rayet stars are found to be restricted to much lower metallicity.

3.3.1.5. GRB/SN circumstellar medium models

The progenitor stars of long GRBs are thought to be Wolf-Rayet stars, which generate a massive and energetic wind. Nevertheless, about 25% of all GRB afterglow light curves indicate a constant density medium close to the exploding star. Van Marle (PhD), Langer, Achterberg and García-Segura (Ensenada) explore various ways of stars to produce this, by creating situations where the wind termination shock arrives very close to the star, as the shocked wind material has a nearly constant density. Several scenarios are investigated to reduce the distance between star and shock needed to produce the afterglow, all of which are possible in a limited parameter space, but none of which are by itself likely to explain the large fraction of constant density afterglows (Fig. 3.35). It is concluded that a low GRB progenitor metallicity and a high GRB energy is more likely. This may be consistent with constant densities being preferentially found for energetic, high redshift GRBs.

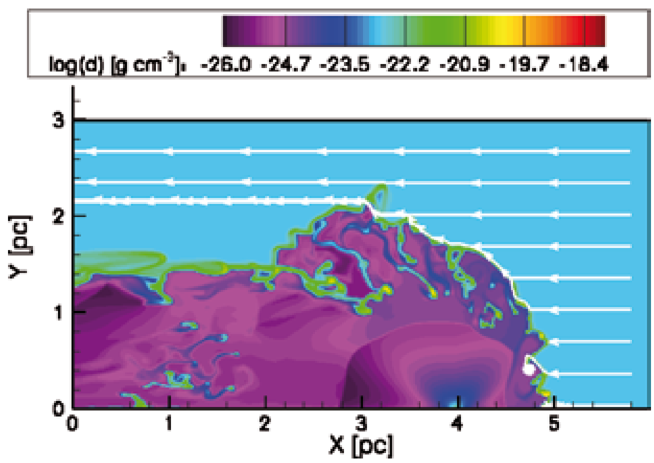

Figure 3.35: The density of the gas around a post-red supergiant Wolf-Rayet star which moves with a space velocity of 80 km/s. The velocity field in the ambient medium is shown as stream tracer. The bowshock-shell system is highly unstable. A constant density can be found just 1 pc ahead of the Wolf-Rayet star (from: van Marle et al. 2006, Astron. Astrophys. 460, 105).

Van Marle, Langer and Garcia-Segura also investigated the initially more massive Wolf-Rayet stars which are thought to evolve through a Luminous Blue Variable (LBV) stage. They performed hydrodynamic simulations of the evolution of the circumstellar medium around a 60 $M_{\odot}$ star and then computed the column density of the circumstellar matter along rays from the central light source to an observer at infinity, as a function of radial velocity, time and angle. This allows a comparison with the number and velocities of absorption components in the spectra of LBVs, Wolf-Rayet stars, Type Ib/c SN and GRB afterglows. Shells with velocities in the range of 100 to 1200 km/s were formed at the beginning of the Wolf-Rayet stage, but these are rather short lived, <50,000 yr. The LBV stage is thought to occur at the beginning of core helium burning, so the remaining Wolf-Rayet life time is expected to be one order of magnitude larger. No intermediate velocity absorption components were predicted to prevail until core collapse. However, a close binary with a late common-envelope phase may produce a circumstellar medium that closely resembles the LBV to Wolf-Rayet evolution, but with a much shorter Wolf-Rayet period.

3.3.2. X-ray binaries

Accreting neutron stars and black holes in X-ray binaries form the brightest X-ray point sources in the sky and by studying the processes around these accreting compact objects important information about the extreme physical processes related to these compact stars can be obtained. In 2006 Lewin (MIT) and van der Klis published their long-expected book 'Compact Stellar X-Ray Sources' with Cambridge University Press. The 690-page volume contains a comprehensive description of the state of the art in the X-ray astronomy of stellar-mass compact objects, contributed by a selection of the leading experts in the field and will be the standard reference in the field.

3.3.2.1. Searching for X-ray transients

Most X-ray binaries are transient systems: they are most of the time very faint in X-rays but occasionally, due to a large increase of the mass accretion rate onto the accretor, they exhibit bright X-ray outbursts during which the X-ray luminosity increases by many orders of magnitude. During outburst, these systems are very similar to the persistent systems and can be used to study the physics related to compact stars. In addition, important information about neutron stars and black holes can be obtained when they are in their quiescent state. However, to study them, X-ray transients have to be discovered first and several programs have been initiated to find more.

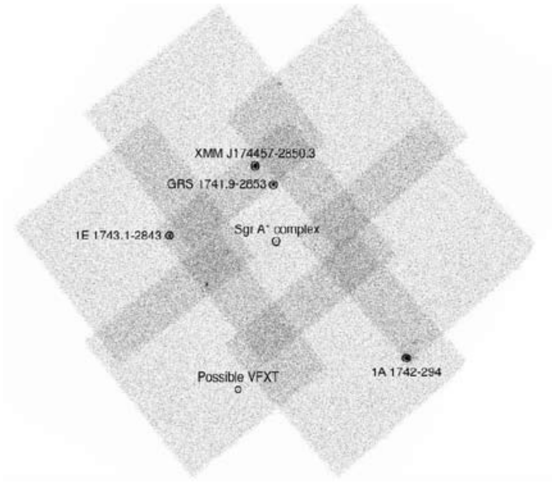

Figure 3.36: The merged image (1.4°x1.4°) of the 7 Chandra/HRC-I observations used to monitor the Galactic center region for very-faint X-ray transients. Two persistent X-ray binaries (1E 1743.1-2843 and 1A 1742-294) are clearly detected, as well as two very faint transients GRS 1741.9-2853 and XMM J174457-2850.3 (from: Wijnands et al. 2006, Astron. Astrophys. 449, 1117).

The Galactic bulge region is full of highly variable high-energy point sources. Since 2005, a large collaboration led by Kuulkers (ESA) including Wijnands is monitoring the source activity in the Galactic bulge region regularly and frequently, i.e., about every three days, with the gamma-ray satellite INTEGRAL. Thanks to the large field of view, the imaging capabilities and the sensitivity at hard X-rays, a detailed homogeneous (hard) X-ray view of a sample of 76 sources in the Galactic bulge region was presented for the first time. Per visibility season, 32/33 sources are detected in the 20-60 keV band and 8/9 sources in the 60-150 keV band, and on average one active bright black-hole candidate X-ray transient and three active weaker neutron star X-ray transients are found.

Recently, a class of very faint X-ray transients has been found in our Galaxy. These enigmatic systems might harbor a neutron star or a black hole accreting from their companion stars at an extremely low rate. Wijnands, van der Klis, Miller-Jones (postdoc, now Jansky Fellow at NRAO) and collaborators initiated in 2005 a X-ray monitoring campaign on a 1.2 square degree region centered on Sgr A* using XMM-Newton and Chandra. Most of the detected sources could be identified with foreground sources, such as X-ray active stars, but in addition two persistent X-ray binaries and two very faint X-ray transients were detected (Fig. 3.36). In additional observations, the activity of the enigmatic transients CXOGC J174535.5-290124 and SAX J1747.0-2853 was studied. Using quasi-daily Swift observations of Sgr A*, Kennea (Penn State), Wijnands and co-workers also found activity of the very-faint transient Swift J174540.2-290005.3. The Chandra/XMM-Newton monitoring and the Swift observations continued in 2007-2008 resulting in the discovery of additional systems and recurrent outbursts of the known ones.

Individual transients were studied in detail by various groups using a variety of instruments. Wijnands, Maitra, Linares and co-workers used Swift/XRT to observe the bright neutron-star X-ray transient Aql X-1, triggered by renewed activity of the source in the J and R bands. The source was found already at a relatively high mass accretion rate only days after it was first detected in outburst at optical, putting new constraints on the models for the outburst mechanism. Cackett (Michigan), Wijnands, and Remillard (MIT) found a new bright X-ray transient (XMMU J181227.8-181234) in the Galactic plane using archival XMM-Newton data. X-ray spectral and timing properties of the source indicate it is a low-mass X-ray binary. The source was missed by the all-sky monitoring X-ray instruments because it is located close to the very bright source GX 13+1, demonstrating that surveying and monitoring instruments need high spatial resolution to find all active systems. Wijnands and collaborators also studied data obtained with Chandra and RXTE taken of the bright new X-ray transient XTE J1817-330, whose spectral characteristics and variability suggest that it harbors a black hole.

3.3.2.2. X-ray transients in quiescence

Thermal X-ray radiation from neutron star soft X-ray transients in quiescence provides the strongest constraints on the cooling rates of neutron stars and thus on the interior composition and properties of matter in the cores of neutron stars. Heinke (Northwestern), Wijnands and collaborators analyzed new (2006) and archival (2001) XMM-Newton observations of the accreting millisecond pulsar SAX J1808.4-3658 in quiescence, which provide the most stringent constraints to date. The X-ray spectrum of SAX J1808.4-3658 in the 2006 observation is consistent with a power law of photon index ~1.8, without requiring the presence of a blackbody-like component from a neutron star atmosphere. Simultaneous fitting of all available XMM-Newton data allows a constraint on the quiescent neutron star luminosity of $<1.1\times10^{31}$ erg s^{-1}. This limit excludes some current models of neutrino emission mediated by pion condensates and provides further evidence of additional cooling processes, such as neutrino emission via direct Urca processes involving nucleons and/or hyperons, in the cores of massive neutron stars.

Cackett, Wijnands, Linares and co-workers used Chandra and XMM-Newton X-ray observations to monitor the neutron star cooling of the quasi-persistent neutron star X-ray transients KS 1731-260 and MXB 1659-29 for approximately 4 yr after these sources returned to quiescence from prolonged outbursts. In both sources the outbursts were long enough to significantly heat the neutron star crust out of thermal equilibrium with the core. In both sources the neutron star crust cools down very rapidly suggesting it has high heat conductivity and that the neutron star core requires enhanced core cooling processes. This is the first time that the cooling of a neutron star crust into thermal equilibrium with the core has been observed in such detail.

Two groups including Wijnands as co-worker (Cackett et al.; Heinke et al.) reported on Chandra observations of the globular clusters Terzan 1 and Terzan 5. In Terzan 1, 14 X-ray sources are detected within 1.4 arcmin of the cluster center. The neutron star X-ray transient, X 1732-304, has previously been observed in outburst within this globular cluster with the outburst seen to last for at least 12 yr. Although four sources were detected that were consistent with their ROSAT position, the most likely quiescent counterpart of the bright transient was identified based on its X-ray spectrum. From the estimated stellar encounter rate of this cluster the number of detected X-ray sources is significantly higher than expected by the relationship found for a survey of other clusters. In Terzan 5, 50 X-ray sources within the half-mass radius of the cluster were detected. Thirty-three of these have X-ray luminosities larger than 10^{32} ergs s^{-1}, the largest number yet seen in any globular cluster. About 13 relatively soft sources may be quiescent low-mass X-ray binaries. No clear metallicity dependence in the production of low-luminosity X-ray binaries in Galactic globular clusters was found.

Cornelisse (Canarias), Homan (NOVA PhD; now at MIT) and Wijnands observed the neutron star X-ray transient 2S 1803-245 in quiescence with XMM-Newton, but did not detect it. An analysis of the X-ray bursts observed during the 1998 outburst gives an upper limit to its distance of 7.3 kpc, leading to an upper limit on the quiescent X-ray luminosity of 2.8×10^{32} erg s^{-1}. Since the expected orbital period of 2S 1803-245 is several hrs, this limit is not much higher than those observed for the quiescent black hole transients with similar orbital periods.

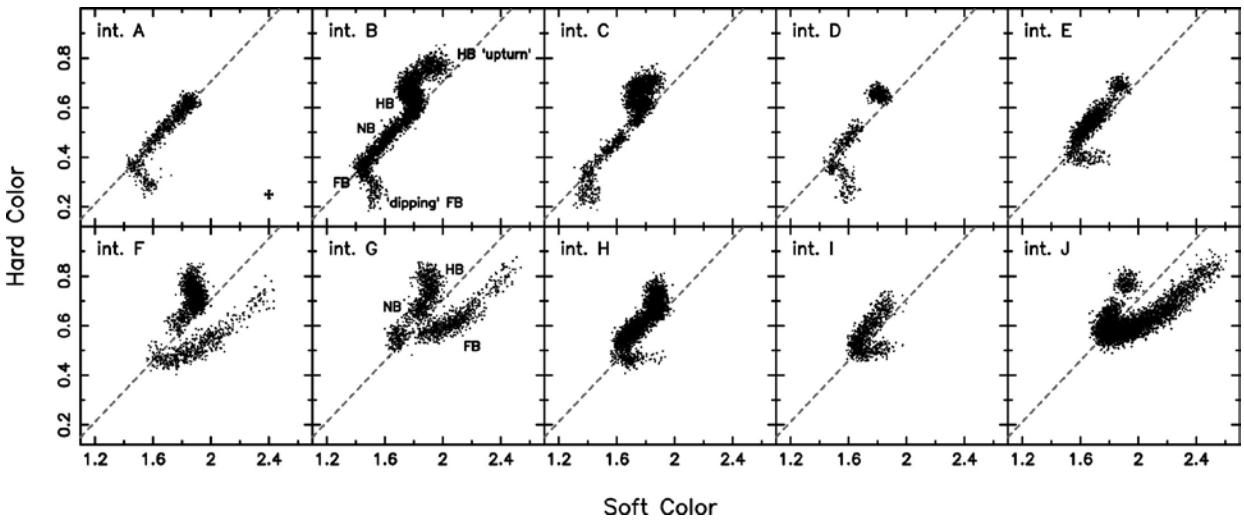

Figure 3.37: The X-ray color-color diagram for 10 intervals (in chronological order) of XTE J1701-462 as observed with RXTE. Clearly, the region that the source traces in such diagram changes shape (becoming less Z like toward the end) and position in the diagram (from: Homan et al. 2007, Astrophys. J. 656, 420).

Homan, Wijnands and collaborators used XMM-Newton to observe the black hole X-ray transient XTE J1650-500 in its quiescent state. The source was not detected and the upper limits on the quiescent X-ray luminosity were found to be in line with those measured of other black-hole X-ray binaries with similar orbital periods (~7-8 hr), but at least an order of magnitude lower than the quiescent luminosities typically observed from neutron-star X-ray transients supporting the black hole classification of the system.

Kaaret and collaborators (including Wijnands) used XMM-Newton to study the X-ray jet in the black hole candidate 4U 1755-33 in quiescence. Although the jet was still detected in X-rays, it could not be seen in sensitive radio observations. This indicates that synchrotron radiation is a viable emission mechanism for the jets and that thermal bremsstrahlung and inverse Compton emission are unlikely on energetic grounds.

3.3.2.3. The first Z source transient

Homan, in collaboration with van der Klis, Wijnands, Klein-Wolt, Méndez and collaborators reported on a RXTE discovery that had been anticipated since the 1980's: the first transient Z source. Z sources, as defined by Hasinger and van der Klis in 1989, are neutron stars accreting matter from a low mass companion star at a rate varying closely around the theoretical maximum (Eddington) rate for a neutron star. A Z source produces the same amount of energy in X-rays in just a day as the Sun does by shining for 300 years. Models for the Z phenomenon had been debated for more than 20 years, where two schools attributed the unique observed properties to either an intrinsic property of the neutron stars involved (a stronger magnetic field) or to just the near-Eddington accretion rate. All known Z sources are persistently very bright in X-rays. The discovery of a Z source that is transient, i.e., a mode of behavior commonly exhibited by accreting neutron stars (and black holes), could decide this issue. Homan et al. found such a Z source and reported on the first ten weeks of observations of the object, XTE J1701-462, demonstrating that it is transient, and has all the characteristics of a Z source, including not only the Z shaped track in the X-ray color-color diagram but also the characteristic kilohertz quasi-periodic oscillations (see section 3.3.2.4) in X-ray flux. During the course of the observations the flux decreased by 50% and a switch in characteristics was observed (Fig 3.37) that was taken to indicate the source was getting ready to shed its 'Z' character and turn into a more ordinary, less bright, accreting neutron star. This has since happened indeed.

3.3.2.4. Kilohertz Quasi-Periodic Oscillations in neutron star X-ray binaries

Accreting low magnetic field neutron stars are expected to most closely resemble accreting black holes as these also have low magnetic fields. Because the field is weak, matter can orbit down very close to the neutron star, in regions where gravity is so strong that orbital velocities are half the speed of light, and the matter orbits the star more than a thousand times per second. This is thought to be the origin of the so-called kilohertz quasi-periodic oscillations (kHz QPOs), which are regular variations in the X-ray flux at just these frequencies. An important and long anticipated discovery by Boutloukos (NOVA visitor Marie Curie host institute program), van der Klis, Altamirano (NOVA PhD), Klein-Wolt, Wijnands, Jonker (former PhD; now at SRON) and Fender was that of kHz QPOs in the neutron star Circinus X-1, whose peculiar properties make it look like a black hole. Thus, finding the QPOs was a reassurance both with respect to the identification of the object as a neutron star and the ubiquity of kHz QPOs in weakly magnetized neutron stars. QPOs do have properties that are different from those seen previously in other neutron stars and confirm a prediction that had been made by the competing relativistic precession model that has been proposed for the phenomenon. This model attributes one of the two frequencies observable in these QPOs to a relativistic precession identical to that contributing to the famous precession of Mercury's orbit around the Sun, but fifteen million billion times faster. It predicts a reversal of the relation between the relativistic radial epicyclic frequency and orbital frequency below orbital frequencies of about 500 times per second. Circinus X-1 was the first neutron star to sample these low frequencies and the predicted reversal was indeed observed, strengthening the model (Fig. 3.38).

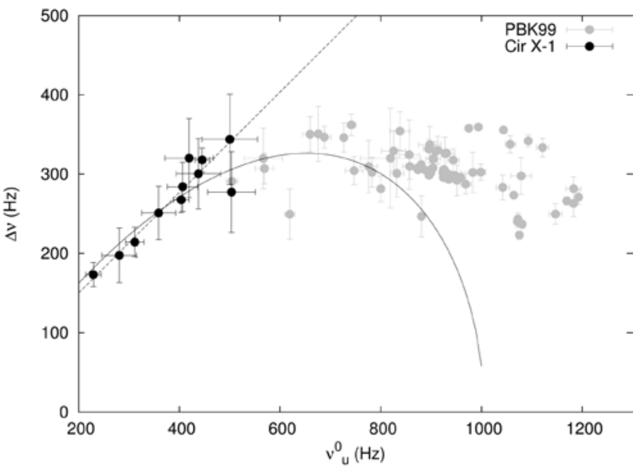

Figure 3.38: The frequency separation δν of the twin kHz QPOs in Cir X-1 as a function of the frequency of the highest-frequency kHz QPO. The curve indicates the prediction by the relativistic precession model (from: Boutloukos et al. 2006, Astrophys. J. 653, 1435).

It has been advocated that the frequencies of the kHz QPOs are directly linked to the spin of the neutron star. The root of this idea is the apparent clustering of the ratio of the frequency difference between the pair of kHz QPOs and the neutron-star spin frequency at around 0.5 and 1 in 10 systems for which these two quantities have been measured. Méndez and Belloni (Brera) have re-examined all available data of sources for which measurements of two simultaneous kHz QPOs and spin frequencies exist, and have shown that the data are consistent with a situation in which the frequency differences are not related to each other. There are a few sources for which the neutron-star spin frequency has been measured, but for which a pair of kHz QPOs have not yet been detected. If the proposal advanced by Méndez is correct and if these sources ever show pairs of kHz QPOs, the ratio of the QPO frequency difference and the neutron-star spin should be significantly different from 0.5 or 1. Interestingly, after the paper by Méndez and Belloni was published, a tentative spin frequency was claimed for 4U 0614+09, for which pairs of kHz QPOs had already been observed and the ratio is 0.78±0.02, supporting their proposal.

It was recently proposed that the coherence and the amplitude of the kHz QPOs respond to the geometry of space-time and that these QPOs provide evidence of the so-called innermost stable circular orbital radius predicted by general relativity. The basis was the slow increase and sudden drop of the amplitudes and coherence of the QPOs as the frequency of the QPOs increased. Méndez found that the maximum rms amplitudes of the kHz QPO in a sample of a dozen sources decreases more or less exponentially with increasing luminosity of the source, and that the maximum coherence of the kHz QPO first increases and then decreases exponentially with luminosity. The maximum rms amplitude and maximum coherence in the sample of sources, and the rms amplitude and coherence of the kHz QPOs in individual sources show a similar behavior with hardness. This similarity argues against the interpretation of the innermost stable circular orbit around a neutron star.

Méndez and collaborators re-examined the correlation between the frequencies of upper and lower kHz QPOs in bright neutron star low-mass X-ray binaries. By including the kHz QPO frequencies of Cir X-1 and two accreting millisecond pulsars in their sample, they show that the full sample does not support the class of theoretical models based on a single resonance, while models based on relativistic precession or Alfvén waves describe the data better. In a subsequent analysis, Méndez and collaborators used observations with RXTE to investigate the atoll-type neutron star low-mass X-ray binary 4U 1636-53 in a campaign spanning more than 1.5 years, and consisting of short (~2ks) pointings separated by ~2 days and regularly monitoring the spectral and timing properties of the source. A long-term oscillation with a period of ~30-40 days was found, already seen in the light curves from the RXTE All-Sky Monitor, which corresponds to regular transitions between the hard (island) and soft (banana) states. KHz QPOs are detected in about a third of the observations, most of which were in the soft (banana) state. The distribution of the frequencies of the peak identified as the lower kHz QPO was different from that previously observed in an independent data set, suggesting that the kHz QPOs in the system show no intrinsically preferred frequency.

Jonker, Méndez, van der Klis and colleagues discovered kHz QPOs in the relatively weak ultra-compact X-ray binary 1A 1246-588 with surprisingly high amplitude: 27 percent of the X-ray flux emitted by the neutron star. This is the strongest kHz QPO so far observed and confirms the enigmatic but quite reliable rule that the weaker the star's X-ray flux, the stronger the kHz QPOs are.

3.3.2.5. Spectral studies of neutron-star X-ray binaries

X-ray spectroscopy was performed of the low-magnetic neutron stars 4U1728-34, Scorpius X-1 and Cygnus X-2 by d'Ai and Lavagetto (Palermo), di Salvo (former NOVA postdoc; now at Palermo), van der Klis, Méndez, and co-workers. In the first-mentioned object, a well know thermonuclear burst source, it was demonstrated that the spectral feature that is usually described in terms of a broad Fe emission line near 6 keV could as well be due to two absorption edges near 7 and 9 keV associated with lowly ionized iron and Fe XXV/XXVI, respectively. This new interpretation has consequences for both the geometry and the physical circumstances of the emitting plasma in this and related systems. In the Z source Sco X-1, the brightest X-ray binary in the sky, observations with INTEGRAL allowed to map out the dependence of non-thermal hard X-ray emission in this source on soft X-ray spectral state. The results agree with those previously obtained on GX 17+2, a closely analogous but much weaker Z source. Interestingly, similar INTEGRAL observations of the Z source Cyg X-2 show no evidence for such non-thermal emission.

3.3.2.6. Neutron-star X-ray binaries at other wavelengths

Migliari (PhD, now at San Diego), Miller-Jones, Fender, Wijnands, van der Klis and collaborators presented the results of simultaneous radio (VLA) and X-ray (RXTE) observations of the Z-type neutron star X-ray binary GX 17+2. These observations allowed them, for the first time, to investigate quantitatively the possible relations between the radio emission and the presence of hard X-ray tails and the X-ray state of the source. The observations revealed (1) a coupling between the radio jet emission and the X-ray state of the source; (2) a coupling between the presence of a hard X-ray tail and source state, qualitatively similar to that found for the radio emission; and (3) an indication of a quantitative positive correlation between the radio flux density and the X-ray flux in the hard tail power-law component.

Jonker, Nelemans and Bassa (NOVA PhD) studied the peculiar X-ray binary Cir X-1 and determined an eccentric orbit. They found evidence for the companion of the compact object to be a super-giant, although the spectrum could also originate in the accretion disc. In 't Zand, Jonker, Nelemans and coworkers studied the candidate obscured high-mass X-ray binary IGR J1940+0951 with Chandra and optical spectroscopy, confirming its identification.

Tudose and collaborators, including Fender and van der Klis, performed multi-epoch observations of the radio nebula around the neutron star X-ray binary Cir X-1 at 1.4 and 2.5GHz with ATCA between 2000 October and 2004 September. A radio nebula can be seen as a result of the interaction between the jet from the system and the interstellar medium. This nebula offers a unique opportunity to estimate for the first time using calorimetry the energetics of a jet from an object clearly identified as a neutron star. The results suggest an age for the nebula of $< 10^5$ yr and a corresponding time-averaged jet power $>10^{35}$ erg s^{-1}.

3.3.2.7. Thermonuclear flashes from accreting neutron stars

Type-I X-ray bursts are thermonuclear flashes that take place on the surface of accreting neutron stars. The wait time between consecutive bursts is set by the time required to accumulate the fuel needed to trigger a new burst; this is at least one hour. Sometimes secondary bursts are observed, approximately 10 min after the main burst. These short wait-time bursts are not yet understood. Méndez and collaborators in a project led by Boirin (Strasbourg) observed the low-mass X-ray burster EXO 0748-676 with XMM-Newton, detecting 76 X-ray bursts. Most remarkably, 15 of these bursts occur in burst triplets, with wait times of 12 min between the three components of the triplet, with a similar situation for 14 doublets. The characteristics indicate that possibly all bursts in this system are hydrogen-ignited, in contrast with most other frequent X-ray bursters in which bursts are helium-ignited, but consistent with the low mass accretion rate in EXO 0748-676. Possibly the hydrogen ignition is the determining factor for the occurrence of short wait-time bursts.

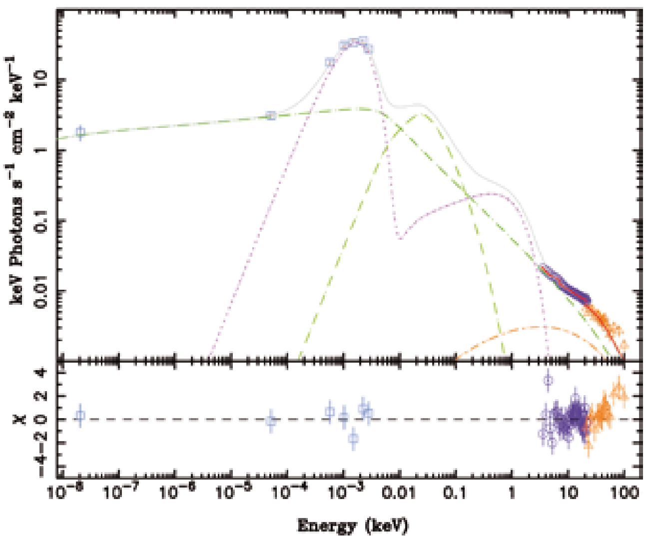

Figure 3.39: Jet model plus blackbody plus companion star fit to the broadband data of Galactic black hole transient GRO J1655-40, with residuals. Various components are indicated, including thermal synchrotron radiation, inverse Compton radiation, thermal disk radiation, a blackbody representing the star, and shock accelerated jet emission (from: Migliari et al. 2007, Astrophys. J. 670, 610).

For example the 12 min wait time may be associated with a nuclear beta decay timescale.

Kong (MIT) with Méndez, Wijnands, van der Klis and co-workers searched for evidence of atmospheric absorption lines gravitationally red-shifted according to Einstein's general theory of relativity. They collected 16 thermonuclear X-ray bursts during 2.3 days of observations with XMM-Newton of GS 1826-34, but unlike the previously reported case of EXO 0748--676 found no evidence of such lines.

3.3.2.8. Spectral studies of black-hole X-ray binaries

X-ray line spectroscopy by Miller (MIT) with Wijnands, van der Klis and co-workers using Chandra on the black holes X-ray binary GRO J1655-40 and H1743-322 during bright X-ray outbursts shows the existence of an outflow ('wind') from the accretion disk in these systems. Theoretical arguments indicate that this wind must be driven by magnetic processes in the disk, possibly the same fundamental processes as those providing the long sought mechanism for the viscosity that makes accretion disks transport matter into the black holes in the first place.

Miller and colleagues, including Wijnands, reported on a very long XMM-Newton observation of the black hole transient GX 339-4 during its low/hard state. The resulting data offer the best view yet of the inner accretion flow geometry in this state, which is thought to be analogous to the geometry in low-luminosity active galactic nuclei. The XMM-Newton spectra clearly reveal the presence of a cool accretion disk component and a relativistic Fe K emission line. The results of fits made to both components strongly suggest that a standard thin disk remains at or near to the innermost stable circular orbit, at least in bright phases of the low/hard state. These findings indicate that potential links between the inner disk radius and the onset of a steady compact jet, and the paradigm of a radially recessed disk in the low/hard state, do not hold universally. The results can best be explained if a standard thin accretion disk fuels a corona that is closely related to, or consistent with, the base of a compact jet.

Caballero-Garcia (Madrid) with Wijnands and van der Klis as part of a large collaboration reported on observations with INTEGRAL of the black hole candidate GRO J1655-40. They conclude that Comptonization by non-thermal electrons must be the dominant process behind the hard X-ray emission in the so-called hard state of the object.

3.3.2.9. State transitions in black-hole X-ray binaries

One of the ongoing debates in the field of black-hole X-ray binary studies is the origin of the hard X-ray power-law detected in the 'hard' accretion state. Traditionally, this state has been explained in terms of a corona of hot, thermal electrons, thought to inverse Compton up-scatter photons from a cooler 'standard thin' accretion disk. Recent discoveries of a strong correlation between these X-rays and the radio and infrared fluxes, however, suggest a stronger link with the magnetized plasma outflowing into jets. Markoff and collaborators have been investigating this question from several angles. With Gallo (former NOVA PhD, now at Santa Barbara) and Migliari, simultaneous data including not just the radio and X-ray bands, but also infrared and optical data, were modeled. Including the IR/optical data provided a tighter constraint on jet models, and helps to quantify the possible contribution of non-thermal processes to the high energies, and the model developed by Markoff provides a very good fit to the broadband data (Fig. 3.39). This model assumes that outflowing plasma near the black hole feeds directly into the jets, thus lending more weight to the suggestion that jets play a larger role than previously thought in the X-ray emission of X-ray binaries.

Belloni, van der Klis, Casella, Méndez and co-workers used RXTE simultaneously with INTEGRAL to study the black hole transient GX 339-4 during

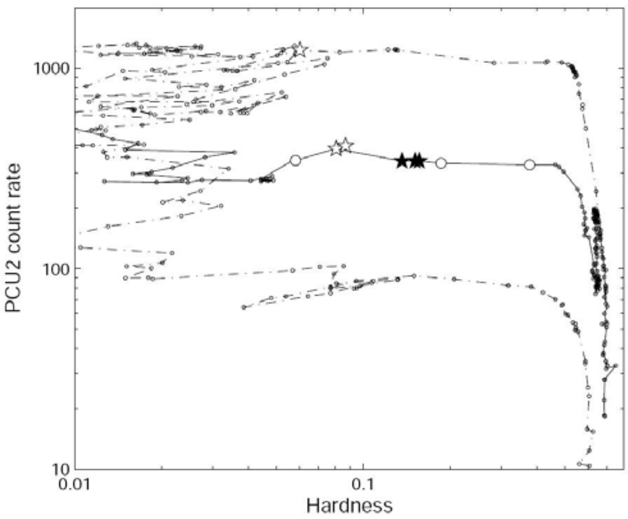

Figure 3.40: Behavior of the X-ray flux of the black hole X-ray binary GX 339-4 as a function of the X-ray spectral hardness during the 2004 outburst (continuous line) and from the 2002/2003 outburst (dot-dashed line) of the source. The time sequence for both curves starts at the bottom right. The tracks took several months to complete. At the start there is only hard X-ray emission from a hot corona (10^8 K) which increases several orders of magnitude in strength. However, then suddenly the source begins to emit progressively softer X-rays indicating that the emission of the cooler (a few million K) accretion disk becomes stronger and that of the corona weaker. During this transition a significant configuration takes place in the geometry of the emission regions around the black hole. From this figure it is clear that this transition not always happens at the same luminosity (from Belloni et al. 2006, MNRAS 367, 1113).

a sudden spectral transition from the hard to the soft spectral state. These state transitions are a well known feature of transient black holes and are attributed to the sudden cooling and possible collapse of the corona of hot plasma responsible for the high-energy X-ray emission. The cause of this collapse is an enigma of black hole physics and the subject of intense investigation. Interestingly, while qualitatively very similar to earlier ones, this transition (during the 2004 outburst of the source) took place at a much (factor 3.5) lower luminosity than a previous one (from the 2002/2003 outburst), clearly demonstrating that some other parameter than X-ray luminosity must play a role in determining when such a transition occurs (Fig. 3.40), thus constraining theoretical models of the geometry and evolution of the accretion onto black holes.

Yu (former PhD, now at Shanghai), Lamb (UIUC), Fender and van der Klis showed that the transient black hole candidate GX 339-4 has a linear correlation of waiting time between outbursts with outburst strength when only the spectrally hard stage is taken into account. Typically, black hole outbursts start with a spectrally hard stage, and then enter a sometimes extended soft state to become hard again near the end of the burst. This finding suggests that a very simple picture may account for much of black hole outburst phenomenology, in which matter accumulates steadily between outbursts, gets stored in the disk of matter circling the hole, and all drops toward the hole during the outburst. This needs to be confirmed using observations of other black holes.

3.3.2.10. Rapid variability studies of black-hole X-ray binaries

Belloni, Muciarelli (Padova), with Soleri, Casella, Migliari, Méndez and co-workers made systematic studies of QPOs in the microquasar GRS 1915+105 and in the extragalactic black hole candidate M 82 X-1 and analyzed the observed frequencies (170 Hz and 50-166 mHz, respectively) in terms of black hole mass estimates of 15 and up to 10^3 $M_\odot$, respectively. Casella et al. reported on the evolution of the time variability of the black hole transient XTE J1859+226 during its 1999 outburst.

3.3.2.11. Multi-wavelengths observations of black-hole X-ray binaries

Miller-Jones (postdoc), Tudose, Fender and colleagues studied the nature of the Galactic X-ray binaries Cygnus X-3 and GRS 1915+105 with e-VLBI. A comparison of pre- and post-outburst images of Cygnus X-3 (Fig. 3.41) showed that the outburst caused the appearance of a bright, curved jet showing evidence of interaction with the ambient medium. In GRS 1915+105, a weak flare occurred during the observations and there is some evidence from elongation of the radio image that this, too, caused jet formation. These observations illustrate the potential of e-VLBI to examine the nature and energetics of outbursts in these accretion-powered objects. In a detailed study of the jets after the Feb 2006 outburst of GRS 1915+105 with various long-baseline interferometers they also studied the proper motion of the jets, finding no evidence that ejecta from the outburst are appreciably decelerated during their outward journey from the core. With his collaborators, Miller-Jones studied the near-IR field surrounding the bursting pulsar GRO J1744-28, using the VLT and found two IR sources within the error circle on the X-ray position, although neither was considered likely on theoretical grounds to be the true counterpart.

XTE J1748-288 is a black hole X-ray transient which went into outburst in 1998 June. The X-ray light curves showed canonical morphologies, with minor

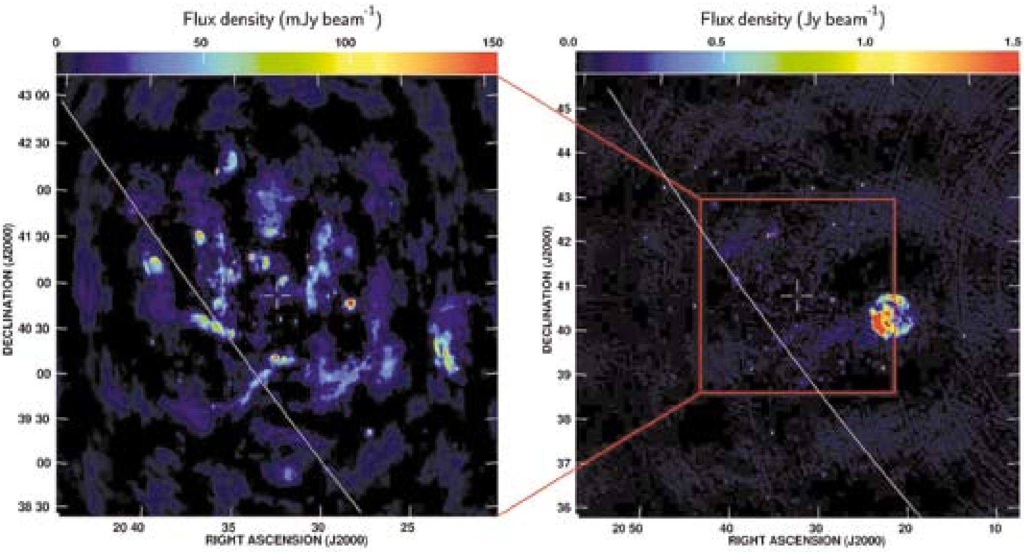

Figure 3.41: The environment of the Galactic X-ray binary Cygnus X-3 at 350 MHz and 170MHz with the WSRT. The very large region imaged around the Galactic anticenter is very complex, with the Galactic plane marked by the white line and Cyg X-3 itself by the cross (from: Miller-Jones et al. 2008, in 'Burst, pulses, and flickering').

variations on the 'fast rise exponential decay' profile. The associated radio source, however, reached an unusually high flux density of over 600 mJy, which was accompanied by an exceptional (>20%) fractional linear polarization, the variability of which was anti correlated with the flux density. Brocksopp, Miller-Jones, Fender, and Stappers used this variability to discuss possible depolarization mechanisms and to predict the underlying behavior of the (unresolved) core/jet components.

There is currently a clear discrepancy in the proper motions measured on different angular scales in the approaching radio jets of the black hole X-ray binary GRS 1915+105. Miller-Jones, Fender and collaborators measured lower velocities with the VLA prior to 1996 than were subsequently found from higher resolution observations made with the VLBA and MERLIN. This campaign used all three arrays simultaneously in an attempt to track the motion of the jet knots by giving unprecedented coverage of all angular scales from milli-arcsecond (mas) out to arcsecond scales. The derived proper motion was found to be 17.0 mas d^{-1}, demonstrating that there has been no significant permanent change in the properties of the jets since 1994. No conclusive evidence for deceleration of the jet knots was found, unless this occurs within 70mas of the core.

Gallo, together with Fender, Miller-Jones, Maccarone (former NOVA PhD; now at Southampton), van der Klis and collaborators performed deep VLA observations of the black-hole transient A0620-00, which resulted in the first detection of radio emission from a black hole binary at X-ray luminosities as low as $10^{-8.5}$ times the Eddington limit. The very low radio flux density is interpreted in terms of partially self-absorbed synchrotron emission from outflowing plasma. Using the estimated outer accretion rate in quiescence, the outflow kinetic power must be energetically comparable to this, if it is to reach the black hole with the standard radiative efficiency of 10%. This favors a model for quiescence in which a radiatively inefficient outflow accounts for a sizable fraction of the missing energy, and, in turn, substantially affects the overall dynamics of the accretion flow. Simultaneous observations with Chandra confirm the validity of a non-linear radio/X-ray correlation for hard state black hole binaries down to low quiescent luminosities, thereby contradicting some theoretical expectations. Taking the mass term into account, the A0620-00 data lie on the extrapolation of the so-called Fundamental Plane of black hole activity, which has thus been extended by more than two orders of magnitude in radio and X-ray luminosity. With the addition of the A0620-00 point, the plane relation provides an empirical proof for the scale invariance of the jet-accretion coupling in accreting black holes over the entire parameter space observable with current instrumentation.

Miller-Jones, Fender, and Nakar (Caltech) presented a collation of the available data on the opening angles of jets in X-ray binaries, which in most cases are small (< 10°). Under the assumption of no confinement, the Lorentz factors required to produce such small opening angles are calculated and are found to be large, with a mean >10, comparable to those estimated for AGN and much higher than the commonly assumed values for X-ray binaries of 2-5. Jet power constraints do not, in most cases, rule out such high Lorentz factors. The upper limits on the opening angles show no evidence for smaller Lorentz factors in the steady jets of Cygnus X-1 and GRS 1915+105. In those sources in which deceleration has been observed (notably XTE J1550--564 and Cygnus X-3), some confinement of the jets must be occurring. It is however possible that all the jets could be confined, in which case the requirement for high bulk Lorentz factors can be relaxed.

3.3.2.12. Comparison between neutron star and black hole systems

Linares (PhD), van der Klis and Wijnands reported on the X-ray fluctuations of the accreting millisecond pulsar IGR J00291+5934. Because the object is a pulsar its identification as a neutron star is secure, yet it displays a characteristic low-frequency flat-topped noise that previously was considered typical of a black hole.

3.3.2.13. Ultra-compact X-ray binaries

Nelemans and Jonker completed their project to obtain optical spectra of all known and candidate ultra-compact X-ray binaries (UCXBs; X-ray binaries with a very small orbital period of <1 hr) using the VLT and Gemini-North in order to determine the chemical composition of the transferred material (and thus of the donor star). Contrary to the AM CVn stars (see section 3.3.4.1.), the donors in UCXBs can be both helium rich as well as carbon/oxygen rich. Another difference is the presence of a jet that Migliari, Fender, Nelemans and coworkers discovered in the ultra-compact X-ray binary 4U 0614+09 using Spitzer.

One of the systems that posed a puzzle is 1H 1905+000, which showed an ordinary G-star spectrum. Careful astrometry and analysis of the available data by Jonker, Bassa and Nelemans showed that the G-star must be a chance alignment and the candidate UCXB is no longer visible in the optical. At the same time the X-ray activity of the source also has diminished.

3.3.2.14. High mass X-ray binaries

Kaper and van der Meer (NOVA PhD) continued their work on the properties and evolution of high-mass X-ray binaries. Kaper, van der Meer and Najarro applied model atmosphere fits to high-resolution optical spectra of Wray 977, and confirmed the B hyper-giant classification of this massive companion to the X-ray pulsar GX301-2. Wray 977 is one of the most luminous stars in the Galaxy and has a strong stellar wind (10^{-5} $M_{\odot}$ yr^{-1}) at a distance of 3-4 kpc. The luminosity of the wind-fed X-ray pulsar agrees well with the Bondi-Hoyle mass accretion rate. The spectra obtained with VLT-UVES cover a full orbit of the system, including periastron passage, from which the radial-velocity curve was derived, yielding 10±3 km/s and a mass ratio M_X/M_{opt} = 0.046±0.014. The 'spectroscopic' mass of Wray 977 is 43±10 $M_{\odot}$, consistent with the range in mass derived from the binarity constraints, and that of the neutron star 1.85±0.6 $M_{\odot}$. Time series of spectral lines formed in the dense stellar wind indicate the presence of a gas stream trailing the neutron star in its orbit.

Van der Meer and collaborators carried out a spectroscopic monitoring campaign of the OB-star companions to the eclipsing X-ray pulsars SMC X-1, LMC X-4 and Cen X-3. High-resolution optical spectra obtained with VLT-UVES were used to determine the radial-velocity orbits with high precision. The high quality data also allow the effect of possible distortions of the line profiles due to for example X-ray heating on the derived radial-velocity amplitude to be derived. The undistorted lines show larger radial-velocity amplitude than the distorted lines, consistent with model predictions. The measured mean radial-velocity amplitudes together with information on the projected rotational velocity of the OB companion, the duration of X-ray eclipse and orbital parameters of the X-ray pulsar, accurate neutron star masses of 1.06±0.11, 1.25±0.11 and 1.34±0.16 $M_{\odot}$ are obtained for SMC X-1, LMC X-4 and Cen X-3, respectively. The mass of SMC X-1 is near the minimum mass of ~1 $M_{\odot}$ expected for a neutron star produced in a supernova. These results show that neutron stars do not have a single canonical mass, but show a mass distribution likely reflecting the progenitor mass distribution (Fig. 3.42).

3.3.2.15. X-ray sources in globular clusters

Verbunt, Pooley and Bassa (PhD) developed an accurate technique to fit the best combination of primordial and collisionally formed X-ray sources to the observed numbers of low-luminosity X-ray sources in globular cluster systems. In particular, this technique allows for the uncertainty in the number of background sources, as well as for Poisson fluctuations around the model prediction of the number of cluster sources. Thus it was shown that the cluster

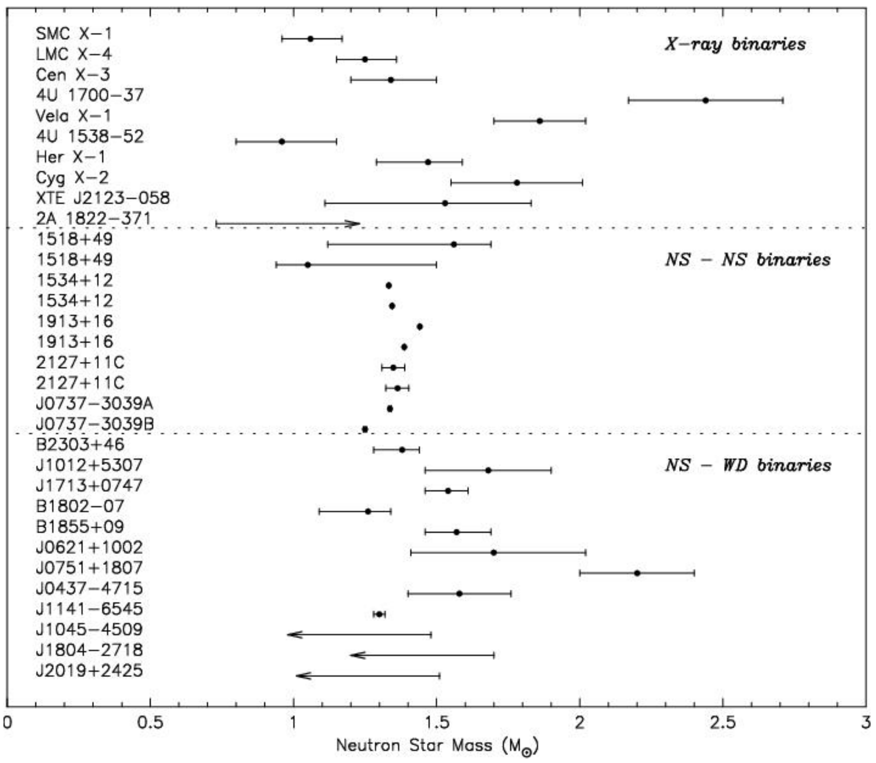

Figure 3.42: Neutron Star (NS) masses in X-ray binaries, NS-NS binaries and NS-White Dwarf (WD) binaries obtained from Stairs (2004, Science 304, 547) and references therein. The indicated masses of SMC X-1, LMC X-4 and Cen X-3 are obtained from the study by van der Meer et al. (2007, Astron. Astrophys 473, 523). The error bars correspond to 1 sigma errors. This plot clearly suggests that neutron stars do not all have the same 'canonical' mass. Note that although 4U 1700-37 most probably is a neutron star, but it could be a black hole as well.

mass (or luminosity) is not a good predictor of the number of collisions, in contrast to the assumption made in the study of (high-luminosity) extragalactic globular cluster systems. Verbunt and co-workers also showed that the number of X-ray sources in low-density clusters is dominated by the primordial binaries, as expected from theory.

Bassa and Verbunt, with van Kerkwijk (Toronto) and Koester (Kiel) used the VLT-FORS1 to obtain high-quality photometry and spectra of the white dwarf companion to PSR J1911-5958A. From positional coincidence this pulsar has been suggested to be a member of the globular cluster NGC 6752. Its (almost) circular orbit then implies that it was scattered from the cluster center by an intermediate mass black hole binary. Bassa and co-workers combined the radial velocities determined from the VLT spectra with the orbit of the pulsar to determine the masses of both components. Their analysis suggests that the pulsar is in fact not a cluster member. The white dwarf has a mass of 0.18±0.02 $M_\odot$, implying a mass for the neutron star of $1.40^{+0.16}_{-0.10}$ $M_\odot$.

3.3.3. Super-massive black holes

3.3.3.1. M81*

In an extensive campaign on the nearby low-luminosity AGN M81*, Young, Nowak (MIT), Markoff and collaborators spent an unprecedented 300ks looking at its core with Chandra. The very first high-resolution X-ray spectrum up to the iron K-α bandpass, from within 1" of the central black hole, was obtained. Many velocity broadened lines are seen, with speeds above 1000 km/s, consistent with collisional ionization within about 10^5 r_g. One of the most important results is that the narrow fluorescent Fe K-α line implies an origin at more than 55 r_g from the black hole, suggesting that the cooler accretion disk does not extend all the way to the innermost stable circular orbit, as suggested by some recent X-ray binary observations.

3.3.3.2. Sgr A*

For many years, the lack of resolved jets from our Galactic Center super-massive black hole has been puzzling to theorists. Despite the fact that the flat/

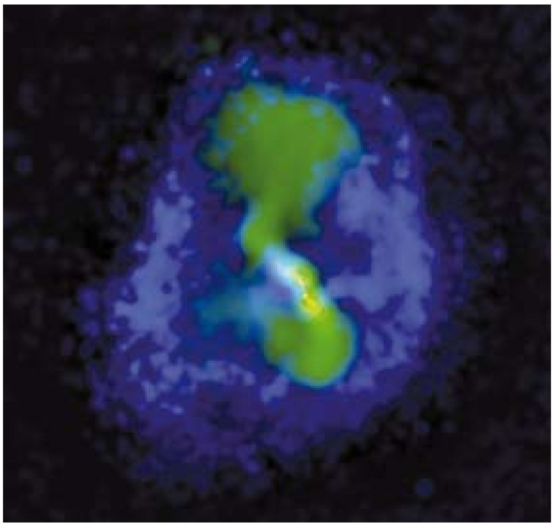

Figure 3.43: Composite color image of Hydra A which illustrates the close connection between the observed, large X-ray cavity system (shown in blue) and the low frequency, 330 MHz radio emission (shown in green). The 330 MHz radio data are from Lane et al. (2004). The familiar 1.4 GHz VLA image of Hydra A is also shown in the core in yellow. The image covers a region of 800 x 800 pc (from: Wise et al. 2007, Astrophys. J. 659, 1153).

inverted radio spectrum and its polarization are very similar to the jets seen in other weak AGN, observations with the highest spatial accuracy using VLBI have not found any noticeable elongation. This fact has been taken by some to imply that jets are lacking in Sgr A*. On the other hand, the scattering screen of electrons in the Galactic plane between here and the Galactic Center could significantly smear out defining features. Markoff, along with collaborators Bower (Berkeley) and Falcke, has developed a new technique to break the current degeneracies in jet models for this elusive source. Starting with a grid of possible models which can fit the broadband spectrum of Sgr A*, with different inclination and position (on the sky in projection) angles, Markoff et al. simulated the resulting VLBI image after traversing the Galactic scattering screen. The most important result is that a physically realistic jet model for Sgr A*'s emission can easily be hidden in our Galaxy, due to a combination of weak particle acceleration in the jets, overall weak emission and the intervening scattering. Furthermore, a strong preference was found for compact jets with high inclination angles, and a position angle on the sky around 105 degrees. Interestingly, an independent group modeling polarization data derived a very similar position angle, suggesting that the geometry of the jet system can be determined even without a full resolution of the jets, via this new technique.

3.3.3.3. The growth of super-massive black holes

Wise (postdoc) and co-workers investigated the feedback between the growth of black holes and bulges and the accretion and starburst activity in galaxies, measuring the black hole growth rate from the cavities they blow into the cluster gas. In some clusters, they found with Spitzer that the IR luminosity of the central galaxy is so high that it would require very intense star formation, with indication that this caused by accreting, cooling cluster gas. For another specific cluster, Abell 1835, the AGN power is enough to prevent a large fraction of the cooling surrounding gas to accrete onto the central cD galaxy, because it gets re-energized by the AGN output.

3.3.3.4. The intergalactic medium

Wise and collaborators studied XMM-Newton and Chandra observations of two clusters in which sustained powerful AGN activity from the central galaxy has evacuated large cavities into the hot IGM of the cluster (Fig. 3.43). These cavities are visible as regions of reduced X-ray emission and enhanced low-frequency radio emission. These observations may help to show how some of the cluster IGM properties are set by power input from AGN, and also how the long-term activity of the AGN can be mapped out by the size and age of the cavities.

3.3.3.5. Comparison of black holes with different masses

The fundamental plane of black hole activity is a non-linear correlation among radio core luminosity, X-ray luminosity and mass of all accreting black holes, both of stellar mass and super-massive, found by Falcke, Körding (Southampton) and Markoff, along with an independent group. Merloni, along with Markoff and others have further examined a number of statistical issues related to this correlation, and have now quantified the bias introduced by samples and distance effects. They conclude that the fundamental plane is definitely not a distance artifact, but rather an intrinsic characteristic of accreting black holes.

A long-standing question is whether AGN vary like Galactic black hole systems when appropriately scaled up by mass. If so, one could then determine how AGN should behave on cosmological timescales by studying the brighter and much faster varying Galactic systems. A characteristic timescale – which potentially could tell us about the mass of the black hole – is found in the X-ray variations from both AGN and Galactic black holes, but whether it is physically meaningful to compare the two has been questioned. Uttley (postdoc), Fender and colleagues report that – after correcting for variations in the accretion rate – the timescales can be physically linked, revealing that the accretion process is exactly the same for small and large black holes. Strong support for this linkage comes, perhaps surprisingly, from the permitted optical emission lines in AGN whose widths (in both broad-line AGN and narrow-emission-line Seyfert 1 galaxies) correlate strongly with the characteristic X-ray timescale, exactly as expected from the AGN black hole masses and accretion rates. So AGN really are just scaled-up Galactic black holes.

3.3.4. Accreting white dwarfs

Van den Besselaar (PhD), Groot, Augusteijn and Greimel characterized for the first time red-dwarf white-dwarf binaries based on their colors and proper motion in the SDSS, leading to a homogeneous dataset that is used to constrain the space density of red dwarf-white dwarf systems. The bright, eclipsing system DE CVn was investigated in detail, which led to the determination of the component masses, radii and the evolutionary history of the system.

The Northern part of European Galactic Plane Surveys (EGAPS) (co-PI Groot) was started in 2003 using the INT. First samples of Hα emission line objects and Cataclysmic Variables are being studied. Synthetic photometry, photometric zero points and colors for the blue northern survey UVEX (PI Groot) were derived by Verbeek (PhD) and Groot.

3.3.4.1. Compact white dwarf binaries

In preparation for the OmegaWhite survey on the VST (400 square degrees) Morales-Rueda (NWO/NOVA PhD) and Groot investigated short-period photometric variables in the Faint Sky Variability survey (22 square degrees), showing them to be dominated by short-periods, blue systems: most likely the compact white dwarf binaries.

AM Canum Venaticorum (AM CVn) stars are interacting binary stars: mass, mainly helium, is constantly flowing from one star to the other. They are ultra-compact, consisting of two degenerate, hydrogen-deficient stars, so that these binaries have extremely short orbital periods, from about one hour down to only a few minutes. Their ultra-compact nature makes them the strongest (and so far only) known sources of gravitational waves that can be detected with the future ESA/NASA satellite mission LISA. To understand the currently known population, Roelofs (PhD), Groot, Nelemans and collaborators used the VLT to derive spectroscopic orbital periods for five systems. They used the SDSS spectroscopic database to increase the total number of systems and calculated a first model population of AM CVns in the SDSS. Based on this 1500 candidates from the SDSS photometry were selected that should hold a further 40 AM CVn stars (with one new system found already). The first accurate distances to AM CVn stars using HST were measured, and their gravitational wave signals derived, showing them to be cornerstone objects for LISA.

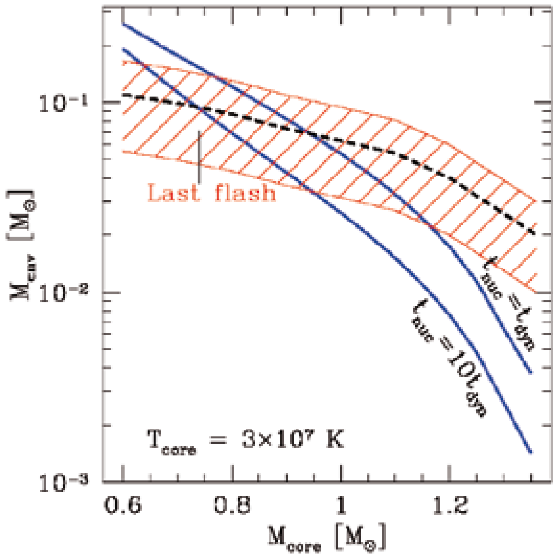

Figure 3.44: Expected accumulated helium mass for the last flash in AM CVn stars. Flashes to the right of the solid lines will result in a dynamical explosion leading to a .Ia supernova (from Bildsten et al. 2007, Astrophys. J. 662, L95).

Nelemans collaborated with Bildsten (Santa Barbara) on detailed calculations of the properties of AM CVn stars with improved treatment of the stellar structure of the donor stars (Fig. 3.44). The accreting white dwarfs in AM CVn systems are heated due to compression of the accreted material. A detailed study of this process showed that at long orbital periods, the heated accretor is the main source of the observed light. When considering the fate of the accreted helium on the surface of the white dwarf, the exciting possibility was found that a sequence of helium shell flashes with increasing strength would result in a 'final flash' that becomes dynamical and leads to an explosion of the accreted layer. These .Ia supernovae (one tenth of the brightness of real Ia supernovae for one tenth of the time) would be visible in the local universe.

Two candidate AM CVn systems are characterized by strongly modulated X-ray light curves and very short periods (9.5 and 5.4 minutes respectively). Groot, Nelemans, Roelofs collaborated with Marsh and Steeghs (Warwick) in observational work using Gemini on these peculiar binaries. In collaboration with Ramsay (UCL/MSSL), Groot and Nelemans used XMM-Newton to complete their survey of the X-ray properties of AM CVn stars.

3.3.4.2. Gravitational waves

Nelemans extended his work on the Galactic population of gravitational wave sources by an investigation of the optical brightness of the population of double white dwarf binaries detectable by LISA. Unfortunately, he found that estimates by other groups were much too optimistic. Nelemans was invited to write an article in Physics Today about ultra-compact binaries.

3.3.4.3. Sub-dwarf B binaries

Sub-dwarf B stars, are hot and luminous objects, believed to be helium burning cores, surrounded by only a very thin hydrogen layer. It is unclear how these objects are formed, i.e., how they have lost their hydrogen envelope. Many ideas start with the assumption that the objects are formed in a binary system and indeed many observed sdB stars are part of a (close) binary. Since pulsations have been detected in a fraction of sub-dwarf binary stars, asteroseismology provides a promising tool to probe the sdB interior. Hu (PhD), Nelemans, Aerts and Groot have studied the possible progenitors of the unique system PG 1336-018 and reconstructed the common-envelope phase, based on new observational work. If the common-envelope evolution is described by the standard α-formalism (based on the energy equation), the progenitor most likely experienced a core-helium flash.

3.3.4.4. Low-mass stars

Deacon (NWO/NOVA postdoc), Nelemans and Hambly (Edinburgh) used the results of their Southern Infrared Proper motion Survey (SIPS) to determine the local initial mass function. Simulations of the local population of low-mass stars, including selection biases, are compared to the SIPS results for different assumptions about IMF and stellar birth rate. After correcting for binarity an IMF power-law index α= -0.62 is found for stars between 0.075 and 0.2 $M_\odot$.

3.3.5. Formation and evolution of compact objects

3.3.5.1. Black-hole X-ray binaries

Yungelson (Moscow), Nelemans, van den Heuvel and Portegies Zwart studied the formation of black hole X-ray binaries and found that the magnetic braking invoked to drive the mass transfer is not compatible with the fact that none of the observed systems are persistent X-ray sources, suggesting that the magnetic braking is less efficient.

3.3.5.2. Very-faint X-ray transients

King and Wijnands studied the origin of the very-faint X-ray transients (§ 3.3.2.1) and found that they cannot have descended from binaries with stellar-mass components of normal composition. Accretion of hydrogen-depleted matter onto the compact object can account for individual systems, but requires that these transients should be observed to repeat within a few years, and does not explain why the class is distinctly faint. Other explanations invoke accretion by neutron stars or stellar-mass black holes from companions that were already brown dwarfs or planets when the systems formed, i.e., which did not descend from low-mass stars.

3.3.5.3. AGB nucleosynthesis

Pols and collaborators have made significant progress in studying nucleosynthesis in AGB stars, both light elements made by proton captures at the base of the convective envelope (hot bottom burning) in intermediate-mass AGB stars and heavy elements made by slow neutron captures (the s-process). One of the tools used in these studies is the rapid nucleosynthesis algorithm developed by Izzard (postdoc) and co-workers. This code uses accurate analytic fits to detailed evolution models, and allows rapid calculations of nucleosynthesis yields from populations of single and binary stars.

Bonacic (PhD), Izzard (postdoc), Lugaro (Veni) and Pols used the rapid nucleosynthesis code to constrain some of the uncertain parameters in s-process nucleosynthesis, by synthesizing populations of AGB and post-AGB stars and comparing the predicted distributions of s-process elements to observed galactic samples of these objects. To reproduce observed post-AGB abundances, dredge-up has to start at a lower core mass than predicted by current theoretical models, in qualitative agreement with the results of studies of the carbon-star luminosity function. Furthermore, a relatively small spread in the efficiency of the ^{13}C neutron source is needed to reproduce the observed abundance patterns, but the required efficiency apparently decreases with decreasing metallicity. The latter conclusion was reinforced in a follow-up study by Bonacic, Lugaro and co-workers in Leuven of the low-metallicity post-AGB RV Tauri star MACHO 47.2496.8 in the LMC.

In collaboration with Karakas (ANU) and Gallino (Torino), Lugaro studied the germanium abundance in AGB stars to compare to recent observations of

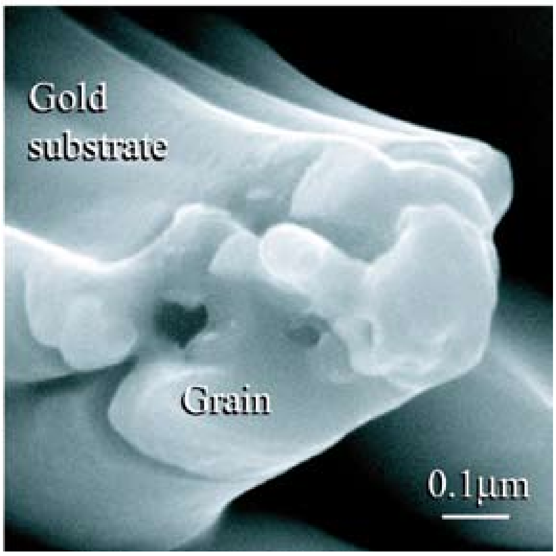

Figure 3.45: High-resolution scanning electron microscope images of meteoritic spinel grain OC2. This ruby-like grain is sitting on a gold pedestal following the ion probe isotopic analysis, because the gold substrate sputters faster than the grain does (from: Lugaro et al. 2007, Astron. Astrophys. 461, 657).

this element in planetary nebulae. Their detailed models can match the observations within the large observational error bars. The best match is obtained by allowing efficient dredge-up of material from the inner layers to the stellar surface towards the end of the AGB phase, just before the last material in the envelope is ejected to form a planetary nebula.

Accurate isotopic abundance measurements from pre-solar dust grains provide an important alternative method to constrain nucleosynthesis models. Pre-solar dust grains were born in circumstellar regions around ancient stars, ejected into the ISM, preserved during the formation of the solar system, and trapped inside primitive meteorites from which they are now extracted and analyzed. Lugaro and a team of co-workers including Pols showed that the peculiar abundances of the meteoritic spinel grain OC2 (see Fig. 3.45) can be explained if this grain formed in an intermediate-mass AGB star, with a mass of 4-7 $M_{\odot}$. This would be the first pre-solar grain to date to have originated in such a star, opening a new opportunity for studying massive AGB nucleosynthesis.

Van Raai, Lugaro and co-workers compared predicted $^{26}Al/^{27}Al$ isotopic abundance ratios from a set of low-mass AGB star models to those measured in silicon carbide grains that formed in C-rich AGB stars. For a particular choice of the uncertain $^{26}Al(p,\gamma)^{27}Si$ rate, the observed spread in $^{26}Al/^{27}Al$ of more than an order of magnitude cannot be reproduced by the models even allowing a range of masses and metallicities. Adopting the lower limit or the recommended value the models overpredict the observed ratios, while if the upper limit for the rate is used, the models predict too low ratios as compared to observations. Given this discrepancy and the strong dependence of the predictions on this rate, the observed spread may be explained either by different dust formation times or by extra-mixing processes in AGB stars.

Intermediate-mass AGB stars undergoing hot bottom burning may be the sources of gas contributing to the anomalous abundances observed in some globular cluster stars, the sites of origin of peculiar pre-solar oxide grains (as outlined above), and the production site of the long-lived radioactive isotope ^{26}Al present in the early solar system. Izzard, Lugaro and co-workers used the rapid nucleosynthesis code to examine the sensitivity of nucleosynthesis predictions of intermediate-mass AGB star models to nuclear physics uncertainties. They found that the calculation of the yields of both Na and ^{26}Al are very much hampered by large error bars in the reaction rates of $^{22}Ne(p,\gamma)^{23}Na$ and $^{26}Al(p,\gamma)^{27}Si$ rate, the latter giving a variation of a factor 40 in the ^{26}Al yield. The studies described above strongly demonstrated the importance of constraining the latter rate and have hence motivated a proposal to the TRIUMF nuclear facility in Vancouver, to build a target rich in the radioactive isotope ^{26}Al in order to perform a better measurement of this rate.

Lugaro and co-workers also studied the effect of a newly evaluated $^{18}F(\alpha,p)^{21}Ne$ reaction rate on AGB nucleosynthesis. The recently estimated upper limit affects the production of ^{19}F and ^{21}Ne in AGB stars, with implications on the matching of observational constraints such as spectroscopic observations of fluorine and the $^{21}Ne/^{22}Ne$ ratio measured in meteoritic silicon carbide grains.

3.3.5.4. **Low- and intermediate-mass binary evolution**

Many stars show chemical peculiarities (most notably enrichments in carbon and s-process elements) that appear to be the result of mass accretion from a former AGB companion in a binary system. These include barium stars among the Galactic disk population and carbon-enhanced metal-poor (CEMP) stars in the Galactic halo. The barium stars are indeed binaries with cool white-dwarf companions in wide and eccentric orbits, and most CEMP have recently been shown to have similar binary properties. In an ongoing effort by Pols and co-workers to understand these systems, their evolution is studied by means of a combination of detailed binary evolution and nucleosynthesis calculations and binary population simulations. In particular, it is usually assumed that the accreted matter remains on the surface of the star until convective dredge-up occurs. Stancliffe (Cambridge), Glebbeek (PhD), Izzard and Pols showed that due to the higher molecular weight of the accreted matter, thermohaline mixing causes strong dilution of this material already on the main sequence. This has a significant effect on the surface abundances of CEMP stars, decreasing the carbon content and subsequently increasing the nitrogen abundance after partial CN-cycling and dredge-up.

An existing puzzle in binary evolution is the large eccentricities of the barium stars and of similar white-dwarf binaries like Sirius. Tidal interaction during the AGB phase should have led to circularization of the orbit. Bonacic, Glebbeek and Pols developed a model for eccentricity growth in such binaries by means of enhanced and variable mass loss of the AGB star along its orbit. This mechanism competes with the circularizing effect of tides and can reproduce the period and eccentricity of Sirius AB. Similarly, the eccentricities of most barium stars can be explained in this way, as was demonstrated in a follow-up binary population synthesis study by Bonacic and Pols.

A different class of carbon-rich stars is the early-type R stars, which are core helium-burning stars that are – surprisingly – all single. Conventional single-star evolution models cannot explain such stars. Izzard in collaboration with Jeffery (UK) and Lattanzio (Australia) studied the possibility that they are the remnants of binary mergers. Using a binary population synthesis technique, several possible merger channels were found that lead to a rapidly rotating helium core inside a giant envelope that undergoes a helium flash and mixes carbon to the surface. This scenario can in principle account for the observed properties of the R stars and yields a birth rate more than sufficient to explain their observed numbers.

3.3.5.5. Massive single and binary stellar evolution

A major uncertainty in close binary evolution is the efficiency of mass transfer, i.e., the fraction of transferred mass that is accreted by the companion star. De Mink (NOVA PhD), Pols and Hilditch (St Andrews) attempted to constrain this uncertainty by computing a large grid of detailed binary evolution models and systematically comparing these to a sample of 50 double-lined eclipsing binaries in the SMC. Although the models were found to be a good match to detached binaries, the observed temperature ratio for many systems currently undergoing mass transfer is more extreme than predicted by any of the models. A large spread in mass transfer efficiencies is needed to fit the observed semi-detached systems, with a hint that initially wider systems tend to fit better to less conservative models.

In collaboration with Eldridge and Tout (Cambridge UK), Izzard studied the effect of massive binaries on stellar population counts and supernova rates. A set of detailed single and binary evolution models were compared to observed number ratios of blue to red supergiants, supergiants to Wolf-Rayet stars and of Wolf-Rayet subtypes, and to the relative rate of Type Ib/c to Type II supernovae. The agreement between the observed and predicted values is reasonable provided a significant fraction of binaries is included in massive stellar populations. However, discrepancies remain especially in the ratio of red supergiants to Wolf-Rayet stars, pointing to the need to improve the physical ingredients of the models by means of rotation and enhanced mass loss.

Petrovic (postdoc), Pols and Langer studied the effect of mass loss and metallicity on the radii of Wolf-Rayet stars. Luminous and metal-rich Wolf-Rayet stars have been found to be significantly inflated, possessing an extended low-mass and low-density envelope surrounding the hydrostatic core. This phenomenon is related to the proximity of such stars to the Eddington limit. Petrovic et al found that for mass-loss rates above a critical value, the radii decrease and the stellar structure becomes compact.

Stellar oscillations are excited in non-synchronously rotating stars in binary systems due to the tidal forces. Tangential components of the tides can drive a shear flow which behaves as a differentially forced rotating structure in a stratified outer medium. Within a single-layer approximation for the calculation of the forced oscillations Detmers (PhD) and Langer, together with Toledano, Moreno and Königsberger (all UNAM, Mexico) obtained results that are consistent with the predictions for the synchronization timescales in circular orbits, thus providing a simplified means of computing the tidal energy dissipationrates.Furthermore,bycalibratingtheirmodel to relationship between synchronization timescales and orbital separation, they are able to constrain the value of the kinematic viscosity parameter in stellar envelopes in the presences of tides.

3.3.5.6. Formation of double white dwarfs

In binaries in which both components are white dwarfs, the mass ratio is usually close to unity. This is remarkable, as standard evolutionary scenarios predict rather unequal masses. If mass transfer from the progenitor of the first white dwarf to its companion is stable, the orbit expands: this implies that the second star has a rather larger radius, and therefore larger core mass, when it starts mass transfer, than the first star. The result is a binary in which the white dwarf that formed last has a higher mass than the one formed first. Conversely, if mass transfer is unstable, the standard prescription of spiral-in leads to a much smaller orbit: the second white dwarf then has a much smaller mass than the one formed first.

Van der Sluys (NOVA PhD), Verbunt and Pols argued that the standard description of spiral-in, which is based on conservation of energy, is wrong, since it does not consider conservation of angular momentum, which in fact is a much more severe constraint, since energy can be produced or radiated away. They investigate the binary evolution under the assumption that the mass lost from the binary – corresponding to the convective envelope of the giant at the start of unstable mass transfer – takes its specific angular momentum with it. They consider three cases: mass loss with the specific angular momentum of the mass donor, with the specific angular momentum of the mass receiver (i.e., the mass is transferred first and then lost), and with the specific angular momentum of the binary (i.e., the mass is lost from a common envelope). They show that all three prescriptions can describe the observed mass ratios in the ten well-observed double white-dwarf binaries. However, if also the age difference between the white dwarfs, as measured from their effective temperatures, is used as a constraint, then mass loss with the specific angular momentum of the donor is the only acceptable model.

3.3.6. Dense stellar clusters

Portegies Zwart and an interdisciplinary group of astronomers and computer scientists studied the ecology of dense stellar systems through numerical simulations. This work combines the developments of numerical algorithms and theoretical tools to study the gravitational, chemical, nuclear and photonic evolution of solar systems, star clusters and galaxies. The development of an advanced particle integration methodology plays a prominent role.

3.3.6.1. Supernova 2006gy

SN 2006gy near the center of the galaxy NGC 1260 is the most luminous recorded supernova. Arguments have been made that its progenitor was a very massive star (>100 $M_\odot$), but that fails to explain the hydrogen observed in the supernova. Stars with masses >40 $M_\odot$ are expected at the time of the explosion to be Wolf-Rayet stars (helium stars) that have shed their hydrogen envelopes several hundred thousand years prior to the explosion. An alternative explanation that the progenitor arose from the merger of two massive stars appears more promising. Portegies Zwart and van den Heuvel reported that the collision frequency of massive stars in the kind of dense cluster expected near the center of a galaxy is sufficient to make this the most likely explanation for SN 2006gy. They also predicted that when the supernova has faded sufficiently, probably in 2008, a dense cluster of massive stars should become visible.

3.3.6.2. N-body techniques

Portegies Zwart and collaborators have been exploring the efficiency of using graphical processing units for gravitational N-body simulations. For this purpose they used the NVIDIA Quadro FX1400 and GeForce 8800GTX architectures and compare the results with GRAPE-6Af special purpose hardware. In contrast to earlier attempts to port the N-body problem to the GPU they adopted a high-accuracy 4^{th} order predictor-corrector Hermite integrator with block time steps. Also the speed-up achieved was better than earlier results.

Gualandris (PhD), Portegies Zwart and collaborators have been working on the optimization of the gravitational N-body kernel on massively parallel and distributed computer architectures. Their results indicate that the gravitational N-body problem can be optimized for parallel computers quite efficiently if the network bandwidth is sufficiently large, and the latency is small. Intercontinental grid of special purpose of GPU hardware seems not to be an efficient way of computing systems with fewer than a million particles, but for larger N-body systems an intercontinental grid will be efficient. This makes grid computing inefficient for direct N-body kernels, but possible and even beneficial for treecode or other approximate methods.

3.3.6.3. Cluster simulations

Van den Berk and Portegies Zwart in collaboration with McMillan (Drexel) performed the first large scale N-body simulations of open star clusters with primordial triples. Such simulations were not done before, mainly due to excessive complications in the integration of the chaotic equations of motion of these systems. Their calculations indicate that the presence of higher order multiple systems in open star clusters and the field cannot be explained by initial configurations with only triples and binaries, but primordial quadruple and higher order hierarchies must be present in young star clusters.

Gaburov and Portegies Zwart in collaboration with Chen-chen (Taiwan) performed detailed simulations of the Arches star cluster. Their main question was initiated by the puzzling observations of an unusually flat mass function in the inner parts of this cluster. Based on their simulations the unusual mass function of the Arches cluster can be explained satisfactorily with a normal primordial mass function that evolved due to the dynamical evolution of the cluster. In addition, they argue that the cluster, in that case, should be about half way towards core collapse.

Gieles (NOVA PhD) and Portegies Zwart in collaboration with Athanassoula (LAM) have performed detailed simulations of the effect of the spiral pattern in galaxies on the evolution of globular star clusters. They conclude that near the Lyndblad resonances in the galactic disc the effect of tidal destruction due to the potential of the spiral arms is sufficiently effective to destroy the star clusters.

3.3.7. Radio pulsars and magnetars

Radio pulsars are rapidly spinning neutron stars which produce periodic radio pulses. They have stable averaged pulsar profiles; however each individual pulse varies in intensity, shape and polarization. These fluctuations provide excellent insights into the way in which radio pulsars shine.

3.3.7.1. Finding pulsars

Hessels (postdoc working on PuMa) and collaborators, primarily Ransom (NRAO), discovered >30 new pulsars in a 350-MHz survey of the Northern Galactic Plane with the GBT. The new group of pulsars includes several sources discovered in searches for bright single pulses. These intermittent pulsars are similar to the recently identified “Rotating Radio Transients” (RRATs). In contrast however, several of them are very nearby to Earth (within 1 kpc). Their proximity makes them interesting targets for multi-wavelength follow-up (e.g., X-ray). Follow-up studies of these objects have started to determine how they, and the RRATs in general, are related to the population of ‘normal’, more regularly pulsing radio pulsars.

3.3.7.2. Glitches in pulsars

Janssen (PhD) and Stappers analyzed 5.5 years of timing observations of 7 ‘slowly’ rotating radio pulsars, made with WSRT. They presented improved timing solutions and 30, mostly small, new glitches. Particularly interesting are their results on PSR J1814-1744, which is one of the pulsars with similar rotation parameters and magnetic field strength to the anomalous X-ray pulsars (AXPs). Although the high-B radio pulsars do not show X-ray emission, and no radio emission is detected for AXPs, the roughly similar glitch parameters provide another tool to compare these classes of neutron stars. Furthermore, glitches one to two orders of magnitude smaller than before were detected. The total number of known glitches in PSR B1737-30 was doubled, and statistics on glitch sizes for this pulsar individually and pulsars in general were improved. No significant variations in dispersion measures for PSRs B1951+32 and B2224+65 were found, two pulsars located in high-density surroundings.

3.3.7.3. Studies of individual pulsars

Weltevrede (NOVA PhD; now at CSIRO), Wright (Sussex), and Stappers reported on single-pulse radio WSRT observations of PSR B1702-19 and their implications for pulsar emission theories. Earlier conclusions that the dipole axis of this pulsar is almost perpendicular to its rotation axis and that both its main pulse and interpulse are modulated with a periodicity around 10.4 times the pulsar’s rotation were confirmed. Different models to explain their results were explored, but whichever model turns out to be correct, the answer will have important implications for emission theories.

The recently discovered RRAT sources are characterized by very bright radio bursts that, while being periodically related, occur infrequently. Weltevrede, Stappers, Rankin (NOVA visitor) and Wright (Sussex) found bursts with the same characteristics for the known pulsar B0656+14. These bursts represent pulses from the bright end of an extended smooth pulse-energy distribution and are shown to be unlike giant pulses, giant micropulses, or the pulses of normal pulsars. The extreme peak fluxes of the brightest pulses indicate that PSR B0656+14, were it not so near, could only have been discovered as an RRAT source. Longer observations of the RRATs may reveal that they, like PSR B0656+14, emit weaker emission in addition to the bursts.

3.3.7.4. Drifting sub-pulses

There are pulsars that show exceptional behavior such that the individual pulses consist of small sub-pulses that slowly ‘drift’ through the profile from pulse to pulse. One of those ‘drifting sub-pulses’ pulsars is PSR B0031-07 and was studied in detail by Smits (PhD), Stappers and Kuijpers. Multi-frequency radio observations, using the GMRT, WSRT and Effelsberg telescopes, were used to construct a detailed model of the geometry of the pulsar emission region. The remarkable result of their study is that the emission heights, which range from 2 to 14 km, are much lower than those found by previous studies of different pulsars.

Weltevrede, Stappers, and Edwards (former NOVA postdoc; now at CSIRO) observed a large sample of pulsars to study their subpulse modulation at an observing wavelength (when achievable) of both 21 and 92 cm using WSRT. The main goals were to determine what fraction of the pulsars has drifting subpulses, whether those pulsars share some physical properties and to find out if subpulse modulation properties are frequency dependent. At least half of the total population of pulsars is estimated to have drifting subpulses when observed with a high enough S/N. It could well be that the drifting subpulse mechanism is an intrinsic property of the emission mechanism itself, although for some pulsars it is difficult or impossible to detect. The large number of new drifters allows, for the first time, to do meaningful statistics on the drifting phenomenon. It appears that the youngest pulsars have the most disordered subpulses and the subpulses become more and more organized into drifting subpulses as the pulsar ages.

One class of models explains the observed drifting sub-pulses as emission from a carousel rotating around the stellar magnetic axis. Fung and Kuijpers, together with Khechinashvili (Leuven/Georgia), studied the diocotron instability - also known as 'rotational shear' instability - as a possible mechanism explaining the carousel that would give rise to drifting subpulses. Application of the model to two pulsars with sufficiently detailed carousel observations, PSRs B0943+10 and B0826-34, showed that in both cases the model could, at least qualitatively, explain the observations. In particular, the model is able to account for the reversal of the drift, as observed in PSR B0826-34.

3.3.7.5. Magnetars

Two years of INTEGRAL monitoring of the soft gamma-ray repeater SGR 1806-20 covered this magnetar from quiescence to frenzy, as reported by Götz (Milan) with van der Klis and co-workers.
In this period the source went from a quiescent state into a very active one culminating in a giant flare on December 27, 2004. During the run-up to this flare hundreds of weaker bursts were detected, including a flurry of activity comprising a hundred bursts within just ten minutes, that can be attributed to an avalanche of reconnection events in the neutron star magnetosphere.

With Granot (Stanford) and others, the UvA GRB group developed a model for the giant outburst of soft gamma-ray repeater SGR1806-20, which was observed to have led to an expanding radio nebula. This nebula can be modeled well by assuming that mildly relativistic material was ejected with fairly little collimation into a cavity created by earlier source activity and then hits a thin shell of swept-up material at the cavity's outer edge. Some support for this idea comes from a Merlin and VLBI study of the nebula led by Fender, which found that the outflow is not completely symmetric, and that a significant fraction of the flux comes from fairly small scales relative to the overall nebula size.

Den Hartog (PhD), Hermsen, Rea (postdoc), Stappers and colleagues reported on the first ever quasi-simultaneous multi-wavelength campaign on the anomalous X-ray pulsar 4U 0142+61 from the radio to the hard X-ray band. The source was an INTEGRAL target for 1 Ms in July 2005. During these observations it was also observed in the X-ray band with Swift and RXTE, in the optical and NIR with Gemini North and in the radio with the WSRT. The spectral results obtained in the individual wave bands do not connect smoothly; apparently components of different origin contribute to the total spectrum. Remarkably, the INTEGRAL hard X-ray spectrum is now measured up to energies of ~230 keV with no indication of a spectral break. Extrapolation of the INTEGRAL power-law spectrum to lower energies passes orders of magnitude underneath the NIR and optical fluxes, as well as the upper limit in the radio band.

Levin considered the torsional oscillations of magnetars. This problem features rich dynamics due to the strong interaction between the normal modes of a magnetar's crust and a continuum of MHD modes in its fluid core. It is shown that global torsional modes only exist when one introduces unphysically large dissipative terms into the equations of motion. Second, the sudden release of an initially strained crust has been simulated. The crustal torsional modes quickly exchange their energy with the MHD continuum in the core, and decay by several orders of magnitude over the course of ~10 oscillation periods, after which the crustal motion is stabilized and several time-varying QPOs are observed. The dynamical spectrum of the simulated crustal motion is in qualitative agreement with that of the X-ray light curve in the tail of a giant magnetar flare. The asymptotic frequencies of some of the QPOs are not related to those of the crust. The observed steady low-frequency QPO at 18 Hz is almost certainly associated with the lowest frequency of the MHD continuum, or its first overtone. Drifting QPOs get amplified when they come near the frequencies of the crustal modes, explaining why some of the observed QPOs have frequencies close to the expected crustal frequen-

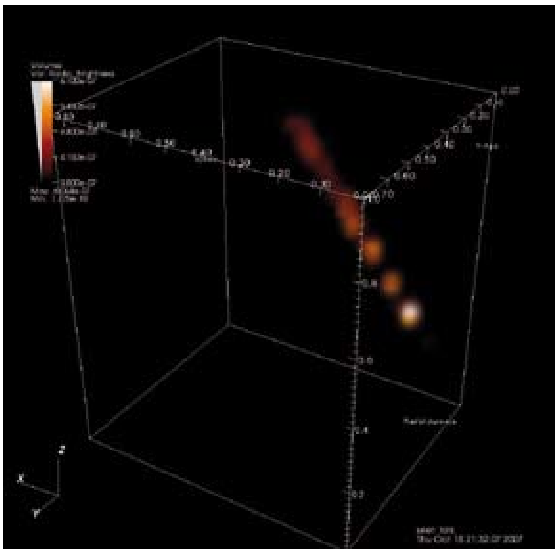

Figure 3.46: A three dimensional image of nanosecond radio flashes produced by cosmic rays hitting the Earth atmosphere (from: Falcke, private communication).

cies, and why these QPOs are highly variable with time.

3.3.7.6. Precessing single neutron stars

Vink and Verbunt, in collaboration with De Vries and Méndez (SRON), Haberl (MPE), Turolla (Padua) and Zane (MSSL) obtained a series of XMM observations of the single neutron star RX J0720.4-3125. This object was originally a flux calibrator for XMM, but was found by De Vries et al. in 2004 to be variable. De Vries et al. suggested that the variability is due to precession, in analogy with the radio pulsar PSR B1828-11. The new observations show that the changes in black-body temperature, emission area and soft X-ray absorption have indeed reversed sign in late 2005. The interpretation as precession, if confirmed, is interesting as it requires a deformation of the neutron star from sphericity which is larger than any current model for the neutron star glitches allows, and thus effectively invalidates these models.

3.3.8. Cosmic rays

For a long time the link between cosmic ray acceleration and radio astronomy was merely indirect, through the observation of synchrotron radiation of high-energy electrons produced in cosmic sources (e.g., supernova remnants and plasma jets from black holes). However, the direct detection of cosmic ray particles using low-frequency radio antennas has seen a major revival in recent years. Radio emission of air showers from ultra-high energy cosmic particles offers a number of interesting advantages. Since radio waves suffer no attenuation, radio measurements allow the detection of very distant or highly inclined showers, can be used day and night, and provide a bolometric measure of the leptonic shower component. The LOPES experiment (in which the cosmic ray group led by Falcke is strongly represented) has detected the radio emission from cosmic rays, confirmed the geosynchrotron effect for extensive air showers, and finally provided a good calibration formula to convert the radio signal into primary particle energy. The radio signal seems to have much lower statistical fluctuations in the energy determination than any other technique, thus allowing a major improvement in the energy measurement of cosmic rays in the future.

Also, the radio imaging technique of cosmic rays has been further developed allowing (uncleaned) 3D images of nanosecond radio flashes produced by cosmic rays hitting the Earth atmosphere to be obtained (Fig. 3.46). The technique is currently being further developed to be introduced in LOFAR. This will allow searches for short-time astrophysical transients, such as the recently detected millisecond radio sparkers and clearly distinguish them from terrestrial signals. In this respect, Falcke and collaborators have continued their efforts to find radio flashes from cosmic rays hitting the lunar surface using the WSRT. An improved limit on the flux of cosmic rays beyond the Greisen-Zatsepir-Kuzmin (GZL) cutoff ($E>10^{21}$ eV) is forthcoming.

Future steps will be the installation of radio antennas at the Auger experiment to measure the composition of ultra-high energy cosmic rays. A first test-setup has detected already the first radio events at Auger. Moreover, the contribution of Falcke and co-workers to the Auger collaboration has born fruits in 2007, with the first major breakthrough result of the observatory. Using data collected at the Pierre Auger Observatory during the past 3.7 years, it was demonstrated that a correlation exists between the arrival directions of cosmic rays with energy above 6×10^{19} eV and the positions of AGN lying within ~75 Mpc. They rejected the hypothesis of an isotropic distribution of these cosmic rays with at least a 99% confidence level from a prescribed a priori test. The observed correlation is compatible with the hypothesis that the highest-energy particles originate from nearby extragalactic sources whose flux has not been substantially reduced by interaction with the cosmic background radiation. AGN or objects having a similar spatial distribution are possible sources. One of the most intriguing candidates for the origin of some of the excess is the nearby radio galaxy

Cen A. Also firm evidence for the existence of the long-sought GZK-cutoff was presented.

3.3.9. Supernova remnants

3.3.9.1. Properties of supernova remnants

Langer, with Badenes (Rutgers), Hughes (Princeton) and Bravo (Barcelona) explored the relationship between models for progenitor systems of Type Ia SN and the properties of the supernova remnants that evolve after the explosion. Most models for Type Ia progenitors in the single-degenerate scenario predict substantial outflows during the pre-supernova evolution. Langer and co-workers estimated the imprint of these outflows on the structure of the circumstellar medium at the time of the SN explosion, and the effect that this modified circumstellar medium has on the evolution of the ensuing supernova remnant. Their simulations are compared with the observational properties of known Type Ia SN remnants in the Galaxy (Kepler, Tycho, SN 1006), the LMC (0509-67.5, 0519-69.0, N103B), and M31 (SN 1885). It is found that optically thick outflows from the white dwarf surface (sometimes known as 'accretion winds') with velocities above 200 km/s excavate large low-density cavities around the progenitors, which are incompatible with the dynamics of the forward shock and the X-ray emission from the shocked ejecta in all the examined Type Ia remnants.

3.3.9.2. Cosmic ray acceleration by the historical supernova remnant RCW 86/SN 185

Vink and collaborators completed a study on the non-thermal X-ray emission from the supernova remnant (SNR) RCW 86. Over the last thirty years there has been an ongoing discussion whether this object is the remnant of a supernova observed by Chinese astronomers in AD 185. The discussion has focused on the age of the SNR and on whether the Chinese records refer to a supernova or some other kind of transient object. The northeastern part of the SNR was observed in 2004 by Chandra and XMM-Newton, which has the peculiar feature that the shell of the SNR changes its X-ray emission from predominantly thermal to synchrotron emission. In previous work, Vink and Laming have shown that the width of X-ray synchrotron emission filaments can be used to infer the magnetic field. In general it turns out that the magnetic fields are higher than expected. For young SNRs like Cas A and Tycho fields are measured in the range of 100-500 μG. For RCW 86 the width of the synchrotron filament (Fig. 3.47) is as wide as the shell of RCW 86 itself which implies a magnetic field of 20-30 μG, comparable or slightly larger than the compressed interstellar magnetic field. This makes RCW 86 a SNR with one of the lowest measured magnetic fields.

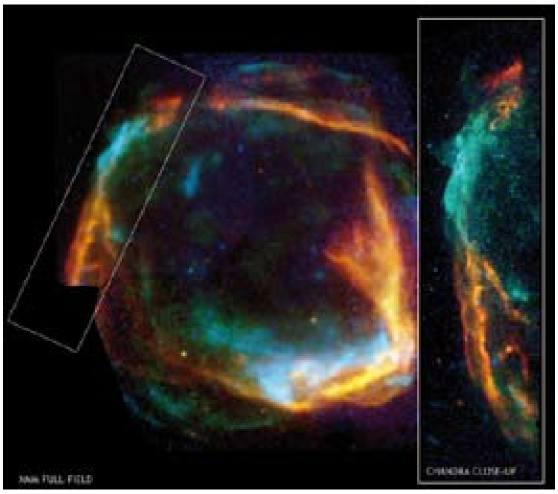

Figure 3.47: Chandra/XMM-Newton press release image of RCW 86 by Vink and collaborators. The large map shows the overall structure of RCW 86 as seen by XMM-Newton. The inset shows the Chandra map of the northeastern region. The color coding is such that X-ray synchrotron emission shows up in blue and thermal X-ray emission in red. The diameter of RCW 86 is approximately 40 arcmin (adapted from Vink et al. 2006, Astrophys. J. 648, L33).

From the presence of X-ray synchrotron emission it can be inferred that in the northeast the shock velocity has to be higher than ~2500 km/s, much higher than ~600 km/s derived from optical spectroscopy of other regions of the SNR. The high shock velocity in the northeast is probably a result of a, locally, low density. The shock velocity has therefore not much decelerated. A low density also implies a low thermal X-ray emission as observed. Large contrasts in shock velocity can be obtained if in parts of the SNR the shock has encountered a dense shell created by the wind of the progenitor star. An interesting implication is that the northeastern shock velocity can be used to infer the age of the SNR, namely ~2000 yr, consistent with an explosion date in AD 185.

3.3.9.3. Cosmic ray acceleration at the reverse shock of Cassiopeia A

There are few very young SNRs (ages <1000 yr) but all of them show X-ray synchrotron radiation at the forward shock. This emission is considered as evidence for very fast cosmic ray acceleration, since the acceleration of the highest energy electrons is countered by severe X-ray synchrotron losses. However, Cas A shows some anomalies in that X-ray synchrotron emission also comes from the inside of the SNR. This is often attributed to projection effects.

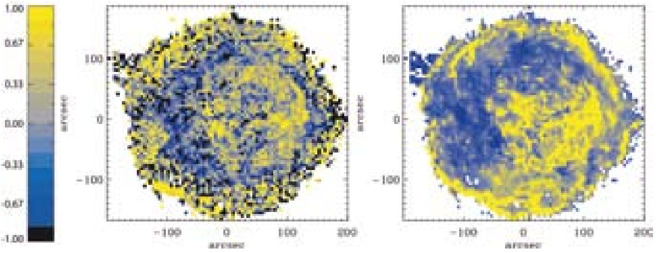

Figure 3.48: Left: Spectral index map of the 4-6 keV continuum emission (with respect to a spectral index of 3.1). The yellow color indicates regions emitting X-ray synchrotron emission, whereas the other regions are dominated by thermal continuum emission. Right: the ratio of the continuum with respect to the overall X-ray emission. The X-ray synchrotron emitting region stand out, but some regions with X-ray synchrotron emission also emit copious X-ray line emission (from: Helder & Vink 2008, Astrophys. J. in press).

Helder (PhD) and Vink have applied a deprojection technique to 1 Ms of Chandra data. In addition they characterized for each 1" pixel the power law slope of the continuum emission, which turns out to be a good indicator of whether the emission is due to thermal bremsstrahlung or synchrotron radiation (Fig. 3.48). Together these results indicate that a large fraction of the X-ray synchrotron radiation comes from the reverse shock region, which heats the supernova ejecta. However, X-ray synchrotron emission seems to come from the Western part of the reverse shock in Cas A. The likely reason is the different kinematics in this part: in the West the reverse shock is almost at a stand-still in our reference frame, which means that the shock velocity is determined by the ejecta velocity, which is almost 6000 km/s. The results are surprising, since for acceleration of cosmic rays one needs a reasonable magnetic field.

3.3.9.4. The radio-active material ^{44}Ti in Cassiopeia A

Most heavy elements from oxygen to nickel originate from supernovae. Some of the elements, like most oxygen, are synthesized during the late stages of a stars life, but the more heavy elements are directly made during the explosion. Some of these elements are radio-active, and detecting the signatures of this radio-activity provides direct evidence for the presence of fresh nucleosynthesis in supernova explosions. The most abundant radio-active element is ^{56}Ni, which decays in about 9 days to ^{56}Co. Since the radio-activity releases energy, the decay of ^{56}Ni is important for the luminosity of supernovae up to a year after the explosion. After that period ^{44}Ti, which has a lifetime of 86 yr, becomes the most important source of energy. The long lifetime also makes that one can observe this element in young SNRs. Evidence had been found for the presence of ^{44}Ti in Cas A. In order to confirm these detections and to determine the amount of ^{44}Ti and its kinematics, Vink, Devourchelle (CEA) and collaborators obtained a deep (6 Ms) observation of the Cassiopeia region with INTEGRAL of the 68 keV and 78 keV lines, which were indeed detected (Fig. 3.49). This implies a ^{44}Ti production of ~10^{-4} $M_{\odot}$, in excess of model predictions, possibly indicating a strong explosion asymmetry, or a more energetic explosion. In addition, continuum emission from Cas A was detected up to 100 keV. The nature of this continuum is not well known. Possible explanations are X-ray synchrotron emission from electrons with energies of around 100 TeV, or non-thermal bremsstrahlung from electrons of 10-200 keV. Apart from Cas A the project is also of interest for providing a deep look at a region of the Galactic plane of 9 by 9 degrees, where 2 hard X-ray emitting anomalous X-ray pulsars and the young SNR Tycho (SN1572) are located.

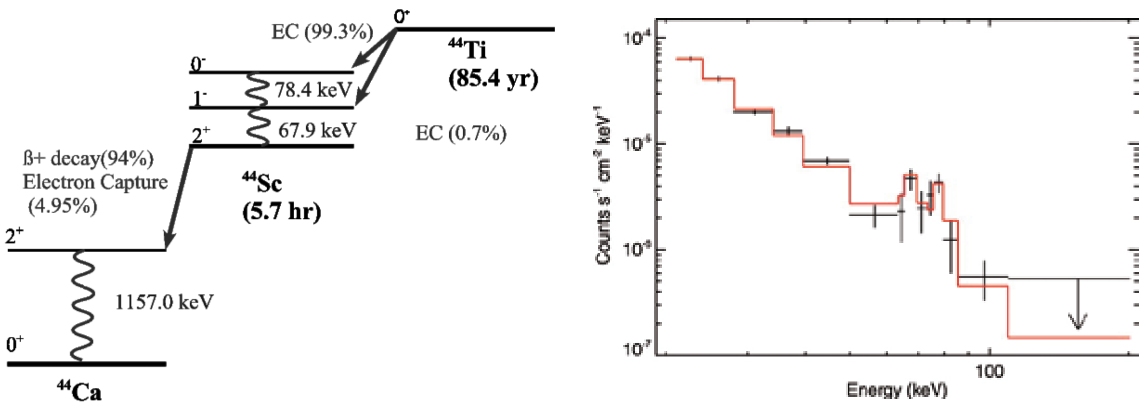

Figure 3.49: Left: the decay scheme of ^{44}Ti showing the three de-excitation lines that can be detected in the hard X-ray/Gamma-ray bands. Right: The hard X-ray spectrum of Cas A as measured by the INTEGRAL-ISGRI instruments. Note the clear signatures of line emission around 70keV and continuum emission up to 100 keV (after Renaud et al. 2006, Astrophys. J. 647, L41).

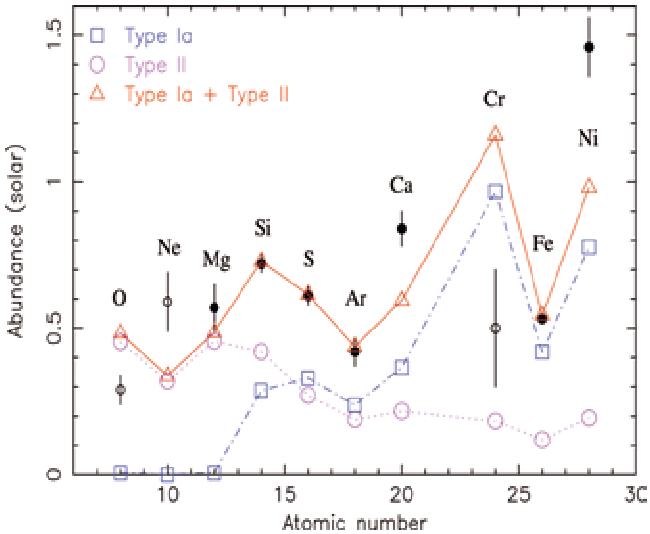

Figure 3.50: Relative abundances of elements in the intracluster medium of the cluster of galaxies 2A0335+096 as determined with XMM-Newton (black bullets). The circles and squares show the contributions of supernovae of type II and Ia, respectively; the solid line the total abundances predicted by the model (from Werner, Kaastra et al. 2006, Astron. Astrophys. 449, 475).

3.3.9.5. Element production in supernovae and the intracluster medium

Vink and Verbunt participated in a study led by Werner and Kaastra (SRON) which used XMM data to determine the abundances of several elements in the cluster 2A0335+096. Supernovae of type Ia produce mainly heavy elements such as iron and nickel; supernovae of collapsing high-mass stars (II, Ib, Ic) mainly less massive elements such as oxygen, neon and magnesium. From the ratio of high- to low-mass elements in the intracluster gas Werner and collaborators derived the number ratio of supernovae of type Ia to II as 1 to 3. From the amount of gas they derive a past average supernova rate for type Ia of about 1 per 200 year.

An interesting problem is the large observed ratio of calcium to argon, which is not reproduced by either the type II or type Ia model, indicating that the element production of supernova models needs to be improved (Fig. 3.50).

3.3.10. Physics of the fastest shocks

Wiersma (NOVA PhD) studied the spontaneous generation of magnetic fields by the Weibel Instability that operates in ultra-relativistic shocks, a mechanism that is often invoked to explain the non-thermal emission in Gamma Ray Burst Afterglows. The overall conclusion is that magnetic field generation does take place in ultra-relativistic shocks. The magnetic energy created in this fashion comes close to equipartition with the hot, shocked electrons and there is much less than the energy that is (in principle) available in such a situation. For comparison the energy residing in the protons streaming into the shock is a factor ~ $m_p/m_e \sim 2\times10^3$ times larger, because of the large proton mass. The Weibel Instability is simply unable to tap that enormous energy reservoir. Still, for typical parameters the magnetic field generated in this fashion is 100-1000 times stronger than that resulting from another well-known process: the compression of the very weak interstellar fields that are swept across the same shock as it expands into the interstellar gas.

Wiersma and Achterberg, together with Norman (StScI) showed that further field amplification due to merging of the current filaments left behind by the Weibel Instability does not lead to rapid further field amplification, as suggested by others. The same electron screening currents that impede the ion-driven Weibel Instability also slow down the merging process. Once the current filaments are more than one skin depth apart the merging time increases almost exponentially with filament-filament distance. The current filaments created by the Weibel Instability have a radius comparable to this skin depth. This means that the inter-filament distance is already close to the skin depth to begin with. After a few mergers the filaments are so far apart that merging essentially stops. These conclusions were reached using analytical arguments, and have recently been confirmed by others using numerical simulations.

3.3.11. The search for cosmic neutrinos

With the support of Physics, Achterberg, van Eijndhoven (Subatomic Physics) and Heise (SRON) joined the IceCube consortium, which currently deploys and operates the (already partially completed) km3 volume neutrino telescope in the Antarctic Ice. The focus is the search of cosmic neutrinos from transient high-energy sources, such Blazars (a class of active galaxies that show strong bursts of high-energy photons) and Gamma Ray Bursts. The strategy is to use satellite observations in X-rays or gamma-rays as a trigger to search for neutrinos from these sources. This allows selection of an observation time window and a rough position on the sky, strongly reducing the detector background due to the atmospheric neutrinos that are created in the Earth's atmosphere by cosmic rays, and which light up the detector. Even then, it will be necessary to stack the observations of many Gamma Ray Bursts (or flares from Blazars) in order to discern the very weak neutrino signal that is expected from these sources.

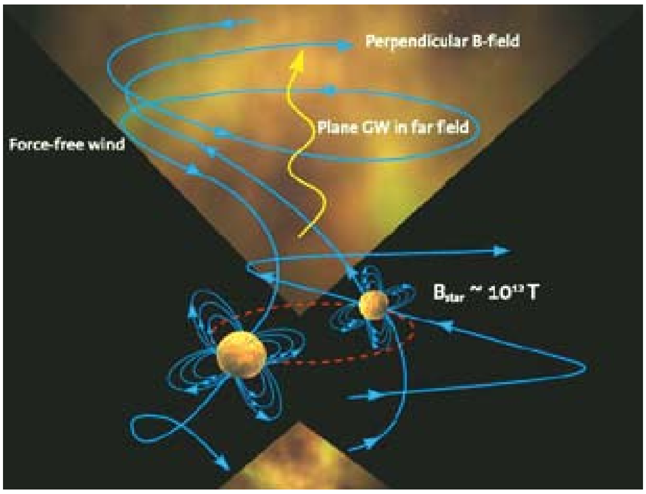

Figure 3.51: Schematic picture of a close neutron star binary emitting gravitational waves into a strongly magnetized plasma (from: Moortgat & Kuijpers 2006, MNRAS 368, 1110).

Most effort has been put into developing the necessary software for the acquisition and reduction of the data, the track reconstruction for up going muons in the detector that come from neutrinos that have traversed the Earth and the astrophysical interpretation from the IceCube detector signals. A search for a cosmic neutrino signal in archival data from IceCube's predecessor Amanda, a neutrino observatory at the same location but with a much smaller detector volume, has started.

This research ties in with that of Achterberg into the theory of cosmic particle acceleration and high-energy cosmic rays, and the observational work carried out at SRON. In particular, the detection of neutrinos produced by collisions between high-energy hadrons (mostly protons and neutrons) in conjunction with radio, X-ray and gamma-ray observations could yield important clues about the acceleration mechanism and the physical conditions inside the explosive Gamma Ray Bursts and in Blazars and other active galaxies.

3.3.12. Plasma physics

Moortgat (NOVA PhD) en Kuijpers extended their work on the interaction of gravitational waves with strongly magnetized plasmas. They investigated the possibility of inverse Compton scattering of the gravitational wave excited electro-magnetic wave in the plasma to bring the signal into the LOFAR regime (Fig. 3.51), but this did not prove efficient enough to provide an observable radio signal. The most efficient radiation mechanism is still up in the air, but potentially the energy deposited by the gravitational wave into the plasma could produce a radio signal in GRB that would precede a GRB and manifest itself as a short burst of radio waves at a specific frequency, preceding the afterglow.

Magnetic fields are observed on all scales but it is still a mystery where the seed fields originate from. Moortgat started to work on this problem collaboration with Marklund (Umeå). General relativistic density perturbations in a two-temperature cosmological plasma were investigated together with the corresponding consequences for structure formation. A perturbation in either the charge density or the total density causes an initial temperature difference to grow during gravitational collapse. Furthermore, the generalized Jeans criterion is governed by the species with the largest sound velocity, as one would expect.

4. PhD's in astronomy awarded in 2006 - 2007

In 2006 a total of 20 PhD's in astronomy were awarded in the Netherlands and 31 were awarded in 2007. Of these PhD's 11 were obtained through funding from NOVA. The table below lists all PhD's in astronomy over 2006-2007 specified for each university.

	PhD date	Funding	Promotor	Thesis title
UvA				
A. van der Meer	09 03 2006	NOVA	van den Heuvel	X-ray and optical spectroscopy of high-mass X-ray binaries
M.R. Mokiem	27 04 2006	NWO/UvA	van den Heuvel co: de Koter	The physical properties of early-type massive stars
N.L.J. Cox	09 06 2006	NOVA	Ehrenfreund, Kaper	Diffuse interstellar bands and interstellar carbon chemistry in the galaxy and beyond
A. Gualandris	12 09 2006	NWO	van den Heuvel, Sloot Co: Portegies Zwart	Simulating self-gravitation systems on parallel computers
T. Kouwenhoven	19 09 2006	NWO	Kaper	The primordial binary population in the association Sco OB2
R.S. Schnerr	07 02 2007	UvA	Henrichs	Magnetic fields and mass loss
P. Weltevrede	16 03 2007	NOVA	van der Klis, Stappers	The modulation and propagation of the radio emission of pulsars
A. van de Horst	07 09 2007	UvA	Wijers	Broadband view of blast wave physics. A study of gamma-ray burst afterglows
K. Wiersema	13 09 2007	NOVA/UvA	Wijers	Delving into the dragon's den: the host galaxies of gamma-ray bursts
J. Meijer	19 09 2007	NOVA/NWO	Waters	Theoretical studies of the infrared emission properties of proto-planetary disks
H. Koers	21 09 2007	UvA	Gaemers, Wijers	The astrophysical Herald. Neutrinos as probes for particle physics and astronomy
RuG				
A. Labiano Ortega	24 02 2006	Foreign	Barthel, O`Dea co: Vermeulen	Host galaxies and environments of compact extragalactic radio sources
E. Noordermeer	10 03 2006	NWO	van der Hulst, Sancisi, van Albada	The distribution of gas, stars, and dark matter in early-type disk galaxies
B. Emonts	24 11 2006	RuG	van der Hulst co: Morganti	Nearby radio galaxies: the interplay of gas, star- formation and active nucleus
W.E. Schaap	19 01 2007	RuG	van de Weijgaert, van Albada	DTFE: The Delaunay Tessellation Field Estimator
K. Kovac	19 01 2007	NWO	van der Hulst, Verheijen co: Oosterloo	Searching for the lowest mass galaxies: an HI perspective
R. Boomsma	26 01 2007	RuG	van der Hulst, Sancisi co: Oosterloo	The disk-halo connection in NGC 6946 and NGC 253
B. Letarte	30 03 2007	NWO	Tolstoy, Hill	Chemical analysis of the Fornax dwarf galaxy
F.F.T. Christen	27 04 2007	NOVA	Kuijken, Valentijn	OmegaCAM and gravitational lensing
M.A. Brentjens	29 06 2007	RuG	de Bruyn	Radio polarimetry in 2.5D
G. Battaglia	07 09 2007	RuG	Tolstoy, Helmi	Chemistry and kinematics of stars in Local Group galaxies
N.M.A Mohamed	07 09 2007	Foreign	Sanders	The simulation of cooling flows in clusters of galaxies
D.R. Poelman	26 10 2007	SRON/ RuG	Spaans	Emission characteristics of water in the universe
M.A. Aragon Calvo	16 11 2007	NWO	van de Weijgaert, van der Hulst	Morphology and dynamics of the cosmic web
UL				
I.L. ten Kate	26 01 2006	UL/NWO	Ehrenfreund, van Loosdrecht	Organics on Mars. Laboratory studies of organic material under simulated Martian conditions

	PhD date	Funding	Promotor	Thesis title
UL				
R.A. Overzier	30 05 2006	NWO	Miley co: Röttgering	Emergence of cosmic structures around distant radio galaxies and quasars
B.J. Jonkheid	28 06 2006	NWO	van Dishoeck	Chemistry in evolving protoplanetary disks
S.J. Paardekooper	28 06 2006	UL	Icke co: Mellema	Growing and moving planets in disks
R. Meijerink	08 11 2006	UL	Israel co: Spaans	Models of the ISM in galaxy centers
J. Ritzerveld	14 02 2007	NWO	Icke	The simplicity of transport. Triangulating the first light
F. Lahuis	09 05 2007	NWO/SRON	van Dishoeck	Molecular fingerprints of star formation throughout the Universe - a space-based infrared study -
S. Hekker	18 09 2007	UL	Quirrenbach, Aerts co: Snellen	Radial velocity variations in red giant stars: Pulsations, spots and planets
M. Kriek	26 09 2007	NWO	Franx, van Dokkum	The many phases of massive galaxies
S. Wuyts	27 09 2007	NWO	Franx co: van Dokkum	Red galaxies at high redshift
V.C. Geers	23 10 2007	NWO	van Dishoeck	Polycyclic aromatic hydrocarbons in disks around young solar-type stars
S.E. Bisschop	08 11 2007	NOVA/UL	van Dishoeck co: Linnartz	Complex molecules in the laboratory and star forming regions
L. Snijders	28 11 2007	UL	Franx co: van der Werf	Extreme star formation in starburst galaxies
UU				
M. van der Sluys	02 05 2006	NOVA	Verbunt	Formation and evolution of compact binaries
A-J. van Marle	03 05 2006	NWO	Langer	Models for the circumstellar medium of long gamma-ray burst progenitor candidates
M. Gieles	20 10 2006	NOVA/UU	Lamers co: Portegies Zwart	Star clusters
A.G. de Wijn	24 11 2006	UU	Rutten, Keller	Dynamics of fine structure in the solar chromosphere
C.G. Bassa	11 12 2006	NWO	Verbunt, van Kerkwijk	Optical studies of compact binaries in globular clusters and the Galactic disk
A.J.Th. Poelarends	24 01 2007	NWO	Langer	Stellar evolution on the borderline of white dwarf and neutron star formation
J. de Plaa	12 02 2007	SRON	Bleeker co: Kaastra	Enrichment study of hot intra-cluster gas through X-ray spectroscopy
J. Wiersema	29 05 2007	NOVA	Achterberg	Magnetic fields inside extremely fast shock waves
J. Leenaarts	14 09 2007	UU	Rutten, Carlsson, Keller	Numerical simulations of the solar atmosphere
A. Bonacic Marinovic	31 10 2007	UU	Langer co: Pols	Nucleosynthesis and evolution of AGB stars in binary systems
RU				
J.B. Moortgat	08 05 2006	NOVA/RU	Kuijpers	General relativistic plasma dynamics
J.M. Smits	24 10 2006	RU	Kuijpers co: Stappers	Properties and geometry of radio pulsar emission
G. Roelofs	16 04 2007	NWO	Groot	The AM Canum Venaticorum stars
E. van den Besselaar	27 11 2007	NWO	Groot	Red dwarf white dwarf binaries in our Galaxy

5. Instrumentation Program

5.1. ALMA high-frequency prototype receiver

The NOVA-ALMA group at RuG and SRON is involved in three projects: the development and prototype production of the 600-720 GHz receiver cartridges for the ALMA project; the integration and commissioning of the CHAMP+ heterodyne array receiver on APEX and the development of 600-720 GHz side-band separating mixers. The first project is discussed here, while the others are discussed in sections 5.1.2 and 5.1.3.

5.1.1. The 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 5000m 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 are developing 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).

Figure 5.1: ALMA Band-9 Cartridges #3-8 tested and awaiting acceptance (August 2007).

The first ALMA Band-9 receiver cartridge was assembled in 2005 using a non-optimal prototype Local Oscillator (LO) while LO development at NRAO in the USA continued. Halfway through 2006, this continued development led to the manufacturing and delivery of an improved LO that was integrated into the first cartridge. Using this upgraded LO, cartridge performance was significantly improved relative to the prototype, offering state-of-the-art performance and stable operation. All tests on the upgraded cartridge were completed in

Figure 5.2: Signing of the ESO-NOVA contract for the ALMA Band-9 Production by S. Kuipers, the chairman of the Executive Board of the RuG, on 24 August 2007. Image courtesy of J. Robot.

the summer of 2006 and the cartridge was formally accepted by the ALMA project and delivered to the Front End Integration Center at NRAO in the USA in November 2006. This was a major milestone for the Band-9 Cartridge group and the ALMA project, and the cartridge has since been used in ongoing development and design verification of the ALMA Front End.

In 2007 a number of major milestones in the Band-9 cartridge program were completed. First, a Critical Design Review (CDR) was held in February. During this review, a panel of 20 external experts, ESO representatives, and partners in the ALMA project reviewed the results of the Band-9 development effort to determine if the cartridge design, manufacturing, and test plans meet the project's requirements. The conclusions of the review panel were extremely positive, and the project commended the Band-9 team for their hard work and for the excellent quality of the Band-9 cartridges. The first half of 2007 also saw the completion of the assembly and testing of the first 8 Band-9 cartridges, which confirmed the quality of the cartridge design, both with respect to its performance and suitability for series production.

The successful completion of the CDR and good progress on the assembly and testing of the first 8 cartridges also triggered the start of negotiations between ESO and NOVA regarding the production of the remaining Band-9 cartridges needed to complete the ALMA array. These negotiations culminated in the signature of a contract between ESO and NOVA in the summer of 2007, for the production of the next 48 Band-9 cartridges. Since the signature of this contract, work has been split between efforts to complete the deliveries of the first 8 cartridges, and to start up the production effort, in particular by expanding assembly and test facilities, adding additional staff members to the Band-9 group, and placing sub-contracts for the manufacturing of cartridge components.

The ALMA Band-9 group in Groningen consisted of the following persons: Jackson (project manager), Baryshev (project scientist), Adema, Bekema, Barkhof, Gerlofsma, Hesper, Keizer, Koops, Koops van der Jagt (from fall 2007), Mena and Panman (from November 2007). The SIS junction group in Delft included Klapwijk (group leader), Lodewijk, Loudkov, Zijlstra and Zhu. The progress of the ALMA Band-9 work packages were regularly reviewed by a Steering Committee consisting of Boland, de Graauw and Wild with support of van Dishoeck and Klapwijk.

5.1.2. CHAMP+

CHAMP+ is a 14-element SIS heterodyne array receiver for the 600-720 GHz (same as ALMA Band-9) and 790-950 GHz (same as ALMA Band-10, large overlap with HIFI band 3) atmospheric windows for use on the Atacama Path finder EXperiment (APEX) telescope at the Chajnantor site in Chile. The project is a collaboration between the Netherlands and the Max Planck Institut für Radioastronomie (MPIfR) in Bonn, Germany. In the Netherlands the NOVA-ALMA group and TU Delft have extended their collaboration to also build the SIS mixers for CHAMP+ using the experience and technology developed for the ALMA Band-9 and HIFI band-3 receivers. In return to the hardware contribution to the CHAMP+ instrument astronomers in the Netherlands obtained 42 guaranteed observing nights on APEX spread over six years (2007-2012). NOVA holds formal responsibility for this project which received a NWO-EW grant of 653 k€.

The low band mixer array was delivered to MPIfR in August 2005, and the high band mixer array was delivered to MPIfR in March 2006 (Fig. 5.3). The hardware of the predecessor CHAMP receiver was fully refurbished at MPIfR. After integration of the SIS mixers and testing the instrument was shipped to APEX by the end of 2006. Baryshev supported the MPIfR team in the technical commissioning of CHAMP+ in January 2007. The first commissioning data led to the conclusion that several changes in the instrument optics (MPIfR task, anti-reflection coatings) were needed to improve the sensitivity of the instrument. Furthermore the NOVA-SRON group needed to adapt the mixers for the hi-band array to reduce the magnetic field cross-talk. All modifications to the hi-band array were successfully implemented with Baryshev and Hesper during the second commissioning run at the APEX site in April 2007. Instrument noise temperatures of 300 K SSB at 690 GHz and 600 K SSB at 810 GHz were measured. These results demonstrated that CHAMP+ was performing up to its specifications.

Scientific commissioning of the CHAMP+ instrument took place in June 2007. The first observing campaign in June 2007 was prepared in close collaboration with the Dutch astronomical community and our colleagues at the MPIfR. Due to exceptionally bad weather at the site the full program could not be done. Some first light observations were possible at the end of the allocated period and demonstrated the instrument potential.

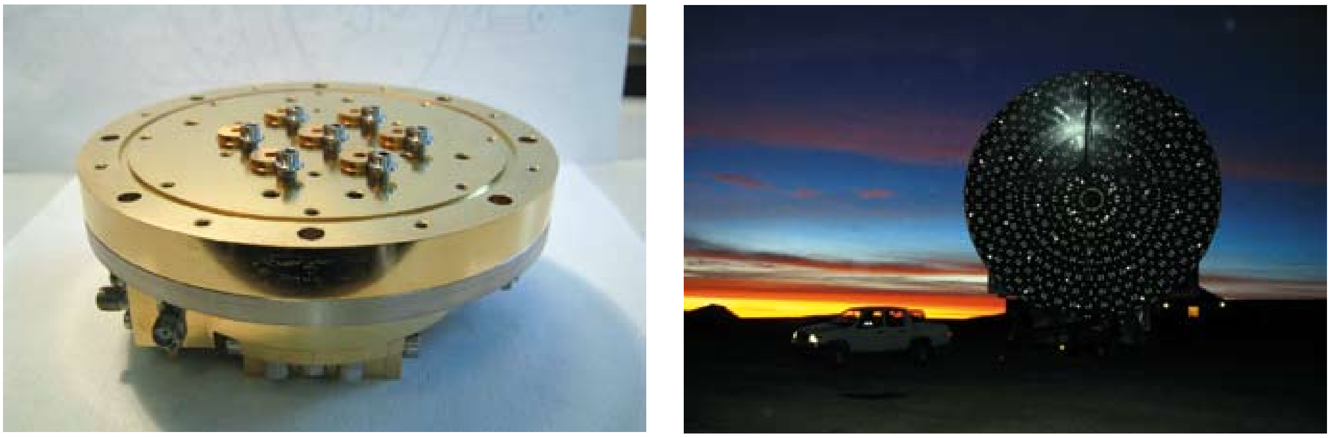

Figure 5.3: Left: the CHAMP+ hi band heterodyne mixer array. Using the experience gained with the ALMA Band-9 project and the HIFI mixer development SRON and the NOVA-ALMA group designed and manufactured the heart of this receiver consisting of the very sensitive SIS mixers and the cold 4 K array bracket which combines DC and IF signals; Right: the APEX telescope

5.1.3. ALMA R&D phase-2

The main advantage of a sideband-separating (2SB) receiver compared with the 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-2 project develops a 2SB mixer at 650 GHz for use at ALMA and other ground-based submillimeter observatories. Wild (SRON-RuG) is PI of the project. Key people for this work are Baryshev, Mena, Gerlofsma and Adema (all of them members of the ALMA Band-9 group and shared between both projects). The project benefited from visits of Kooi (Caltech).

By the end of 2005, the detailed mixer design was completed and high-precision machining techniques started to be explored. In 2006 and 2007, a first prototype mixer was built, tested, and optimized. Performance measurements of the prototype 2SB mixer showed that this prototype meets ALMA specifications. It is worth pointing out that this is the first 2SB mixer operating at the submillimeter frequency of 650 GHz worldwide. One main difficulty in producing the mixer consisted in the required high-precision machining of waveguide structures with micron sized dimensions and submicron precision. Several technology paths were followed, and a recent mixer block insert fabricated from copper using a thick photo resist photolithography technique developed by Chalmers University of Technology delivered waveguide structures of high quality (Fig. 5.4).

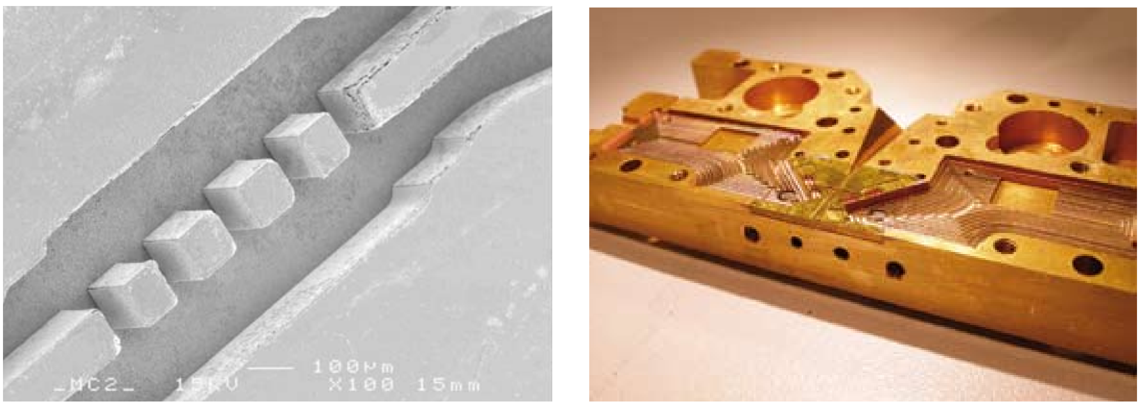

Figure 5.4: Left: SEM image of the NOVA 2SB mixer block waveguide structure produced by a new method developed at Chalmers University of Technology (Sweden). Right: OSO mixer block integrated into the center of the NOVA 2SB block.

The design and performance measurements were reported at various international meetings including the IRMMW2006 conference (September 2006, Shanghai, China, oral presentation by Mena), the 18th International Symposium on Space Terahertz Technology (March 2007, Caltech, USA, oral presentation by Mena), and EUCAS 2007 (September 2007, Brussels, Belgium).

5.1.4. ALLEGRO

Following its establishment in 2005, Allegro (ALMA Local Expertise Group), the Dutch node of the European ALMA Regional Center (ARC) network, was further developed in 2006 and 2007. During these two years, the ALMA project saw the signing of the contracts for the delivery of the antennas, the joining of East Asia as a third partner to the project, and the arrival of the first antennas at the Operations Support Facility in Chile. Currently, early science observations with ALMA are expected to commence in 2011, with the array reaching completion in 2013.

In Europe, the network of ARC nodes was placed on a firm footing with the appointment of Paola Andreani as European ARC manager at ESO. She is responsible for the activities at the ESO ARC core node such as the handling of the proposals, the maintenance of the data archive, and the staffing of the telescope with astronomers. Andreani also maintains a close contact with the North American and East Asian ARCs, and coordinates the European ARC network. The latter is overseen by the ARC Coordinating Committee (ACC) with representatives from each ARC node. The ACC meets once or twice per year and holds monthly teleconferences. So far, its main activities have been focused on defining the respective expertise areas of each node, coordinating funding proposals for the nodes, and negotiating a Memorandum of Understanding that defines the ARC network. In addition to Andreani, the European ALMA Project Scientist Leonardo Testi also is closely involved in the ARC network.

The activities of Allegro will 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) using advanced science analysis tools for the interpretation of atomic and molecular line data from ALMA. In 2006 and 2007, Allegro focused on building up the general expertise required for the face-to-face user support tasks and on initial steps toward the specialists' tasks (1) and (3). The development and activities of Allegro are overseen by a small steering committee, consisting of Barthel (Groningen), Oosterloo (ASTRON), van Langevelde (JIVE), van Dishoeck (Leiden), and Roelfsema and Wild (SRON). This committee is kept informed and consulted by e-mail by Hogerheijde as needed, and meets approximately once a year in person.

As coordinator of Allegro, Hogerheijde participated in the ACC face-to-face meetings in Garching and in the monthly teleconferences. As member of the ESAC and ASAC, he also coordinated the update of the ALMA design reference plan and calibration requirements. Because of the slippage in the ALMA time line, the hiring of the staff for Allegro has been slower than originally planned.

Van der Tak focused on the further development and maintenance of the Leiden Atomic and Molecular Database for Astrophysics (LAMDA), and the publication of a versatile web-based / stand-alone tool for radiative transfer (RADEX). He also regularly participates in the ACC teleconferences.

Hill started her position with Allegro in August 2006. She developed the public web site for Allegro and set up wiki pages, that contain her notes on the interferometer data, as well as her experience with using and testing CASA, the dedicated ALMA offline software package. She participated in a CASA tutorial given by the developers in Garching in July 2007. She also attended the IRAM interferometry school in October 2006 and a meeting on Water Vapor Radiometers in Germany also in October 2006. Before Hill left Allegro in February 2008 to take up another research position, she carefully documented her expertise, including that gained with observations at the SMA and with APEX on Chajnantor.

Hogerheijde and Hill both attended the ALMA Community Day and Workshop in Garching in September 2007, and Hill and van der Tak went to the international ALMA meeting in the Fall of 2006 in Madrid.

5.2. Dutch Open Telescope (DOT)

The Dutch Open Telescope (DOT, http://dot.astro.uu.nl) at the Observatorio del Roque de los Muchachos on La Palma is an innovative optical telescope for high-resolution imaging of the solar atmosphere. It was designed by Hammerschlag and built under his guidance at the university workshops at Delft and Utrecht. It achieves sustained diffraction-limited image quality through the combination of an excellent site, revolutionary wind-flushed open construction, and post-detection image restoration

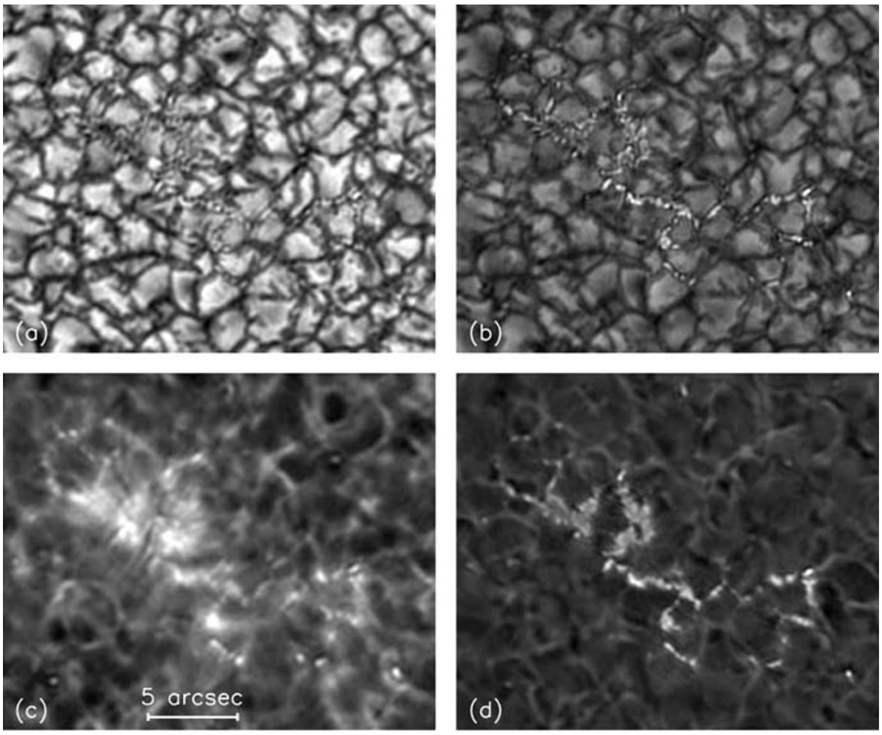

Figure 5.5: Dutch Open Telescope (DOT) observations of a magnetic network patch in the solar photosphere and chromosphere, taken on April 12 2007. (a) blue continuum; (b) G band at 430.5 nm; (c) Ca II H line center; (d) Ca II H offband (-0.235 nm). The network patch consists of many small flux elements of sub-arcsec size. The bright network grains seen in the Ca II H line center image coincide with G-band bright points, indicating that the chromospheric heating is localized directly above the photospheric flux elements. The Ca II network grains are more diffuse than the G-band bright points, probably due to the spreading of flux tubes with height. Figure from a study on chromospheric heating by magneto-acoustic waves by Hasan and van Ballegooijen 2008, Astrophys. J. 680, 1542.

through speckle reconstruction in an advanced on-site processor farm. During NOVA Phase-1 the DOT became the pioneering demonstrator of open-telescope technology as viable alternative to traditional solar-telescope technology relying on vacuum to avoid internal turbulence. Its example is now followed in the German GREGOR (1.5m aperture) project and in the new 1.6m telescope for the Big Bear Solar Observatory, and it inspired both the US national Advanced Technology Solar Telescope (ATST, 4m aperture) project and the plans for a European Solar Telescope (EST) of 2-4m aperture. In the meantime, the 45-cm DOT itself became an outstanding supplier of solar-atmosphere image sequences sampling the photosphere and chromosphere simultaneously at 0.2 arcsec resolution.

The present report period constituted the final phase of a four-year DOT science harvesting program funded by Utrecht University with a contribution from NOVA and executed by Hammerschlag, Bettonvil, Sütterlin and Rutten. Many observing campaigns were performed with Sütterlin as principal observer, often in international concert combining the DOT with the Swedish 1m Solar Telescope on La Palma, the German VTT and/or French THEMIS telescopes on Tenerife, and SOHO, TRACE, and more recently Hinode in space. During 2006 high-quality data were obtained on 30 days, during 2007 on 44 days, attesting to the relatively frequent occurrence at La Palma of seeing good enough to permit diffraction-limited wavefront restoration. Each data set consists of 6-8 synchronous image sequences taken in different spectral diagnostics.

All DOT data are made publicly available at the DOT database (ftp://dotdb.phys.uu.nl). A user-friendly search engine (http://dotdb.phys.uu.nl/search) was completed in 2007. The data base presently offers 642 Gbyte of downloadable DOT data. As a result, DOT data are increasingly used by outside scientists: of the two dozen DOT research papers that appeared since 2006, two-thirds came from teams outside Utrecht. In addition, the DOT engineers wrote another dozen on DOT-related technology, and DOT outreach descriptions appeared in three languages.

Although the DOT science harvesting program ended on January 1 2008, including termination of the contracts of Bettonvil and Sütterlin, the DOT team (now led by Keller since Rutten retired in 2007) obtained permission to maintain the DOT as open facility through 2008 and 2009. The major scientific motivation is its capability to supply high-resolution images in the Balmer H-α line. The original expectation was that the Japanese Hinode mission would take over this role but, unfortunately, this is not the case due to malfunction of the satellite's tunable filter. The major technological motivation for DOT continuation is the EC-funded startup of design studies for a European Solar Telescope (EST) for which the DOT is likely to be an important technology testbed, as it is also for studies funded by STW into fold-away dome technology.

During the report period Rutten continued the "Student-to-the-DOT" education program, which altogether brought 28 students to La Palma, usually in pairs during two weeks. They worked on DOT data analysis and gained on-site telescope experience. Rutten also led Utrecht-Stockholm-Oslo schools for graduate students on La Palma in 2006 and 2007.

5.3 OmegaCAM

OmegaCAM is the wide-field camera for the VLT Survey Telescope (VST). Its focal plane contains a 1x1 degree, fully corrected field of view, which is tiled with 32 2048x4096 pixel CCD detectors for a total of about 16,000 × 16,000 pixels – a quarter of a giga-pixel. 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 was 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.

Figure 5.6: The "OmegaCAM Christmas tree": OmegaCAM in storage in ESO-Garching, ready for shipping to Paranal observatory.

In 2006 OmegaCAM was completed and delivered to ESO, where it awaits shipping to Paranal for installation on the VST. Unfortunately the telescope project was hit by a series of delays, and at the time of writing it appears that the telescope will not be ready to accept the camera 2009.

5.3.1. Science with OmegaCAM

ESO recognized that the VLT Survey Telescope, in combination with the near-infrared survey telescope VISTA, should mostly be used for large coherent projects that are supported scientifically and technically by the community. They therefore went through an open selection process for large public surveys in order to define ambitious projects with strong backing from research groups outside the ESO organization itself. The outcome of this process was that three large surveys were awarded on the VST, and six on VISTA. Two of the VST (as well as two of the VISTA) surveys have very significant involvement of NOVA: KiDS (PI Kuijken) and VPHAS+ (co-PI Groot).

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. It will enable the statistical measurement of the halo properties of galaxies in different environ-

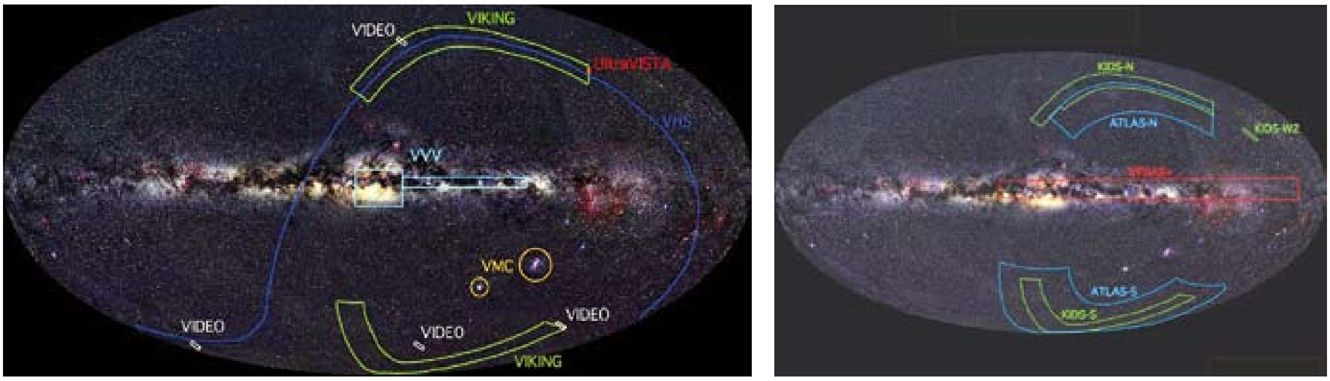

Figure 5.7: Sky coverage of the VST (right) and VISTA (left) public surveys awarded by ESO. KiDS, VPHAS+, VIKING and ULTRAVISTA are all led or co-led by NOVA scientists.

ments through the lensing effect on more distant background galaxies, and, by incorporating photometric redshift information, will also allow the study of the evolution of halo properties. 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 astronomy institute (co-PI Groot). It complements a similar survey of the Northern Galactic plane carried out with the La Palma Isaac Newton Telescope.

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

5.3.2. The OmegaCEN data center

OmegaCEN is the datacenter for wide-field imaging and the expertise center for astronomical information technology at the Kapteyn Astronomical Institute of the University of Groningen. About 15 scientists (postdocs, PhD students and scientific programmers) work at the center. OmegaCEN is coordinator of Astro-WISE, which is a unique advanced survey information system for astronomy. Astro-WISE connects in real-time databases and processing and storage grids available at national datacenters and satellite nodes in the Netherlands, Germany, Italy and France. The system allows distributed production and research analysis of large volumes of astronomical wide field imaging data.

The Astro-WISE information system has been successfully completed as an EU FP5 project and was delivered to the EC on 30 November 2006. The entire information system has been built and is distributed over the community. The system has been qualified using astronomical wide field imaging data from the WFI@2.2m telescope, the wide field imager at La Palma, test data of OmegaCAM, the MDM telescope (USA) and the Suprime-Cam Camera at the 8m Subaru telescope (Hawaii). Extensive web services have been put into operations. National Astro-WISE data center nodes were put into operation at Groningen, Munich, Napoli and Paris, while Astro-WISE satellite nodes were put into place at Leiden and Bonn, also serving research groups in Nijmegen, Bochum, Heidelberg and Santiago (Chile). The system is ready to be filled with the 100's of Terabyte of imaging data from the VST/OmegaCAM and VISTA surveys. The integrated approach to the data ingestion, reduction, analysis and archiving is intended to make it as straightforward as possible for both individual users and large groups to handle huge volumes of data without getting bogged down in tedious data management. Furthermore, it allows virtual, 'after the fact', surveys and projects can be carried out. The result is a 'Virtual Survey system' and is connected to the Virtual Observatory (VO), which focusses on the dissemination and publishing of astronomical data.

The Astro-Wise information system was presented at several conferences like the IAU General Assembly in Prague, the ADASS XVI in Tucson (USA). Several papers were published which describe Astro-WISE or components of it. Advanced courses were held to introduce the user community to the system at the Lorentz Center in Leiden (40 persons) and local courses at the partner sites München, Bonn and Napoli (15-25 persons).

In 2007, the storage and processing resources of the Astro-WISE system were expanded at several nodes. In Groningen, a 100 Tb of disk storage was added and placed at the Donald Smits Center for IT. Real-time data stream connections were improved between the databases and processing grids of nodes. The advanced research and analysis capabilities of the system were expanded with code for photometric redshift determination (PhotZ) and variability analysis using image differencing (MDIA and VODIA). The code was written by the Astro-WISE consortium. The surface photometry packages GALFIT and GALPHOT and the GAAP (Gaussian Aperture And PSF) photometry package were also incorporated into the Astro-WISE infrastructure.

OmegaCEN functions as the national representative for European Virtual Observatory (EURO-VO) programs. It is partner in the EU FP6 EURO-VO Data Center Alliance (EURO-VO DCA) and the FP7 EURO-VO Astronomical Infrastructure for Data Access (EURO-VO AIDA). Astro-WISE was connected to the European Virtual Observatory and OmegaCEN shared its expertise with other Dutch parties to connect their resources to the EURO-VO. OmegaCEN organized the course "Virtual Observations" for master students in early 2007. It included guest lectures by EURO-VO experts from France, the UK and the Netherlands. During the course master students also analyzed astronomical data using the Virtual Observatory and Astro-WISE.

Finally, the success of the e-science aspects of the system triggered other parties to use it as a platform. In particular the novel concept of 'entire backward chaining', i.e. the linking of data products to the input raw data, draws attention as it provides a unique backbone for the infrastructure for advanced distributed e-science in general. OmegaCEN is leading the TARGET project group at the Donald Smits Center for Information Technology (CIT) at the University of Groningen. A main aim is to disseminate Astro-WISE to other fields of research inside and outside astronomy. The project includes the collaboration by OmegaCEN and CIT with LOFAR and IBM to create the architectural design for the long term archive and user interface for the LOFAR radio telescope via kick-off workshops at the Kapteyn Institute in November 2007. The project group is participating in the long term EU program "Enabling Grids for E-Science in Europe (EGEE)". TARGET is developing the LOFAR application of the EGEE-3 Astronomy and Astrophysics cluster. TARGET is also coordinating other multidisciplinary e-Science initiatives which include several departments at the RUG: Artificial Intelligence, alpha informatics and UMCG-Lifelines.

5.4. Sackler Laboratory for Astrophysics

The Raymond and Beverly 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 is well equipped with state-of-the-art experiments focusing on the spectroscopy of molecular transients of astrophysical interest and processes in inter- and circumstellar ice analogues ultimately leading to the formation of complex molecules. The Laboratory led by Linnartz, is fully embedded within the infrastructural settings of Leiden Observatory. Experimental results are used to interpret and guide astronomical observations and as input for astrochemical models. Detailed information is available at: http://www.laboratory-astrophysics.eu. Scientific highlights are reported in section 3.2.

5.4.1. Solid state experiments

5.4.1.1. CRYOPAD – CRYOgenic Photo-product Analysis Device

CRYOPAD has been designed to study the impact of heating and intense UV irradiation on interstellar ice, such as found in hot cores around protostars and protoplanetary disks. Thermally and photon induced desorption processes have been studied using spectroscopic (RAIRS – reflection absorption infrared spectroscopy) and mass spectrometric (TPD – temperature programmed desorption) techniques. Ices are grown typically with monolayer precision under ultra-high vacuum conditions.

The highlight in this reporting period has been a series of systematic photo desorption studies by Öberg (PhD) and co-workers on CO, N_2, CO_2 and H_2O, simulating the inter/circumstellar UV radiation field by a special microwave driven H_2-discharge lamp. The results show that the process is substantially more effective than assumed so far in astrochemical models for molecules which have an allowed electronic transition in the wavelength range of the lamp.

5.4.1.2. **SURFRESIDE – SURFace Reaction Simulation DEvice**

It has been suggested 25 years ago that complex molecules in space may form through atom bombardment of icy dust grains. To study such processes, SURFRESIDE has been constructed and became operational in 2006 (see figure on back cover). This is an UHV setup in which ices are grown under fully laboratory controlled conditions and can be monitored using both RAIRS and TPD. The ice is subsequently bombarded by H-atoms, using a special thermal cracker source. Hydrogenation schemes of CO (resulting in formaldehyde and methanol) and acetaldehyde (resulting in ethanol) have been studied by Fuchs (postdoc), Bisschop (PhD), Ioppolo (NOVA PhD) and co-workers. Besides the fact that it is possible to show that new molecules form at temperatures as low as 10 K, the reaction schemes have been characterized quantitatively which is important in astrochemical models. In parallel, a second beam line, capable of producing atomic beams of N- and O-atoms, using a special MW discharge source has been designed and constructed by Fuchs, Romanzin (postdoc) and collaborators which will be implemented into SURFRESIDE with the goal to fully explore potential solid state reactions schemes.

5.4.1.3. **CESSS – Cavity Enhanced Solid State Spectrometer**

A new detection scheme based upon incoherent broadband cavity enhanced absorption spectroscopy is used by Bouwman (PhD) and co-workers to study systematically the optical spectra of inter/circumstellar ice analogues. The technique is sensitive, covers large spectral ranges with reasonable (and for ices more than sufficient) resolution and is very fast. As a consequence it is also possible to monitor molecular dynamics in the ice. The setup consists of a special intense 'white' lamp, a regular vacuum setup in which ices are grown from 10 K onwards and a state-of-the-art monochromator in combination with a sensitive multi-array detector. The setup is used to systematically study the spectral appearance of PAHs in water ice in collaboration with Allamandola (visitor).

5.4.1.4. **HV-setup – High Vacuum setup**

The HV-setup has been used in a number of projects to provide the astronomical society with systematic spectroscopic input of infrared features in mixed interstellar ice analogues. The experiment comprises a regular HV setup in which ices are monitored by a Fourier transform infrared spectrometer. By changing ice composition and by varying temperature accurate information is obtained that can be used to compare with astronomical ice spectra. In the last two years studies have been performed on CO_2:H_2O, CO:H_2O, NH_3:CH_3OH:H_2O and HCOOH:H_2O ices by master students Ludwig and Beckwith in collaboration with Bouwman, Öberg and Bisschop. These data have been included in the Leiden Database for Interstellar Ices, accessible via the Laboratory website.

5.4.2. Gas phase experiments

5.4.2.1. **SPIRAS – Supersonic Plasma InfraRed Absorption Spectrometer**

Because of the radiation fields in space, it is not surprising that many gas phase molecules are open shell species, typically radicals and ions. SPIRAS is a unique setup capable of detecting high resolution spectra of molecular transients at low rotational temperatures in direct absorption using special plasma and modulation techniques. The experiment comprises a tunable diode laser spectrometer (1000-3000 cm^{-1}, 0.001 cm^{-1} resolution) monitoring an intense planar plasma expansion. It provides the interesting option to extend applications towards ionic complexes. As found by Verbraak (PhD) these species have a remarkably high binding energy because of charge induced interactions and may offer an alternative to study spectroscopically ion-molecule reactions in space. Furthermore, during a six months collaboration with the Radboud University Nijmegen it was possible to use a tunable OPO laser system in a cw cavity ring down detection scheme to further increase the sensitivity (Fig. 5.8).

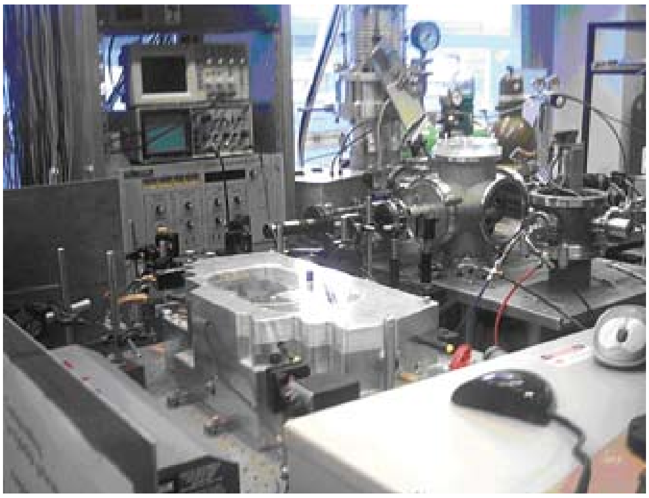

Figure 5.8: The tunable OPO laser system in a continuous cavity ring down configuration for monitoring molecular transients of astrophysical interest in direct absorption.

In the nearby future a sub-millimeter spectrometer will be incorporated in SPIRAS in support of HIFI and ALMA.

5.4.2.2. LEXUS – Laser Excitation setup of Unstable Species

LEXUS has been constructed to observe emission spectra in hydrocarbon plasma with the aim to identify emission features as observed on the extended red emission of the Red Rectangle nebula, in a project led by Wehres (NOVA PhD). The setup comprises a Nd:YAG pumped dye laser system that is focused into an expanding pinhole plasma in a large vacuum chamber. Time gated fluorescence spectroscopy is applied to monitor fluorescence spectra of molecular transients of astrophysical interest.

5.4.3. Theoretical support

The experiments benefit substantially from theoretical models – particularly continuous rand-walk Monte Carlo simulations by Cuppen – that put a physical-chemical basis under the observations and that allow to extend conclusions beyond experimentally accessible conditions.

5.5. JWST-MIRI

5.5.1. Project overview

The Mid-Infrared Instrument (MIRI) is a combined imager / integral field spectrometer covering 5-28 μm on board the ~6m James Webb Space Telescope (JWST), the successor of HST to be launched around 2013. 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 unprecedented 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:

- design, build and deliver the Dutch part of the spectrometer to the European consortium according to specifications;
- ensure strong Dutch participation in the scientific exploitation of MIRI;
- maintain and develop mid-infrared scientific and technical expertise in the Netherlands, important for securing a Dutch role in future infrared missions.

The MIRI instrument is designed and built by a joint US/European consortium. The European Consortium (EC) is led by the UK (PI G. Wright), with Germany, France, The Netherlands, Belgium, Spain, Switzerland, Ireland, Sweden and Denmark as partners. Europe will design and build 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 until end 2007, and in which Brandl participates as instrument scientist. Significant MST activities in 2006-2007 include writing of the MIRI calibration and operation plan documents, selection of the flight detector arrays, and planning for analysis of MIRI test data.

The Dutch project office is located at ASTRON, with R. Jager as the Dutch project manager. 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 the European MIRI Consortium and ESA on behalf of the Netherlands. A European MIRI steering committee was formed in spring 2003, with representatives from the various agencies contributing financially to MIRI, including Boland on behalf of NOVA. In late 2007, NOVA also granted support 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.

5.5.2. Technical progress in 2006 - 2007

The optical design of MIRI spectrometer was frozen in 2003. In brief, 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 re-assembled 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 1024×1024 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. From a functional point of view the MIRI spectrometer is one integrated module but 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 2006-2007, the detailed (opto-)mechanical design of the SMO, led by Kroes (ASTRON), was finished and documented, including the light baffles and mirror covers. The SMO requirements specification and verification control documents were finalized, led by Meijers (ASTRON), and the optical ground support equipment (OGSE) was designed and tested. The Qualification Model (QM) of the SMO box and various subsystem components (mirrors, grating wheel) were built and alignment and vibration tests were successfully carried out. The Verification Model (VM) containing an active short wave arm and a dummy long wave arm was built and delivered to RAL, after a series of bake-out, gravity release and thermal vacuum cycling tests. The VM grating wheel assembly was delivered to MPIA (Heidelberg) and integrated in the SPO at ATC (Edinburgh). First light of the entire MIRI VM cold system was obtained in December 2007 (back cover of this report). The image quality is very good; this is a major accomplishment of the MIRI team and at the same time retires significant risks for the flight model.

Another major milestone was the MIRI Critical Design Review (CDR) which took place in late 2006 and was passed in early 2007. Preparation and documentation for the CDR, together with the subsystem CDRs earlier in 2006, took significant efforts. The Flight Model (FM) SMO hardware has subsequently been manufactured and integrated (Fig. 5.9), and will be delivered to RAL in mid 2008 after thorough testing and characterization at ASTRON. Due to delays at the grating manufacturer, the delivery of the Flight Model Grating Wheel Assemblies will take place in January 2009.

Planning for integration, testing and calibration on the ground and in-orbit has ramped up considerably in the reporting period. Brandl is involved in the MIRI calibration working group, led by Friedman (StScI), with activities including design of astronomical observing templates, data acquisition scenarios (especially for faint sources), dithering schemes, and mitigation of latent images and cosmic rays. The MIRI EC 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.

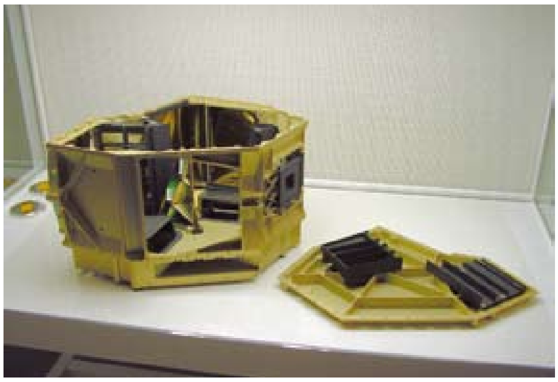

Figure 5.9: The long wavelength arm of the MIRI flight model, manufactured in 2007 at ASTRON, shown before closing the lid.

Dutch participation in EC test and calibration team has been defined and secured over the past two years, and includes Kendrew (NOVA postdoc), Martinez (NOVA PhD), Merin (ESTEC) and Lahuis (NOVA, SRON, Leiden). In 2007, they received full training at RAL on the test operations, software and scripting language, and they participated in the design and execution of the first VM tests. Lahuis, together with Roelfsema (SRON) and Brandl, are 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, with a focus on the medium resolution spectrometer modes.

5.6. Multi Unit Spectroscopic Explorer (MUSE)

5.6.1. General description of the project

MUSE, the Multi Unit Spectroscopic Explorer, is a second-generation panoramic integral-field spectrograph for the VLT, developed by a F-NL-D-CH consortium led by CRAL at Lyon and expected to begin operation in 2012. The instrument consists of

24 combined identical integral-field spectrograph units, covering simultaneously the spectral range 0.480 - 0.930 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 × 1 arcmin) field of view, which will be used for conducting uniquely sensitive deep-field surveys, with the key goal of understanding the progenitor population of present-day 'normal' galaxies. Through a series of nested surveys of different area and depth, MUSE will detect Lyman-alpha emission from large numbers of (proto-)galaxies up to redshift z ~ 6. The deepest exposures will reveal emission from the gas around galaxies, enabling the study of gas flowing into and out of galaxies. At low redshifts MUSE will allow detailed two-dimensional mapping of the kinematics and stellar populations of a variety of 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× 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. Implicit in the MUSE project is the development of new enabling technologies that will have an impact on future extremely large telescope facilities. The modular structure of the instrument provides a model for future research — industry partnerships. The integrated role of a multi-laser adaptive optics facility, which will certainly be part of future instrument developments, highlights the challenges in designing, building and managing such complex systems. The development of the DSM itself presents significant challenges both in manufacturing and, more importantly, in system control.

An important element 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 under NOVA responsibility and is due to start operation at ESO, Garching, early 2011, in time for the DSM delivery.

The MUSE consortium consists of 6 core institutes: Astrophysikalisches Institut Potsdam (AIP); Centre de Recherche Astronomique de Lyon (CRAL); ESO; Leiden Observatory (NOVA); Eidgenössische Technische Hochschule (ETH), Zürich; Laboratoire d'Astrophysique Observatoire Midi-Pyrénées (LAOMP), Toulouse; and the University of Göttingen.

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: coordinating the MUSE science team and Guaranteed Time Observation (GTO) allocation, and providing key operations-based deliverables;
- The Interface Control Document: 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 ASSIST test-bench: facility for testing and integrating the ESO DSM and AO-Facility instruments.

Starting as a NOVA seed funding project in 2003-2004, continuation of the Dutch participation in MUSE was secured through funds from the NOVA Phase-2 and Phase-3 instrumentation programs and Leiden Observatory, with additional contributions from the Netherlands Organization for Scientific Research (NWO), the Leiden Observatory Fund (LSF) and the European funded OPTICON program.

5.6.2. Progress in 2006-2007

MUSE has passed both its Preliminary Design Review and its Optical Final Design Review (OFDR) and is now in the Final Design Phase, to be closed with the Final Design Review in November 2008. With the passing of the OFDR, the road was cleared for the ordering of the first optical components, specifically the spectrographs and detectors.

MUSE and its AO system GALACSI are now developed as two independent units, with GALACSI being solely developed by ESO. This requires a well defined interface between the two components of the MUSE facility. The interface control is maintained by NOVA, as a semi-independent entity, led by Stuik. The interface stability is controlled by two systems: In the Wide Field Mode, an independent Slow Guiding System maintains the location of

guide stars outside the MUSE field, while in Narrow Field Mode the Tip-Tilt sensing of GALACSI will be done as close as possible to the MUSE focal plane, allowing the AO system to correct for differential motion between GALACSI and MUSE.
NOVA also maintains the interfacing between the simulations of the AO system and the MUSE instrument. NOVA started the development of a simplified simulation system, calibrated to the detailed simulations by the GALACSI team, and the development of advanced PSF reconstruction codes for multi-LGS AO systems.

The VLT AO Facility was approved and officially entered the Preliminary Design Phase, with the Kick-off on February 16, 2006. The AO Facility consists of the Deformable Secondary Mirror (DSM) for one of the UTs, a Laser Guide Star Facility (the baseline being 4x Na LGS), 2 AO modules (GALACSI for MUSE and GRAAL for the IR wide-field imager HAWK-I) and a real-time control architecture for these AO modules (SPARTA). ASSIST will be the test facility for both the DSM and the two AO systems GALACSI and GRAAL and falls fully under the responsibility of NOVA.

ASSIST has passed its Preliminary Design Review and is now, like MUSE, in its Final Design Phase. The optical design was fixed and the Call for Tender for the first optical components will be issued in early 2008. After several iterations with ESO and reduction of the requirements, while maintaining nearly full functionality, the optical design of ASSIST has now been fully optimized for the DSM and GALACSI testing, while the testing of GRAAL is possible with relatively simple adjustments. The current opto-mechanical design is shown in Fig 5.10.

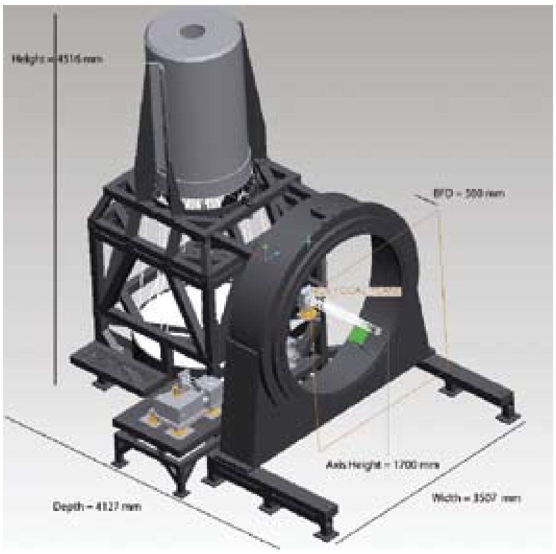

Figure 5.10: Overview of ASSIST. Clearly visible are the DSM support structure (DSM in gray), containing the large mirror, and the Rotator Bench which will hold the instrument under the tests.

In 2006 the agreement between the MUSE consortium and ESO was signed for the development and building of MUSE; and in 2007 the agreement between NOVA and ESO was signed on the design and construction of ASSIST. The two projects together will yield a total of 255 nights of GTO time for the MUSE consortium to be mainly used in a coordinated deep survey. In parallel with the development of the MUSE instrument, several science team meetings were held to discuss the use of the GTO time and required preparatory observations to be done. Furthermore, the science team has been keeping a close eye on the impact of the design of MUSE with regard to the scientific performance of MUSE.

The MUSE team in the Netherlands is led by Schaye, who replaced De Zeeuw as NL Co-I on the international MUSE consortium. Franx is the MUSE Survey Scientist, while McDermid as the former Deputy Instrument Scientist left the MUSE consortium in late 2007. Further contributions to MUSE science were made by Brandl, Quirrenbach, Tolstoy, Verheijen and van der Werf. Stuik is the national MUSE project manager and the ASSIST project manager. The simulations of the AO performance for MUSE, GALACSI and ASSIST are done by Jolissaint. The development of ASSIST is done by Hallibert (optical design), Deep (opto-mechanical design, replacing Vink), Wiegers (mechanical construction), Kendrew (analysis) and Pauwels (product assurance and MAIT).

5.7. X-shooter

X-shooter is the first second-generation instrument for the VLT to be installed on the telescope in 2008. It is intended to become 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 X-shooter consortium members are from Denmark, France, Italy, The Netherlands and ESO.

The concept of X-shooter was defined with one single main goal in mind: the highest possible throughput for a point source at a resolution which is just sky limited in about an hour of exposure over the broadest possible wavelength range, without compromising throughput at the atmospheric

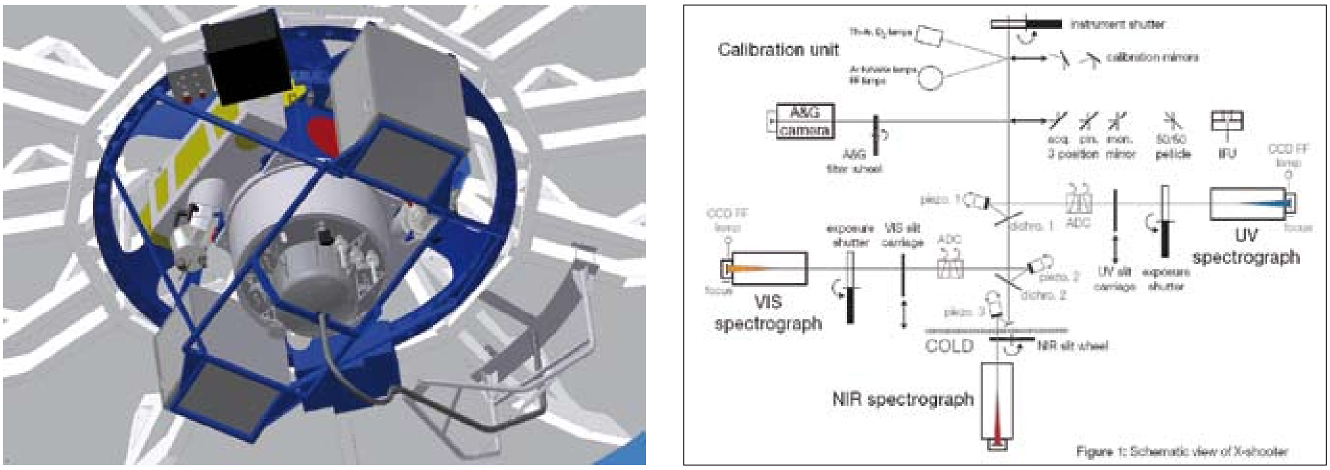

Figure 5.11: Left: the X-shooter spectrograph depicted in the Cassegrain focus below the M1 mirror cell of the VLT. To reduce flexure, the center of gravity is located as close as possible to the telescope, and the stiff elements are light-weighted. The UV and VIS spectrograph arms are mounted to the side; the NIR arm is at the bottom of the instrument; Right: Schematic view of X-shooter (from Vernet et al. 2007, ESO Messenger 130, p. 5).

UV cutoff. The moderate size of X-shooter is, as opposed to most existing or planned VLT instruments, compatible with implementation at the Cassegrain focus.

The instrument design is based on multiple dichroics to split the light between the three spectrograph arms (Fig. 5.11). The central backbone supports three prism cross-dispersed echelle spectrographs. The backbone contains the calibration and acquisition units, an IFU that can be inserted in the lightpath, the two dichroics that split the light into the three arms and relay optics to feed the entrance slits of the three spectrographs. The spectral performance and efficiency (better than 95%) of the two dichroics turn out to be exceptionally good, especially when considering the enormous wavelength range covered by X-shooter.

About 75% of the costs of the X-shooter hardware, as well as labor, is funded by the external members of the consortium. ESO is responsible for the detector systems, project management, and commissioning. More than 60 people were involved in the project at nine different institutes distributed over four ESO member states and at ESO. The overall cost of the project is 6.4 M€ and the staff effort amounts to ~70 FTEs. The consortium is compensated for the project investment with guaranteed time (156 nights over a period of three years). Even with the complex distribution of work over many different sites, the X-shooter project has advanced well on a relatively short timescale: ~5 year from the official kickoff to installation at the telescope in 2008.

First light of the visual spectrograph was achieved in the laboratory in July 2007; the NIR arm had first light in December 2007 (back cover of this report). In January 2008 integration of the full instrument started in ESO at Garching. The final delivery (the near-infrared arm) is planned for March 2008.

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. Funding of the NL work packages is fully secured with contributions from the NOVA Phase-2 instrumentation program (1125 k€), a NWO-M grant (744 k€), a grant from the University of Amsterdam (300 k€), and in-kind contributions from the University of Nijmegen and ASTRON. The UvA contribution covered the construction costs of some hardware components for the near-IR spectrograph (carried out by the Section Mechanical Construction at the UvA) and a postdoc for the development of data reduction software. Kaper is the Dutch PI and member of the Project Board, Groot is the national co-PI and chairman of the X-shooter Science Team, and Navarro (ASTRON) is the national Project Manager.

X-shooter passed the Final Design Review in June 2006; a large investment of time and money concerned the redesign of the NIR arm cooling system. Vibrations induced by the planned closed-cycle cooler would compromise VLTI observations, so that a new cooling system had to be designed based on liquid-nitrogen cooling. This redesign also affected the weight and flexure budget of the instrument, requiring extreme light-weighting techniques. Fortunately, these technical problems could be solved, resulting in first light of the NIR arm in December 2007.

5.8. Spectro-Polarimetric Exoplanet Research (SPHERE)

SPHERE is one of the four second-generation VLT instruments under development. The science goals of SPHERE include

- the direct detection at optical and near-infrared wavelengths of giant exo-planets orbiting solar type stars in wide orbits;
- imaging of proto-planetary disks surrounding young stars;
- imaging of the circumstellar environment of (evolved) stars with stellar winds.

The SPHERE instrument consists of an extreme Adaptive Optics system and three science arms: ZIMPOL, the imaging polarimeter, IRDIS, the near-IR imaging and slit spectrograph, and IFS, the near-IR integral field unit. SPHERE will push the capabilities of the VLT to its limits, and the survey nature of the routine observations differs from that of other VLT common user instruments. In order to make full use of the potential of SPHERE intimate knowledge of calibration and data reduction techniques will be required.

SPHERE is the result of merging two studies for a second generation exo-planetary camera (Planet finder and CHEOPS) for the VLT. The successful merging of the two consortia resulted in a smooth cooperation between the consortium partners. PI of SPHERE is J.-L. Beuzit, and the project manager is P. Puget. The Dutch contribution focuses on ZIMPOL, the Zürich Imaging Polarimeter. This science arm is designed and constructed in close collaboration with the group at ETH Zurich, and led by H.-M. Schmid. The Dutch effort is led by Waters (UvA, also member of the SPHERE executive board), and the project manager is Pragt (ASTRON).

5.8.1. Direct detection of exo-planets

Since the first discovery of a planet around a solar-type star in 1995, the search for extra-solar planets, or exoplanets, has developed into one of the main goals of astronomy. To date more than 250 exoplanets have been found, a number of them in multi–planet systems. These exoplanets have been found using indirect detection methods, in which not the planet itself is observed, but rather its influence on the star. Indirect detection methods have proved to be very successful in finding extra-solar planets. However, they provide little information on the planet itself, apart from its mass or size, and some orbital parameters. In addition, these methods have generally little sensitivity to exoplanets that are in orbits as wide as those of the giant planets in our own solar system. To get information on a planet's physical parameters, such as temperature and pressure, chemical composition and atmospheric structure, which provide key information on planet formation and evolution, direct detection of radiation from the planet is required. This method also enables the detection and study of planets in systems like our own solar system. It thus covers a parameter space that is complementary to that of the radial velocity method, and is important in view of searches for terrestrial-type exoplanets.

SPHERE aims at the direct detection and characterization of Extra-solar Giant Planets (EGPs). The instrument is based on two detection strategies: one is optimized to detect the polarized, reflected light of old, cold EGPs, and the other is optimized to detect the thermal radiation of young, hot EGPs.

5.8.2. Proto-planetary disks and exo-zodiacal clouds

Almost all young, low-mass stars appear to have an accretion disk through which matter flows towards the central star. After the accretion stops, a disk of gas and dust remains, that slowly dissipates. There is growing evidence that these disks are the sites of ongoing planet formation. Imaging and imaging polarimetry of proto-planetary disks reveals important information about its structure and of the composition of the dust in the disk surface layers. Both are strongly affected by the process of planet formation. SPHERE has the capability to image the disks to a distance of 0.1 arcsec from the star, which is much better than current instrumentation is able to provide. SPHERE on the VLT will be a very sensitive instrument to detect exo-zodiacal emission in nearby stars, as well as standard debris disks in stars further away from the Sun.

5.8.3. Guaranteed Observing Time

The GTO exo-planet program will focus on establishing the frequency of gas giant exo-planets as a function of stellar mass and age. This approach will leave ample room for substantial exo-planet surveys in the open time. Other topics of the GTO program will be proto-planetary disks and evolved stars. The Consortium will spend ~200 GTO nights on exo-planet searches using the near-IR arms of SPHERE (IRDIS and IFS), 20-25 nights on exo-planet searches using ZIMPOL and ~20 nights on studies of proto-planetary disks.

5.8.4. SPHERE Consortium

The SPHERE Consortium consists of 12 members from institutes located in France, Italy, Swiss, Germany and the Netherlands. The Consortium partners are Institut National des Sciences de l'Univers du Centre National de la Recherche Scientifique

(INSU/CNRS), acting on behalf of its laboratories: Laboratoire d'Astrophysique de Grenoble (LAOG), Laboratoire d'Astrophysique de Marseille (LAM), Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique, Observatoire de Paris (LESIA), Laboratoire Universitaire d'Astrophysique de Nice (LUAN); Max Planck Institute for Astronomy (MPIA); Istituto Nazionale di Astrofisica (INAF), with activity coordinated by the Osservatorio Astronomico di Padova; Eidgenössische Technische Hochschule Zürich (ETH); Observatoire de Genève (OG); NOVA, representing the involvement of the University of Amsterdam and Utrecht University; Office National d'Etudes et de Recherches Aérospatiales (ONERA); and ASTRON.

Kick-off of the SPHERE project was in March 2006 in Paris, where the organization of the consortium was discussed. In 2006 a consortium agreement and statement of work were formulated. The latter also included detailed work packages for each of the partners and interface control requirements. In 2007 the consortium agreement was finalized and signed by all partners.

5.8.5. Staff and funding in the Netherlands

In the Netherlands Waters (UvA) is the national PI, and Pragt (ASTRON) is the national project manager. The optical design work is done by Rigal (ASTRON) and the mechanical design and thermal analyses by Roelfsema (ASTRON). The design work was supported by Snik (UU), Tinbergen and Venema (ASTRON).

The national science team consists of Waters, Stam (SRON, TUD), Keller (UU), Jeffers (UU), Dominik (UvA), Min (UvA), de Koter (UvA), Tolstoy (RUG), Snellen (UL), and Hovenier (UvA).

Together with the Swiss the Netherlands will design and build the imaging polarimeter arm of SPHERE named ZIMPOL. The funding of the Dutch work package up to commissioning at Paranal was secured with contributions by NOVA (~750 k€), by a NWO-M grant (400 k€), a contribution from the UvA (200 k€), an in-kind contribution from ASTRON (~100 k€) and in-kind contributions of the members of the science team and technical advisory work at UU.

5.8.6. Progress in 2006 and 2007

The project SPHERE, including the sub-system ZIMPOL, successfully passed its PDR in September 2007 and the Preliminary Design Phase (Phase B) was formally closed after the SPHERE Progress Meeting held on 19 December 2007. The ZIMPOL project expects to complete its FDR phase by the end of 2008; Preliminary Acceptance Europe is scheduled for December 2010 and commissioning in Chile in 2011.

The project is running smooth, with a lot of open communications between all partners. There are bi-weekly management telecons and systems telecons. The ZIMPOL team also organizes bi-weekly telecons to discuss technical progress and science issues. Roughly every three months a formal progress meeting with ESO is held; five such meetings were held in the reporting period.

The most critical item in the design of ZIMPOL (Fig. 5.12) is the optical quality of the Ferro-Liquid-Crystals; close contacts with the manufacturer are established to optimize this optical component. The other critical aspect is the AO system performance. Ongoing efforts also include optimization of the coronagraph, allowing smaller inner working angles. Current sensitivity estimates indicate that ZIMPOL should be able to work photon noise limited, giving access to about the 10 brightest stars in the sky.

5.9. LOFAR for Astronomy

LOFAR, the Low Frequency Array, is a next-generation low frequency radio telescope currently being constructed in the Netherlands. The initial array will comprise minimal 36 stations distribut-

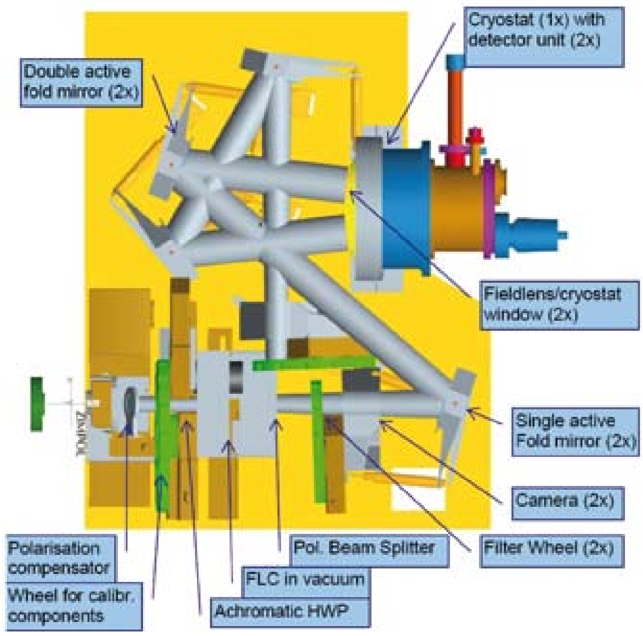

Figure 5.12: Top view of the ZIMPOL optical design with the two arms for an 8 arcsec diameter field-of-view.

ed over an area of diameter of 100 km observing in the frequency range of 10 to 240 MHz. This array is planned to be completed in 2009. Further extensions on a European scale are being pursued by a number of countries, including Germany, UK, Sweden, Poland, France and Italy. 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, Jarvis, 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 via the Gerasimova-Zatsepin effect; (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.

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

The LOFAR radio telescope is being built by a Dutch consortium led by ASTRON. 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:

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

Partial funding of the DCLA project was obtained from NOVA, NWO-M and SNN (Samenwerkingsverband Noord Nederland, a collaboration of the three Northern Provinces of the Netherlands). In addition, the DCLA was supported by grants allocated to individual astronomers as VIDI, VICI, FOM and KNAW awards, and ASTRON provided the program management.

The DCLA management team (DMT) is responsible for the DCLA budget and for ensuring that the DCLA achieves its objectives. Members of the DMT are the PI (Röttgering), the PIs of each of the Key Project Teams (KP-PI's) or their designated replacements (Koopmans), the DCLA Program Manager (Vogt) and the LOFAR International Project scientist (Falcke). The Astronomy Research Committee (ARC) represents the interest of the astronomy community and overviews all aspects of the project that are relevant in making LOFAR a success as a radio observatory.

5.9.2. Progress of key DCLA projects

The first LOFAR core station (CS1) was constructed in the fields of Exloo during the summer of 2006 (Fig. 5.13). 96 low band antennas were distributed over 4 station locations; 48 antennas were placed in a central field and the remaining were distributed over 3 stations yielding a variety of baselines of up

Figure 5.13: A low band LOFAR antenna in the fields of Exloo where 96 of those are distributed. In the background, single prototype high band antenna can be seen.

to 450 m. The set-up was chosen to enable performance tests of a single station at full bandwidth and to emulate a small test version of a LOFAR-type interferometer with 24 micro-stations at reduced bandwidth. In summer 2007, the first six prototype HBA tiles were put into the fields of Exloo.

The LOFAR prototype station CS1 started operations at the beginning of October 2006. After three months, the entire imaging pipeline had all its main software elements in place. Beams are formed at the station level and transported to the BlueGene correlator through an optical fiber network and subsequently visibilities were produced. The hard work to understand the calibration resulted in impressive all-sky maps (Fig 5.14).

The four teams of the key projects made the following progress in the reporting period:

Epoch of Reionisation: Most of the members of the EoR group worked (part-time or fulltime) on CS-1 technical, software and astronomical commissioning. Bernardi made good progress with the polarization calibration of several extensive WSRT 150 MHz datasets and the first signs of significant polarization at these low frequencies were found. Yatawatta (NOVA postdoc) worked on imaging and calibration strategies for CS1 images. He generated images taken with the Low Band Antennas (LBAs) and High Band Antennas (HBAs) of unprecedented quality. V. Pandey (NOVA position) took these algorithms and integrated these in collaboration with ASTRON staff into the LOFAR on-line calibration and imaging pipeline.

Surveys: Members of the survey team (including Intema, NOVA PhD) carried out observation campaigns with low frequency facilities such as the GMRT to study the ionosphere and actively develop calibration strategies in collaboration with ASTRON. Mohan in collaboration with Usov released a first version of a source extraction algorithm to detect sources and measure source characteristics fitting the needs of the survey KSP and LOFAR. The software was also tested successfully on CS1 images. M. Pandey and Omar contributed to commissioning work of CS1.

Transients: The transient KSP detected a pulsar together with staff at ASTRON. Swinbank, Spreeuw (NOVA PhD) and Scheers developed a strategy for

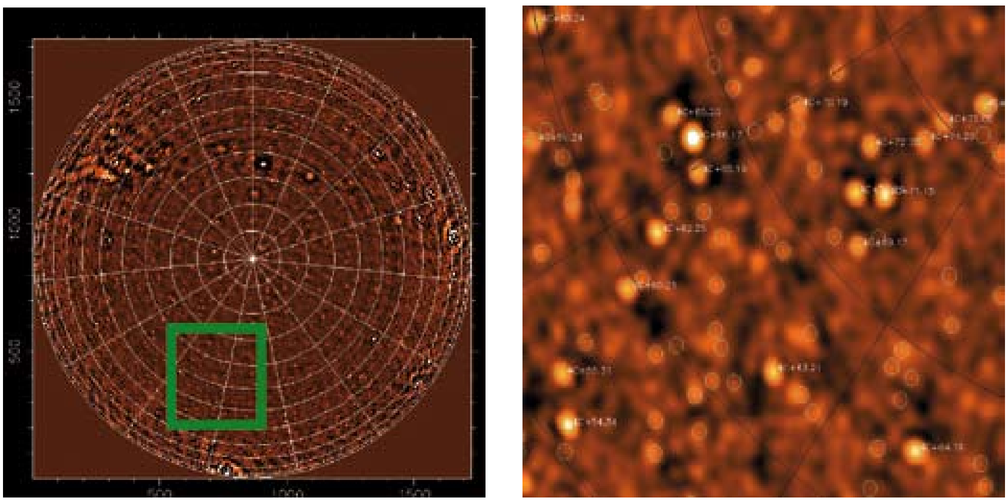

Figure 5.14: Images of CS1 data at 60 MHz generated by Yatawatta (NOVA DCLA postdoc). The detection and identification of the sources have been carried out using the Leiden imaging pipeline (Courtesy Mohan, DCLA postdoc) indicating that the image contains about 800 sources.

a first version of a transient detection pipeline and wrote a prototype of such a pipeline.

Cosmic Rays: The Cosmic ray trigger algorithms were further developed and implemented with the help of ASTRON staff. With the Transient Buffer Boards (TBB) becoming available for test observation, the cosmic ray team (Horneffer, NOVA postdoc; Bahren) took and analyzed the first dynamic spectra. A TBB data reader was developed, written and tested by the team members.

5.10. Photometric instrument algorithms for the Gaia mission

Gaia is the ESA mission which will provide a stereoscopic census of our Galaxy through the measurement of high accuracy astrometry, radial velocities and multi-color photometry. Gaia is scheduled for launch in late 2011 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 color, at 15th magnitude and 100-300 μas at 20th magnitude. Multi-color photometry will be obtained for all objects by means of low-resolution spectro-photometry between 330 and 1000 nm. In addition radial velocities with a precision of 1-15 km/s will be measured for all objects to 17^{th} 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-color photometry) for massive numbers of stars throughout 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. The photometric instrument algorithms form 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 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.

5.10.1. (Inter)national context and collaborations

There is a long tradition in the Netherlands of research into the structure and formation history of the Milky Way and other galaxies and the investigations that can be undertaken with Gaia data fit in perfectly with this tradition. In addition Gaia will provide a wealth of data on all stages of stellar evolution, on the Galactic binary population and on extra-solar planets. This fits in with the existing studies in the Netherlands of the birth and death of stars and the final stages of stellar evolution.

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, de Zeeuw (until September 2007), Levin, Le Poole, Marrese, Perryman, Snellen (all Leiden); Helmi, Trager, Tolstoy (Groningen); Kaper, Portegies Zwart (Amsterdam); Pols (Utrecht); Nelemans (Nijmegen).

Internationally this work is done in the context of the Gaia DPAC, 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, Bologna and Rome in Italy, and Bordeaux in France.

5.10.2. **Progress and achievements in 2006-2007**

Funding: During this period the positions of Brown and Marrese at Leiden Observatory were funded through an NWO-M grant (365 k€, PI Perryman). 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 since the end of 2006 and will enable the appointment of 9 PhD students and 5 postdocs distributed over the 14 network nodes. One PhD student and one postdoc will be located in Leiden. The PhD student, Prod'homme, started in September 2007.

Photometric instrument and algorithms: The design of the photometric instrument was drastically changed during the selection phase (second half of 2005) by the prime industrial contractor for Gaia. The previous design implemented a system of 5 broad and 14 intermediate band filters, whereas the current design employs prisms to produce low dispersion spectra. This design change required a large effort to optimize the scientific capabilities of the new photometric instrument. Brown and Marrese participated in this effort by writing detailed instrument simulations which were used to provide simulated photometric data for further analysis. The simulated data were used to assess the astrophysical parameterization performance of the new photometers and to address crowding issues in dense sky regions. The resulting recommendations by the Gaia science team were accepted by the prime contractor EADS-Astrium as the baseline for the detailed design of the photometers. The photometric instrument simulations written in Leiden were incorporated in the general Gaia instrument simulator.

During 2007 the efforts of the photometric coordination unit within DPAC were mainly focused on putting together a detailed design of the photometric processing pipeline. This includes the requirements specifications, designing the process flowcharts, and the data model. Toward the end of 2007 this effort led to a well defined IT infrastructure for the photometric processing pipeline which will form the basis for the subsequent detailed development of the individual algorithms. Brown and Marrese participated intensively in this process.

During 2006–2007 Marrese and Brown researched calibration methods for the new photometric instrument and in collaboration with the groups in Rome and Teramo investigated methods of dealing with the dispersed images produced by the photometer in crowded regions on the sky. Trager contributed to the ground-based preparations for Gaia which are primarily aimed at obtaining accurately calibrated spectra for a sufficient number of standard sources so that the measurements from the various instruments of Gaia can be tied to a physical scale.

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.

International context: The Gaia Data Processing and Analysis consortium started its work in June 2006. The first major activity for DPAC was to write a proposal describing how DPAC intends to implement and carry out the data processing for Gaia. Brown participated in the writing of this proposal which was submitted in response to ESA's announcement of opportunity in December 2006. The DPAC proposal was formally approved by ESA's Science Program Committee in May 2007. At the same time ESA initiated the negotiation of a multilateral agreement (MLA) between the partners in the DPAC consortium. The purpose of the agreement is to ensure continued funding of the data processing efforts up to the final Gaia catalogue production (expected in 2020). NOVA entered the MLA negotiations as the Dutch partner and the agreement will be formally in place by the beginning of 2008.

During 2006 and the first half of 2007 Brown was a member of the Gaia Science Team. In addition Brown was a member of the management team of the photometric coordination unit and 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.

5.11. Preparation Phase-3 instrumentation program

Preparations of the NOVA Phase-3 program started in October-November 2006 with visits of the NOVA Directorate to each of the university astronomical institutes discussing the on-going activities and exploring the wishes for the Phase-3 (2009-2013) program. In its meeting of 9 November 2006 the NOVA Board decided on the procedures to select the projects for the Phase-3 instrumentation program. A call for instrumentation projects was issued on 14 February 2007. Fifteen proposals were received by mid May. All proposals were presented to the community at an open national instrumentation day held in Utrecht on 4 July 2007. The proposals were reviewed by the Network Key Researchers (KRs) on their scientific merit and by the NOVA Instrument Steering Committee (ISC) on their technical feasibility, finance, project management and risks. The KRs also ranked the proposals on their scientific priority and on their importance for the national astronomy program. Initial decisions on project allocations were prepared in the NOVA Board meeting on 22 November 2007 taking into account the recommendations of the KRs and the ISC. Confirmation of the allocations is planned for early 2008.

5.12. Towards a NOVA Optical-IR instrumentation group

In November 2007 the General Board of NWO decided to restructure ASTRON with the new focus on radio astronomy and a planned termination of the activities on optical-IR instrumentation. Because the existence of such a group is essential to implement NOVA's strategic line on instrumentation for ESO's VLT and VLTI and in the future for the European Extremely Large Telescope (E-ELT), NOVA initiated negotiations with ASTRON and NWO to secure the existence of this group. By the end of 2007 NOVA, ASTRON and NWO reached in principle agreement about a NOVA-lead Optical-IR instrumentation group hosted at ASTRON in Dwingeloo with staff employed by NWO for a period of four years (2008-2011). This agreement also secured the completion of a number of ongoing instrumentation projects under NOVA responsibility in which the group at Dwingeloo was involved, in particular the Spectrometer Main Optics for MIRI on the James Webb Space Telescope (§ 5.5) and the near-IR spectrograph for X-Shooter on ESO's VLT (§ 5.7).

5.13. Preparations for the involvement in the E-ELT

One of NOVA's strategic lines is its involvement in the ESO program which includes the development of a European Extremely Large Telescope (E-ELT) on a competitive timescale. In the reporting period NOVA astronomers Franx (co-chair) and Tolstoy participated in ESO's E-ELT Science Working Group to write the science case of the E-ELT. Brandl (PI MIDIR) and Keller (co-PI EPICS) led European consortia to undertake instrument feasibility studies.

NOVA's strategy is to be involved from the start in instrument design and development, building on the strong Dutch track record at mid-infrared wavelengths (ISO, VISIR, MIDI, MIRI) and in adaptive-optics assisted integral-field spectroscopy (SAURON, OASIS/GLAS, SINFONI, MUSE, SPHERE), with a recent revival of expertise in polarimetry (SPHERE-ZIMPOL).

5.13.1. SmartMix proposal

In 2006 the Dutch government initiated a new grants program to stimulate collaboration between universities, knowledge institutes and industry, to enable knowledge transfer and to strengthen the national economy. A national consortium led by NOVA (PI Boland) submitted a proposal "Pushing the technological frontiers of next-generation astronomical instruments". The proposal passed the first selection cut and was ranked amongst the top 10%, but was unfortunately not successful in the final selection because other proposals promised higher economic returns. The proposal aimed

- To develop novel technological solutions to the most critical design issues of ELT instruments;
- To secure a significant involvement of Dutch industry in at least one major, international ELT instrument by building a key technology demonstrator for an existing large telescope to successfully demonstrate the technological advances enabled through this program;
- To strengthen the current scientific forefront position of Dutch astronomy.

The technological challenges for METIS (§ 5.13.2.2.) formed the core of the proposal although its goals were applicable to modern state-of-the-art instrumentation in general. The Consortium consisted of NOVA (PI), 3 technical universities (Delft University of Technology, Eindhoven University of

Technology, University of Twente), 4 knowledge institutes (ASTRON, SRON, TNO-TPD and TNO-Industry) and 9 industry partners (Airborne Composites, ASML, Cosine research, Dutch Space, Flexible Optical BV, Hemtech, JPE, SUMIPRO, Thales). Many promising contacts with industry were established during the preparation of the proposal.

5.13.2. Phase-A studies on ELT instrumentation

In September 2007 ESO issued a call for proposals from the community for Phase A studies on 'first light' instruments on the E-ELT. The call in particular asked for studies for a

- Single-Field, Wide-Band Spectrograph for the E-ELT
- High Angular Resolution Camera for the E-ELT

NOVA astronomers participated in two consortia, one bidding for the wide-band spectrograph using the acronym 3DESIRES, and the other bidding for the high angular resolution camera under the name MICADO. The latter one was selected by ESO (§ 5.13.2.1).

In November 2007 ESO issued another call for proposals from the community for a Phase-A study for a mid-IR instrument for the ELT for which a consortium led by NOVA (PI Brandl) submitted a proposal in early 2008 (§ 5.13.2.2).

Earlier in 2007 ESO and several institutes in Europe including NOVA and ASTRON agreed to undertake a conceptual design study to specify E-ELT telescope requirements for an instrument aiming for the direct detection and imaging on exo-planets (§ 5.13.2.3).

5.13.2.1. MICADO, the MCAO Imaging Camera for Deep Observations for the E-ELT

Upon selection by ESO at the end of 2007 following a call for proposals (§ 5.13.2) the Max-Planck-Institut für extraterrestrische Physik (consortium lead), Max-Planck-Institut für Astronomie, Universitäts-Sternwarte München, NOVA and Osservatorio Astronomico di Padova started their collaboration with ESO in the Phase A Conceptual Design Study of a high resolution imaging camera known as MICADO that will ultimately work with a multi-conjugate adaptive optics system. It is also intended that the camera will work initially with an alternative (e.g. ground layer) adaptive optics system, and be available as one of the first instruments on the E-ELT. The planned study will consist of two phases. During Phase 1, the science cases will be developed specifically to address scientific trade-offs necessary for selecting the appropriate opto-mechanical design. Several opto-mechanical designs will be developed in parallel, addressing specifically technical/cost trade-offs. At the end of this Phase, the consortium will select a single opto-mechanical 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 will be developed further in a full Phase A study, addressing all technical issues. Phase 1 is planned to be completed in December 2008 and the final Phase A Conceptual Design report will be completed by November 2009.

Kuijken is project PI for the Netherlands and co-PI on the European Consortium. Work packages to be done in the Netherlands include contributions to the science case (Kuijken, Franx, and Tolstoy), optical-mechanical design (NOVA optical-IR instrumentation group) and design of the data flow system (Valentijn).

5.13.2.2. METIS, the Mid-Infrared ELT Imager and Spectrograph

METIS, formerly known as MIDIR, is a combined imager/spectrometer for the E-ELT. In the reporting period a conceptual study of METIS has been performed that led to the following specifications: METIS will cover the wavelength range from 3-14 μm (L, M, and N bands) with a possible extension to include the Q band up to 27μm. It will operate at the diffraction limit, providing an unsurpassed spatial resolution of a few tens of milliarcseconds at mid-IR wavelengths at point source sensitivities comparable to space telescopes. METIS will include the observing modes imaging, medium resolution spectroscopy, and very high spectral resolution (R~100.000) IFU spectroscopy (Fig. 5.15).

The METIS key science drivers are (1) the formation history of the Solar System, (2) the formation and evolution of proto-planetary disks, (3) the physical and chemical properties of exoplanets, and (4) the growth of super-massive black holes in galactic nuclei. Additional areas in which METIS promises breakthrough discoveries are the formation of massive stars, our Galactic center, the life-cycle of cosmic dust, IMF studies in massive star forming regions, the morphologies and dynamical properties of sub-mm galaxies, and Gamma-Ray Bursts as cosmological probes.

The METIS consortium has evolved during 2006 and 2007. In September 2005 the small study for METIS (at that time still called MIDIR) was started by an international team, led by the PI (Brandl) and co-PI Lenzen (MPIA), the project manager Molster (NOVA from 1-1-2006), the project engineer Venema (ASTRON), and the consortium partners ESO

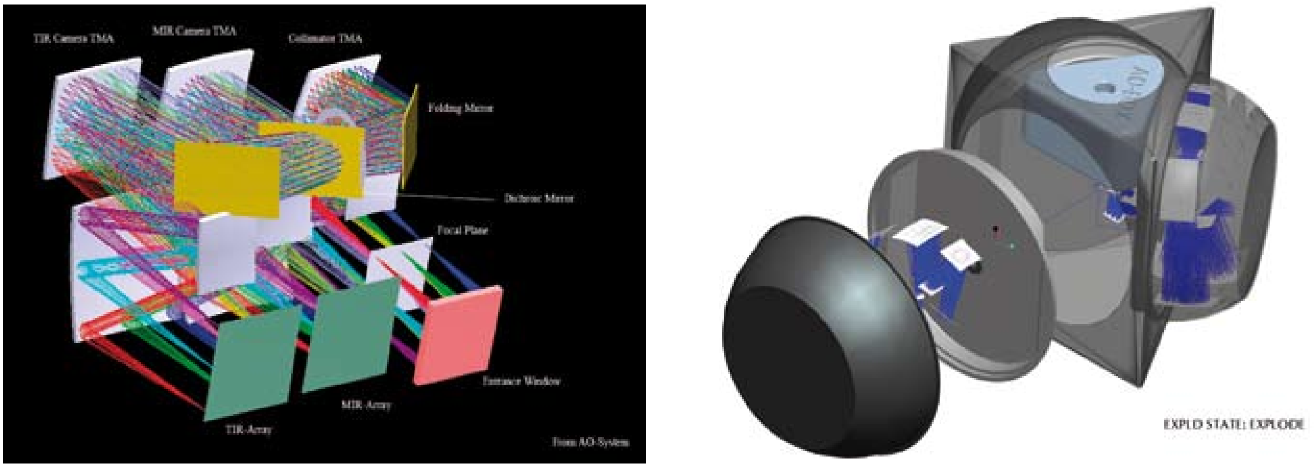

Figure 5.15: Left: conceptual design of the METIS imager and low/medium resolution spectrograph based on a double TMA design. Right: conceptual layout of the cryostat with the imager optics in the center and the high resolution IFU spectrograph arms as add-on modules.

and ATC (UK). The fertile boundary conditions of the project were based on the large expertise that Dutch astronomers have acquired over many decades in the previous projects like IRAS, ISO-SWS, VISIR, HIFI, MIDI and MIRI. The technical team from Dutch universities included Pel, Pelletier, Stuik, Keller, de Graauw, Tinbergen and Hallibert, and received valuable scientific input from van Dishoeck, van der Werf, Tolstoy, Barthel, Waters, Tielens and Wijers. In June 2006 the Small Study Report was completed and delivered to ESO as the project office for the EU-FP6 design study for the E-ELT.

Following the METIS Science Team meeting at ESO in October 2007, the so-called Point Design study started in November 2007 and will be completed by the end of 2008. METIS is one of three instruments studies selected by the EU-FP6 ELT design study consortium. The first milestone is the establishment of the detailed METIS science case, from which the top level instrument requirements will be derived. The Dutch technical team was enlarged by NOVA post-docs Kendrew and Jolissaint and several people from SRON and ASTRON. The Dutch science team was also enlarged, including more than a dozen science co-investigators; most actively involved at that stage were van Dishoeck, van der Werf and Kaper.

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 enlarged to also include the interested groups from KU Leuven (Belgium) and CEA-Saclay (France). Together with the already existing team of NOVA (PI), MPIA, and UK-ATC, this consortium comprises most of the relevant mid-IR expertise in Europe. This consortium will submit a Phase-A proposal in early 2008 and is eager to perform the phase-A study (which has many activities in parallel with the Point Design activities).

5.13.2.3. EPICS – Exo-Planet Imaging Camera and Spectrograph

EPICS aims for the direct imaging and characterization of extra-solar planets with the E-ELT. It will be optimized for observations at visible and near-IR wavelengths and have photometric, spectroscopic and polarimetric capabilities. The conceptual design studies started in 2007. The goals of EPICS Phase A study also include requirements to the technical specifications of the telescope design and feedback to the ESO Science working group conducting the E-ELT Design Reference Missions. NOVA (co-PI Keller) and the ETH Zurich (co-PI Schmid) are responsible for the investigation and conceptual design study of a differential polarimeter focal plane instrument. Work packages to be done 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).

6. NOVA funded astronomical research

The tables in this chapter list all research and technical support staff positions whose employment was – partially – funded through the NOVA program in 2006 - 2007.

Project	Title	Project leader	Univ	Researcher	Yrs	Start	End	Remarks
Network #1								
10.1.2.01	Circumstellar dust in galaxies	Barthel	RuG	Drs. Guido van der Wolk	2,5	Jan 1, 2007		c
10.1.2.02.1	Diffuse radio emission in clusters	de Bruyn	RuG	Drs. Roberto Pizzo	1,5	Jul 1, 2005	Dec 31, 2006	a
10.1.2.02.2	Diffuse radio emission in clusters	Röttgering	UL	Drs. Huib Intema	1,5	Jul 1, 2006	Dec 31, 2007	a
10.1.2.03	2D spectroscopy of distant galaxies	Franx	UL	Drs. Maaike Damen (50%)	4,0	Sep 12, 2005		a
10.1.2.04	Void hierarchy and cosmic web	van de Weijgaert	RuG	Drs. Erwin Platen	2,5	Mar 15, 2005	Sep 15, 2007	c
10.1.2.05	Infant mortality rate in star clusters	Lamers	UU	Drs. Remco Scheepmaker	2,0	Jun 1, 2005	May 31, 2007	a
10.1.2.07	3D astrophysical hydrodynamics	Icke	UL	Drs. Jan-Pieter Paardekooper	2,0	Sept 1, 2006		
10.1.2.08	Integral field spectroscopy of galactic nuclei	de Zeeuw	UL	Dr. Richard McDermid	1,0	Apr 1, 2006	Mar 31, 2007	
10.1.2.09	Network postdoc position	Franx	UL	Dr. Kim-Vy Tran	1,2	Oct 1, 2005	Nov 30, 2006	
10.1.2.09.1	Network postdoc position	Franx	UL	Dr. Ryan Quadri	1,8	Nov 15, 2007		
10.1.2.10	Network postdoc position	van der Hulst	RuG	Dr. Spyros Basilakos	0,5	Oct 1, 2005	Mar 15, 2006	
10.1.2.10.1	The disk-mass project	Verheijen	RuG	Drs. Thomas Martinsson	1,9	Mar 1, 2007		a
10.1.2.10.2	Resolving M32's main sequence	Trager	RuG	Drs. Antonella Monachesi	1,9	Oct 1, 2006		a
Network #2								
10.2.2.01	Probing the inner envelopes of protostars	van Dishoeck	UL	Drs. Dave Lommen	2,7	May 1, 2005	Dec 31, 2007	b
10.2.2.03	Gas-grain chemistry	Linnartz	UL	Drs. Sergio Ioppolo (40%)	4,0	Sept 1, 2006		
10.2.2.04	Massive young stars	de Koter	UvA	Drs. Lianne Muijres	4,0	May 1, 2006		
10.2.2.05	Photo dissociation regions	Spaans	RuG	Drs. Juan Pablo Perez Beaupuits	2,5	Sep 1, 2006		c
10.2.2.06	Search for large carbonaceous molecules in space	Kaper	UvA	Drs. Nick Cox	2,0	May 1, 2004	Apr 30, 2006	
10.2.2.09	Mass loss during the AGB phase	Tielens	RuG	Drs. Christiaan Boersma	3,0	Feb 1, 2005		c
10.2.2.10	AGB pulse dust formation	Icke	UL	Drs. Chael Kruip	2,8	May 1, 2007		a
10.2.2.11	Network postdoc position	Waters	UvA	Dr. Michiel Min	1,0	Apr 1, 2005	Mar 31, 2006	
Network #3								
10.3.1.02	Radio pulsar studies using PUMA on the WSRT	van der Klis	UvA	Drs. Patrick Weltevreden	4,1	Dec 1, 2002	Dec 31, 2006	
10.3.1.04.1	Neutron stars and black holes	van der Klis	UvA	Drs. Diego Altamirano	3,1	Nov 1, 2003	Nov 30, 2006	
10.3.2.01	X-rays from accreting compact objects	Langer	UU	Drs. Laurens Keek (50%)	4,0	Nov 15, 2004		a
10.3.2.02	GRB light curves and the GRB environment	Wijers	UvA	Drs. Hendrik van Eerten	4,0	Oct 1, 2005		
10.3.2.03	Relation between radio and non-radio emission from pulsars	van der Klis	UvA	Drs. Eduardo Rubio Herrera	4,0	Oct 1, 2005		
10.3.2.04	Timing accretion millisecond pulsars	van der Klis/ Wijnands	UvA	Drs. Alessandro Patruno	2,0	Jan 1, 2006	Dec 31, 2007	b
10.3.2.05.1	X-ray spectroscopy	Verbunt	UU	Dr. Elisa Costantini	2,0	Mar 1, 2006		
10.3.2.05.2	X-ray spectroscopy	Verbunt	UU	Dr. Marc van der Sluys	0,5	Jul 1, 2006	Dec 31, 2006	
10.3.2.06	Different manifestations of accretion onto compact objects	van der Klis	UvA	Drs. Diego Altamirano	1,0	Nov 15, 2006	Nov. 14, 2007	
10.3.2.07	GRB progenitors	Langer	UU	Drs. Matteo Cantiello	2,0	Jan 1, 2007		a
10.3.2.10	Network postdoc position	Verbunt	UU	Dr. Jean in 't Zand	1,0	Jul 1, 2005	Jun 30, 2006	
10.3.2.11.3	OmegaWhite survey	Groot	RU	Dr. Luisa Morales Rueda	0,3	Apr 1, 2007	Jul 31, 2007	
Miscelleneous projects								
10.4.2.01	Postdoc NOVA Director	de Zeeuw	UL	Dr. Jesús Falcon-Barroso	0,6	Jul 1, 2005	Feb 28, 2006	
10.4.2.02	Postdoc NOVA Director	de Zeeuw	UL	Dr. Michele Cappellari	0,3	May 1, 2006	Aug 31, 2006	
10.4.2.03	Postdoc NOVA Director	de Zeeuw	UL	Dr. Richard McDermid	0,6	Apr 1, 2007	Oct 31, 2007	
Overlap appointments								
10.5.1.03	Protoplanetary disks	van der Klis	UvA	Dr. Carsten Dominik	5,3	Jan 1, 2006		
10.5.1.04	Computational astrophysics	van der Klis	UvA	Dr. Simon Portegies Zwart (50%)	2,3	Jan 1, 2007		
10.5.2.01	Evolution of galaxies	van der Kruit	RuG	Dr. Amina Helmi	5,3	Sep 1, 2003		

Project	Title	Project leader	Univ	Researcher	Yrs	Start	End	Remarks
Overlap appointments								
10.5.2.02.1	Astronomical instrumentation	van der Kruit	RuG	Dr. Reynier Peletier	3,4	Sep 1, 2003	Dec 31, 2006	
10.5.2.02.2	Physics of compact objects	van der Hulst	RuG	Dr. Mariano Méndez	2,2	Sep 1, 2007		
10.5.3.01	Laboratory astrophysics	van Dishoeck	UL	Dr. Harold Linnartz (50%)	3,0	Sep 1, 2005		
10.5.3.02	Optical-infrared instrumentation	Miley	UL	Prof. Andreas Quirrenbach	3,7	Sep 1, 2002	Apr 30, 2006	
10.5.3.03	Optical-infrared instrumentation	Miley	UL	Dr. Bernhard Brandl	5,0	Jul 1, 2003		
10.5.3.04	Physics of supermassive black holes	de Zeeuw	UL	Dr. Yuri Levin	1,1	Jul 1, 2006	Jul 31, 2007	
10.5.4.02	Stellar evolution	Achterberg	UU	Dr. Onno Pols	4,5	Sep 1, 2001	Feb 28, 2006	
10.5.4.03	Astronomical instrumentation	Langer	UU	Prof. Christoph Keller	2,0	Jul 1, 2005	Jun 30, 2007	
10.5.4.04	Numerical solar physics	Keller	UU	Dr. Alexander Vögler	2,8	Jan 1, 2007		
10.5.4.05	Extragalactic star clusters	Langer	UU	Dr. Søren Larsen	1,8	Apr 1, 2006		

Remarks

a Additional funding up to 4 year in total is covered by the university
b Addional funding from NWO Spinoza grant
c PhD fellowships

Instrumentation Program

Project/job description	Project leader	Inst	Researcher	Yrs	Starting date	Ending date	Remarcs
ALMA Band-9 development and prototyping, CHAMP+, ALMA phase-2 technical R&D							
Project Manager	Wild	SRON	Dr. Brian Jackson	P	Oct 1, 2003		
Manager industrial contracts	Jackson	RuG	Drs. Joost Adema	Pw	Mar 1, 2003		
Instrument scientist	Jackson	RuG	Dr. Andrey Baryshev	Pw	Nov 15, 1999		
Front-End scientist	Jackson	RuG	Dr. Ronald Hesper	Pw	Sep 1, 2000		
Front-End technician	Jackson	RuG	Gerrit Gerlofsma	Pw	Oct 10, 2001		
Documentalist	Jackson	RuG	Albert Koops	Pw	Dec 1, 2004		
Receiver scientist	Jackson	RuG	Dr. Patricio Mena	3,5	Sep 1, 2004		
Receiver scientist	Jackson	RuG	Jan Barkhof	Pw	Mar 16, 2004		
Assembly technician	Jackson	RuG	Marielle Bekema (40%)	Pw	Jan 1, 2005		
Assembly technician	Jackson	SRON	Klaas Keizer	Pw	Mar 1, 2005		
Assembly technician	Jackson	SRON	Jarno Panman	Pw	Nov 1, 2007		
Assembly technician	Jackson	SRON	Jacques Koops van der Jagt	2,0	Nov 1, 2007		
Various staff University of Delft	Klapwijk	TUD					
Allegro							
Technical astronomer	Hogerheijde	UL	Dr. Tracy Hill	1,5	Sept 1, 2006		
Champ+							
Support astronomer	Boland	SRON	Dr. Floris van der Tak	2,8	Feb 1, 2005	Oct 31, 2007	
OmegaCAM/CEN							
Calibration software scientist	Kuijken	RuG	Dr. Edwin Valentijn	Pw	Apr 1, 1999		
Programmer calibration software	Valentijn	RuG	Danny Boxhoorn	Pw	Apr 1, 1999		
Programmer	Valentijn	RuG	Michiel Tempelaar	1,0	June 1, 2006		
Programmer	Valentijn	RuG	Dr. Gijs Verdoes Kleijn (80%)	5,0	Dec 1, 2006		
Postdoc commissioning	Valentijn	RuG	Dr. John McFarland	5,0	May 1, 2005		
Postdoc commissioning	Valentijn	RuG	Dr. Philippe Heraudeau	0,5	July 1, 2006	Dec 31, 2006	

Project/job description	Project leader	Inst	Researcher	Yrs	Starting date	Ending date	Remarcs
Sackler Laboratory for Astrophysics							
Surfreside technical PhD student	Linnartz	UL	Drs. Sergio Ioppolo (40%)	4,0	Sep 1, 2006		b
Technical postdoc	van Dishoeck	UL	Dr. Guido Fuchs	1,5	Sep 1, 2005	Mar 1, 2007	a
SINFONI							
Postdoc commissiong 2K camera	van der Werf	UL	Dr. Juha Reunanen	2,0	Jun 1, 2005	May 31, 2007	
PhD student	van der Werf	UL	Drs. Liesbeth Vermaas	2,0	Feb 1, 2006		b
MIRI							
NL project manager	van Dishoeck	SRON	Drs. Ir. Rieks Jager	P	Jun 1, 2003		
Postdoc instrument calibration	van Dishoeck	SRON	Dr. Fred Lahuis	Pw	May 1, 2007		
Postdoc test/calibration	Brandl	UL	Dr. Sarah Kendrew	2,0	Feb 1, 2007		
PhD student instrument calibration	Brandl	UL	Drs. Juan Rafael Martinez Galarza	2,0	Dec 1, 2007		
Several ASTRON staff	Jager	ASTRON					
X-Schooter							
NL project manager	Kaper/Groot	ASTRON	Ramon Navarro (parttime)	P	Mar 1, 2005		
Several ASTRON staff	Navarro	ASTRON					
MUSE/Assist							
Project manager Assist	Franx	UL	Dr. Remko Stuik	P	Dec 1, 2003		c
Optical designer	Stuik	UL	Pascal Hallibert	4,0	April 1, 2005		
Mechanical designer - system engineer	Stuik	UL	Dr. Ramon Vink/ Dr. Sarah Kendrew	2,1	Jan 1, 2005	Jun 30, 2007	
Postdoc ASSIST hardware	Stuik	UL	Dr. Atul Deep	2,0	April 1, 2007		
Postdoc AO control	Stuik	UL	Dr. Laurent Jolissant	2,0	Mar 1, 2007		
LOFAR							
Postdoc Reionization	de Bruyn	RuG	Dr. Sarod Yatawatta	3,0	July 1, 2005		
PhD student Transient sources 1	Wijers	UvA	Drs. Hanno Spreeuw (50%)	4,0	Sept 1, 2005		
PhD student Transient sources 2	Wijers	UvA	Drs. Bart Scheers (50%)	4,0	Sept 1, 2005		
Postdoc high-energy cosmic rays	Falcke	RU	Dr. Andreas Horneffer	2,5	May 1, 2005	Oct 31, 2007	
Postdoc surveys	Röttgering	UL	Dr. Niruj Mohan Ramanujam	3,0	July 1, 2005		

Remarks

a Addional funding from NOVA overlap program
b Additional funding up to 4 year in total is covered by the university
c Also partially funded from OPTICON FP6 JRA1
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 2006-2007

The table below lists the workshops which received financial support from NOVA. The table is followed by a description of each meeting. Some workshops held in 2005 but not reported in previous annual report are included. In addition the university astronomical departments in Amsterdam, Groningen, Leiden, Nijmegen and Utrecht received NOVA funding up to 3400 € per institute per year (Nijmegen about one third of it) to strengthen the local colloquium program through inviting more foreign speakers. The common approach is to co-ordinate the colloquium programs in various places in such a way that foreign speakers visit two or more institutes during their stay in the Netherlands.

Organizer	Organizing	Institute	Subject	Duration	Start in days
W-77	Van de Weijgaert	RuG	From strings to the cosmic web	3	30-11-2005
W-85	Habing	UL/LC	Spitzer's view on mass-losing AGB stars	5	28-11-2005
W-86	Franx	UL/LC	The study of near-IR selected high-redshift galaxies	5	31-10-2005
W-87	Van de Weijgaert	RuG/LC	The world a jigsaw: tessellations in the sciences	5	06-03-2006
W-89	Mellema	UL/LC	Cosmological radiative transfer	3	12-12-2005
W-90	Langer	UU	Mass loss from stars and the evolution of stellar clusters	3	29-05-2006
W-91	Trager, Peletier	RuG/LC	Fine-tuning stellar population models	5	26-06-2006
W-92	Kuijpers	RU	2nd international summer school on astroparticle physics	14	29-08-2006
W-93	Helling	UL/LC	From browns dwarf to planets: chemistry and cloud formation	4	24-10-2006
W-94	Portegies Zwart	UvA	MODEST 6d satellite workshop	28	21-03-2006
W-95	Helmi	RuG/LC	Dissecting the Milky Way	5	06-11-2006
W-96	Olthof		KNVWS symposium on water	1	07-10-2006
W-97	de Zeeuw	UL/LC	Galactic nuclei	5	24-07-2006
W-98	FMF – Groningen	RuG	Universal origins, uncovering astronomical roots	1	22-05-2006
W-99	Peletier	RuG	High-velocity clouds and the origin of neutral gas in nearby galaxies	2	20-10-2006
W-100	van de Weijgaert	RuG	KNAW colloquium on cosmic voids	4	12-12-2006
W-101	Groot	RU	IMAPP symposium: origins of the universe	1	13-10-2006
W-102	Franx	UL/LC	Studies of infrared selected galaxies	5	13-11-2006
W-103	Kuijken	UL/LC	Gravitational lensing	5	31-07-2006
W-105	Schaye	UL/LC	Computational cosmology	5	15-01-2007
W-106	Wijers, Kaper	UvA	The next decade of gamma-ray burst afterglows	5	19-03-2007
W-107	Peletier	RuG	SAURON meeting	3	17-01-2007
W-108	Barthel	RuG	Between Cepheids and mid-infrared instrumentation	1	13-04-2007
W-109	Levin	UL/LC	Oort workshop: the near-Keplerian n-body problem	4	29-05-2007
W-110	van Woerden, Haas		Amateurs meet professionals	3	29-06-2007
W-111	Portegies Zwart	UvA	Multiscale multiphysics software environment (Muse)	5	10-06-2007
W-112	Waters	UvA	Probing the early evolution of young high-mass stars	2	19-04-2007
W-113	Olthof	UvA	KNVWS 2007 symposium 'Het extreme heelal'	1	06-10-2007
W-114	Vink	UU/LC	From massive stars to supernova remnants	12	06-10-2007
W-115	van de Weijgaert	RuG	9th National astroparticle physics symposium	1	12-10-2007
W-117	Katgert	UL	Symposium Rudolf le Poole	1	30-11-2007

W-77: From strings to the cosmic web

The conference 'From strings to the cosmic web: the search for the origin of our Universe' was held from 30 November until 2 December 2005 in Groningen. It was attended by 86 scientists, including 17 keynote speakers. The meeting addressed the existence of dark energy or variability of the cosmological constant causing the acceleration of the expansion of the universe. This problem was viewed from two different disciplines: by high energy physicists and astrophysicists.

W-85: Spitzer's view on mass-losing AGB stars

This workshop had been organized for astronomers with approved observing programs on NASA's Infrared Space Telescope 'Spitzer' and working in the field of AGB stars. Many participants just had a few months experience in reducing their first Spitzer data. The workshop brought together observers and theoreticians to develop common strategies for data reduction and calibration. Furthermore first science results were discussed.

W-86: The study of near-IR selected high-redshift galaxies

Several groups of astronomers were brought together working on different aspects of high redshift galaxies. The common theme was the study of high redshift galaxies in the optical and near-infrared. The goal was to improve our understanding of the high redshift universe, and to measure the evolution and formation of galaxies. Specifically, participants of the FIRE-survey, Musyc survey, and IRAC-GTO team were present to discuss results from the ongoing surveys, and related programs.

The program was flexible, and presentations filled the program for about half the time. Since the meeting was meant to be a workshop in the true sense of the word, many presentations addressed 'work in progress'. Many informal discussion sessions were organized. At the end of the meeting, new projects and new collaborations were planned.

W-87: The world a jigsaw: tessellations in the sciences

Tessellations, geometrical divisions of space, and in particular Voronoi and Delaunay tessellations have been established as essential concepts for modelling and analyzing a great many physical, biological and human systems. The basic and simple concept of these tessellations makes them into intuitively appealing constructs finding a widespread application in a large variety of applied sciences. The morphology of soap bubbles, the distribution of GSM network antennae, the shape of crystals, regions of influence of neolithic clans, and the large scale structure of the Universe are a few of the subjects for which tessellations turned out to provide useful descriptions. Tessellations do represent one of the few branches in mathematics for which contributions from the applied sciences regularly offer keys to new fundamental insights and results.

This interdisciplinary workshop, held at the Lorentz Center in Leiden on 6-10 March 2006, brought together internationally known experts from the fields of mathematics and computer science (stochastic geometry, computational geometry) dealing with tessellations as a topic of study and of various branches of science - ranging from cosmology, astrophysics, geophysics to biology and archaeology - in which the application of tessellations has lead to significant advances and new avenues of research. The essential element of the workshop was the confrontation, interaction and synergy between the (recent) theoretical and fundamental developments on the analytical and computational aspects of tessellations with the wide range of applications in the sciences. Two special items of the program were a lecture about Islamic Tessellations and a tour in the Escher Museum in The Hague.

W-89: Cosmological radiative transfer workshop

Recent years have seen an increase in the interest of modelling radiative transfer in a cosmological setting, mostly driven by the quest to understand both the Epoch of Reionization and the surroundings of young, forming galaxies and the behavior of Ly-α absorbers. This has led to the development of various numerical methods to study radiative transfer in a cosmological context. The various test problems and results were discussed in this workshop, held from 12-14 December 2005, next to 11 science presentations by participants, in which they showed some of the results obtained with their method. 18 scientists participated in various parts of the workshop. A lot of progress was made on the interpretation of the results on test problems: important differences were found between the rates for recombination line cooling various groups were using. Some tests were partly redefined after reviewing the results. The discussions were lively and informative, with active participation from people outside the comparison project.

W-90: Mass loss from stars and the evolution of stellar clusters

The international conference entitled 'Mass loss from stars and the evolution of stellar clusters', which marked the formal retirement of Lamers, was held from 29 May to 1 June 2006 in Lunteren in The Netherlands. The subject was chosen according to Lamers' fields of work. About 100 scientist from 16 different countries participated at his meeting, with the biggest contingents from the US (27), NL (21), the UK (16) and Germany (15). The two keynote speakers, Maeder (Geneva) and Elmegreen (USA) provided outstanding reviews on the main subject which set the background for the whole conference. Most of the 18 contributed talks were given by renowned experts and together with the 50 posters, reporting on new results, fostered many lively discussions. Most remarkably, the process of structure formation in stellar winds, which has never been thoroughly discussed before, has been identified as crucial for many aspects of star and stellar cluster evolution.

W-91: Fine-tuning stellar population models

Models of the integrated light of stellar populations have an increasingly important role in the study of galaxy evolution. On 26-30 June 2006 a technical workshop was held at the Lorentz Center in which stellar population model builders, 'ingredient providers' - those researchers providing new stellar libraries and stellar interior and atmosphere models - and model consumers (i.e., observers) congregated to discuss the use and interpretation of current models and their future directions. The general atmosphere during the meeting - attended by 63 participants - was very positive. It was clear that there is significant progress in the field. Although models are still not able to fully reproduce a galaxy spectrum in great detail, reasonable attempts have recently been made, and model spectra are only getting better. The meeting showed that the models that exist are converging on very similar answers for major issues, such as the chemical enrichment of galaxies and their average star formation histories, suggesting that many previous discrepancies are dissolving away.

W-92: 2nd International summer school on astroparticle physics

This summer school was held from 29 August until 8 September 2006 in Arnhem. 55 participants followed a series of lectures by prominent scientists on the field of astroparticle physics. The personal project, in which groups of four students had to give comments on a research proposal and defend it, was really appreciated and handled very seriously. The proposals were future experiments in astroparticle physics and the students had the possibility to talk to teachers and look up information from the internet.

W-93: From brown dwarfs to planets: chemistry and cloud formation

The study of brown dwarfs and extrasolar planets constitutes a very active field of astrophysical research. Knowledge on their physical structure and chemical composition is gained from the interpretation of complex spectra using a handful of sophisticated numerical codes. Those codes share the basic physics but do no treat the critical influence of the cloud formation on the atmospheric structure in the same way. This maybe partly due to their different origins: low-mass stars on one hand and planetary atmospheres on the other hand.

This workshop brought together theoreticians, observers, and experimentalists to discuss the physio-chemical processes of cloud formation in brown dwarfs and in planets and to compare different model approaches as input for standard model atmospheres which are used to fit observations. Experts from meteorology and engineering also participated and brought cross-discipline scientific aspects to the discussions.

W-94: MODEST 6d satellite workshop

MODEST (MOdeling DEnse STellar systems) constitutes a loosely knit collaboration between various groups in Europe, the USA and Japan working in stellar dynamics, stellar evolution, and stellar hydrodynamics. It provides a software framework for large scale simulations of dense stellar systems, in which existing codes for dynamics, stellar evolution and hydrodynamics can be easily coupled. Two MODEST meetings were held in Amsterdam, one workshop with a small group of half a dozen key researchers (from 21 March until 18 April 2006) and one larger workshop (on 27-28 March 2006). The 4-weeks workshop brought together the world leading experts in parallel computing and N-body simulations to discuss the new developments and algorithmic requirements in depth. This meeting let to the development of a parallel kernel for a direct interaction tree solver. The core parallelization effort can also be used in other branches of science. The original aims were enormously broadened by the presence of a number of experts from different fields, including hydrodynamics, radiation transfer, stellar evolution and software engineering.

W-95: Dissecting the Milky Way

With many observational surveys of the Milky Way underway and with GAIA five years down the road, the timing was ideal for this workshop held on 6-10 November 2006 at the Lorentz Center in Leiden. The extensive and very impressive emergent results from the Sloan Digital Sky Survey were discussed, as well as the very first results from RAVE and from a number of smaller projects on the Milky Way and M31. New puzzles from the properties of the dwarf galaxies populations and the large amount of substructure in the stellar halos of these two large disk galaxies were some of the highlights. The theoretical and modelling efforts were also discussed, and it became clear that these aspects need to be strengthened in the coming years to allow for a proper scientific exploitation of data expected from GAIA. The workshop has begun to chart the path towards linking observations to the 'big questions' in near-field cosmology in the years to come.

W-96: KNVWS symposium on water

On 7 October 2006 the KNVWS organized the symposium 'Water', together with SRON and the Society for Weather studies and Climatology. The program had four lectures on four different places where water can be found: the interstellar clouds in the universe, the atmospheres of other planets in our Solar system, the atmosphere of the Earth and the oceans on Earth. The symposium was attended by 260 participants, mostly amateurs with interest in various disciplines.

W-97: Galactic nuclei

This workshop brought together key members of two international research teams: the European 'SAURON' team, and the American 'NUKER' team to discuss the latest developments in the field of galaxy nuclei, dynamical modeling of galaxies, and galaxy structure and evolution. In addition, key collaborators of these teams were also invited to broaden the discussion topics, which ranged from black-hole mass scaling relations, to massive galaxy formation in clusters. The workshop was well attended, with around 30 participants, including a number of prominent team members. In addition to the enjoyable and informative presentations, the afternoons of the workshop were left free specifically for working groups to tackle key issues regarding the research of the teams and in the general field. Several collaborative projects were started between the teams, including a joint program using the Gemini telescope to study massive black holes in galaxy centers.

W-98: Universal origins, uncovering astronomical roots

The 2006 annual symposium of the 'Fysisch-Mathematische Faculteitsvereniging' at the RuG addressed modern topics of astrophysics for a broad audience including the mysteries of dark matter and dark energy, the understanding of the formation of galaxies, stars and planetary systems.

W-99: High velocity clouds and the origin of neutral gas in nearby galaxies

This symposium was held on 20-21 October 2006 in Groningen in honor of the 80th birthday of Hugo van Woerden and was combined with an open day at the 50th anniversary of 25m Dwingeloo radio telescope.

W-100: KNAW colloquium on cosmic voids

The colloquium was held at the KNAW in Amsterdam on 12-15 December 2006 and attended by 45 invited participants. It was the first worldwide conference focused specifically on cosmic voids. Many speakers addressed recent results from large surveys like SDSS, 2MASS, 6DF and the Alfalfa HI redshift survey in relation to cosmic voids. Others discussed the influence of voids on the formation of galaxies.

W-101: IMAPP symposium: origins of the universe

The symposium, held on 13 October 2006 by the Institute of Mathematics, Astrophysics and Particle Physics of the Radboud University in Nijmegen, was attended by 350 people with many different backgrounds, from high school students in mathematics, physics and astronomy to professors from all over the country. The speakers, including Kung, Penrose, Sunyaev, Engelen and 't Hooft, addressed the subject 'origins of the universe' from the viewpoints of theology, astronomy and physics.

W-102: Studies of infrared selected galaxies

The workshop, held on 13-17 November 2006 at the Lorentz Center in Leiden, brought together 20 scientists from Europe and the USA to discuss the evolution of galaxies from z=4 to z=1. This is the critical redshift interval in which galaxies are assembled. The focus of the workshop was on the study of mass selected samples, to analyze the build-up of mass of galaxies with time. An important aspect was the comparison with theoretical models. The theoretical models are improving significantly, and we are now in a position to make more detailed comparisons between theory and observations. The workshop was a great success, with presentations, and many lively discussions. Half the time was filled with presentations, the other half consisted of discussions, often in small groups, and work at the computer.

W-103: Gravitational lensing

The workshop was held on the occasion of Roger Blandford's stay in Leiden as Oort professor. The topic, gravitational lensing, concerns a cosmological effect that has become a versatile tool in astronomy in which Blandford has been one of the pioneers. About 50 participants from around the world took part in the meeting. The program was rather open: the mornings consisted of two long, didactic, reviews on various aspects of lensing and cosmology, with a few shorter talks on related specialized topics. In the afternoons the participants worked on a set of five assignments, set by the Oort professor on the first day: open questions related to lensing on which we were all encouraged to be as critical as was sensible. On the final day, the most junior member in each group reported on what had been achieved.

W-105: Computational cosmology

Nearly 70 people from 7 countries participated in what turned out to be a very successful meeting, held at the Lorentz Center on 15-19 January 2007. The workshop brought together researchers active in various ongoing collaborative simulation projects such as OWLS, GIMIC, Aquarius, Millennium and Millennium with gas, as well as researchers who would like to get involved. The first three days were filled with plenary talks and discussion sessions in which the latest developments were presented and discussed. The last two days the participants splitted up in smaller groups. These group meetings included from hands-on sessions in which participants were taught to use various software packages developed by the collaborations, discussions of specific problems, and brainstorms about future projects. The workshop brought people up to date, problems were solved, existing collaborations were expanded and new ones were formed.

W-106: The next decade of gamma-ray burst afterglows

Since the discovery of the afterglow of gamma-ray bursts ten years ago, the study of these objects has become a rich and versatile field. Many questions still remain unanswered, even though the number of researchers in this field has increased enormously. Therefore, this symposium was organized at the conference center 'De Rode Hoed' in Amsterdam from 19-23 March, 2007, and attended by 172 people from all over the world. The program consisted of both overview lectures by prominent scientists and lectures by young researchers. The poster session was also very successful: each attendant with a poster got one minute of speaking time in the so-called 'gong' session. The discussion at the end of each session was participated enthusiastically.

W-107: SAURON meeting

The SAURON collaboration held one of their bi-annual meetings in Groningen, from 17-19 January 2007. There were 17 participants, from Leiden, Groningen, Oxford, Lyon and ESO at Garching, all of them working on one particular aspect of the SAURON data. The meeting consisted of small presentations of the various participants to show the others what had been done. Most of the time was spent discussing the future papers in details in subgroups of 5-7 people. At the end the results from these subgroup-meetings were discussed by the whole group. The science addressed included the main SAURON survey of 72 ellipticals, S0s and Sa galaxies, some side-projects, and the preparation for the large SAURON Complete Survey (SCS) which obtained the first observations in April 2007.

W-108: Between Cepheids and mid-infrared instrumentation

On 13 April 2007 a one-day symposium on 'Between Cepheids and mid-infrared instrumentation', was held at the Kapteyn Institute in Groningen in honor of the retirement of Jan Willem Pel. About 80 (ex) colleagues, friends and (PhD) students attended the symposium.

W-109: Oort workshop: the near-Keplerian n-body problem

Dynamics in near-Keplerian potentials plays a central role in planetary science and in the physics of galactic nuclei. Traditional celestial mechanics has focused on low-eccentricity, low inclination orbits, like those of the planets in the Solar System, and most of its tools are based on the perturbation expansions in eccentricity and inclination. By contrast, in galactic nuclei stars typically orbit supermassive black holes on highly eccentric, inclined orbits, and thus their dynamics have been studied using N-body simulations or Fokker-Plank formalism. Astronomical observations over the past decade strongly suggest that theoretical techniques developed in both fields could be mutually beneficial. Firstly, extra-solar planets have been discovered, and many of them have been found to move on highly eccentric, inclined orbits. Secondly, it has been discovered that young stellar discs, which look like scaled up planetary discs, are orbiting supermassive black holes in the centers of the Milky Way and Andromeda Galaxies. The workshop brought together theoretical dynamicists from both communities include Scott Tremaine, the 2007 Oort professor.

W-110: Amateur meets professionals

At the occasion of the 40th anniversary of the Dutch Youth Association for Astronomy (JWG) a three day meeting (9-11 November 2007) was held in Bunnik attended by 95 participants, mostly Dutch amateur astronomers and some international professionals. The meeting was built upon two themes: (1) Cosmology and (2) Amateur meets professional. Highlights included lectures from Robbert Dijkgraaf on 'String theory and the quantum universe'; Carlos Frank on 'Dark matter halo profiles'; and Govert Schilling on 'Why one universe is not enough'. In the workshop other speakers addressed topics like the age of star clusters, optics and spectral lines in astronomy.

W-111: Multiscale multiphysics software environment (Muse)

Muse is designed to realistically model dense stellar systems, such as young star clusters and galactic nuclei. It is a project resulting from the MODEST collaboration. The objective is to couple a variety of currently existing astrophysical codes in a coherent modular way. For this purpose, researchers from different branches of astronomy, computer science and computational astrophysics met at this Modest-7f workshop held in Amsterdam on 10-14 June 2007 to discuss the software tools necessary to further implement Muse, and the ability to simulate dense stellar systems. In particular, the interfaces between the various physical code modules were addressed resulting into an operational N-body dynamics module that includes direct-summation and tree-code for force calculations.

W-112: Probing the early evolution of young high-mass stars

The workshop 'Probing the early evolution of young high-mass stars' was held on 19 and 20 April 2007 in Amsterdam. The 12 participants discussed the first results from a pilot study involving the VLT instruments SINFONI and VISIR to unravel the star formation history in dense star forming regions. Earlier studies showed that massive stars appear to be present in the same region in different stages of their formation process. From the pilot study it was concluded that it is now possible to build a complete census of the population of massive stars in individual star forming regions by combining observational data from both VLT instruments together with existing infrared (Spitzer) and radio studies.

W-113: KNVWS symposium 2007 'Het extreme heelal'

The KNVWS symposium 'Het extreme heelal' was held at October 6, 2007 at the University of Amsterdam and attended by 232 people, mostly amateur astronomers and students. Five speakers addressed the following topics: Hessels discussed possibilities to observe physical processes in the universe with variability on nano-seconds to years at radio frequencies using LOFAR; van der Steenhoven spoke about cosmic neutrinos; Wiersema addressed extreme physics at home; Hermsen highlighted extreme physics as observed with the Integral satellite; and Wijers spoke about gamma ray bursts and their afterglows.

W-114: From massive stars to supernova remnants

This workshop, held from 6-17 August 2007 at the Lorentz Center in Leiden, brought 52 astronomers together for two weeks. The workshop brought together the key experts in the fields of massive star evolution, circumstellar medium evolution, supernova explosions, supernova/GRB-circumstellar medium interaction, and early supernova remnant evolution, to advance the understanding of the various anisotropic processes involved. The approach was to combine the world expertise in the mentioned fields in one workshop to uncover critical physical connections across these fields. For example, the internal rotation of a massive star may lead to anisotropic stellar winds and circumstellar medium structures, but also decide whether the star produces a gamma-ray burst or just a supernova. The processes will determine the explosion/circumstellar medium interaction and shape the supernova remnant. The theoretical understanding of the processes involved, but also the observations of anisotropies around stars, in stellar explosions, and in supernova remnants have reached a stage which makes the time ripe for this approach.

W-115 9th National astroparticle physics symposium

On 12 October 2007, the 9th Astroparticle Physics symposium was organized at the Kapteyn Institute in Groningen and attended by 111 participants. The program consisted of four sessions with ten different speakers. The first two sessions were focussed on cosmology, the third on high energy astrophysics with among others the detection of gravity waves from pulsar observations. Other subjects were ultra high energy cosmic rays and their relation with the distribution of near-by AGN's, physics in the early universe, polarisation of the microwave background radiation, diffuse galactic gamma rays and modified Newtonian dynamics as an alternative for dark matter and gravitational lensing.

W-117: Symposium Rudolf le Poole

On 30 November 2007 a symposium was held at the Leiden University at the occasion of the 65th birthday of Rudolf le Poole. The scientific program reflected Rudolf's wide-ranging interests and expertise, and the latter were illuminated by 9 speakers. Topics ranged from (space) astrometry, via radio- and optical interferometry to adaptive optics. More than 150 people took part in the symposium.

7.2. Visitors in 2006 – 2007

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 of the activities. Visits in 2005 not reported in previous annual report are also included.

	Host	Visitors	Location	Duration (days)	Start
V-85	van de Weijgaert	Prof.dr. B. Jones	RuG	55	01-01-2005
V-90	Langer	Dr. G. Garcia-Segura	UU	42	15-01-2005
V-105	van den Heuvel	Prof.dr. A. Kembhavi	UvA	6	14-06-2005
V-106	van de Weijgaert	Prof.dr. S. Shandarin	RuG	8	22-07-2005
V-107	Waters	Drs. F. J. Perez Caceres	UvA	1y	01-01-2005
V-109	van den Heuvel	Dr. R. Misra	UvA	12	01-08-2005
V-111	van der Klis/Fender	Dr. Ch. Kaiser	UvA	2	15-09-2005
V-112	van den Heuvel	Dr. L. Yungelson	UvA	83	01-09-2005
V-115	Waters	Dr. O. Munoz	UvA	14	12-11-2005
V-116	van der Hulst	Dr. R. Swaters	RuG	9	09-03-2006
V-117	Portegies Zwart	Dr. H. Baumgardt	UvA	3	24-01-2006
V-121	Stappers	Dr. G. Wright	ASTRON	14	12-03-2006
V-122	Pols	Speakers NAC 2006	UU	3	10-05-2006
V-123	de Koter	Dr. J. Puls, Prof.dr. Herrero, Dr. Vink	UvA	3	26-04-2006
V-124	Zaroubi	Prof.dr. A. Ferrara	RuG	7	28-05-2006
V-125	Portegies Zwart	Dr. H. Baumgardt	UvA	2	03-05-2006
V-127	Kuijpers	Dr. M. Marklund	RU	6	07-05-2006
V-128	Pols	Prof.dr. R. Gallino, Prof.dr. A. Davis	UU	16	23-09-2006
V-129	Henrichs	Prof.dr. S.A. Owocki	UvA	7	06-06-2006
V-130	van den Heuvel	Prof.dr. N. Dadhich	UvA	5	05-09-2006
V-131	Wijers	Prof. H.-K. Lee	UvA	6	17-07-2006
V-132	Portegies Zwart	Prof.dr. M. Colpi	UvA	7	10-09-2006
V-133	van de Weijgaert	Prof.dr. C.S. Frenk	RuG	3	05-10-2006
V-134	Portegies Zwart	Dr. S. Harfst	UvA	9	18-10-2006
V-135	Kuijpers	Dr. D. Mitra	RU	7	23-10-2006
V-136	Barthel	Prof.dr. M. Bailes	see text	7	16-10-2006
V-139	Portegies Zwart	Dr. M. Freitag	UvA/UL	9	02-12-2006
V-140	Franx	Drs. R. Quadri	UL	31	see text
V-142	Markoff	Dr. E. Kalemci, Prof. J. Wilms	UvA	2	18-01-2007
V-143	Henrichs	Prof.dr. F. Leone	API	5	03-02-2007
V-144	Henrichs	Dr. E. Verdugo	API	3	06-02-2007
V-145	de Koter	Dr. J. Vick	UvA	5	05-02-2007
V-148	Molster	Dr. J. Bradley	UL	3	14-05-2007
V-149	Nelemans	Ms A. Ruiter	RU	19	26-08-2007
V-150	Hogerheijde	Dr. M. Güdel	UL	60	01-09-2007
V-151	Nelemans	Dr. R. Voss	RU	9	29-05-2007
V-152	Portegies Zwart	Dr. M. Fuji	UvA	21	10-09-2007
V-153	Portegies Zwart	Dr. S. Banarjee	UvA	11	13-08-2007
V-156	van de Weijgaert	Dr. M. Aragon-Calvo	RuG	28	12-11-2007

V-85: Visit of Prof. B.J.T. Jones

In 2004 and 2005 Jones (Copenhagen) has been visiting the Kapteyn Institute in Groningen for 6 days each month to collaborate with van de Weijgaert and his PhD students Aragon-Calvo, Araya and Platen on software development for cosmological/astrophysical projects. Formalisms developed within computational geometry were transferred to analyze distributions of galaxies. Together they developed new algorithms for the calculation of Delaunay diagrams in two and in three dimensions. Two review papers were written including one on 'scaling in the spatial galaxy distribution', and one on applicants of wavelets to analyze astronomical data sets.

V-90: Visit of Dr. G. García-Segura

García-Segura (UNAM, Ensenada, Mexico), stayed in Utrecht from 10 January to 6 March 2005. He collaborated with Langer and van Marle (PhD) on constraints on gamma-ray burst and supernova progenitors as derived from circumstellar absorption lines (published in Astron. Astrophys. 444, 837, 2005). He also was a member of the committee for the thesis defense of van Marle.

V-105: Visit of Prof. A. Kembhavi

Kembhavi of the Inter University Center for Astronomy and Astrophysics (IUCAA) in Pune (India) visited the University of Amsterdam from 14 – 19 June 2005. In IUCAA he is, apart from his tasks in research and teaching, responsible for the contacts with the Indian University community, nationwide. Thanks to his efforts, all Indian Universities have now electronic access to all of the world's leading scientific journals (in all sciences), and also he created the Indian branch of the Virtual Observatory, through which Indian astronomers have access to most of the world's important astronomical databases. In June 2005 he made a visit to institutes in France, Germany and the UK, particularly to discuss Virtual Observatory matters, and used the opportunity to collaborate with van den Heuvel in Amsterdam.

V-106: Visit of Prof. S. Shandarin

Shandarin (Kansas University, Lawrence, USA) visited the Kapteyn Institute in Groningen from 22-29 July 2005 to work together with van de Weijgaert and Jones on two projects: use of the cgal software for computing the Delaunay triangulation and alpha shapes of a particle or galaxy distribution for defining and computing the isodensity surfaces. The Delaunay triangulation is used as linear interpolation grid. The galaxy and N-body particle distribution was analyzed in terms of their morphological shapes at a range of density levels. Analysis has shown this to be a sensitive tool towards characterizing the large scale distribution of matter.

V-107: Visit of Drs. Francisco Javier Perez Caceres

In 2005 Perez Caceres visited the Astronomical Institute Anton Pannekoek to conduct research on the nature of the dust grains in the evolved disk around the star β Pictoris in terms of their light scattering properties. He has used a parameterized model of light scattering by small particles. The obtained light scattering parameters can be compared to those obtained for various types of particles. Perez Caceres constructed a diagnostic diagram which enables comparison of various classes of particles through their light scattering characteristics. The main result from the analysis was that the dust in the disk around β Pictoris is very different from the laboratory measurements and the Zodiacal dust. The results of the analysis are important for our understanding of dust processing and the evolution of circumstellar disks. The diagnostic developed in terms of the parameterized scattering diagram can be valuable for many other studies.

V-109: Visit of Dr. Ranjeev Misra

Misra (IUCAA, Pune, India) visited the Astronomical Institute Anton Pannekoek from 4-15 August 2005 to work with X-ray astronomy group on constructing models for the kilohertz Quasi-Periodic Oscillations (QPO) in galactic low-mass x-ray binaries.

V-111: Visit of Dr. Christian Kaiser

Kaiser (Southampton, UK) visited the Astronomical Institute Anton Pannekoek for two days in September 2005 to work with Fender and Gallo (PhD) on new ideas for testing models of internal shocks in the jets from X-ray binary systems. This is an area of research in which Kaiser has theoretical expertise, and Fender and Gallo had recently suggested that they might have observational support. The discussions and initial calculations confirmed that the model might be applicable.

V-112: Visit of Dr. L.R. Yungelson

Goal of the visit of Yungelson (Russian Academy, Moscow) in the period 20 August – 10 November 2005 was to continue the study - in collaboration with Portegies Zwart, van den Heuvel and Nelemans - of the evolution of very massive stars, with masses of the range of 100 - 1000 $M_\odot$. Such stars may form by stellar collisions in very dense young star clusters. It is important to study the further evolution of such stars as it has been suggested that at the end of their short life they may collapse to so-called intermediate mass black holes. Evidence that such black holes exist comes from the discovery by CHANDRA of the so-called ultra luminous x-ray sources in starburst galaxies. An important breakthrough which Yungelson obtained during his visit was that if one uses a realistic stellar wind mass loss algorithm, stars with masses up to 1000 $M_\odot$ can still stably evolve through hydrogen burning.

V-115: Visit of Dr. Olga Munoz

The main purpose of the visit of Munoz (Andalusia, Spain) at the Astronomical Institute Anton Pannekoek in November 2005 was the presentation of the new light scattering facility that is being built building at the Astrophysical Institute of Andalusia in Granada, Spain. The collaboration with the group in Amsterdam started in 1998 during a postdoctoral stay of Munoz at the Free University in Amsterdam. During that time research on light scattering experiments was conducted. Since the experiments performed in Granada and Amsterdam will be complementary to each other it was considered useful to coordinate the future work of both groups. Therefore, apart from presenting the new setup there were ample discussions about the future of both laboratories and how one may collaborate, e.g. by exchange of samples, and students. Also, discussions about new types of light scattering measurements took place that may become possible with the new equipment.

V-116: Visit of Dr. Rob Swaters

Swaters (University of Maryland, College Park, USA) visited the Kapteyn Institute from 9-17 March, 2006 to work with Sancisi, van Albada and Noordermeer (PhD) on two publications based on the PhD research projects of Swaters and Noordermeer. Both projects involve rotation curves of galaxies based on HI observations obtained from the Westerbork HI survey of spiral and irregular galaxies (WHISP). Two types of galaxies are concerned: small irregular galaxies and large early type galaxies. In general, it was concluded that although dark matter was present, the details of the rotation curves are strongly correlated with the details of the distribution of light.

V-117 + V-125: Visits of Dr. Holger Baumgardt

Baumgardt (University of Bonn) visited Portegies Zwart for three days in January 2006 to discuss possible ways of creating Hyper-Velocity Stars (HVS) in the galactic center. He showed his results on the inspiral of Intermediate Mass Black Holes (IMBH) and the number and velocity distribution of stars ejected due to the IMBHs. Both seem compatible with current observational limits. He found that stars are ejected in a strong burst lasting about 1 Myr and escape preferentially in the plane of the inspiraling IMBH, offering the possibility to indirectly detect IMBHs in the galactic center if enough hyper-velocity stars have been found. They also discussed possible ways to eject stars from the LMC.

The second visit of Baumgardt on 3 and 4 May 2006 resulted in the completion and submission of two papers together with Gualandris (PhD) on the topics described above. They concluded that the IMBHs sink to the center of the Galaxy due to dynamical friction, where they deplete the central cusp of stars. Some of these stars become HVS and are ejected with velocities sufficiently high to escape the Galaxy. They also found that the velocity distribution of HVS generated by inspiraling IMBHs is nearly independent of the mass of the IMBH and can be quite distinct from one generated by binary encounters. Finally, their simulations showed that the presence of an IMBH in the Galactic center changes the stellar density distribution inside $r<0.02$ pc into a core profile, which takes at least 100 Myr to replenish.

V-121: Dr. Geoff Wright

Wright (Sussex, UK) visited Stappers from 12 to 25 March 2006 to complete the planned collaborative work and to define a strategy for future collaboration. A paper was brought to conclusion and submitted to Science. This paper demonstrated that the bright intense pulses found by the Amsterdam-led group in the PSR B0656+14 would, if that pulsar were at a greater distance, have been classified as an RRAT – a new class of recently-discovered rare transient radio sources. A paper on the much longer and more detailed account of the single pulse behaviour of PSR B0656+14 was also completed. A new proposal for observing three pulsars with the WSRT was prepared and submitted. One of the three is a newly-discovered pulsar (J1503+2111) with properties like those of B0656+14 – but with a rotation period of over 3 seconds, unusual for conventional pulsars but very typical of the RRATs. The other two were chosen for the burstlike nature of their emission. It was noted from existing short observations that the bursts came at non-random intervals, sometimes even periodic, and suggest an important physical link to the recently-discovered extraordinary pulsars which share these on-off properties - but on a timescale of days.

V-122: Netherlands Astronomy Conference 2006

The 61st Netherlands Astronomy Conference (NAC) was organized by the Astronomical Institute Utrecht, and held on the island of Ameland from 10-12 May, 2006. As in previous years, the NAC is the platform for the astronomical communities in the Netherlands and Belgium to present and exchange their recent results in an informal atmosphere. The NAC2006 was attended by 175 participants: 44 staff members, 20 postdocs, 58 PhD students and 52 undergraduate students. Review talks were given by Koopmans, Levin, Nelemans and Larsen. With support from NOVA two keynote speakers from abroad were invited: Burrows (Tucson, USA) and Gibson (Preston, UK). The former reviewed the current state-of-the-art in supernova theory and presented new ideas about the explosion mechanism. The latter presented his theoretical work on galactic chemical evolution and reviewed recent developments in that field.

V-123: Visit of Dr. Joachim Puls, Prof.dr. Artemio Herrero, Dr. Jorick Vink

Puls (Universitats-Sternwarte München), Herrero (IAC, Tenerife, Spain), and Vink (Keele, UK) visited the Astronomical Institute Anton Pannekoek from April 26 to 28, 2006 as part of an ongoing long-term collaboration with de Koter and Mokiem (PhD) on the mass-loss properties of massive stars. The new results of the VLT-FLAMES Survey of Massive Stars were assessed and plans were made for follow-up observations and theoretical studies. They discussed (1) the importance of small scale in homogeneities in stellar winds; (2) the role of rapid rotation on massive stars (in the LMC); and (3) the empirical relation between stellar mass loss and metal content. Papers were submitted (Mokiem et al. 2006, 2007) for points (2) and (3), and a strategy was derived to tackle point (1) from both an observational and theoretical perspective as part of the thesis work Muijres.
All three visitors participated in the opposition of the thesis defense of Mokiem (PhD student of de Koter and van den Heuvel) who was awarded his degree with the juditium cum laude.

V-124: Visit of Prof. Andrea Ferrara

Ferrara (Trieste, Italy) visited the Kapteyn Institute in Groningen from 28 May to 3 June 2006 to work with Koopmans, Tolstoy, de Bruyn and Zaroubi on properties of the early universe and the first cosmic light. He also worked with Zaroubi, Ripamonti (postdoc) and co-workers on the signature of decaying of the dark matter candidate, known as Sterile Neutrino, on the epoch of reionization and on structure formation. They concluded that this type of particle will have a very hard time the survive the reionizing Universe, therefore, in order to probe its influence it is better to explore its presence through structure formation, where such a particle will wipe out structure on small scales at high redshifts. We have produced a few plots that show that and are currently working on several other aspects of it. Ferrara, Ripamonti, and Mapelli (another visitor) finalised two papers during the visit: one on the impact of dark matter decay and annihilation on the formation of the first structures by Ripamonti, Mapelli and Ferrara, and the second on intergalactic medium heating by dark matter by the same authors. These two papers also addressed the importance of the influence of dark matter decay and annihilation on structure formation.

V-127: Visit of Dr. Mattias Marklund

Marklund (Umea University) visited the Radboud University from 7-12 May 2006, to continue his cooperation with Moortgat (NOVA PhD, now at Rochester University) and Kuijpers on the interaction between gravitational waves and magnetic fields. They concentrated on the problem of magnetic field generation and amplification in the early universe by extending perturbation techniques under the gauge-invariant covariant formalism. The one-week cooperation allowed to set up the method of approach and a thorough discussion of the physical simplifications. Altogether, good progress was reached in this ongoing work and a number of other problems were discussed for future collaboration.

V-128: Visit of Prof. Roberto Gallino and Prof. Andrew Davis

Gallino (Torino, Italy) and Davis (Chicago, USA) visited the Astronomical Institute in Utrecht from 23 September to 8 October 2006 to collaborate with Lugaro (Veni) on the publication of model predictions for the elemental and isotopic compositions of heavy elements in asymptotic giant stars. These predictions were compared to data from meteoritic presolar silicon carbide (SiC) grains that formed around these stars. They focused on the analysis of the composition of the rare earth elements, i.e. lanthanum to lutetium, and hafnium, given that this year more laboratory data on such elements in SiC grains have been obtained and presented by USA and Japanese groups. Discussion also ensued with other members of the stellar evolution group on the topic of the composition of very metal poor stars, in particular stars showing carbon enrichment, and, in some cases, heavy element enrichment. Nucleosynthesis models produced by Gallino and used in the synthetic stellar population tool of Izzard (postdoc), Bonacic-Marinovic (PhD) and Pols were discussed. Finally means of producing the observed compositions by binary interaction were investigated.

V-129: Visit of Prof. S.A. Owocki

Owocki (Delaware, USA) visited Amsterdam from 6 - 12 June 2006 to collaborate with Schnerr (NOVA PhD), Henrichs and others on a theoretical study of the influence of a magnetic field on the outflowing stellar wind of massive stars. Detailed numerical models were developed, which ran for weeks on PC-clusters, and the results were discussed. A first draft of a paper has been set up during the visit. Owocki was a member of the committee for the thesis defense of Schnerr.

V-130: Visit of Prof. N. Dadhich

Dadhich (director of IUCAA, Pune, India) visited the Anton Pannekoek institute from 5-9 September 2006 for the following two reasons: to work with van den Heuvel and co-workers on physical problems to accrete matter on black holes. The second objective was to investigate possibilities for more collaboration between IUCAA and the University of Amsterdam which was concluded with a declaration of intent for strengthening the collaboration. Dadhich also gave a lecture entitled: 'Why Einstein? Had I been born in 1844' in which he showed that a scientist born in 1844 had already been able to discover the theory of special relativity.

V-131: Visit of Prof. Hyun-Kyu Lee
Lee (Hanyang University, Seoul, Korea) visited the Astronomical Institute Anton Pannekoek from 17-22 July 2006 to work with Wijers and co-workers on neutrino production near black holes as a possible source of neutrinos from gamma-ray bursts. He gave a technical seminar on the subject, which was attended by about 20 people from API and a similar number from NIKHEF. In the following days, he discussed this subject with several members from both institutes. Furthermore Lee and Wijers discussed the possibility to hold annual Korean-Dutch meetings on astroparticle physics. This would take advantage of a bilateral agreement between the national funding agencies in both countries to fund exchanges and bilateral meetings between both countries, and the fact that both countries have an excellent facility for such workshops, namely the Lorentz Center in Leiden and the Asia-Pacific Center for Theoretical Physics in Pohang (of which Lee is a board member).

V-132: Visit of Prof. Monica Colpi
Colpi (Milan, Italy) visited the University of Amsterdam (10-16 September 2006) to attend the PhD defense of Gualandris on 12 September 2006. She also gave a colloquium at the astronomical institute Anton Pannekoek and worked together with Portegies Zwart and Gualandris on the origin of hyper velocity stars.

V-133: Visit of Prof. Carlos Frenk
Frenk (Durham, UK) visited the Kapteyn Institute in Groningen from July 2-4, 2006 to collaborate with van de Weijgaert, Jones (another visitor) and Aragon-Calvo on defining a new numerical program involving the application of the MMF developed by Aragon-Calvo on the new high-resolution simulations of the Virgo cluster by Frenk and his group. The aim was to identify galaxy haloes as well as galaxies within clusters, filaments and walls of the cosmic web. Frenk also gave a seminar at the Kapteyn Institute and joined a special one-day workshop on cosmic origins organized by graduate students.

V-134: Visit of Dr. Stefan Harfst
Harfst (Rochester) visited the Astronomical Institute Anton Pannekoek from 30 October until 7 November 2006 to work with Portegies Zwart, Gualandris, Gaburov and Chen on multi-scale and multi-physics simulations of the Galactic canter. They also worked on parallelizing N-body kernels for large scale star cluster simulations and completed a paper on a performance analysis of direct N-body algorithms on special-purpose supercomputers.

V-135: Visit of Dr. Dipanjan Mitra
Mitra (Pune, India) visited the Radboud University from 23-29 October 2006 to collaborate with Smits (postdoc), Buitink (PhD), Kuijpers and Prof. Janusz Gill (Poland). They analyzed observations of radio pulsars to confirm the recently published work by Fung, Khechinashvili and Kuijpers explaining the drift mechanism of radio pulsars.

V-136: Visit of Prof. Matthew Bailes
Bailes (Swinburne, Australia) visited the Netherlands in October 2006 to give four public lectures entitled 'The most evil stars' including a 3D virtual show. The visit was part of the celebration in both countries at the occasion on the 400th anniversary of the discovery of Australia by Dutch sailors. The lectures were held in The Hague, Haarlem, Groningen and Amsterdam. In return van den Heuvel visited Australia in December 2006 to also give a series of public lectures.

V-139: Visit of Dr. Marc Freitag
Freitag (UK) visited the Astronomical Institute Anton Pannekoek from 2-10 December 2006 to collaborate with Gurkan (Marie Curie fellow) and Portegies Zwart on simulations of galactic nuclei, and on the quantification of mass segregation in young clusters. By using data from a variety of methods, they constructed fitting formulae for the evolution of half-mass radii of stars from various mass ranges. Such formulae are useful in a semi-analytic treatment of processes enhanced by mass segregation. In addition, during his visit, Freitag also visited Leiden Observatory to finish the paper in collaboration with Hopman on gravitational wave bursts from the Galactic massive black hole.

V-140: Visit of Drs. Ryan Quadri
Quadri (Yale) visited the Leiden Observatory from February 20 until March 3, 2007 and June 6-24, 2007. The purpose of these visits was to create high-quality photometric catalogs and to analyze public data from the UKIDSS Ultra Deep Survey. Quadri worked with Franx and Williams (postdoc) to investigate the characteristics of the public

images, including the noise properties, astrometry, and image artefacts, and to create images mosaics. A preliminary catalog was made, which was used to make plots for a successful observing proposal. The updated catalog was used to perform an analysis of the clustering of distant red galaxies. This analysis was described in the last chapter of the PhD thesis of Quadri, which is also submitted to the Astrophysical Journal Letters.

V-142: Visit of Dr. Emrah Kalemci and Prof. Joern Wilms

On 18 January 2007 Markov organized a meeting in Amsterdam to decide if it would make sense to set up a collaboration to apply for EU FP7 funding, under the Marie Curie ITN program. In attendance were Kalemci (Sabenci University, Istanbul), Wilms (University Erlangen-Nürnberg), Corbel (CEA/Saclay, University of Paris), and Wijnands, Klein-Wolt, Maitra and herself. Two other nodes will participate, but could not attend the meeting: INAF in Italy (led by Belloni) and University of Southampton, UK (led by Uttley). The meeting was extremely productive. The participants concluded early on that the ITN was the ideal program for them to work together on multi wavelength stellar black hole studies and encompass many aspects of both observational and theoretical studies.

V-143: Visit of Prof. F. Leone; V-144: Visit of Dr. E. Verdugo

The prime purpose of the visits of Leone (Catania, Italy) and Verdugo (ESA, Madrid) was to take part in the opposition during the thesis defence of Schnerr on 7 February 2007. Together with Henrichs, Schnerr and co-workers they discussed and finished a paper on the reliability of the various methods to measure stellar magnetic fields. Furthermore we worked on the project to determine the binary orbit of β Cephei, which has a period of about 80 years. All the historic data are now collected and they outlined the strategy to add their own data for a final analysis.

V-145: Visit of Dr. Jorick Vink

Vink visited de Koter from 5-9 February 2007 to jointly work on the mass-loss properties of very massive stars in the early universe. They studied this topic in the context of the progenitor history of the recent supernova 2006gy, the brightest supernova which was ever found. They argued that its properties may indicate a pair creation supernova (section 3.3.1.4 for further details).

V-148: Visit of Dr. John Bradley

Bradley (Lawrence Livermore Laboratories) has been the NOVA speaker during the NAC conference (~175 participants) from 14 to 16 May 2007 in Veldhoven. His talk, entitled 'The Stardust mission - new insight about the birth of the Solar System', has been very well received by the audience. Although for the large majority of the audience Solar System science is unknown territory, the amount of interaction afterwards with the speaker showed that they were very interested to hear about this aspect of astronomy.

V-149: Visit of Ashley Ruiter

During the visit (28 August – 14 September 2007) at the Radboud University Ruiter (PhD student at New Mexico State University, Las Cruces, USA) New Mexico gave a colloquium on the impact of Roche-lobe overflow in white dwarf binaries on the LISA signal. Ashley wrote a population synthesis code that is rather different than the one Nelemans and Portegies Zwart developed. She and Nelemans compared both codes and defined a number of tests to compare the codes in detail and to understand some of the different results. They also made some detailed comparisons of the gravitational wave signal of (interacting) double white dwarfs. During the visit a new project was started about the SN type la progenitors, which are believed to be tight binaries, in which a white dwarf explodes.

V-150: Visit of Dr. Manuel Güdel

Güdel (PSI and ETH Zurich, Switzerland) visited Leiden Observatory from 3 September to 31 October 2007, to collaborate with van Dishoeck and Hogerheijde. They worked on the interpretation of the [NeII] emission lines observed with Spitzer as tracer of X-ray induced physics of plasma cooling in a jet of a T Tauri star. They prepared a key observing program on the Herschel satellite to study infrared lines that provide information on stellar X-ray properties of young stars in the latest phase for their formation and planned follow-up programs with Chandra and XMM-Newton to obtain X-ray data of T Tauri stars that have been reported to show strong [NeII] infrared lines. Güdel also participated as an opponent in the thesis defense of Geers.

V-151: Visit of Dr. Rasmus Voss

Voss (PMA, Garching, Germany) visited the Radboud University from 29 May to 6 June 2007 to work with Nelemans on the following projects: SN type Ia progenitors, periods in Galactic LMXBs, and the luminosity function of LMXBs. As a result a paper was published in Nature in early 2008.

V-152: Visit of Dr. Michiko Fuji

Fuji (Tokyo, Japan) visited the University of Amsterdam from 10 – 30 September 2007 to work which Portegies Zwart on numerical simulations of the star cluster IRS13 in the Galactic center. They developed a new library for Muse (Multiscale multiphysics scientific environment). This is a multipurpose software environment for astrophysical simulations. It provides libraries of different existing numerical codes and allows scientists to use combinations of codes to solve coupled problems. The new library provides the Bridge scheme, which is a tree-direct hybrid N-body scheme for fully self-consistent simulations of star clusters and their parent galaxy systems. In such simulations, star clusters need a very accurate scheme, while galaxies need a fast scheme because of their large number of particles. At the end of the visit they performed N-body simulations of star clusters within their parent galaxies with stellar evolutions using the Muse libraries.

V-153: Visit of Drs. Sambaran Banarjee

Banarjee (Tata Institute of Fundamental Research, Mumbai, India) visited the Astronomical Institute Anton Pannekoek from August 13-23, 2007 to work in collaboration with Portegies Zwart and his team on the formation and evolution of hyper velocity stars. During the visit they worked on the problem of a three body encounter of an Intermediate-mass black hole with a stellar binary. Banarjee has learned significantly about 3-body numerical scattering and about the STARLAB package.

V-156: Visit of Dr. M. Aragon-Calvo

Aragon-Calvo (former PhD, now Johns Hopkins University, Baltimore, USA) visited the Kapteyn Institute from 12 November until 9 December 2007 to collaborate with van de Weijgaert and Platen (PhD) on a 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.

8. Public outreach and Education

8.1. NOVA Information Center (NIC)

The NOVA Information Center (NIC) has been established to popularize astronomy and astrophysics. NOVA has a responsibility to report its front-line 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), with temporary help of Annemiek Lenssen (0.2 fte). The NIC is advised by the Minnaert Committee, chaired by de Koter.

Late 2007 the NOVA Board funded the proposal 'Bringing Astronomy into Classrooms' by de Koter, Barthel and Baan to address the problem of the transfer of astronomical knowledge in schools. NIC will hire an education person for 0.6 fte, who will be responsible for developing educational programs for different age groups and corresponding training programs for teachers and volunteer astronomers, and who will actively promote and supervise these programs at schools nationwide.

8.1.1. www.astronomie.nl

In September 2006 the NIC launched a renewed website, www.astronomie.nl, where it reports news and provides information on astronomy and NOVA. Also educational material is available. News is presented on a daily basis through a collaboration with the site www.allesoversterrenkunde.nl by Govert Schilling, and on a more or less weekly basis, through press releases on NOVA activities and news on astronomy in general. In 2007 the site attracted ~100,000 unique visitors, a number that is anticipated to (at least) double in 2008.
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, and information for teachers and (prospective) students. For the latter group, the NIC produced short movies at, and in collaboration with, all five NOVA institutes and SRON and ASTRON with the aim to give information about the study of astronomy.

8.1.2. 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 about 40 times (32 official press releases) in 2006 and 62 times (36 official press releases) in 2007. Some press releases were issued in close collaboration with outreach officers at ESO, ESA, SRON, and ASTRON when appropriate. In a many cases (Fig. 8.1) the press releases got prime media attention.
In October 2006 the 'astronieuwsbrief' was modernised, with two issues in 2006 and 20 in 2007. This newsletter targets the general public, though specifically teachers of primary and secondary schools.

Figure 8.1: Collage of some highlights of the projects and events produced and/or organised by the NIC. From top left in clockwise direction: Former NOVA Director de Zeeuw in his new capacity of Director General ESO interviewed at Paranal by the Dutch RTL News; Journalists at the APEX site filming and taking pictures of the filling up of helium tanks; List of special sections on the www.astronomie.nl site; Poster featuring the Hourglass Nebula MyCn 18 promoting NOVA and its website; NRC article on the "James Bond factor" of ALMA; Logo of the "Kids in Space" educational game, and NOVA logo of the news section of www.astronomie.nl.

8.1.3. Highlights of special events or projects

The NIC participated in the project 'Kids in Space', an educational computer game. The NIC negotiated a web version of this game, which can be accessed through www.astronomie.nl. Partners in this project were ASTRON, SRON, Pabo Meppel, the province of Drenthe, publisher Scala Media, and project management Publicase. The game CD was distributed to 500 primary schools.

The NIC organised a popular astronomy lecture series, given by young promising astronomers at Artis Zoo, using the special projection software at the planetarium.

Figure 8.2: Joost Broens won the first Dutch Astronomy Olympiad: a trip to La Palma Observatory, including a night of observing with the 2.5m Isaac Newton Telescope.

In September 2007 the NIC organised a press visit to the ESO telescope facilities in northern Chili (both at La Silla, Paranal and Chajnantor). Seven Dutch journalists participated, resulting in RTL evening news items of three minutes each on consecutive nights, and at least ten full or multiple page stories in national newpapers and magazines.

At the NOVA Autumn School 2007 for starting PhD students the NIC organised a workshop 'Dealing with the Press', in which also Schilling and Icke participated.

In 2007 the NIC has initiated a Dutch Task Force for the International Year of Astronomy 2009, lead by Baan. The NIC furthermore joined the ESERO Network 'SpaceLink' for Space and Astronomy education.

8.2. Astronomy Olympiad

In 2007 Leiden Observatory hosted the first Dutch Astronomy Olympiad: a contest for high school students. This Olympiad was developed and organized by a committee of PhD and Master students, and supported by NOVA, the Ministry of Education, Science and Culture, NWO, Leiden University and several other sponsors.

The Olympiad started with a selection round on the internet. High school students could download a test on astronomy, answer the questions and send in their solutions. Forty students from all over the Netherlands participated, and the 20 best were invited for a Masterclass in Astronomy. During one week, they attended lectures and working classes, taught by university astronomy lecturers from Leiden, Groningen, Utrecht and Amsterdam. The Masterclass was concluded with a final at the Space Expo in Noordwijk, with Joost Broens (from the village Leusden) as the winner. He won a digital camera and an observing trip to the 2.5m Isaac Newton Telescope at La Palma. Masha Galperina (Enschede) came second and Jorryt Matthee (Roermond) third.

From 2007 onwards the Astronomy Olympiad is an annual event, and its organization will alternate between the NOVA institutes. It will be organized by Utrecht in 2008 and Groningen in 2009.

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 (§ 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', which is taught every year in Utrecht for undergraduate 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).

The topics of the 'Interacademy Course' were interferometry in 2006 and astrobiology/exoplanets in 2007.

8.3.2. The 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 (§ 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 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.

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. 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.

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 discuss their progress, problems and future prospects with the review committee. The results are discussed with the thesis-advisor. The chairman of the review committee of each university reports the results to NOVA.

Graduate students also receive training in reporting scientific results in papers, in oral presentations and as posters. 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 Astronomy 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. Courses are taught dealing with topics that were missed during the undergraduate studies. 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. Each stream consists of a general part and a specialized part. The topics of the latter part are different each year. 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. 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 organised by Barthel with local support from Moller. The lecturers in 2006 were de Bruyn and Brandl (on galaxies) and Markoff and Pols (on stars). In 2007 the lectures were given by Schaye (on galaxies and cosmology), Vink (on stars) and Baan (on writing a press release).

9. Organization

9.1 Board

Prof.dr. P.C. van der Kruit (chair)	RuG, Chair	until September 2007
Prof.dr. M. van der Klis (chair)	UvA, Chair	since September 2007
Prof.dr. M. Franx	UL	until July 2007
Prof.dr. P. Groot	RU	since October 2006
Prof.dr. J.M. van der Hulst	RuG	
Prof.dr. K.H. Kuijken	UL	since July 2007
Prof.dr. J. Kuijpers	RU	until October 2006
Prof.dr. N. Langer	UU	

9.2 International Advisory Board (since November 2007)

Prof.dr. F.H. Shu (chair)	University of California, San Diego, USA
Prof.dr. R.D. Blandford	Stanford University, Palo Alto, USA
Prof.dr. R.C. Kennicutt	University of Cambridge, UK
Prof.dr. H-W. Rix	MPIA, Heidelberg, Germany
Prof.dr. A. Sargent	Caltech, Pasadena, 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,	since July 2007
Prof.dr. M. Franx	UL	
Prof.dr. P. Groot*	RU	since October 2006
Prof.dr. E.P.J. van den Heuvel	UvA	until July 2007
Dr. M. Hogerheijde	UL	since July 2007
Prof.dr. J.M. van der Hulst*	RuG	
Prof.dr. C.U. Keller	UU	
Prof.dr. M. van der Klis*	UvA	
Dr. L.V.E. Koopmans	RuG	since July 2007
Dr. A. de Koter	UvA	since July 2007
Prof.dr. K.H. Kuijken*	UL	
Prof.dr. H.J.G.L.M. Lamers	UU	until July 2007
Prof.dr. N. Langer*	UU	
Dr. S.S. Larsen	UU	since July 2007
Prof.dr. G.K. Miley	UL	until July 2007
Dr. R.F. Peletier	RuG	since July 2007
Dr. S.F. Portegies Zwart	UvA	since July 2007
Prof.dr. A. Quirrenbach	UL	until July 2007
Dr. H.J.A. Röttgering	UL	since July 2007
Dr. J. Schaye	UL	since July 2007
Dr. M.C. Spaans	RuG	since July 2007
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	since July 2007

* The members of the NOVA Board and the NOVA scientific director are key researchers at large.

9.4 Coordinators research networks

Prof.dr. J.M. van der Hulst	RuG	Network 1, until July 2007
Prof.dr. M. Franx	UL	Network 1, since July 2007
Prof.dr. E.F. van Dishoeck	UL	Network 2, until July 2007
Prof.dr. L.B.F.M. Waters	UvA	Network 2, since July 2007
Prof.dr. A. Achterberg	UU	Network 3, until July 2007
Prof.dr. H. Falcke	RU	Network 3, since July 2007

9.5 Instrument Steering Committee

Dr. R.G.M. Rutten (chair)	ING, La Palma	
Prof.dr. R. Bacon	Univ. Lyon	since Nov 2007
Dr. B. Brandl	UL	since Nov 2007
Dr. M. Casali	ESO	since Nov 2007
Prof.dr. M.W.M. de Graauw	SRON/UL	until Nov 2007
Prof.dr. P. Groot	RU	until Oct 2006
Dr. H.J. van Langevelde	JIVE	
Prof.dr. L. Kaper	UvA	since Nov 2007
Prof.dr. C.U. Keller	UU	
Prof.dr. K.H. Kuijken	UL	until June 2007
Prof.dr. G. Monnet	ESO	until Nov 2007
Dr. G. Nelemans	RU	since Feb 2007
Prof.dr. A. Quirrenbach	Heidelberg	until Mar 2007
Prof.dr. P. Roche	Oxford	
Dr. B. Stappers	ASTRON/UvA	until Nov 2007
Prof.dr. E. Tolstoy	RuG	until Nov 2007
Dr. M. Verheijen	RuG	since Nov 2007
Dr. M. de Vos	ASTRON	
Prof.dr. W. Wild	SRON/RuG	since May 2007

9.6 Education Committee

Prof.dr. J. Kuijpers (chair)	RU	
Prof.dr. P. Barthel	RuG	
Drs. N. Degenaar	UvA	from Sep 2007
Drs. H. Hu	RU	from Sep 2006
Prof.dr. F.P. Israel	UL	
Prof.dr. L. Kaper	UvA/VU	from Sep 2006
T. van der Laan	RuG	from Sep 2007
Dr. H.J. van Langevelde	JIVE	until Sep 2006
Drs. J. Moortgat	RU	until Sep 2006
Steven Rieder	UU	
Dr. R.J. Rutten	UU	until Sep 2006
Dr. G.J. Savonije	UvA	until Sep 2006
E. Starkenburg	RuG	until Sep 2007
Prof.dr. F. Verbunt	UU	from Sep 2006
Drs. A.M. Weijmans	UL	
Drs. K Wiersema	UvA	until Sep 2007

9.7 Minnaert Committee

Dr. A. de Koter (chair)	UvA
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 Instrument Principal Investigators

Dr. B. Brandl	UL	MIDIR (now named METIS)
Dr. A.G.A. Brown	UL	GAIA
Prof.dr. E.F. van Dishoeck	UL	MIRI, ALMA Band-9 prototype
Prof.dr. M. Franx	UL	MUSE
Dr. M.R. Hogerheijde	UL	ALLEGRO
Prof.dr. L. Kaper	UvA	X-Shooter
Prof.dr. K.H. Kuijken	UL	OmegaCAM/CEN
Dr. H.V.J. Linnartz	UL	Sackler Laboratory for Astrophysics
Dr. R. Röttgering	UL	LOFAR DCLA
Dr. R.J. Rutten	UU	DOT
Dr. W. Jaffe	UL	VLTI
Prof.dr. L.B.F.M. Waters	UvA	SPHERE-ZIMPOL
Prof.dr. W. Wild	RuG/SRON	ALMA receivers technical R&D

9.9 NOVA Information Center (NIC)

Drs. M. Baan	UvA
Drs. A. Lenssen	UvA

9.10 Office

Prof.dr. P.T. de Zeeuw (director)	UL	until August 2007
Dr.W.H.W.M. Boland (deputy director)	NOVA	until August 2007
Prof.dr. E.F. van Dishoeck (scientific director)	UL	since September 2007
Dr. W.H.W.M. Boland (executive director)	NOVA	since September 2007
C.W.M. Groen (management assistant)	NOVA	

10. Financial report 2006 - 2007

In k€	2006	2007
ASTRONOMICAL RESEARCH		
Overlap Appointments	**1206**	**791**
Research Networks		
Formation and evolution of galaxies	414	338
Formation and evolution of stars and planets	217	230
Final stages of stellar evolution	363	338
Other research projects	116	116
Workshop and visitors	110	52
Total research funding	**1220**	**1074**
TOTAL ASTRONOMICAL RESEARCH	**2426**	**1865**
INSTRUMENTATION (NOVA funded)		
ALMA mixer development + ALLEGRO	206	246
OmegaCAM/CEN	378	281
MUSE	42	163
X-Shooter	836	856
SINFONI	106	66
Sackler laboratory for astrophysics	111	106
LOFAR DCLA	294	175
PUMA	61	0
New initiatives	19	0
TOTAL instrumentation NOVA funded	**2053**	**1893**
INSTRUMENTATION (externally funded)		
MIRI	1382	1231
ALMA Band-9 prototype receiver	1229	803
ALMA Band-9 production	0	59
Champ+	140	12
EU funded projects	0	279
TOTAL instrumentation externally funded	**2751**	**2384**
TOTAL INSTRUMENTATION	**4804**	**4277**
OVERHEAD		
NOVA office	182	198
Outreach – NIC	104	39
TOTAL OVERHEAD	**286**	**237**
TOTAL EXPENDITURE	**7516**	**6379**

11. List of abbreviations

2dF	Two-degree Field
2dFGRS	Two-degree Field Galaxy Redshift Survey
2MASS	Two Micron All Sky Survey
2SB	Sideband-Separating (submm) receiver
AAO	Anglo-Australian Observatory
ACS	Advanced Camera for Surveys (on the HST)
ADC	Analog to Digital (signal) Convertor
AGN	Active Galactic Nuclei
AIP	Astrophysical Institute Postdam
AIPS	Astronomical Image Processing System
ALMA	Atacama Large Millimeter Array
AM CVn	AM Canum Venaticorum (type star)
AMBER	Astronomical Multiple Beam Recombiner
AMP	Accreting Millisecond Pulsar
ANU	Australian National University
AO	Adaptive Optics
APEX	ALMA Pathfinder Experiment
ASSIST	Adaptive Secondary Simulator and InStrument Testbed
AST/RO	Antarctic Submillimeter Telescope and Remote Observatory
ASTRON	Stichting Astronomisch Onderzoek in Nederland (Netherlands Foundation for Research in Astronomy)
ATCA	Australia Telescope Compact Array
ATF	Astrometric Telescope Facility
AU	Astronomical Unit
BCD	Blue Compact Dwarf
BIMA	Berkeley Illinois Maryland Association
c2d	cores to disks (Spitzer Legacy proposal)
Caltech	California Institute of Technology
CARMA	Combined Array for Research in Millimeter-wave Astronomy
CCD	Charge-Coupled Device
CDM	Cold Dark Matter
CESSS	Cavity Enhanced Solid State Spectrometer
CfA	(Harvard-Smithsonian) Center for Astrophysics
CFHT	Canada France Hawaii Telescope
CHAMP+	CHAMP+ is a dual-frequency heterodyne submillimeter array receiver built by MPIfR and NOVA/SRON/TuD for APE
CHANDRA	NASA's X-ray space observatory
CHEOPS	CHaracterizing Extrasolar planets by Opto-infrared Polarimetry and Spectroscopy
CMB	Cosmic Microwave Background
CRAL	Centre de Recherche Astronomique de Lyon
CRs	Cosmic Rays
CRYOPAD	CRYOgenic Photo-product Analysis Device
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
CWI	Centrum voor Wiskunde en Informatica
CWRU	Case Western Reserve University
DART	Dwarf Abundances and Radial velocities Team
DCLA	Development and Commissioning of LOFAR for Astronomy
DDL	Differential Delay Lines (component of the VLTI)
DFG	Deutsche Forschung Gemeinschaft
DIB	Diffuse Interstellar Band
DLAs	Damped Ly-α systems
DMA	Direct Memory Access
DMT	DCLA Management Team
DOT	Dutch Open Telescope
DRGs	Distant Red Galaxies
dSph	dwarf Spheroidal
DTFE	Delaunay Tessellation Field Estimator
DUEL	Dark Universe through Extragalactic Lensing
EGAPS	European Galactic Plane Surveys
ELD	Edge-Lit Detonations
ELODIE	The fibre-fed echelle spectrograph of Observatoire de Haute-Provence
EoR	Epoch of Reionization
ESA	European Space Agency
ESO	European Southern Observatory
ETH	Eidgenössische Technische Hochschule (Zürich)
EU	European Union
EURO-VO	EU funded virtual observatory for astronomy
EVN	European VLBI Network
FEL	Free Electron Laser
FIRES	Faint Infrared Survey (at the VLT)
FLAMES	Fibre Large Array Multi Element Spectrograph (at the VLT)
FOM	Fundamenteel Onderzoek der Materie (NWO division for physics)
FORS	Focal Reducer and low dispersion Spectrograph
FoV	Field of View
FP6	Framework Program 6 (EU)
FUSE	Far Ultraviolet Spectroscopic Explorer
FWHM	Full Width at Half Maximum
GAIA	Global Astrometric Interferometer for Astrophysics
GALACSI	Ground Layer Adaptive Optics System (for MUSE)
GALEX	Galaxy Evolution Explorer
GBT	Green Bank Telescope
GIM2D	Galaxy Image 2D
GLAST	Gammy Ray Large Area Space Telescope
GMC	Giant Molecular Cloud
GMRT	Giant Metrewave Radio Telescope (in India)
GPP	General Purpose Processor
GRB	Gamma Ray Burst
GT	Guaranteed Time
GTO	Guaranteed Time Observations
GWs	Gravitational Waves
GZL	Greisen-Zatsepir-Kuzmin cutoff
HECRs	High Energy Cosmic Rays
Herschel	Far-infrared Submillimeter satellite (see also HSO)
HI	Hydrogen 21 cm line
HIFI	Heterodyne Instrument for the Far-Infrared for HSO
HR	High Resolution
HSO	Herschel Space Observatory
HST	Hubble Space Telescope
HVS	Hyper-Velocity Stars
HV-SETUP	High Vacuum setup
HzRGs	High-redshift Radio Galaxies
IAC	Instituto de Astrofisica de Canarias
IAP	Institut d'Astrophysique de Paris
IDE RAID	Integrated Drive Electronics - Redundant Array of Inexpensive Disks
IFU	Integral Field Unit
IGM	Inter galactic matter
IMBH	Intermediate Mass Black Holes
IMF	Initial Mass Function
ING	Isaac Newton Group of the Roque de los Muchachos Observatory on La Palma
INT	Isaac Newton Telescope (part of ING)
INTEGRAL	ESA's gamma-ray space observatory
IoA	Institute of Astronomy (in Cambridge, UK)
IRAC	Infrared Array Camera
IRAM	Institut de Radio Astronomie Millimétrique
IRAS	InfraRed Astronomical Satellite
IRS	InfraRed Spectrograph
ISAAC	IR (1 - 5 μm) imager and spectrograph on ESO's VLT
ISM	InterStellair Medium
IUCAA	Inter-University Centre for Astronomy and Astrophysics (Pune, India)
JCMT	James Clerk Maxwell Telescope
JPL	Jet Propulsion laboratory
JWG	Dutch Youth Association for Astronomy
KBO	Kuiper Belt Object

KIDS	Kilo-Degree Survey (planned for VST/OmegaCAM)
KNVWS	Koninklijke Nederlandse Vereniging voor Weer- en Sterrenkunde
LAM	L'Observatoire Astronomique de Marseille-Provence
LANL	Los Alamos National Laboratory
LBV	Luminous Blue Variable
LEXUS	Laser EXcitation setup for Unstable Species
LFFE	Low Frequency Front End (new receiver on WSRT)
LGS	Laser Guide Star
LINEAR	Lincoln Near-Earth Asteroid Research
LINER	Low Ionization Nuclear Emission line Region
LIRTRAP	Laser Induced Reactions TRAPping device
LISA	Laser Interferometer Space Antenna
LMC	Large Magellanic Cloud
LMXBs	Low-Mass X-ray Binaries
MAMBO	Max-Planck Millimeter Bolometer
MDM observatory	Michigan-Dartmouth-MIT Observatory
MEGA	Microlensing Exploration of the Galaxy and Andromeda
MERLIN	Multi-Element Radio Linked Interferometer Network
MHD	magnetohydrodynamics
MIDI	MID-Infrared instrument (for the VLTI)
MILES-library	Medium resolution INT Library of Empirical Spectra
MIPS	Microprocessor without Inerlocked Pipeline Stages
MIT	Massachusetts Institute of Technology
MODEST	MOdelling DEnse STellar systems collaboration
MPA	Max-Planck-Institut für Astrophysik (Garching, Germany)
MPE	Max-Planck-Instituts für Extraterrestrische Physik (Garching, Germany)
MPI	Max-Plank-Institut
MPIA	Max-Planck-Institut für Astronomie (Heidelberg, Germany)
MPIfR	Max-Planck-Institut für Radioastronomie (Bonn, Germany)
MSSL	Mullard Space Science laboratory
MUSE	Multi Unit Spectroscopic Explorer (2nd generation instrument for VLT)
Muse	Multiscale multiphysics scientific environment
MUSYC	Multiwavelength Survey by Yale-Chile
NAC	Nederlandse Astronomen Club
NACO	Nasmyth Adaptive Optics System (VLT instrument)
NEVEC	NOVA ESO VLTI Expertise Center
, NIKHEF	Nationaal Instituut voor Kernfysica en Hoge-Energiefysica
NIR	Near Infrared Spectroscopy
nm	nanometer
NOAO/IPAC	National Optical Astronomy Observatory/ Infrared Processing and Analysis Center
NOVA	Nederlandse Onderzoekschool Voor Astronomie (Netherlands Research School for Astronomy)
NWO	Nederlandse organisatie voor Wetenschappelijk Onderzoek (Netherlands Organization for Scientific Research)
NWO-EW	NWO department for Physical Sciences
NWO-M	NWO-middelgroot
OASIS	Organization for the Advancement of Structured Information Standards
OmegaCAM	Wide-field camera for the VLT Survey Telescope OmegaCEN OmegaCAM data center
OVRO	Owens Valley Radio Observatory
PACS	Photodetector Array Camera & Spectrometer
PAH	Polycyclic Aromatic Hydrocarbon molecule
PCSN	Pair Creation Super Novae
PDR	Photon-Dominated Region
PI	Principal Investigator
PN.S	Planetary Nebula Spectrograph
Pne	Planetary Nebula
PRIMA	Phase Referenced Imaging and Micro-arcsecond Astrometry (facility in development for the VLTI)
PuMa	Pulsar Machine (in use on WSRT)
RAIRS	Reflection Absorption InfraRed Spectroscopy
RAVE	RAdial Velocity Experiment
RGB	Red Giant Branch
ROSAT	ROentgen SATellite
RRATs	Rotating Radio Transients
RTD	Research and Technical Development (an EU program)
RTN	Research and Training Network (an EU program)
RXTE	Rossi X-Ray Timing Explorer
SAURON	Spectroscopic Areal Unit for Research on Optical Nebulae
SCUBA	Submillimetre Common-User Bolometer Array (on JCMT)
SDSS	Sloan Digital Sky Survey
SED	Spectral Energy Distribution
SiC	silicon carbide
SINFONI	Spectrograph for Integral Field Observations in the Nea Infrared
SIPS	Southern Infrared Proper motion Survey
SIS	Superconductor Insulator Superconductor (mixer)
SISCO	Spectroscopic and Imaging Surveys for Cosmology (EU-RTN network in astronomy)
SLACS	Sloan Lens ACS Survey
SMA	Smithsonian Millimeter Array (on Mauna Kea, Hawaii)
SMC	Small Magellanic Cloud
SNN	Samenwerkingsverband Noord Nederland
SNR	SuperNova Remnant
SPH	Smoothed Particle Hydrodynamics
SPHERE	Spectro-Polarimetric High-contrast Exoplanet Research
SPIRAS	Supersonic Plasma InfraRed Absorption Spectromete
SRON	Netherlands institute for space research
STIS	Space Telescope Imaging Spectrograph
STScI	Space Telescope Science Institute
SURFRESIDE	SURFace REaction SImulation DEvice
TA	Timing Argument
TNO	Nederlandse organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (Research Institute for applied physics in the Netherland
TPD	Temperature Programmed Desorption
TU	Technical University
TUD	Technical University Delft
UCLA	The University of California, Los Angeles
UIUC	University of Illinois at Urbana-Champaign
UKIDSS	UK Infrared Deep Sky Survey
UKIRT	United Kingdom Infrared Telescope
ULIRG	Ultra Luminous Infra-Red Galaxy
UNAM	Universidad Nacional Autónoma de México
UNSW	University of New South Wales Australia)
UT	Unit Telescope
UV	ultra violet
UvA	Universiteit van Amsterdam
UVES	Ultraviolet and Visual Echelle Spectrograph (on VLT)
VIMOS	VIsible MultiObject Spectrograph
VLA	Very Large Array
VLBA	Very Long Baseline Array
VLBI	Very Long Baseline Interferometry
VLT	Very Large Telescope (ESO)
VLTI	Very Large Telescope Interferometer (ESO)
VLT-VISIR	VLT-Imager and Spectrometer for mid InfraRed
VST	VLT Survey Telescope
WFC	Wide Field Camera
WFI@2.2m	Wide Field Imager on ESO's 2.2m telescope
WHISP	Westerbork HI Survey of Spiral and Irregular Galaxies
WHT	William Herschel Telescope (part of ING)
WMAP	Wilkinson Microwave Anisotropy Probe
WSRT	Westerbork Synthesis Radio Telescope
X-Shooter	single target spectrograph for the VLT
YSO	Young Stellar Object
ZIMPOL	Zurich IMaging POLarimeter