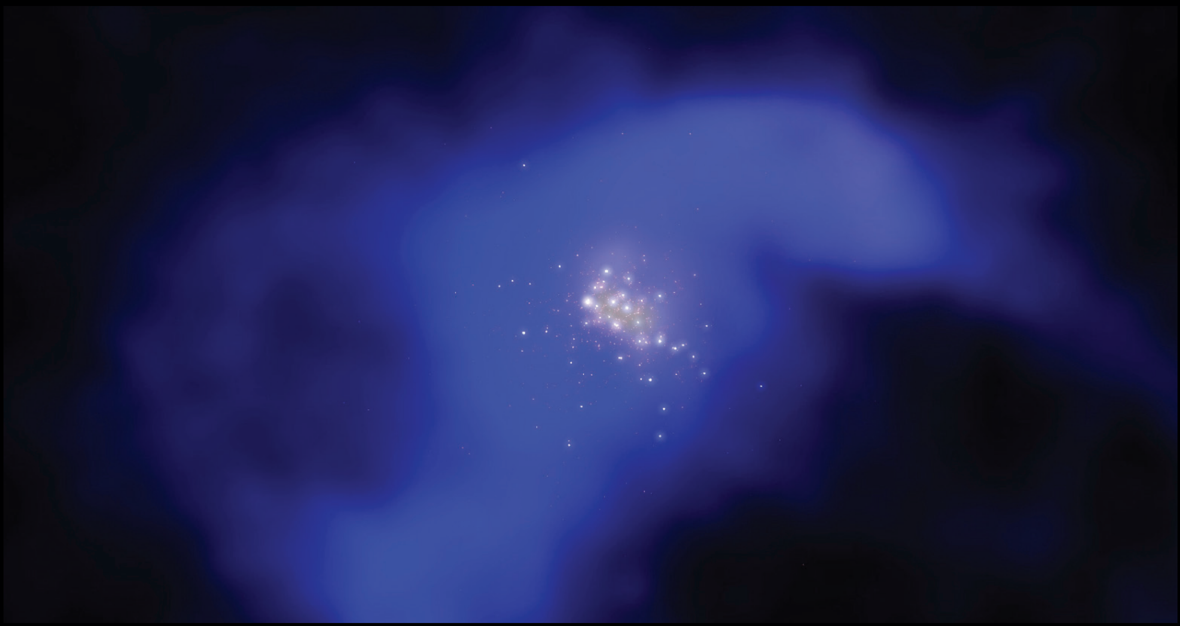
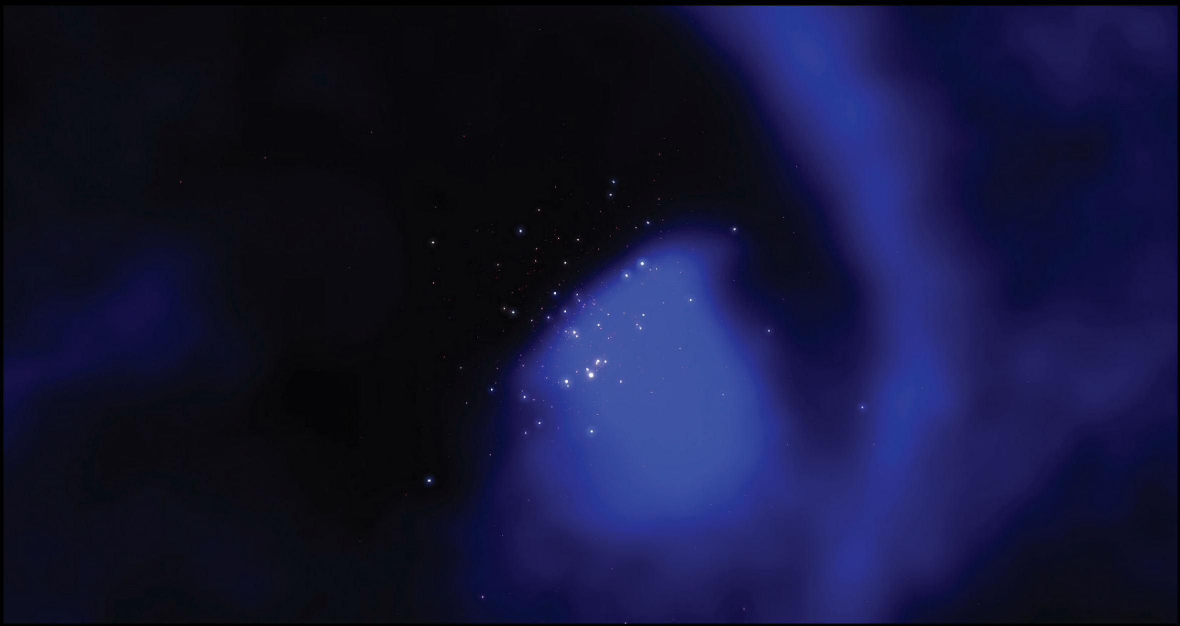
NOVA REPORT
2013 - 2014 - 2015





Ilustrations on front cover

Top:
Snapshot of a simulation of an embedded star cluster at the moment that all stars have arrived on the zero-age main sequence (by construction). This cluster consist of 300 $M_{\odot}$ in stars distributed in a Plummer sphere with a Salpeter IMF, and 1000 $M_{\odot}$ in ambient gas (with the same spatial distribution as the stars).

Lower:
Snapshot of the same embedded cluster as middle panel, but now after the majority of the gas has been expelled (at an age of about 8 Myr, the first supernova in this cluster occurs at about 10 Myr).

Ilustrations on back cover

NOVA personnel working on different instrumentation projects. Clockwise from top left: assembly of ALMA Band-5 receivers; polishing optics for the WEAVE spectrometer; designing part of the MATISSE cold optical bench; assembling the MIRI engineering qualification model.

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NOVA

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NOVA is the alliance of the astronomical institutes of the universities of Amsterdam, Groningen, Leiden and Nijmegen, legally represented by Leiden University.

Table of contents

1. Introduction

Astronomy is a unique discipline which combines top science, cutting-edge technology and education, and inspires and excites the general public. Thanks to powerful new telescopes and instruments, many new discoveries have been made in recent years. Constraints on the nature of the mysterious dark energy and dark matter, which comprise 95% of the Universe, are being made. Light from the earliest galaxies, emitted when the Universe was only 3% of its current age, demonstrates even more vigorous star formation than expected at that early stage. Large scale computer simulations provide increasingly realistic insight into the physical processes that shape galaxies. Mergers of dying stars are at the origin of the most powerful explosions in the Universe, the origin and composition of cosmic ray particles produced in some of these explosions is being unraveled. The formation history of our Milky Way and neighboring galaxies is being revealed through detailed studies of the motions and elemental abundances of individual stars. Within our Galaxy, more than 3000 exoplanets have now been found, the majority of which have masses between those of Earth and Neptune, surprisingly different from our Solar System planets. New facilities allow astronomers to zoom in on the construction sites of new stars and planets, where increasingly complex organic molecules, the precursors of life, are found. Astronomy clearly continues to thrive in all its aspects.

Because astronomical signals are extremely weak, astronomy is a driver for the development of advanced technology, such as the most sensitive detectors of light and radio waves and the fastest computers processing big data streams. Strong national and international collaboration allows the construction of large telescopes and satellites that lead to exciting discoveries. NOVA coordinates university astronomical research in the Netherlands, instrumentation, education and outreach into a coherent program and is the Dutch link to the European Southern Observatory (ESO), co-founded by the Netherlands.

Astronomy spans a wide range of disciplines, including physics, chemistry, mathematics, and informatics, and now even biology and geology. New interdisciplinary topics such as astroparticle physics, computational astrophysics, astrochemistry and astrobiology are emerging worldwide, with the Netherlands having a leading position in several of these areas. Astrophysicists study phenomena involving enormous scales of length and mass (the entire Universe), huge densities (e.g., neutron stars), enormous gravitational fields (black holes), ultra-high vacua (interstellar and circumstellar media), and immense energies and intense fluxes of particles and radiation (gamma ray bursts and supernovae, accreting neutron stars and black holes). The basic curiosity about this fascinating Universe in which we live is shared by virtually all of humanity. Astronomy has a powerful story of adventure and discovery, and thus provides a unique opportunity to enhance appreciation of the younger generation for the natural sciences.

The Netherlands Research School for Astronomy (NOVA) carries out astronomical research at the highest international levels centered around the theme 'The life-cycle of stars and galaxies: from high-redshift to the present' and trains the next generation of astronomers in this area (Chapter 3+4, 6+7). Essential for the success of the research program is access to state-of-the-art observational facilities. An integral component of the NOVA program is therefore to build and develop new astronomical instruments, often in concert with industry, and smart software pipelines to analyze large data streams (Chapter 5). NOVA shares the excitement of astronomical discoveries with the general public through its outreach program, the NOVA Information Center (NIC) (Chapter 8). This report covers the numerous scientific and technical achievements by the university astronomical community united in NOVA in the years 2013-2015.

Major developments of the NOVA program

During the reporting period 2013 – 2015 the major development was the start of its Phase-4 cycle running from 2014 to end 2018. In 2013 many decisions were taken to implement the program including the selection of ~45 new PhD and postdoc projects equally distributed over the three research networks. In parallel 16 instrumentation projects were approved to start or continue of which four relate to the ESO's new flagship program for the European Extremely Large Telescope (E-ELT): NOVA contributions include leading the consortium that designs and builds the mid-infrared imager and high-resolution spectrometer named METIS of which NOVA astronomer Brandl is the Principal Investigator. In addition NOVA is a minor partner in the first-light instrument MICADO providing imaging and low spectral resolution capabilities in the near-infrared wavelength region. Furthermore NOVA contributes to the Phase-A study on a multi-object spectrometer MOSAIC and undertakes technical R&D studies on an instrument that aims to characterize exoplanets some 15 years in the future (more in Chapter 5).

NOVA had its mid-term review on 19-21 March 2014 at the Radboud University in Nijmegen. Main conclusion was: *'NOVA and its four constituent university institutes continue to conduct astrophysical research and instrumentation development consistent with the highest international standards. Collaboration between the institutes, and with ASTRON and SRON, has produced a quantity and level of scientific and technical achievements that could not have been achieved by the universities acting individually. NOVA is an outstanding exemplar for an effective cross-university virtual institute'.*

In March and April 2014 a delegation of the NOVA Board and Directorate visited the CvB's of each of the participating universities explaining the NOVA program and arguing the need for long-term baseline funding. The universities expressed their strong support including approaching the ministry of Education, Culture and Science (OCW in Dutch) to discuss the arguments for funding stability to enable NOVA to undertake large programs with international partners, including a leading role in the development and construction of instrumentation for the E-ELT. Final result was achieved in early 2016 with the decision by the minister of OCW to extend funding for NOVA for another period of five years up to end 2023. In the same letter NOVA was instructed to participate in the competition for 'Zwaartekracht' programs if it wants to continue to receive funding from this budget line beyond 2023.

Overview and highlights

Dutch university astronomy continues to be highly productive, with ~740 unique refereed papers per year in 2013-2015, most of them led by young PhD students and postdocs. In this period a total of 122 PhD's in astronomy were awarded. Scientific highlights include

- Characterization of galaxies in the highest redshift Universe by measurements of the UV luminosity functions to z=10 based on HST imaging, and putting the strongest constraints on radio emission from the era of reionization with LOFAR;
- Derivations of mass functions of galaxies from z=2 to 5 from the Ultravista survey, and improved masses and kinematics/spectroscopy from X-Shooter and MUSE, showing that galaxies as massive as the Milky Way or larger were already present in the first few billion years of cosmic time;
- EAGLE simulation of the history of the Universe, successfully modelling galaxies with masses, sizes and ages that are similar to those observed;
- Delineation and quantification of the cold + warm water reservoirs in protoplanetary disks with Herschel;
- First detection of a dust trap in a protoplanetary disk and evidence for cavity clearing by one or more giant planets with ALMA-Band 9, and surprising structures in disks found by VLT-SPHERE;
- First determination of the length of a day on an exoplanet, showing that its rotational period is in line with the radius-rotation relation found for solar system gas giants using VLT-CRIRES;
- Determination of a very high mass of 2 $M_\odot$ of the radio pulsar PSR J1614-2230 from a strong Shapiro delay, ruling out the presence of pion/kaon condensates at high density, challenging our understanding of hyperon interactions;
- Proof that the low frequency (10-100 Hz) quasi-periodic oscillations in neutron star low mass X-ray binaries are not due to frame-dragging of material in the inner disk;
- Breakthrough in the radio detection of air showers: all cosmic-ray parameters (direction, energy, and particle type) are now routinely measured with LOFAR.

The instrumentation program saw the completion of the NOVA contribution to the MUSE instrument (2013) including the ASSIST tower needed to verify the new deformable secondary mirror of the VLT to enable MUSE operating in adaptive optics mode. Further the Zimpol unit of the SPHERE instrument was delivered (2013). Both instruments are for ESO's VLT. In 2014 the four key projects to implement astronomy with LOFAR were completed targeting (1) the epoch of reionization, (2) mapping the northern sky at low radio frequencies, (3) studies of cosmic rays, and (4) radio transients to study extreme astrophysics. Finally, in 2014 and 2015 the cryogenic beam combiners optimized for mid-infrared wavelengths were completed and delivered to the consortium partners for integration in the MATISSE instrument for ESO's VLT interferometer.

In the reporting period the NOVA program involved ~365 fte scientific staff members spread over the participating universities. This number includes ~56 fte senior staff members in permanent and tenure-track positions, ~10 fte senior postdocs, 5 fte co-workers from ASTRON and SRON, 83 fte postdoctoral fellows, 171 PhD students and ~40 instrumentalists.

Many astronomers in the Netherlands received prestigious research grants during the reporting period. The table below gives an overview.

Prize/grant	2013	2014	2015
ERC Synergy	Falcke		
ERC Advanced	de Bruyn		
ERC Starting	Hekker	Watts	Desert
	Hessels		Snik
ERC Consolidator	van Leeuwen		Baselmans
			Caputi
			Jonker
NWO-VICI		Koopmans	Schaye
			Helmi
			Verheijen
NWO-VIDI	Hessels	Ormel	Degenaar
	Patruno		Costantini
	Rea		Petrignani
NWO-VENI	Walsh	Ingram	Akamatsu
	Jelic	Zandanel	Archibald
		Tobin	Candian
			de Gasperin
NWO-TOP-1	Hogerheijde	Kuijken	
	Kaastra	Wijnands	
	Tielens	Oosterloo	
		Falcke	

Major personal research grants obtained in 2013 - 2015

In addition many NOVA researchers received awards and honors, including:

- Election to the Royal Academy of Sciences (KNAW) for Falcke (2014)
- Election to the Young Academy of the KNAW for Hessels (2015)
- Election to foreign member KNAW for Kouveliotou (2015)
- Election to Royal Holland Society of Sciences and Humanities for Helmi, Kuijken and Falcke (2015)
- Honorary doctorate of the University of Padua for de Zeeuw (2014)
- Lise Meitner Gothenburg physics award for van Dishoeck (2014)
- Albert Einstein Award World Cultural Council for van Dishoeck (2015)
- Lodewijk Woltjer prize lecture EAS for van Dishoeck (2015)
- Halley lecturer Oxford University (2013), and Sackler lecturer Tel Aviv (2013) for van Dishoeck
- George Darwin lecture UK Royal Astronomical Society for Tolstoy (2013)
- Astronomy group award UK Royal Astronomical Society for SAURON team including de Zeeuw and Peletier (2013)
- Pastoor Schmeits price for best young researcher aged less than 40 years for Bouwens (2013)
- German power woman engineering award for Kroes (2014)
- Willem de Graaf prize for public outreach for Barthel (2013)
- Royal knighthood to Barthel (2015)
- Knighthood commander in the Star of Italy to Morganti (2014)

2. Mission statement and research program

NOVA is the alliance of the four university astronomy institutes in the Netherlands - in Amsterdam, Groningen, Leiden and Nijmegen. Leiden University is the legal representative of NOVA.

2.1. NOVA's mission and objective(s)

NOVA's mission is to carry-out front-line astronomical research, to train young astronomers at the highest international levels, and to share discoveries with society. NOVA coordinates all of Dutch university astronomy research, instrumentation, PhD education and outreach activities in a coherent and collaborative national program called "The lifecycle of stars and galaxies".

NOVA's objective is to ensure a front-line role in the next generation of astronomical discoveries and to share our new knowledge with society. The first part of its strategy is to foster a stimulating scientific atmosphere which allows astronomers to pursue their scientific dreams and push boundaries, and in which young scientists can develop and grow. To enable these dreams, new observations, instruments and technology, together with theory and models, are essential. The second part of NOVA's strategy is therefore to design and build advanced instrumentation for state-of-the-art observing facilities, in particular for ESO, which provide priority access to observations of particular importance for Dutch astronomy. This strategy maximizes the science return of major telescopes in which the Dutch government has invested. NOVA also stimulates development of specialized data reduction software, numerical modelling and laboratory astrophysics at the universities. NOVA thereby empowers the university astronomers in several key areas, providing them with a longer-term planning horizon and a higher impact than would otherwise be possible.

Research and instrumentation are strongly interlinked in the NOVA program. NOVA astronomers use a wide variety of telescopes and instruments but new breakthroughs often come from a close involvement in instrumentation itself: by building instruments, astronomers define their functionality, steer their science capabilities to Dutch interests, and safeguard them throughout the complete instrument-building cycle. Through guaranteed time, NOVA astronomers are among the first to use the instrument, thus reaping the hottest early science harvest. Leading or being part of the instrument team is key to doing modern frontline astronomy.

NOVA is fully committed to share its knowledge with society. Its activities are grouped around three main pillars (i) outreach and education; (ii) pushing technology boundaries and spin-offs with industry; and (iii) human capital development. In outreach the NIC strategy is (a) to inform the general public in the Dutch language about new astronomical discoveries with a focus on results in which NL astronomers had a leading role, through the widest possible range of (social) media; (b) to identify and engage with societal developments where astronomy can contribute, and (c) to stimulate and support education in astronomy (and sciences in general) in primary and secondary schools through providing attractive material for school books, training and coaching for teachers, and operating three mobile planetaria to visit schools. Each of the university institutes also has a wide range of outreach activities, often centered around their own small telescopes. They complement the NIC activities by being aimed at their local and regional communities (typically thousands of people), but they join forces with the NIC when appropriate to reach broader audiences at the national level (up to millions of people).

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

The research program carried out by NOVA 'The lifecycle of stars and galaxies: from high-redshift to the present' is organized along the following three interconnected thematic programs (also called 'networks'):

- Network 1: Formation and evolution of galaxies: from high redshift to the present
- Network 2: Formation and evolution of stars and planetary systems
- Network 3: Astrophysics in extreme conditions

Each network consists of 15-20 active staff researchers with strong scientific records. The networks have regular (two to three times per year) face-to-face meetings with scientific presentations, mostly by PhD students and postdocs. Subgroups of researchers from different universities focusing on more specialized topics also meet regularly.

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

Network 1 studies the formation and evolution of galaxies across time and space, from the Milky Way to the first observable objects in the Universe. Its main themes for the coming 5-10 years are: (i) The dawn of the Universe (ii) The nature of the main constituents of the Universe: putting constraints on dark matter and dark energy; (iii) The process of galaxy assembly: towards a theory of galaxy evolution.

Network 2: Formation and evolution of stars and planetary systems

Network 2 studies the physics and chemistry of the interstellar medium, its collapse to form new stars and protoplanetary disks, the formation of planets, and the subsequent evolution of those stars and planets. Its main themes for the coming 5-10 years are: (i) Massive stars: how do they form and shape their environment and the Universe? (ii) Planet formation in disks: what determines the architecture of planetary systems? (iii) Extrasolar planets: towards characterization of Earth-like planets; (iv) The molecular Universe: inventory, chemical pathways and diagnostic applications.

Network 3: Astrophysics in extreme conditions

Network 3 investigates the extremes of physics, as encountered at the highest temperatures, densities and energies in objects with the strongest gravitational potentials: neutron stars (NS), white dwarfs (WD) and black holes (BH). Its main themes for the next 5-10 years are (i) Extreme physics with compact objects and in their mergers; (ii) Accretion, ejection and particle acceleration; (iii) Formation and evolution of (binary) BHs, NSs and WDs in diverse environments.

2.3. Instrumentation

NOVA's instrumentation program is focused on ESO. The top-level strategy of the program is therefore that it will be, at any given time, Principal Investigator on at least one ESO instrument. For the coming decade, this will be the METIS instrument for the E-ELT. The NOVA instrumentation program also invests in smaller-scale instrumentation and R&D projects where new concepts and technologies will be developed, implemented and matured before being applied. Two areas of R&D focus have been chosen for the coming years: (i) high contrast imaging; and (ii) multi-pixel submillimeter instrumentation.

3. Scientific highlights

3.1 Formation and evolution of galaxies

The research within Network 1 focuses on the evolution of the Universe and its constituents, with particular emphasis on the formation and evolution of galaxies, from high redshift to the present. As in previous periods, the research may be split in themes associated to (1) the young universe and the earliest galaxies; (2) the physics of galaxy evolution, and (3) the local Universe and its fossil record.

The past period saw significant advances in the study of the dark matter distribution using weak gravitational lensing, e.g. the final results from the CFHT Legacy Survey are in slight tension with measurements from Planck but in agreement with cluster abundance studies. Moreover the first results from the KiloDegree Survey have demonstrated its potential as a competitive probe for cosmology. Closer to home, the kinematics of stars in dwarf galaxies around the Milky Way have been used to constrain the distribution of dark matter in these systems. It has been found that the slopes of their dark halo density profiles at the half light radii, which have been measured for the first time in a model independent fashion, are consistent with cosmological expectations. On the other hand, the stellar content of these dwarf galaxies has been found to depict interesting differences in the populations of Carbon rich stars at low metallicities compared to the Milky Way, yielding new insights on the first populations of stars and the chemical enrichment in the early Universe.

Using a more traditional approach to study the early Universe, deep observations have led to the discovery of remarkably massive galaxies in the first billion years of cosmic time. These galaxies are likely host of the first generations of stars ever formed as is apparent from the brightest galaxy discovered to date in the early Universe. Significant progress has been made in measuring the luminosity distribution of galaxies at these epochs, which is crucial to constrain the origin of reionization, which is studied directly using LOFAR. State-of-the-art cosmological simulations are essential to interpret the wide range of observational results. EAGLE, a large sophisticated cosmological simulation of the formation of galaxies across cosmic time, is able to produce systems that match basic observed properties of galaxies, such as size and masses, thanks to better implementations of feedback processes. Such processes have also been studied in detail using a range of instruments. For example, observations of molecular gas in colliding galaxies have demonstrated the importance of mechanical heating, whereas high-resolution VLBI and ALMA observations revealed that radio plasma jets ejected by a supermassive black hole, clear cold gas from galaxies at velocities over 1000 km/s.

These studies have benefited from the instruments that have been developed by, or received contributions from NOVA over the years, such as LOFAR, OmegaCam on the VST, MIDI, X-Shooter, ALMA and APEX. Just over one year ago, the MUSE spectrograph has gone online, and the first impressive results are briefly reported here. We expect a lot more for the coming period from MUSE, as well as from space missions such as Gaia, which was launched in 2013, and JWST which is scheduled for launch in 2018. These are truly exciting times just ahead of us.

Cosmology and early galaxy formation

Mapping the dark matter distribution in galaxy groups

In 2015, the first lensing results from the Kilo-Degree Survey (KiDS), a large imaging survey at the ESO VLT Survey Telescope, were published (Fig. 1.1). KiDS (PI Kuijken, Leiden) aims to map 1500 square degrees of sky, and the first results concentrate on the overlap of this survey with the ground-breaking GAMA spectroscopic survey at the Anglo-Australian Observatory, allowing Brouwer (PhD), Cacciato, Hoekstra, Kuijken, Sifon (PhD), Viola (Leiden) and collaborators, to study the relation between dark halo mass and galaxy properties. Viola and collaborators presented a detailed study of galaxy groups, the most

Fig. 1.1: *An example of a massive group of galaxies at z~0.25 in a 3x3Mpc region in the Kilo Degree Survey. The dark matter distribution as measured from weak lensing is shown in pink (Viola et al. 2015, MNRAS, 452, 3529).*

common environment in which galaxies are found, but for which it is difficult to determine masses in traditional ways. This work showed that it is possible to differentiate between feedback recipes that are used in models of galaxy formation, already ruling out models without AGN feedback.

The KiDS lensing analysis follows the earlier CFHTLenS project, which concluded in 2013 with significant Dutch participation led by Hoekstra and Kuijken. CFHTLenS was the most sophisticated wide-field weak lensing analysis to date, and focused on measuring the large-scale structure of matter as a cosmological probe. In addition to tests of the large-scale theory of gravity, and measurements of galaxy halo masses out to radii that are inaccessible by other techniques, CFHTLenS determined the amplitude of density fluctuations to be $\sigma 8=0.799\pm0.015$, which is in slight tension with more recent results from the cosmic background radiation using *Planck.*

Accurate masses of galaxy clusters

Hoekstra, Herbonnet (PhD), Muzzin (Leiden) and collaborators used deep CFHT imaging of a sample of fifty massive galaxy clusters to determine their masses using weak gravitational lensing. This study included significant advances in the measurement of the lensing signal and the determination of the redshift distribution of the sources. The results represent the current state-of-the-art in cluster mass measurements and are essential for the determination of cosmological parameters using the number density of galaxy clusters. The measurements were used in studies of the Planck and the South Pole Telescope teams, resulting in low values for the parameter $\sigma 8$, in tension with the *Planck* primary CMB results, but in agreement with other low redshift measurements, such as those from CFHTLenS.

Evolution and catastrophes of cosmic web

Galaxies are embedded in a Cosmic Web consisting of voids, walls, filaments and cluster nodes. Cautun (PhD), van de Weygaert and Jones (Groningen) and collaborators, have studied the hierarchical buildup of the cosmic web in large cosmological computer simulations. Using sophisticated algorithms previously developed by the group, they found that filaments are clearly the dominant feature in the cosmic mass distribution. More than 50% of the mass in the Universe finds itself in filaments, whose substantial surface density makes them also the most prominently visible feature on large scales. Moreover, while voids and walls only contain a population of low mass halos, most medium- to large-sized halos are predominantly found in these elongated features.

Structure formation from beginning to end

The LOFAR Epoch-of-Reionization (EoR) Key Science Project, led by Koopmans, Zaroubi (Groningen) and de Bruyn and Brentjens (ASTRON), collected up to one thousand hours of data on two deep windows in the years 2013-2015, accumulating several petabytes of data. The aim is to detect neutral hydrogen, via its redshifted 21-cm line, emitted during the first one billion years of the Universe and using it to study, amongst others, the structure and formation of the first stars, galaxies and black holes. This has spurred a large number of publications by the team ranging from theoretical predictions of the expected signal and its interpretation, as well as studies of the technical challenges in processing these data, and announcement of the deepest observations ever taken at a wavelength of two meters lead by team-member Yatawatta in 2013. The depth of these observations are now approaching the theoretically predicted signals and there is good hope of a detection in the coming year(s), building on the foundations laid down in the last decade.

To assess the impact of refractive and diffractive effects due to the time and spatially varying ionosphere on the faint redshifted 21-cm signal, regarded as one of the largest challenges on these experiments, Vedantham (PhD) and Koopmans (Groningen) embarked on a comprehensive theoretical study, working out its full theory as well as for the first time predicting the impact of these effects as function of the strength of the ionosphere showing that it is manageable under most observational circumstances of LOFAR. With Asad (PhD), Koopmans also studied the leakage of the

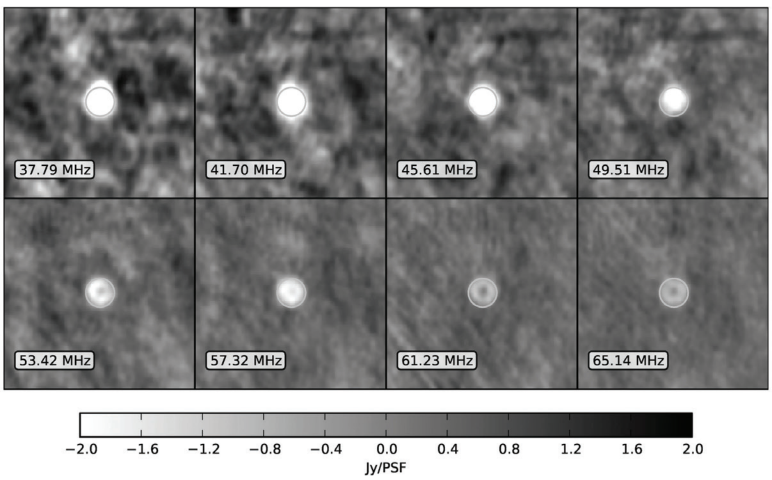

Fig. 1.2: *Synthesis images of the Moon at eight different frequencies: 0.5 deg wide grey circles are drawn centered on the expected position of the Moon. Each image is made over a bandwidth of 3.9 MHz (20 sub-bands) for 7 h of synthesis. The lunar flux increases towards zero with increasing frequency as the contrast between the Galactic background and lunar thermal emission is decreasing as expected (Vedantham, Koopmans, de Bruyn, et al. 2015, MNRAS, 450, 2291).*

strongly polarized sky to the 21-cm signal, and with Ghosh developed a new Bayesian formalism to image the sky in a maximum-likelihood manner.

Observationally, besides the main LOFAR EoR key program, Vedantham, Koopmans, de Bruyn and collaborators, made very-low frequency observations of the moon, for the first time showing lunar occultation. Whereas this is fun in its own right, and technically challenging to image a moving target, the negative lunar disc as seen against a much brighter Galactic foreground (Fig. 1.2) also allows one to measure the spectrum of the lunar surface, the Milky Way and when done carefully, potentially even measure the global 21-cm emission signal from the early Universe, i.e. the Cosmic Dawn. Follow-up observations are currently being analyzed, after this initial encouraging result.

Galaxies in the first billion years of the Universe

Smit (PhD), Bouwens, Labbé (Leiden) and others presented the strongest unambiguous evidence for prominent nebular line emission (from hot stars) in the spectra of galaxies in the first billion years of the universe. They did so by looking at galaxies in the redshift range in z~6.6-6.9, identifying systems which appeared to be very bright in the 3.6 micron channel of *Spitzer*, but which were not especially bright in the 4.5 micron channel. While such a signature could not be produced by stellar continuum light, it could be produced by line emission (i.e. [OIII]+ H; see Fig. 1.3 for an example). Quantifying the strength of the line emission is important for studies of galaxies at early times. If such line emission is strong, the apparent flux would be higher at rest-frame optical wavelengths, making galaxies at high redshift look brighter and more massive than they really are. This measurement enables astronomers to measure the mass of galaxies in early Universe much more accurately than before.

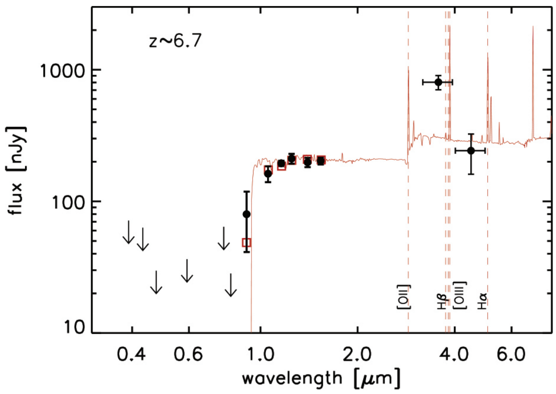

Fig. 1.3: *Example of a star-forming galaxy at high-redshift showing evidence for strong [OIII] +H emission in the 3.6 micron-band observations with the Spitzer-Space Telescope which contrasts with the much fainter flux measurement of the stellar continuum in the Spitzer 4.5 micron band. This source is just one of many sources Smit and Bouwens discovered showing evidence for strong nebular line emission in early high-redshift galaxies (Smit et al, 2014, ApJ, 784. 58).*

The luminosity function of galaxies contains information of the prevalence of galaxies as a function across cosmic time and can be used as a way of looking at the build-up rate of galaxies. Bouwens (Leiden) finished a study providing new constraints on the evolution of the luminosity function using the most comprehensive data set available to the present, leveraging some 900 arcmin2 of observations from HST over the five CANDELS fields. Significant evidence was presented for a flattening of the luminosity function towards later points in cosmic time, as well as providing evidence for there being a substantial number density of luminous galaxies as early as 700 million years after the Big Bang. Both findings were consistent with the expected evolution based on the growth of the collapsed dark matter structure ('halos') from theoretical simulations.

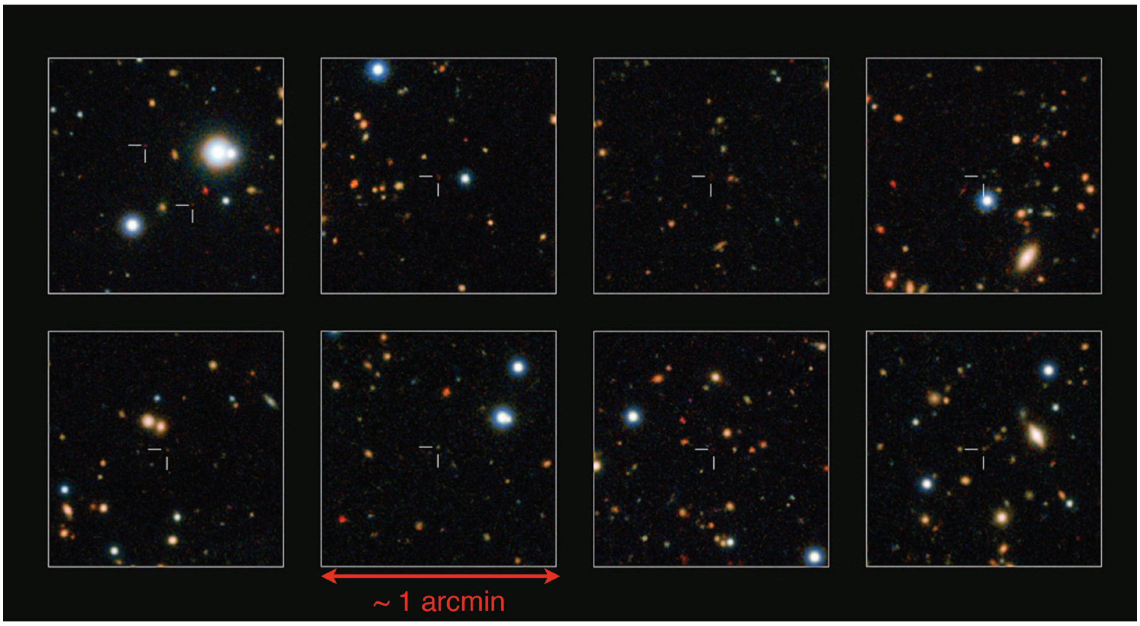

Fig. 1.4: *Some of the massive 3<z<6 galaxies newly discovered by Caputi et al. (2015, ApJ, 810, 73) in the UltraVISTA maps. All of them are faint even in the deepest UltraVISTA images. Source: ESO Science Release 1545b (November 2015).*

Pinpointing first massive galaxies in Universe

A team led Caputi (Groningen) has discovered that many galaxies as massive as the Milky Way or larger were already present in the first few billion years of cosmic time (Fig. 1.4). The discovery has been done using *Spitzer* Space Telescope images and the ESO public UltraVISTA near-infrared survey in the COSMOS field, and it has been possible thanks to the unique combination of area and depth of the UltraVISTA maps. Although UltraVISTA has enough sensitivity to detect these galaxies up to very high redshifts, remarkably, the team has found none at z=6, implying that the most massive galaxies only appear in the Universe when it was about one billion year old. Alternatively, it could be that these very massive galaxies existed earlier in cosmic time and still remain undetected because they are significantly obscured by dust. This possibility, which would challenge current galaxy formation theories, will be tested with the forthcoming JWST.

Stars were born in significantly denser regions in the early Universe

Through a combined study of the emission line properties of distant and nearby galaxies, Shirazi (PhD), Rahmati (PhD) and Brinchmann (Leiden) showed that high redshift galaxies have significantly more extreme conditions in their H II regions than in otherwise similar galaxies at low redshift. The focus of the study was the evolution in intrinsic properties of galaxies, in particular the state of the interstellar medium. To this end the [O III] 5007/[O II] 3727 line ratio was compared for a sample of both high- and low-redshift galaxies, with similar gravitational potential wells (stellar mass) and energy input into the interstellar medium (star formation rates). At low redshift they used the Sloan Digital Sky survey, while for high redshift (2.6<z<3.4) a heterogeneous sample of galaxies from various surveys was carefully put together. Low redshift galaxies have lower [O III]/[O II] ratios than similar galaxies at high redshift (Fig. 1.5). The most natural interpretation is that the distant sample has higher HII region densities.

Best observational evidence of first generation stars in the Universe

Sobral, Matthee (PhD) and Röttgering (Leiden) used the VLT, Keck and Subaru telescopes to discover by far the brightest galaxy yet found in the early Universe and the best evidence that first generation stars lurk within it (Fig. 1.6). This newly found galaxy is three times brighter than the brightest distant galaxy known up to now. X-SHOOTER and SINFONI spectroscopy of this object revealed the presence of a strong HeII emission line, which is associated with extremely hot stars such as predicted for the first generation of stars. Furthermore, no signs of heavy elements such as carbon, oxygen or nitrogen are apparent in the spectra. This indicates that the metallicity is smaller than 0.005 times the metallicity of the sun, making this the lowest metallicity galaxy known in the Universe.

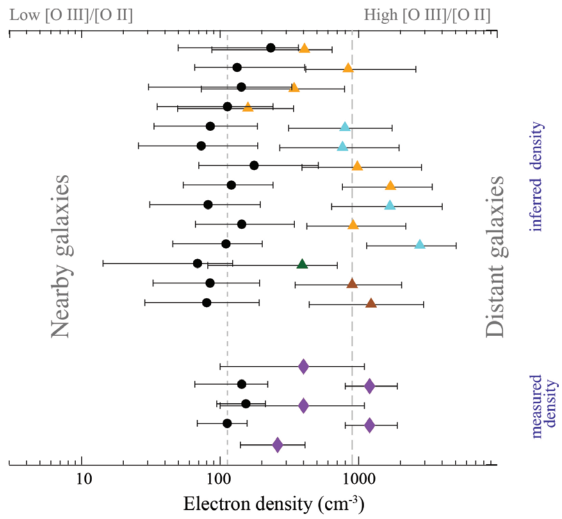

Fig. 1.5: *Low redshift galaxies (black discs) have lower [O III]/[O II] ratios than similar galaxies at high redshift (coloured symbols). Since the galaxies have similar star formation rates and metal content, the most natural interpretation of this result is that it is caused by a difference in density. For most high redshift galaxies this can only be inferred from the [O III]/[O II] ratio and this is uncertain, but for a few galaxies it was possible to measure the density directly - these are the purple diamonds at the bottom (Sharazi, Brinchmann & Rahmati 2014, ApJ, 787, 120).*

As shown in Fig. 1.6, HST observations resolved the galaxy in three distinct clumps, where two clumps appear to be somewhat older. This means that we are likely observing a third wave of the formation of the first generation of stars in a single galaxy. These massive, brilliant objects were the creators of the first heavy elements in our Universe — elements that are necessary to forge the stars seen around us today.

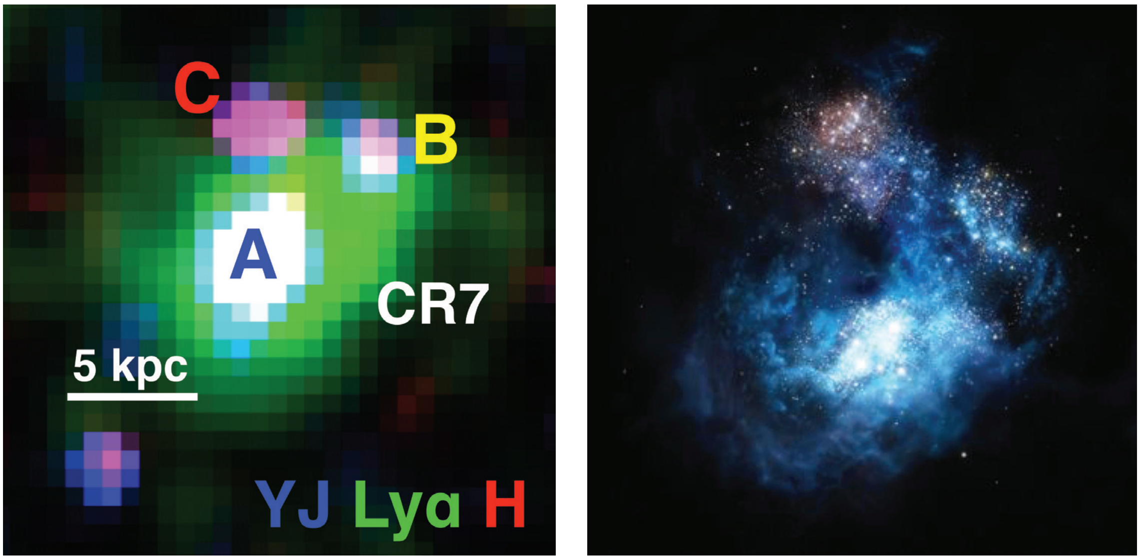

Fig. 1.6: *The image on the left shows a false colour composite of CR7 by using Subaru-NB921/Suprime-cam imaging (Lyα) and two HST/WFC3 filters: F110W (YJ) and F160W (H). This shows that while component A is the one that dominates the Lyα emission and the rest-frame UV light, the (likely) scattered Lyα emission seems to extend all the way to B and part of C, indicating a significant amount of gas in the system. The image on the right shows an artist's impression of this remarkable distant galaxy discovered using ESO's Very Large Telescope. This newly found galaxy is three times brighter than the brightest distant galaxy known up to now (Sobral, Matthee et al. 2015, ApJ, 808, 139).*

Gamma ray afterglows and reionization

The reionization of the Universe is thought to have ended around redshift z~6, as inferred from spectroscopy of distant bright background sources, such as quasars and gamma-ray burst (GRB) afterglows. Furthermore, spectroscopy of a GRB afterglow provides insight in the properties of its host galaxy, which is often too dim and distant to study otherwise. Hartoog (PhD), Kaper and collaborators obtained a high-quality spectrum of the distant Swift GRB130606A at z=5.913 with X-shooter on the ESO Very Large Telescope. Measurements of the Lyα, β , and γ wavelength regions confirm that the Universe is already predominantly ionised over the redshift range probed in this work, but was slightly more neutral at z> 5.6. Column density measurements obtained of several elements show a very high value of [Al/Fe]=2.40±0.78 that may be due to a proton-capture process (such as the CNO cycle) connected to the stellar population history. Potentially this could be a relic of the first stars.

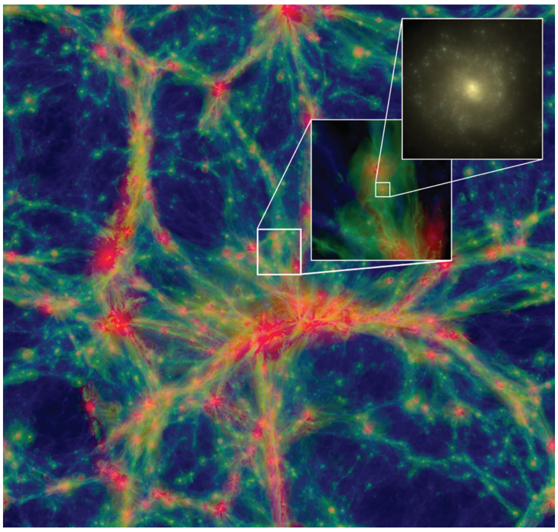

Fig. 1.7: *100 x 100 x 20 Mpc (where 1 Mpc is 3.3 million light-years) slice through the largest EAGLE simulation showing the distribution of gas at the present time. The intensity shows the gas density while the colour encodes the gas temperature. The insets show regions of 10 Mpc and 60 kpc on a side and zoom into an individual galaxy with a stellar mass of 3 x 10^{10} $M_{\odot}$. The 60 kpc image shows the stellar light and accounts for dust extinction (Schaye et al. 2015, MNRAS, 446, 521).*

The physics of galaxy formation

State of the art simulations of the history of galaxies in the Universe

An international team of astronomers led by Schaye (Leiden) developed a simulation of the history of the Universe in which galaxies are created with masses, sizes and ages that are similar to those of observed galaxies. For years, astronomers have studied the formation of galaxies using computer simulations, but with limited success: galaxies in previous simulations were typically too massive, too small, and too old.

The galaxies formed in the EAGLE-simulation (Evolution and Assembly of GaLaxies and their Environments) are a much closer reflection of real galaxies (Fig. 1.7) thanks to the strong galactic winds, which blow away the gas supply needed for the formation of stars. EAGLE's galaxies are lighter and younger because fewer stars form and they form later. In the EAGLE simulation these galactic winds - which are powered by stars, supernova explosions and supermassive black holes - are stronger than in earlier simulations.

MUSE opens its 24 eyes

The panoramic integral field spectrograph MUSE saw first light on the VLT in January 2014 with light coming from Kapteyn's star, emitted when MUSE was first conceived. MUSE provides spectra in 0.2''x0.2"regions across a field of view of 1'x1' and has had significant participation from NOVA (NL PI Schaye). The 90,000 spectra obtained in a single exposure offer great scientific potential in panoramic observations of nearby star-forming regions, stellar systems and nearby galaxies. Arguably the most dramatic step forward with MUSE is its ability to carry out deep spectroscopy of every pixel-sample of the sky.

The potential of this pixel spectroscopy was demonstrated with an ultra-deep 27 hr MUSE observation of the Hubble Deep Field South during commissioning (Fig. 1.8). The analysis of this data set, co-led by Brinchmann (Leiden), increased the number of known redshifts in the field by an order of magnitude. This reveiled a plethora of star forming galaxies across cosmic time - from an ultra-faint dwarf at z~0.1 with stellar mass less than 10^6 $M_\odot$ to 26 distant Ly-alpha emitting galaxies that are not visible in the ultra-deep HST images.

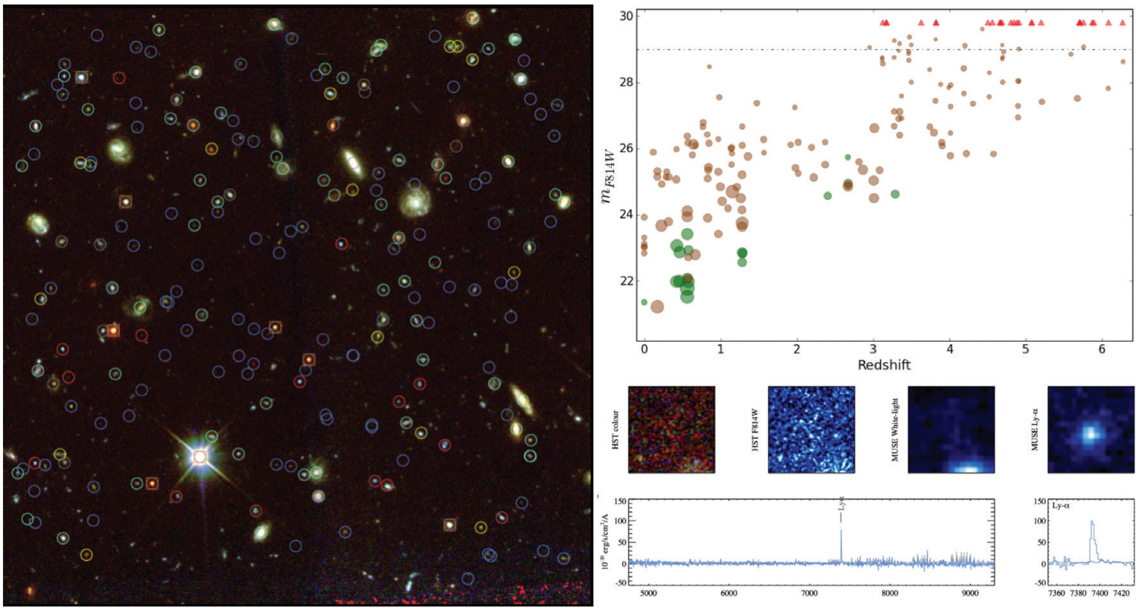

Fig. 1.8: Left: The location of objects with redshifts determined with the MUSE observations of the Hubble Deep Field South overlaid on the HST colour image of the field (1x1 arcminute). The redshift distribution is shown in the top right panel with redshifts known before MUSE in green, and objects seen with MUSE that are invisible in the ultra-deep HST image, indicated with the red triangles. An example of this latter class of objects is shown in the bottom figure where the HST images in two filters, the MUSE white-light image and the MUSE narrow-band image over the Ly-α line, seen in the spectrum at the bottom, is shown in the last postage stamp (based on Bacon, Brinchmann et al. 2015, A&A, 575, 75)

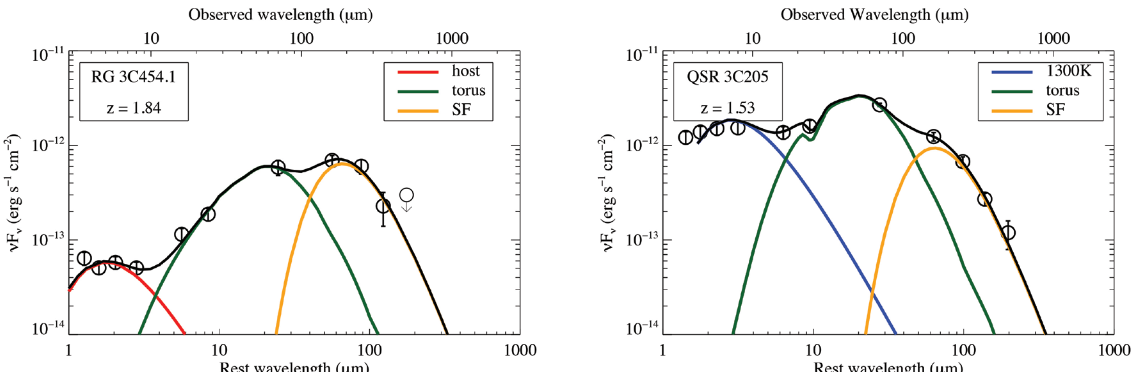

Fig. 1.9: Characteristic infrared spectral energy distributions (SEDs) of hosts of radio galaxies (RGs) on the left and radio-loud quasars (QSRs) on the right. The multi-components model used to fit the observed SEDs includes emission from an AGN-heated torus (green), star-formation heated cold dust (yellow) and hot graphite dust (blue) or old stars (red) for QSRs and RGs respectively. The star formation rates inferred from the SED decomposition are of order several hundred solar masses per year (Podigachoski et al. 2015, A&A, 575, A80).

AGN and starbursts

Using *Herschel* Space Observatory data, Barthel, Podigachoski (PhD) (Groningen) and colleagues studied the infrared properties of the host galaxies of powerful radio-loud AGN in the early Universe. Despite the very strong AGN activity, prodigious star formation is detected in a large fraction of these hosts, firmly rejecting suggestions that black hole growth inhibits the formation of new stars. When *Spitzer* observations are added, the infrared properties of radio galaxies and quasars support the unification model which explains the observational differences in these two classes of objects in terms of viewing angle. Follow-up ALMA Cycle 3 observations will zoom in on the star formation activity, and establish the possible connection with the radio-jets associated with the AGN activity.

The molecular circumnuclear disk in Centaurus A and its outflow of gas

Israel (Leiden) analyzed a very extensive set of CO and [CI] spectral line measurements of the compact circumnuclear disk in the center of Cen A with *Herschel* and the ground-based SEST, JCMT, and APEX (sub) millimeter telescopes. Together with Meijerink, Loenen, van der Werf (Leiden) and colleagues, they discovered that the ^{12}CO line intensities ladder is quite different from those found in starburst galaxies and galaxies with an AGN. Another remarkable difference is that relative to CO, [C I] is much stronger than in any other galaxy. The CO-H_2 conversion factor is twice the local Milky Way value. The overall physical state of dense gas in the central 500 pc of the circumnuclear disk was further investigated by using other far-infrared lines. The disk itself is traced primarily by emission from dust, CO and [C I]. On the other hand, the outflow is particularly well-traced by ionized nitrogen (Fig. 1.10) but it is also seen by ionized carbon and oxygen that peak towards the nucleus. More than a quarter of the gas in the outflow is fully ionized; everywhere else the ionized gas fraction is about 10%. The outflow is remarkably massive, roughly 25% of that of the disk mass. Most likely it originates from a small shock-dominated cavity in the disk surrounding the central black hole. The mass outflow rate is about 2 $M_\odot$ per year, which is a thousand times higher than the present accretion rate of the black hole. At this rate, the entire disk will be depleted in only 15-120 million years. However, the actual outflow velocities are almost certainly too low to allow the gas to escape from Cen A altogether.

Mechanical heating of molecular gas in galaxies

Rosenberg (PhD), Meijerink, Israel, Van der Werf (Leiden) and colleagues studied the very luminous colliding galaxy group Arp 299 in which one component harbors an AGN and two more are experiencing intense star formation using *Herschel* and JCMT. Photon-dominated regions (PDRs) are unlikely to heat all the gas, but mechanical heating in combination with UV heating fits all molecular transitions observed. Complementary to this work, Kazandjian (PhD),

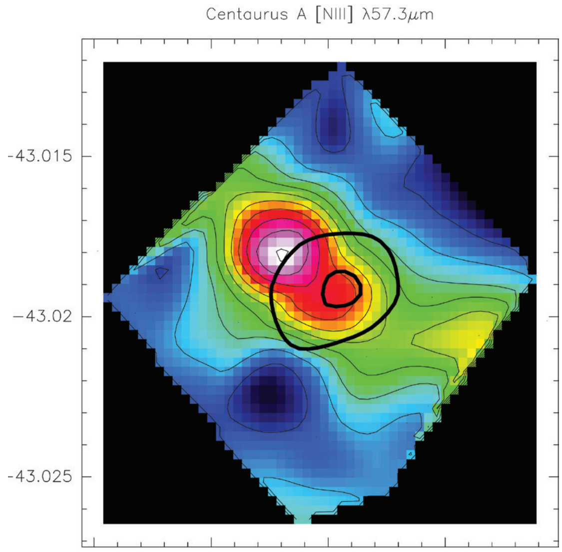

***Fig. 1.10:** The outflow of interstellar gas from the center of the nearby radio galaxy Centaurus A is prominent in the light of doubly ionized nitrogen, obtained with the PACS instrument onboard the Herschel Space Observatory. The black contours mark the continuum emission from the dusty circumnuclear disk at the same wavelength as the [NIII] line. The extent of the image is 0.81x0.86 arcminutes corresponding to a projected size of 900x955 pc (Israel, Güsten, Meijerink, et al. 2014, A&A, 562, A96).*

Meijerink, Israel, Pelupessy (Leiden) and Spaans (Groningen) developed models exploring the effect of dissipated turbulence on the thermal and chemical properties of PDRs in the interstellar medium. They concluded that mechanical heating is a key factor in determining the kinetic temperature of the gas in molecular clouds, even when its contribution is as small as 1% of the UV heating in a PDR. Neglect of mechanical heating in analyses of molecular lines can lead to potentially large errors in inferred densities, gas masses and temperatures and UV fluxes.

It takes jet power to clean a galaxy!

Observations from Very Long Baseline Interferometry (VLBI) and ALMA led by Morganti and Oosterloo (ASTRON, Groningen) have provided the best evidence so far that radio plasma jets ejected by the supermassive black hole in the center of a galaxy clears cold gas from the galaxy at velocities of more than 1000 km/s. The fact that many galaxies in the Universe seem to be depleted of cold gas and, as a consequence, are not able to form new stars any more, has been puzzling for some time. In particular, cold gas represents the fundamental building block of new stars and if this gas is expelled, star formation stops. The new results show the key role of radio plasma jets in this process (Fig. 1.11). A remarkable finding is that, despite the enormous energies involved, the larger part of the gas flowing out of the galaxy is in cold form as it consists of both HI and molecular gas.

VLTI-MIDI reveals polar nuclear dust structures in Seyfert galaxies

Mid-Infrared observations of the nuclei of two nearby Seyfert galaxies with unprecedented resolution by Jaffe (Leiden) and collaborators show dust structures in the "wrong" place", at least according to the standard model of these AGN. The observations were taken with VLTI-MIDI, co-built by NOVA. MIDI combines light from two VLTI telescopes and achieves an angular resolution of better than 10 milliarcsec. This reveals structures of less than a light-year at the nearest AGNs, and is three times smaller than the ELT can achieve at the same wavelengths. The observations of NGC-1068 and the Circinus galaxy show that the bulk of the emission from warm dust near the nuclei arises along the AGN axis, rather than in a torus in the equatorial plane of the central black hole (Fig. 1.12). The existence of such an equatorial torus is central to the canonical models of AGNs, because it is essential to explain the difference between type I AGNS (bright visible nucleus; viewed perpendicular to the torus) and type II AGNs (view of nucleus blocked by torus). These results indicate that the model of torus formation from dust accreting toward the black hole is far too simple. Revision of this model has implications both for the feeding mechanism of the black hole and for the transfer of mechanical energy out of the disk region to the host galaxy. The results will be followed up by a program of AGN observations with the MIDI successor, MATISSE, being built by NOVA together with MPIA, MPIfRA (Bonn) and the Observatoire de Cote de Azur Nice).

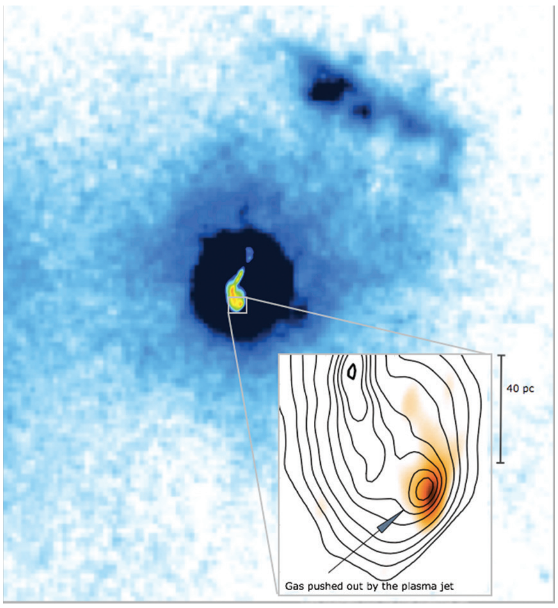

Fig. 1.11: *Optical image (blue) of the galaxy 4C12.50. The inset shows a zoom in of the plasma jet and the cold gas (orange). The gas is distributed in a compact cloud (dark orange) and filaments (light orange) as a result of the strong impact with the plasma jet. (Optical: HST/STSci/Tadhunter et al.; radio: VLBI, Morganti et al. 2013, Science, 341, 1082)*

Archaeology of radio galaxies

Observations with LOFAR have expanded our view of the life cycle of one of the most spectacular type of AGN: radio galaxies. Brienza (PhD Groningen), Morganti and collaborators have serendipitously discovered a rare case of a relic radio galaxy (Fig. 1.13). By studying the radio emission of the source at different frequencies, it is found that the radio jets have switched off a long time ago and that this "fossil" phase lasts much longer than the active one. The reason is likely connected with the energetics of the plasma, which is also a key parameter for understanding the impact of radio galaxies on the surrounding medium. The emission from low frequency electrons captured by LOFAR can last long after the nuclear activity has stopped, providing a powerful tool for revealing the existence of such extreme (and rare) objects. The hunt for more of these fossils will now continue using the on-. going LOFAR surveys.

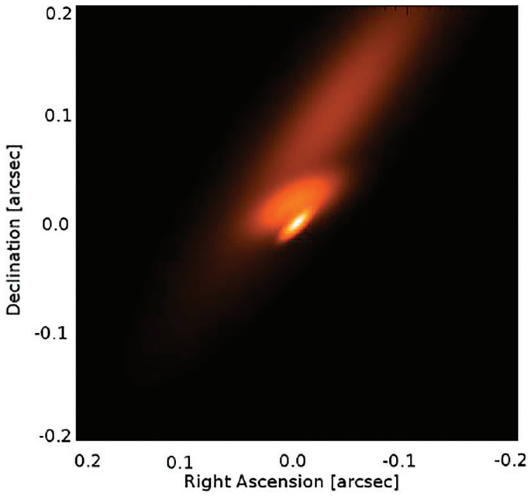

Fig. 1.12: *Reconstruction of the AGN dust emission at 10 micron wavelength from NGC-1068. The radio jet axis is straight up. 0.1 arcsecond on this image corresponds to 7 parsec (Lopez-Gonzaga, Jaffe, et al. 2014, A&A, 565, 71 and Tristram, Burtscher, Jaffe, et al. 2014, A&A, 563, 82).*

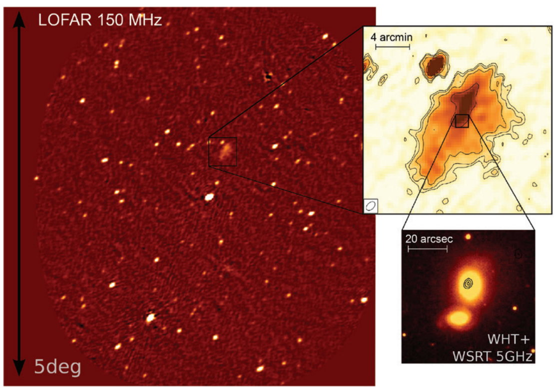

Fig. 1.13: *The LOFAR image at 150 MHz covering an area of 5 sq degrees with the "BLOB1" clearly seen. On the top right, zoom-in on the radiogalaxy at 150 MHz. On the bottom right, zoom-in on the host galaxy detected with WHT (Brienza et al. 2016, A&A, 585, 29)*

Galaxies in different environments

The Void Galaxy Survey led by Beygu (PhD), van de Weygaert, van der Hulst, Peletier (all Groningen) and collaborators focuses on the study of galaxies in voids selected using robust geometrical methods (Fig. 1.14 for an example). The structure of some 60 objects using deep B band and *Spitzer* IR data, and their star formation properties and stellar masses have been addressed using Hα, UV and IR data (Fig. 1.14). In general the Void Galaxies are small disk galaxies, with stellar masses of less than ~3 10^{10} $M_{\odot}$, and relatively normal gas contents and star formation rates for their mass and size. There is a tendency for the smaller Void Galaxies to have slightly elevated star formation rates and efficiencies compared to galaxies of similar stellar mass in denser environments. In terms of structure most of the Void Galaxies are small late type disks, but their size and compactness appears more similar to those of dwarf elliptical galaxies.

Peletier (Groningen) and collaborators have been investigating the angular momentum in dwarf galaxies in the Virgo Cluster. In a series of papers led by Toloba they show that, just like for giant ellipticals, there are fast and slow rotators. This is surprising, since dwarf ellipticals look like puffed-up disks with exponential surface brightness profiles, which are expected to be rotationally supported. The fast rotators in the outer parts of the Virgo Cluster rotate significantly faster than fast rotators in the inner parts of the cluster. Moreover, 10 out of the 11 slow rotators are located in the inner 3° (D < 1 Mpc) of the cluster, and in addition, two of them have kinematically decoupled cores. These properties suggest that Virgo Cluster dwarf ellipticals may have originated from late-type star-forming galaxies that were transformed by the environment after their infall into the cluster. The correlation between angular momentum and the cluster-centric distance can be explained by a scenario where low luminosity star-forming galaxies fall into the cluster, their gas is rapidly removed by ram-pressure stripping, although some of can be retained in their core, their star formation is quenched but their stellar kinematics are preserved. After a long time in the cluster and several passes through its center, several galaxies are heated up and transformed into slow rotating ellipticals. Follow up work focuses now on the Fornax cluster using the VST and OmegaCam camera funded by NOVA.

Fig. 1.14: *HI properties of Void Galaxies demonstrate that galaxies in voids also often have companions and show clear signs of interactions. An extremely interesting system is that of VGS 31 (a/b/c): three galaxies that appear to be embedded in an HI filament suggesting ongoing interaction and accretion, perhaps demonstrating how galaxies form from a tenuous large scale filament inside a void. This figure shows the HI superposed on an SDSS composite optical picture (Beygu et al. 2013, AJ, 145, 120).*

Stellar populations and gas in massive galaxies

Combining lensing, dynamical and stellar population observations, using in particular VLT X-shooter data, Spiniello (PhD), Koopmans, Trager (Groningen) and collaborators for the first time managed to infer both the slope and lower-mass cutoff of the IMF in massive elliptical galaxies, showing it to be consistent with Salpeter and a cut-off slightly above the hydrogen burning limit, as well as hinting at an anti-correlation between stellar density and IMF slope.

Understanding the formation of massive galaxies requires an understanding of how gas forms stars over the history of the Universe. Popping, Trager, Spaans (Groningen) and collaborators modified powerful galaxy formation models to follow separately hydrogen gas into its atomic and molecular states. These new models predict for the first time the evolution of both atomic and molecular hydrogen (Fig. 1.15) and what telescopes like Westerbork with its APERTIF upgrade, SKA and ALMA (including the NOVA-built Band 9 receivers) can or will see. As an example, these models correctly predict the luminosity of the CO and [C I] lines in distant galaxies.

ATLAS^{3D} survey of early-type galaxies completed

The international ATLAS3D team, which has participation from de Zeeuw (Leiden) and Morganti and Oosterloo (ASTRON, Groningen) completed their comprehensive study of a volume-limited sample of 260 nearby early-type galaxies with the SAURON integral-field spectrograph on the 4.2m WHT, supplemented by very deep optical imaging and auxiliary data at other wavelengths, as well as theoretical modeling and numerical simulations. Over the reporting period 16 refereed team papers were published covering the physical properties of the neutral and molecular cold gas, the nature and physical state of the ionized gas, the low efficiency of star formation, the internal distribution of angular momentum and the relation with the nuclear surface brightness profile, the nuclear radio emission, the intrinsic shape distribution, the presence of stellar discs, the scaling relations relating mass, size and stellar velocity dispersion, the properties of the internal stellar populations, the constraints provided on numerical simulations of formation via galaxy mergers, and the derivation of star formation histories for each of the galaxies.

McDermid (Sydney) and collaborators investigated the distribution of stellar population parameters and showed that at fixed mass, compact early-type galaxies

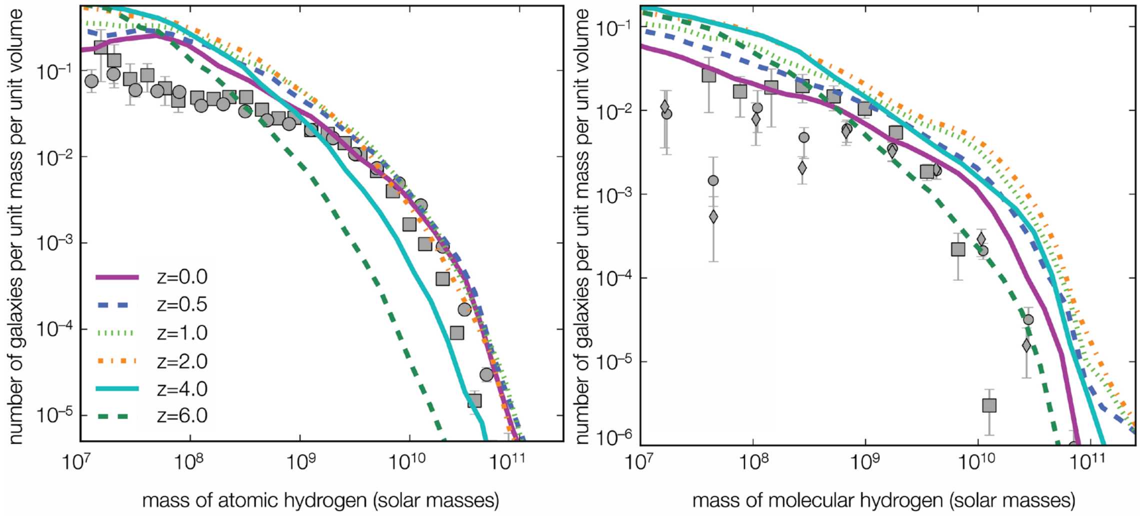

Fig. 1.15: *The evolution of the number of galaxies with a given mass of atomic (left) and molecular (right) hydrogen gas as a function of cosmic time. Grey points are observations of the atomic and molecular gas masses of galaxies in the local Universe (z=0). The curves are predictions of the galaxy evolution models presented in Popping, Somerville & Trager (2014, MNRAS, 442, 2398). The models suggest that the molecular gas mass function, from which stars form, decreases only slightly with the evolution of the Universe since a time when it was only 10% of its current age (z=4), while the atomic hydrogen mass function does not change at all since the Universe was one-quarter of its current age (z=2).*

are on average older, more metal-rich, and more alpha-enhanced than their larger counterparts. The duration of star formation is systematically more extended in lower mass objects. Assuming that the sample represents most of the stellar content of today's local Universe, approximately 50% of all stars formed within the first 2 Gyr following the Big Bang. Most of these stars reside today in the most massive galaxies ($>10^{10.5}$ $M_{\odot}$), which themselves formed 90% of their stars by z~2 (Fig. 1.16) . The lower mass objects, in contrast, have formed barely half their stars in this time interval. Stellar population properties are independent of environment over two orders of magnitude in local density, varying only with galaxy mass. In the highest density regions of the volume studied (which is dominated by the Virgo cluster), galaxies are older, alpha-enhanced, and have shorter star formation histories with respect to lower density regions.

The local Universe

Galaxies with stellar explosions at their heart

Rossi (Leiden) and collaborators have investigated possible observational consequences of the presence black holes at the centers of galaxies to obtain a more complete picture of galaxy-supermassive black hole co-evolution, so fundamental to understand galaxy formation. Black holes gravitationally interact with stars and gas in their vicinity, and Rimoldi (PhD) and Rossi proposed that explosions of young stars (i.e. supernova explosions) in the vicinity of supermassive black holes can be used to map their environment, which may be otherwise difficult to observe directly because of stellar crowding and dust obscuration (Fig. 1.17). Contrary to what had been previously assumed, they showed that the combined light from supernova explosions may be the brightest X-ray source in those regions when black holes are quiescent. Detecting and modelling this X-ray emission can allow to indirectly infer the star formation rate and gas content of galactic nuclei and therefore to understand their evolution.

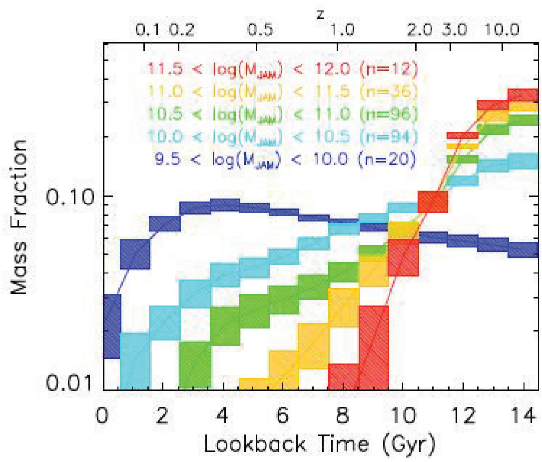

Fig. 1.16: *The average star formation history of the corresponding bin in dynamical mass, M_{JAM}. The star formation history is quantified as the relative fraction of stellar mass formed at each epoch, derived from the regularized weighted combination of stellar population models fitted to the aperture spectrum. Hatched regions indicate the standard error on the mean at each look-back time. The upper horizontal scale indicates corresponding redshift (McDermid et al. 2015, MNRAS, 448, 3484).*

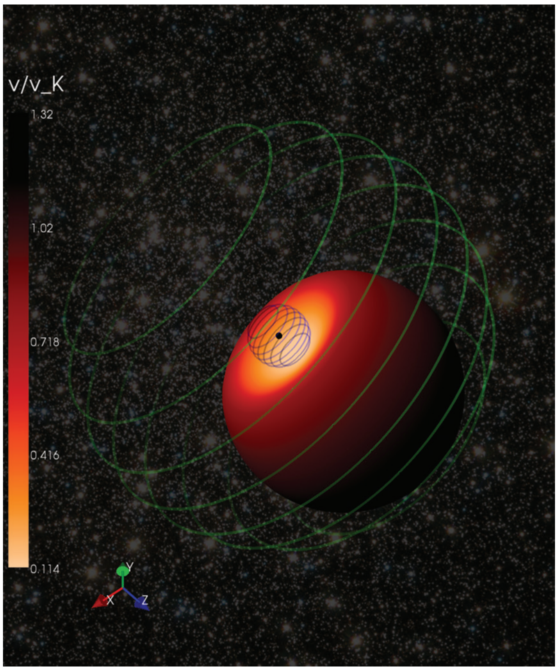

***Fig. 1.17:** Three-dimensional visualization of a simulation of a supernova explosion in the environment of a supermassive black hole (central black dot), performed with the code developed by Rimoldi et al. (2015, MNRAS, 456, 2537; MNRAS, 447, 3096). While expanding, the supernova is decelerated more towards the compact object, where densities are higher. There, it will eventually be sheared apart, shortening prematurely the supernova's duration. The green spherical region is the size of the black hole sphere of influence (where its gravity dominates over stars). The inner blue region around the black hole is where the density in gas and star is the highest. The colour bar indicates the velocity of the remnant with respect to the Keplerian velocity due to the gravitational field of the black hole.*

Spectral atlases of stars and galaxies

Brandl (Leiden) and co-workers have compiled an atlas of 129 spectral energy distributions for nearby galaxies, with wavelength coverage spanning from the ultraviolet to the mid-infrared. This comprehensive atlas spans a broad range of galaxy types, including ellipticals, spirals, merging galaxies, blue compact dwarfs, and luminous infrared galaxies – highlighting the wide diversity of galaxy SEDs. It is based on accurate spectro-photometry from numerous ground- and space-based facilities and includes 26 photometric bands. Apart from its wide wavelength coverage it provides improved K-corrections, photometric redshifts, and star-formation rate calibrations with smaller systematic errors than existing atlases. The atlas offers an invaluable resource for modeling galaxy SEDs at high redshift (Fig. 1.18).

The X-shooter Spectral Library (XSL) is the largest near-ultraviolet--optical--near-infrared library of medium resolution spectra of stars in the Milky Way and Magellanic Clouds, obtained with VLT X-shooter and led by Trager and Peletier (Groningen). It had its first public data release by Chen (PhD, also Groningen) in 2014. XSL provides a ground-breaking multiwavelength catalogue of stellar spectra over the wide spectral range enabled by X-shooter, providing basic data for a wide variety of projects ranging from calibrating the temperatures of red supergiants, extremely bright stars that can help measure the chemical composition of distant galaxies, to forming the basis of new stellar population models.

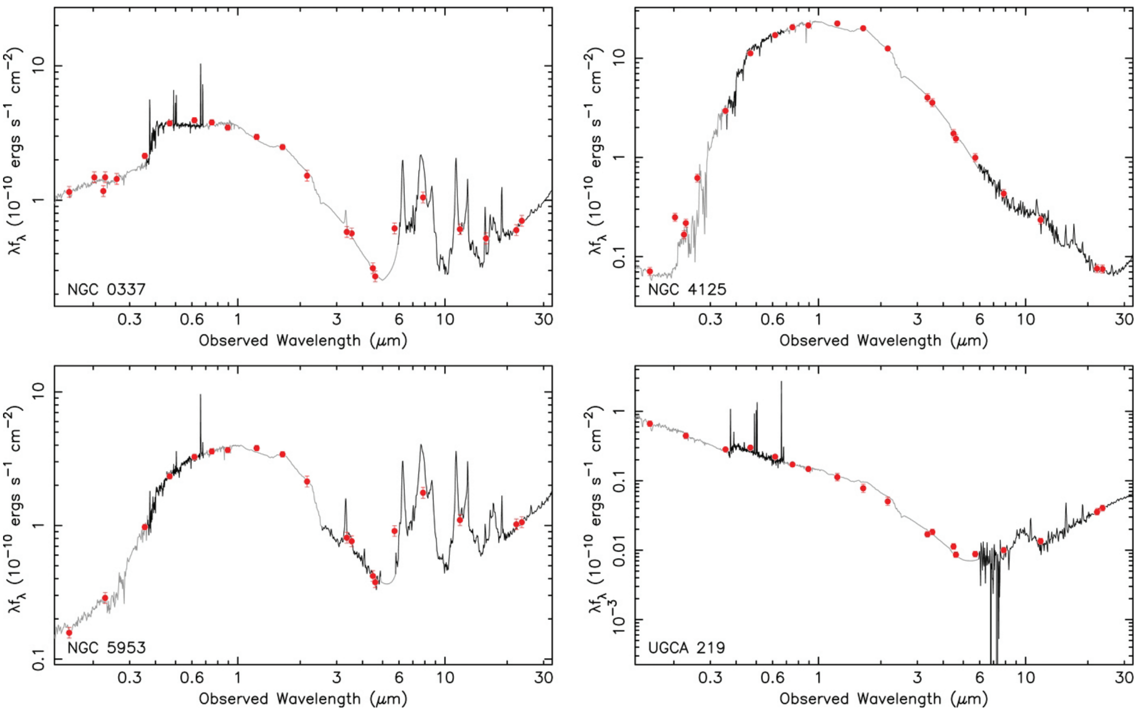

***Fig. 1.18:** Spectra of NGC 337, NGC 4125, NGC 5953, and UGCA 219 to illustrate the rich set of 129 galaxy SEDs. Observed spectra are shown in black, MAGPHYS models are shown in gray, and photometry points used to constrain and verify the spectra are shown with red dots (Brown et al. 2014, ApJS, 212, 18).*

LOFAR discovery of largest Carbon atoms outside our Milky Way

Morabito (PhD), Oonk, Salgado (PhD), Röttgering, Tielens (all Leiden) and collaborators used LOFAR to discover extragalactic low frequency Carbon radio recombination lines (CRRLs) in M82 (Fig. 1.19). This is the first extragalactic detection of RRLs from a species other than hydrogen, and below 1 GHz. These low frequency CRRLs (< 500 MHz) come from Carbon atoms that are present in the heart of the starburst galaxy M82, and trace the cold, diffuse atomic phase of the interstellar medium, which is otherwise difficult to observe. The CRRLs were detected in absorption in the frequency range of 48-64 MHz, corresponding to quantum levels of n=468-508. Recombination to such high quantum levels means that the Carbon atoms are about 2.1 micron (!) in size.

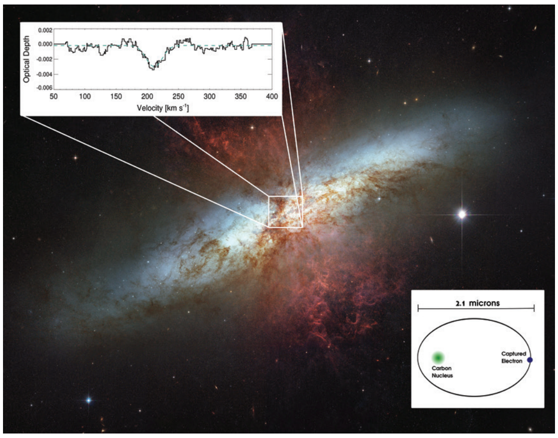

Fig. 1.19: *This mosaic image of nearby galaxy M82 shows the blue disk and filaments of hydrogen being expelled from the central region. The LOFAR detection of Carbon recombination lines is in the upper left with a cut-out showing the region where absorption is thought to originate (Morabito et al. 2014, ApJ, 795, 33). The 8.5-sigma detection was achieved by stacking the 22 individual CRRL transitions in this frequency range to provide an average line profile. A sketch of a Carbon atom with the captured electron responsible for the recombination lines is presented in the lower right corner, with the approximate size of the Carbon atom marked (Background image: Gallagher et al.).*

The origin of multiple populations in globular clusters: clues from dwarf galaxies

Globular clusters in dwarf galaxies tend to be significantly more metal-poor than their counterparts in larger galaxies, such as the Milky Way. Moreover, they also tend to be more metal-poor than the majority of field stars in their own parent galaxies. In some dwarf galaxies, as many as 20-25% of the metal-poor stars (i.e. those with a metallicity less than 1% of the Solar value) belong to the GCs as shown by Larsen and collaborators (Nijmegen). This result puts strong constraints on some popular scenarios for the origin of chemically anomalous "second-generation" stars in GCs, which require the clusters to have lost 90% or more of their initial masses. This scenario assumes that the GCs in dwarf galaxies share the same chemical abundance anomalies as those in the Milky Way. Using HST photometry, Larsen and collaborators established that this is indeed the case, and showed that stars within GCs in the Fornax dwarf display about the same spread in nitrogen abundance as those in the metal-poor galactic GC, M15 (Fig. 1.20).

Searching for C-rich stars in nearby dwarf spheroidal galaxies

Tolstoy (Groningen) and collaborators studied ancient stellar populations in nearby galaxies in great detail star by star to determine the processes that dominated their chemical evolution at the earliest times. Such studies have shown that the stellar populations in the Milky Way halo and dwarf galaxies can have markedly different abundance patterns. The Sculptor dwarf spheroidal (dSph) is one of the few systems where it is possible to obtain a full picture of the early star formation and chemical enrichment from observations of individual stars, because this galaxy has a simple ancient star formation history. It also has a sufficiently large stellar population to be able to sample the global enrichment processes due to star formation and evolution throughout its history. E. Starkenburg, Tolstoy (Groningen) and collaborators presented detailed abundances for seven red giant branch stars in the extremely low-metallicity tail of the Sculptor galaxy using VLT-X-shooter (Dutch GTO time) spectra. Five of the stars observed were confirmed to be extremely metal-poor (i.e., [Fe/H] < −3 dex), and all have [Fe/H] ≤ −2.5 dex. These values agree with predictions made based on the Ca II triplet lines, by E. Starkenburg in an earlier work. The [α/Fe] ratios measured for these 7 stars show a range from +0.5 to –0.5, which is a larger variation than in Galactic samples. There are no deviations from the Galactic abundance trends in chromium and the heavy elements barium and

Fig. 1.20: *HST image of four globular clusters in the dwarf galaxy Fornax studied by Larsen and collaborators (Larsen et al. 2014, A&A, 565, A98; 2014, ApJ, 797, 15; images credit NASA/ESA)*

strontium. A surprising result of this study, given the number of C-rich stars found in this metallicity range in the Galactic halo and in ultra-faint dwarf galaxies, is that none of these seven stars was found to be carbon-rich. This could indicate a lower fraction of carbon-rich extremely metal-poor stars in Sculptor compared to the Milky Way halo and also ultra-faint dwarf galaxies.

In a VLT-FLAMES survey to measure [S/Fe] in a sample of 90 randomly selected red giant branch stars in the Sculptor dSph, a star that just falls into the category of C-rich (and metal poor, with [Fe/H]~-2) was found serendipitously by Skúladóttir (PhD), Salvadori and Tolstoy (Groningen), using CN lines. Thanks to DDT time with VLT-UVES a very detailed analysis could be made of the abundance properties of this particular star. Once a correction is made for mixing, [C/Fe]=+0.8 and [N/Fe]=+1.18. Apart from enhanced C and N abundances, this star shows no peculiarities in other elements lighter than Zn, and no enhancement of the heavier neutron-capture elements (Ba, La, Ce, Nd, Sm, Eu, Dy), making this a Carbon Enhanced Metal-Poor-no star, in the terminology used for the Galactic halo (Fig. 1.21). However, this star does show signs of the weak r-process, with an overabundance of the lighter neutron-capture elements (Sr, Y, Zr). These abundance patterns were compared to predictions from a range of first star models, and no single model can explain these patterns.

A theoretical investigation into the possible origins of the carbon-enhanced metal poor stars in Local Group dwarf galaxies by Salvadori, Skúladóttir and Tolstoy showed that the range of global properties of these dwarf galaxies as well as the variation of the observed frequency of these stars can be understood. The probability to observe a carbon-enhanced metal poor star within a given [Fe/H] range is predicted to strongly depend on the luminosity of the dwarf galaxy, which is an order of magnitude lower in `classical' Sculptor-like dwarf spheroidal galaxies than in the least luminous ultra-faint dwarfs. Thus this provides a possible explanation why carbon enhanced metal poor-no stars may be easier to find at [Fe/H] ≈ -2 in the Sculptor dwarf spheroidal galaxy.

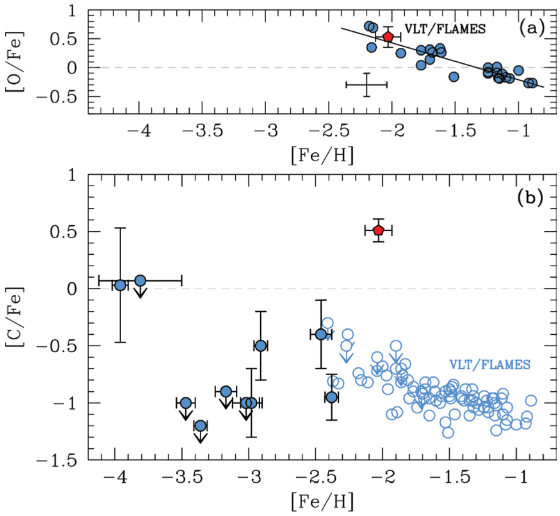

__Fig. 1.21:__ Top: Oxygen in Sculptor as a function of [Fe/H]. Representative error bar for the measurements is shown; Bottom: Carbon in Sculptor as a function of [Fe/H]. Solid points are direct carbon measurements of the stars from previous studies. Open circles show estimates of C abundances for 85 stars (VLT/FLAMES spectra) from CN molecular lines in the wavelength range 9100–9250 Å. The red filled circle is the C-enhanced star (Skúladóttir et al. 2015, A&A, 574, A129).

Measuring dark matter distribution in nearby dwarf spheroidal galaxies

Dwarf spheroidal galaxies satellites of the Milky Way are the most dark matter dominated systems in the Universe. These makes them ideally suited to test detailed predictions of cosmological models regarding the distribution of dark matter around galaxies. Using the powerful Schwarzschild technique, Breddels (PhD) and Helmi (Groningen) and collaborators, have modeled the kinematics of hundreds of stars in four nearby dwarf galaxies. Breddels and collaborators

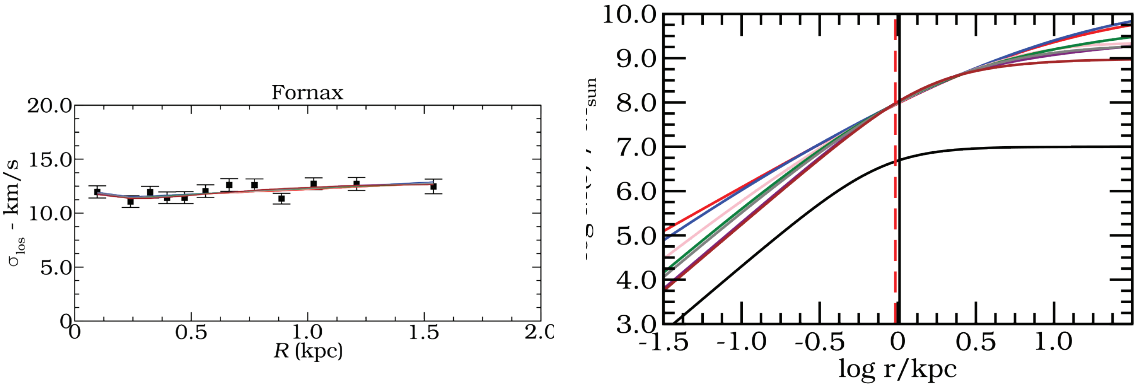

__Fig. 1.22:__ The left panel shows the line-of-sight velocitiy dispersions of stars in the Fornax dwarf spheroidal, a satellite of the Milky Way, which have been used by Breddels and Helmi (2013, A&A, 558, A35) to infer the distribution of mass of the system in the right panel. Notably all models that fit the data well (curves with different colours) are indistinguishable as they have the same mass distribution over a range in distances of roughly 1 kpc in extent as shown in the right panel (where the lower curve corresponds to the distribution of luminous mass). This result thus allows to infer the slope of the dark matter density profile at the half-light radius of the system.

found that it is not possible with current data to distinguish the traditionally cosmologically motivated cusped profiles from cored ones. On the other hand, they were able to measure for the first time in a robust manner the mass distribution of these dwarf galaxies across a relatively large region. This places strong constraints on the slope of the dark matter density profile at a radius close to that containing half of the light for each of the systems (Fig. 1.22). These new constraints have been used to show that dark matter halos from cosmological simulations could well host the dwarf galaxies that we see, given their stellar populations.

The impact of dark satellites on dwarf galaxies

The concordance cosmological model predicts that below a certain mass scale, most dark matter halos remain dark, i.e. they do not contain any gas or stars. It is therefore imperative to establish whether this is plausible and to find ways to detect their presence. As shown by T. Starkenburg (PhD) and Helmi (Groningen) and collaborators using numerical hydrodynamical simulations, small dark halos merging with dwarf galaxies have a significant impact on the morphological and structural properties of the dwarfs. They may induce significant starbursts and in this way effectively reveal the presence as dark culprits (Fig. 1.23).

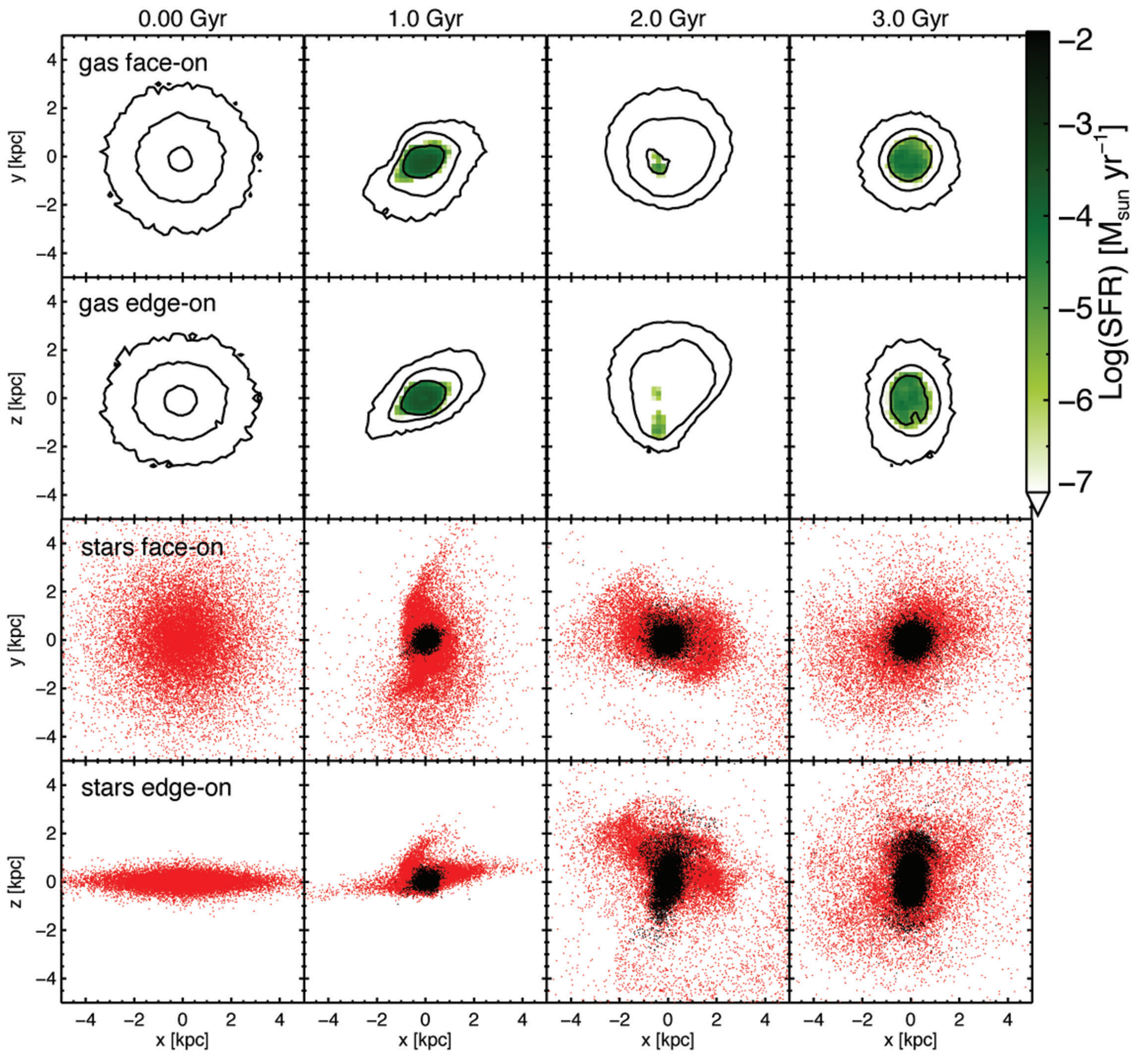

Fig. 1.23: *Example of the evolution of a dwarf galaxy merging with a dark satellite from a suite of simulations by T. Starkenburg and collaborators. The dwarf's morphology, structure and kinematics are visibly distorted and this is caused by the interaction with a dark object, with 20% of the mass of the dwarf, but which does not emit any electromagnetic radiation. Hence its presence is only felt dynamically. Such interactions and mergers may be a mechanism to explain the large variety in the population of dwarf galaxies (Starkenburg & Helmi, 2015, A&A, 575, A59, Starkenburg, Sales and Helmi, 2016, A&A, 587, A24).*

3.2. Formation and evolution of stars and planetary systems

NOVA network 2 studies the formation and evolution of stars and planetary systems. In 2013-2015, new pioneering observatories and instruments became available, especially the ALMA observatory and SPHERE on the VLT. These new instruments are allowing first views into forming planetary systems around young stars at resolutions of 10 AU and better. Also data from the *Herschel* Space Observatory continue to produce exciting results on water and on feedback processes in the interstellar medium. Other VLT instrumentation including X-Shooter and CRIRES deliver crucial data for the study of extrasolar planets, jets and winds from protoplanetary disk systems, and massive stars in the Galaxy and in the Magellanic clouds. On the experimental side, the Sackler Laboratory for Astrophysics continues to play an important role underpinning our understanding of the physical and chemical processes that occur during star and planet formation. Theoretical studies of physical processes and extensive modeling of observed data are the backbone for understanding the new results, and an integral part of all projects.

NW2 had 4 major themes in the 2013-2015 period: (1) Massive stars and their formation; (2) Disk structure and evolution; (3) Characterization of exo-planetary systems, and (4) Water and molecular complexity.

Massive stars form as binaries or higher order multiples

Multiplicity is one of the most fundamental observable properties of massive O-type stars and offers a promising way to discriminate between massive star formation theories. Nevertheless, companions at separations between 1 and 100 milli-arcsec (mas) − corresponding to 2-200 AU at a typical distance of 2 kpc − remain mostly unknown due to intrinsic observational limitations. Wider binaries can be identified in images; closer binaries can be identified from Doppler motion in their spectra or eclipses. The Southern Massive Stars at High Angular Resolution survey (SMaSH+), led by Sana and de Koter (both UvA), was designed to fill this gap by providing the first systematic interferometric survey of galactic massive stars. Using the VLTI-Pionier instrument to explore the 1−45 mas separation range, the Sparse Aperture Masking mode of VLT-NACO to survey the 30-250 mas separation regime, and the NACO Field of View to image a field of 8 arcsec, well over 100 galactic O-type stars in the Southern sky brighter than 7.5 mag in the H band were observed. Accounting for known but unresolved spectroscopic or eclipsing companions, the multiplicity fraction within 8'' is 91%. The fraction of dwarf O-type stars, i.e. stars thought to be relatively young, that has a bound companion reaches 100% at 30 mas while their average number of physically connected companions within that separation is 2.2 ± 0.3. This demonstrates that massive stars form nearly exclusively in multiple systems. So far, identifying the formation mechanism of massive stars has proven to be elusive. The finding that all massive stars form in pairs or small groups now places firm constraints on these models. It too shows that to understand the evolution of massive stars and their end products one needs to realize that they do not live their life in solitude.

A breakdown of the theory of radiation-driven stellar winds at low metallicity?

The first sources of light in the cosmos are thought to have been massive stars, formed out of the pristine gas forged in Big Bang nucleosynthesis. These stars likely played an important role in the re-ionization of the universe and in galaxy formation. Unfortunately, it is difficult – if not impossible – to directly observe the first generation of stars. The objects that are closest in chemical composition that can be studied are massive stars in metal-poor galaxies surrounding the Milky Way. Tramper, de Koter, Kaper (all UvA) and colleagues used the VLT X-shooter instrument to observe the optically brightest sources in the dwarf galaxies IC 1613, WLM, and NGC 3109 to study the properties of O-type stars in the mass range of 30 to 55 solar masses. The main purpose was to study a potential breakdown of the correlation between wind strength and metal content of the star, as predicted by theory. Early studies (by Tramper and colleagues) reported stronger than expected outflows, which would profoundly affect our understanding of the properties of the metal-free first stars (Fig. 2.1). For instance,

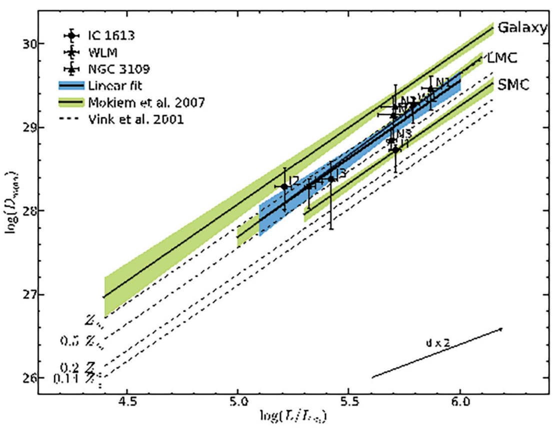

Fig. 2.1: The wind strength (in modified wind momentum) as a function of luminosity for ten stars distributed over the Local Group galaxies IC 1613, WLM, and NGC 3109 derived from VLT X-Shooter spectra. Using newly derived estimates of the metal content of these galaxies, finding them to be similar to that of the Small Magellanic Cloud, the expectation was that the blue bar would align with the lowest green bar. However, the wind strengths of these ten O-type stars are reminiscent of those of stars in the metal-richer Large Magellanic Cloud (Tramper et al. 2014, A&A, 572, A36).

they might not leave massive black holes after their supernovae explosions. The authors now find indications that the iron content of these host galaxies is higher than originally thought. Though this decreases the discrepancy with theory, the wind strengths remain significantly higher than expected. This may imply that our current understanding of the wind properties of massive stars, in the local universe as well as at cosmological distances, remains incomplete.

Massive stars on the verge of exploding

At the end of their lives the most massive stars will have expelled their outer envelopes, revealing a hot core composed of products of nucleosynthesis. These "bare stars" are referred to as Wolf-Rayet stars and they come in three classes: WN, WC and WO stars. Most unique are the WO stars of which there are only nine known. Tramper (PhD), Straal (PhD), de Koter, de Mink, Kaper (all UvA) and co-workers analyzed X-Shooter spectra of the six that are thought to be single objects and found that they originate from stars initially being 40 to 60 solar masses that are now in their post core-helium burning stage. The latter implies that they must be very close to exploding as Type Ic supernovae. Using tailored stellar evolution predictions, their remaining lifetimes are estimated, finding that the first one expected to explode, WR102, will do so 1500 years from now (Fig. 2.2). All of them will end their lives well within 20,000 years. Given the typical uncertainties of these predictions, some may explode sooner, others later, it appears that we have a slim chance (of a few percent) to actually witness the end of one of these stars within the next fifty years, i.e. within our lifetimes!

Dust waves by radiation pressure in Orion

Observations obtained with the *Spitzer Space Telescope* and the WISE satellite have revealed a prominent arc-like structure at 50" (≃ 0.1 pc) from the O9.5V/B0.5V system σ Ori AB (Fig. 2.3). Ochsendorf (PhD Leiden), Kaper, Tielens and collaborators measure a total dust mass of 2.3 ± 1.5 × 10^{-5} M⊙. This dust structure is attributed to the interaction of radiation pressure from the star with dust carried along by the IC 434 photo-evaporative flow of ionized gas from the dark cloud L1630 (Horsehead nebula). Ochsendorf developed a quantitative model for the interaction of a dusty ionized flow with nearby (massive) stars where radiation pressure stalls dust, piling it up at an appreciable distance (>0.1 pc), and force it to flow around the star. The model demonstrates that for the conditions in IC 434, the gas will decouple from the dust and will keep its original flow lines. Thus, this dust structure is the first example of a dust wave created by a massive star moving through the interstellar medium. Dust waves (and bow waves) stratify dust grains according to their radiation pressure opacity, which reflects the size distribution and composition of the grain material. It is found that in the particular case of σ Ori AB, dust is able to survive inside the ionized region. The results show that for late O-type stars with weak stellar winds, the stand-off distance of the resulting bow shock is very close to the star, well within

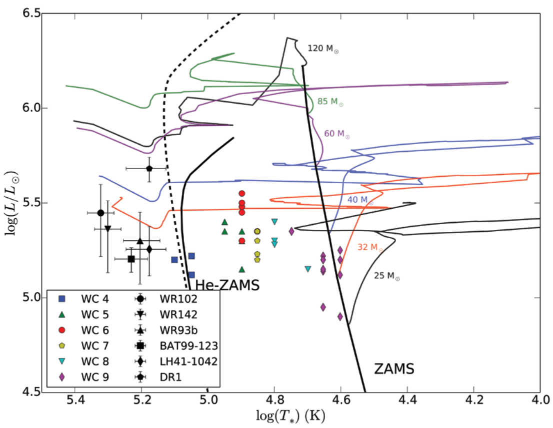

Fig. 2.2: *The location of six of the known nine WO stars in the Hertzsprung-Russell diagram. Plotted as well are evolutionary tracks that extend all the way to the moment of final explosion. The WO stars are all located near the end of these tracks, when they are post-helium burning and within thousands of years of their life-ending Type Ic supernova explosion (Tramper et al. 2015, ApJ, 581, A110).*

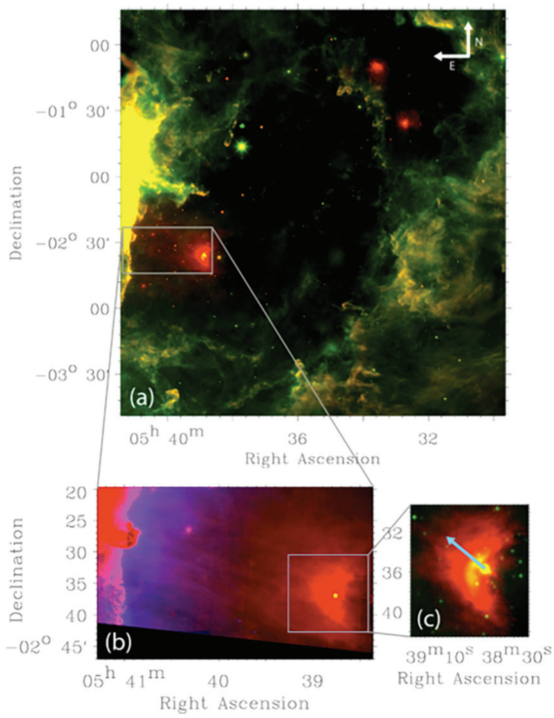

Fig. 2.3: a) *Mid-IR view of the IC 434 region. The total field-of-view is 3.1° × 2.9°. Green is the WISE-3 12 μm band; red is the WISE-4 22 μm band.* ***b)*** *Blow-up part of the upper image with different scaling to accentuate the extended emission around σ Ori AB. The Horsehead nebula is located at the top left. Here, blue represents Hα taken with the KPNO 4m telescope, whereas red is MIPS 24 μm emission. The KPNO image does not extend over the entire field of view but cuts around 6′ eastwards of σ Ori AB.* ***c)*** *Close up of the environs of σ Ori AB. Green is WISE-3, while red is MIPS 24 μm. Overplotted is the proper motion vector which displays the movement in the plane of the sky (Ochsendorf et al 2014, A&A, 563, 65).*

the location of the dust wave. In general, dust waves and bow waves should be common around stars showing the weak-wind phenomenon, i.e., stars with log(L/L⊙)< 5.2, when moving through a high density medium. These structures are best observed at mid-IR to FIR wavelengths, depending on the stellar spectral type. Moreover, they provide a unique opportunity to study the direct interaction between a (massive) star and its immediate surroundings.

Probing dense gas conditions in PDRs

Dense clouds experience radiative feedback from UV photons and X-rays from stars. This radiative feedback affects the chemistry and thermodynamics of the gas. Pérez-Beaupuits (PhD), Spaans (both Groningen) and collaborators used SOFIA-GREAT, APEX and JCMT to probe the chemical and energetic conditions created by radiative feedback through observations of [C II] and multiple CO, HCN, and HCO^+ transitions. The spectral line energy distributions imply a mixture of cold and warm components. The cloudlets associated with the cold component of the models are magnetically subcritical and supervirial at most of the selected positions. The warm cloudlets instead are all supercritical and also supervirial. The magnetic pressure of a constant magnetic field throughout all the gas phases can support the total internal pressure of the cold components, but cannot support the internal pressure of the warm components. A large fraction of the atomic gas seen in [C II] emission is not associated with star-forming gas.

Water from cores to disks: the WISH legacy

The "Water in star-forming regions with *Herschel*" (WISH) guaranteed time key program, obtained unique (spectrally resolved) data on water and related molecules for a large sample of protostars using the HIFI and PACS instruments. The international consortium was led by van Dishoeck (Leiden) with van der Tak (Groningen), Hogerheijde (Leiden), Dominik (UvA) and Mottram as co-Is, and Yildiz, Karska, Harsono, San José García and Choi as PhDs in Leiden and Groningen. WISH was designed to answer three questions (i) how and where is water formed in space; (ii) which physical components does water trace; and (iii) what is the trail of water from clouds to the planet-forming zones of disks. About 80 sources from low- to high-mass protostars and from cores to disks were targeted (Fig. 2.4). Combined with follow-up programs, large enough samples were obtained to allow statistically significant conclusions. Analyses involved extensive radiative transfer and chemical modeling, as well as experiments in the Sackler laboratory led by Linnartz and molecular dynamics simulations of critical processes together with theoretical chemists. Overall, WISH has produced 70 refereed papers, 36 of which were published in 2013-2015, including two major reviews in Chemical Reviews and Protostars & Planets VI.

The main conclusions are: (i) Water is formed mostly as ice on the surfaces of grains prior to cloud collapse, leading to a small amount of cold gaseous water detected with *Herschel* that is well reproduced by chemical models. These ices thermally desorb at high temperatures close to the protostars where water vapor abundances derived from isotopolog lines are greatly enhanced, although not as much as expected. (ii) Warm water vapor lines seen with *Herschel* are bright and have large linewidths (Fig. 2.5); they trace primarily dense shocks along the cavity outflow wall where the jets and winds interact with the envelope and provide mechanical feedback. Line profiles can be decomposed into three physical components which are surprisingly similar from low- to high-mass protostars. Line ratios are constant with velocity and suggest high densities (up to 10^8 cm^{-3}) and temperatures (up to 1000 K) with small emitting areas (<200 AU). H_2O-to-CO and H_2O-to-OH line ratios are one to two orders of magnitude lower than predicted by existing shock models pointing to a new class of UV irradiated shock models. (iii) Water is incorporated mostly as ice into young disks where it is locked up quickly into pebbles settled in the midplane. Several thousand oceans of water ice are available for planet formation in protoplanetary disks.

Low water spin temperatures in Orion

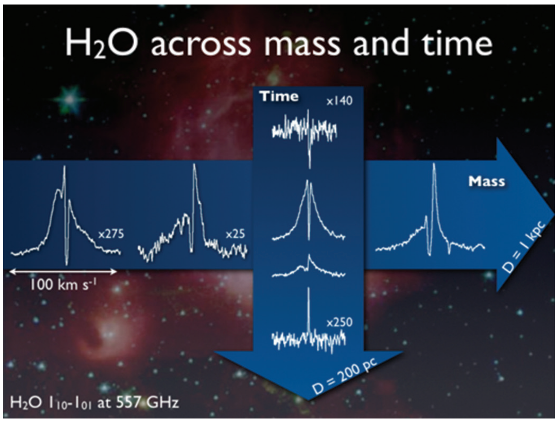

Fig. 2.4: *Water line profiles obtained with Herschel-HIFI in star-forming regions as part of the WISH program. The profiles reveal a rich array of kinematics: warm fast-moving water in outflows, infalling and expanding envelopes, as well as cold absorption and weak emission in cores and disks. The arrows indicate the two axes of WISH: from low to high-mass protostars and from cores to disks (based on van Dishoeck et al. 2014, Protostars & Planets VI, p. 835).*

Choi (PhD Groningen), van der Tak, and collaborators have found that the ratio between the two spin states of water is unusually low in two gas clouds in Orion. Using the *Herschel*-HIFI instrument, a spin temperature of water of only 20 K was found from the ortho/para ratio, which is much lower than the temperatures of the gas (85 K) and the dust (50 K) in these clouds (Fig. 2.5). This record-low spin temperature suggests that water in these clouds is first formed on the surfaces of cold dust grains, and is then returned to the gas by a process called photodesorption as a result of strong ultraviolet radiation from the nearby Trapezium stars.

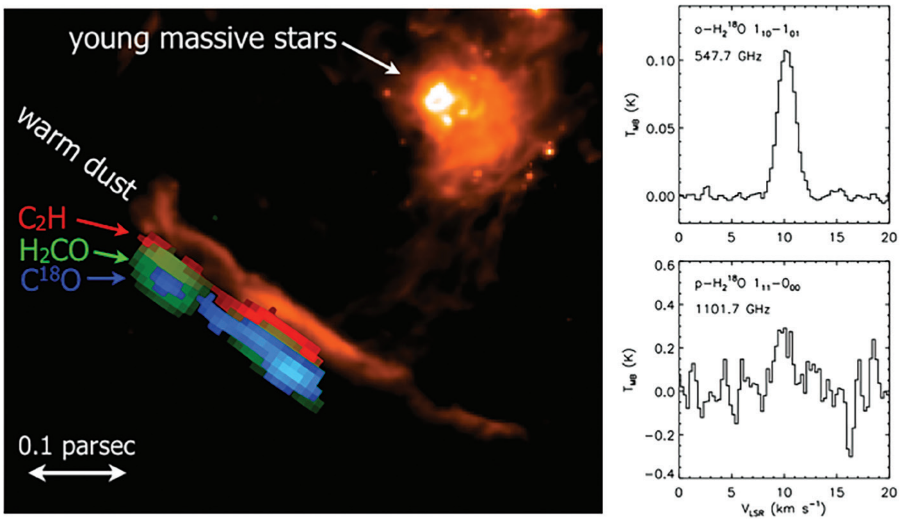

Fig. 2.5: Image of the Orion Bar (left, courtesy van der Wiel) with spectra of the ground-state lines of ortho- and para-H_2O as measured with the HIFI instrument (right). The record-low ortho/para ratio in this gas cloud indicates an unusual origin for the water, as discussed by Choi et al (2014, A&A, 572, L10). Nagy et al. (2013, A&A, 550, A96), and van der Tak et al. (2013, A&A 560, A95).

Exotic molecular ions in the Orion region

The origin of interstellar CH^+ is a long-standing puzzle, since the formation of this species requires much higher temperatures than found in most gas clouds in the Galaxy. Nagy (PhD Groningen), van der Tak, and collaborators have found that at least in the case of the Orion Bar, the strong ambient radiation field due to the nearby Trapezium stars provides an explanation. From *Herschel*-HIFI observations of CH^+, they conclude that this energy can be efficiently stored in vibrational motions of H_2 molecules, which can then lead to the formation of CH^+. The group also discovered that the Orion Bar is a source of OH^+ line emission, the first known case in the Galaxy. Model calculations indicate that this unusual behavior is due to the high density of electrons and hydrogen atoms in this region. Similar conditions may apply to the nuclei of active galaxies, where OH^+ line emission is seen more frequently.

Accretion of jets from young stellar objects

Jets around low- and intermediate-mass young stellar objects contain a fossil record of the recent accretion and outflow activity of their parent star-forming systems. With the aim to understand whether the accretion/ejection process is similar across the entire stellar mass range, Ellerbroek (PhD), Kaper, De Koter (all UvA) and collaborators obtained optical to near-infrared spectra of HH 1042 and HH 1043, two newly discovered jets in the massive star-forming region RCW 36, using VLT-X-shooter. Over 90 emission lines are detected in the spectra of both targets. High-velocity (up to 220 km/s) blue- and redshifted emission from a bipolar flow is observed in typical shock tracers (Fig. 2.6). Low-velocity emission from the background cloud is detected in nebular tracers, including lines from high ionization species. The measured mass outflow rates are $\dot{M}_{jet} \sim 10^{-7}$ M⊙/yr, whereas a high accretion rate for the driving source of HH 1042 is measured ($\dot{M}_{acc} \sim 10^{-6}$ M⊙/yr). For this system the ratio is $\dot{M}_{jet}/\dot{M}_{acc} \sim 0.1$, which is comparable to low-mass sources and consistent with models for magneto-centrifugal jet launching. The knotted structure and velocity spread in both jets are interpreted as fossil signatures of a variable outflow rate. While the mean velocities in both lobes of the jets are comparable, the variations in mass outflow rate and velocity in the two lobes are not symmetric. This asymmetry suggests that the launching mechanism on either side of the accretion disk is not synchronized. The knotted structure and velocity spread can be reproduced qualitatively with a ballistic model. The results of the simulation indicate that the outflow velocity varies on timescales on the order of 100 yrs.

CO snow line in planet-forming disks

Mathews, Hogerheijde, van Dishoeck (all Leiden) and collaborators used Science Verification ALMA data of the planet-forming disk around the young star HD163296 to search for the location in the disk where CO starts to freeze out. Snow lines of common species like water and carbon monoxide are thought to play important roles in the processes that lead up to planet formation: icy grains are heavier and stickier than bare grains, and this may help speed up the growth of grains into planetesimals. Furthermore, this frozen record lives on in comets and other icy bodies in our own Solar System. Finding the CO snow line simply by looking where CO disappears from the gas phase is difficult, because copious amounts of CO remain present in warmer layers closer to the disk surface, effectively veiling the cold midplane free of CO gas. A much more powerful route to find CO snow lines is the use of `signal molecules', species that react rapidly with gas-phase CO - if it exists - but that remain present when CO freezes out. One such molecule is DCO^+. It is expect to be only present at temperatures around 19 K, where chemical reactions in the cold gas and the scarcity of CO drive deuterium into molecules. By

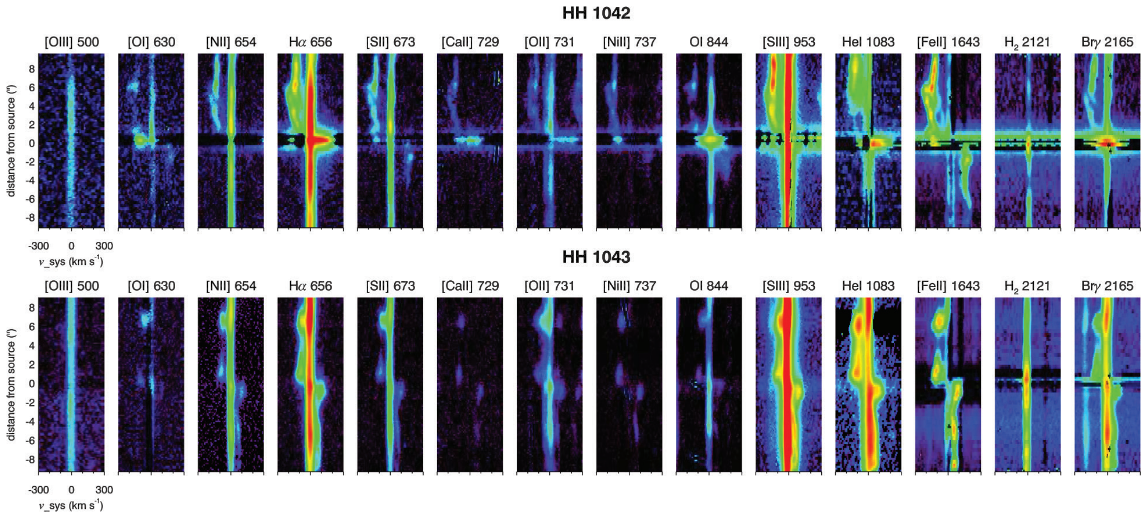

Fig. 2.6: *Position-velocity diagrams of HH 1042 (top) and HH 1043 (bottom) for various lines, as labeled. The absolute flux scale is logarithmic. The underlying stellar continuum (at location = 0''), where present, was subtracted using a Gaussian fit. The ambient cloud produces emission in most lines at zero velocity (by definition) over the full length of the slit. In most lines the blue lobe of the HH 1042 jet is very prominent, while the red lobe suffers from extinction. The measured radial velocities in HH 1043 are significantly lower than those in HH 1042 (Ellerbroek et al. 2013, A&A, 551, 5).*

analysing the ALMA data, Mathews et al. found a ring of DCO^+ emission coincident with the expect location of the 19 K isotherm (Fig. 2.7). Whether DCO^+ is a unique tracer of CO freeze out, or if other factors also are important (e.g., the ortho-to-para ratio of molecular hydrogen, or other pathways for deuterium inclusion) will require more sensitive ALMA observations. In collaboration with Qi, Öberg and others (Harvard-CfA), they also used another tracer, N_2H^+, to locate the CO snowline in the well characterized TW Hya disk in a paper published in Nature.

Water in planet forming regions of disks

Kamp (Groningen) and collaborators detected warm water (several 100 K) for the first time with *Herschel*-PACS in the disk around TW Hya. The inner few au of this disk have to be enriched in gas with respect to the dust, possibly related to disk dispersal and/or ongoing planet formation processes. Podio, Kamp and collaborators detected an abundant outer water reservoir (100 au scale) in the disk around DG Tau with *Herschel*-HIFI; the intense UV radiation field of this young accreting protostar heats water at the disk surface to temperatures >100 K out to 100 AU. In contrast, very deep HIFI searches of a dozen other disks by Hogerheijde (Leiden) and collaborators fond mostly upper limits on cold water vapor. Antonellini

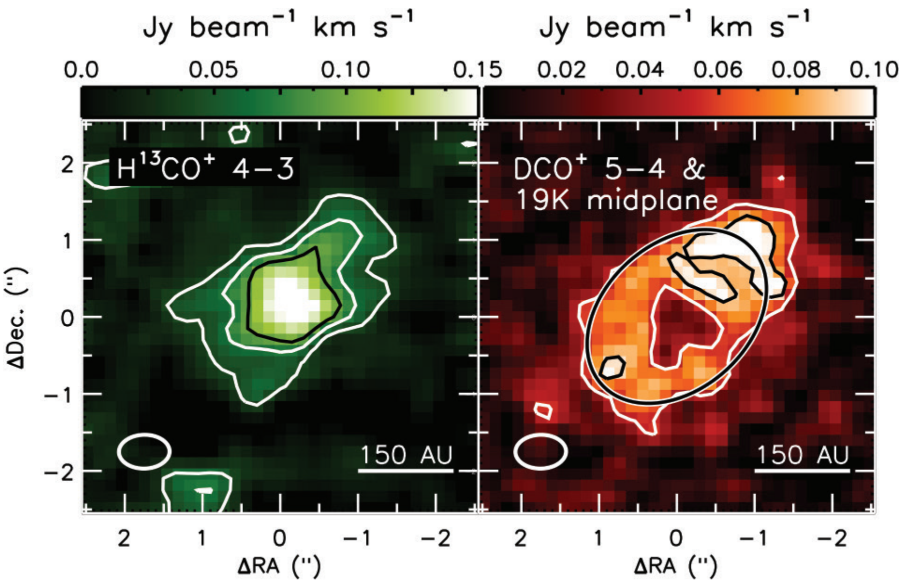

Fig. 2.7: Left: *$H^{13}CO^+$ emission in the planet-forming disk around the young star HD163296.* ***Right:*** *DCO^+ emission forms a ring in this same disk coincident with the radius where CO freezes out (indicated by the ellipse) and where DCO^+ is expected to be abundant in the gas. The relative chemistry of these two HCO^+-isotopomers dramatically illustrates the powerful diagnostics of disk conditions that have become accessible with ALMA (Mathews et al. 2013, A&A, 557, A132).*

(PhD Groningen), Kamp and collaborators found that gas phase chemistry always leads to abundant water (and water ice) in planet forming regions (inside a few 10 AU) even around stars more massive than the Sun. Our ability to detect this water hinges largely on the dust opacity in those regions and on the sensitivity of past and future observatories (line-to-continuum ratio, spectral resolution).

Fedele (MPE), van Dishoeck (Leiden) and collaborators used the *Herschel*-PACS DIGIT Key Program to constrain the CO ladder in a sample of disks around Herbig stars and determine the gas temperature structure in the surface layer using HIFI spectra and Kepler's law to locate the emission. They also found weak H_2O compared with OH emission, likely due to photodissociation of water in the surface layers by the UV radiation from the A-type star. For cooler T Tauri stars, the H_2O emission becomes relatively stronger.

Gas evolution in protoplanetary disks

As a heritage of the *Herschel* Open Time Key Program GASPS, the group of Kamp with Rivière-Marichalar (Groningen) established that the correlation of the fine structure cooling line [OI] 63 μm with the local dust continuum (70 μm) is universal in protoplanetary disks of various ages (0.3 - 8 Myr) (Fig. 2.8). Aresu (PhD Groningen), Kamp and collaborators found that X-rays play a minor role compared to UV in determining the correlation. The constancy of the correlation can provide a tool to (a) assess the strength of disk gas emission even in younger sources with outflow/jets and (b) predict the discovery space for future far-IR space missions such as SPICA.

Detection of the youngest rotationally supported disks with ALMA

Rotationally supported disks are critical in the star formation process. When they form and what factors influence or hinder their formation are questions that have been studied extensively but are debated intensely. Murillo (PhD MPE/Leiden), in collaboration with van Dishoeck and others, observed the deeply embedded protostar Oph VLA1623 with ALMA. Kinematical modeling of the $C^{18}O$ 2-1 line emission clearly reveals a disk out to 150 AU with Keplerian rotation (Fig. 2.9). The central stellar mass is only 0.2 $M_\odot$. VLA1623A is the youngest source to date for which a rotationally supported disk has been found, perhaps assisted by the weak magnetic field.

To further investigate the origin of these disks, Harsono (PhD Leiden), van Dishoeck and collaborators used 3D magnetohydrodynamic simulations with aligned and mis-aligned magnetic fields, together with a 2D semi-analytical model, to demonstrate how spatially-resolved line observations can differentiate between pseudo-disks and young Keplerian disks. The latter are only found for mis-aligned magnetic fields. To investigate their chemistry, full radiative transfer models were used

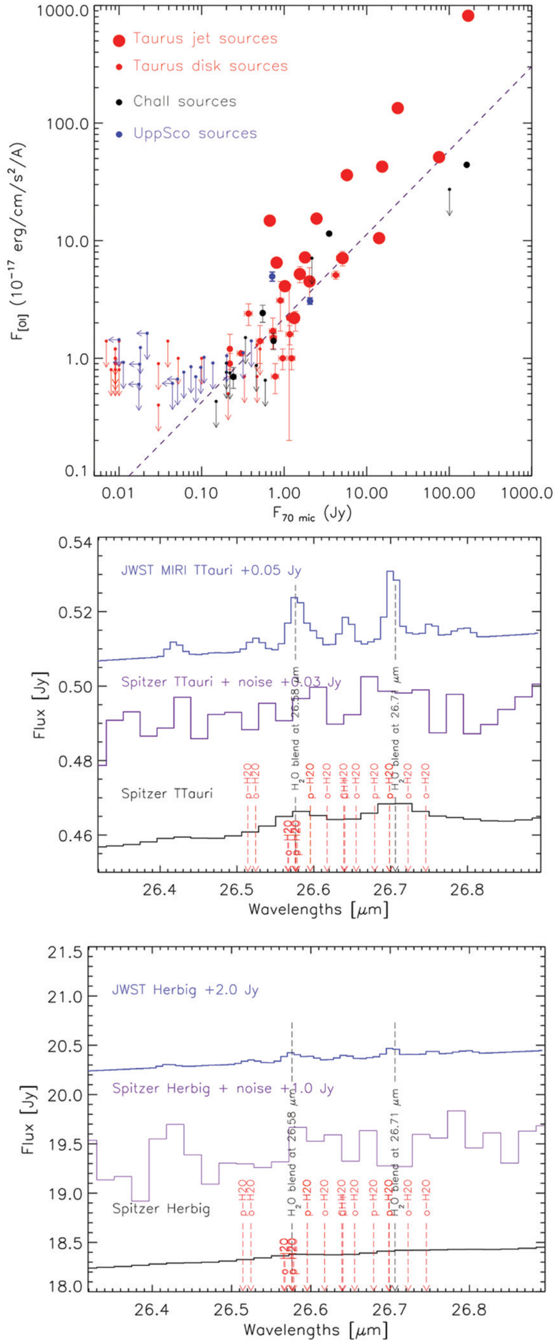

Fig. 2.8: ***Top:*** *Universal correlation between the [OI] 63 mm fine structure line flux and the continuum at 70 μm (Rivière-Marichalar et al. 2015, A&A, 575, A19).* ***Bottom:*** *Modeled mid-IR water spectra of a typical T Tauri and Herbig disk re-binned to the spectral resolution of Spitzer (also noise included) and JWST (Antonellini et al. 2016, A&A, 585, A61).*

to calculate the temperature structure of embedded disks, with heating due to viscous accretion added through the diffusion approximation. The midplane water snowline increases from 3 to 55 AU for accretion rates through the disk onto the star between 10^{-9} - 10^{-4} M_{sun}/yr. Thus, the chemical content inherited from the envelope can be reset in these young disk in periods of high accretion rates (>10^{-5} $M_\odot$/yr).

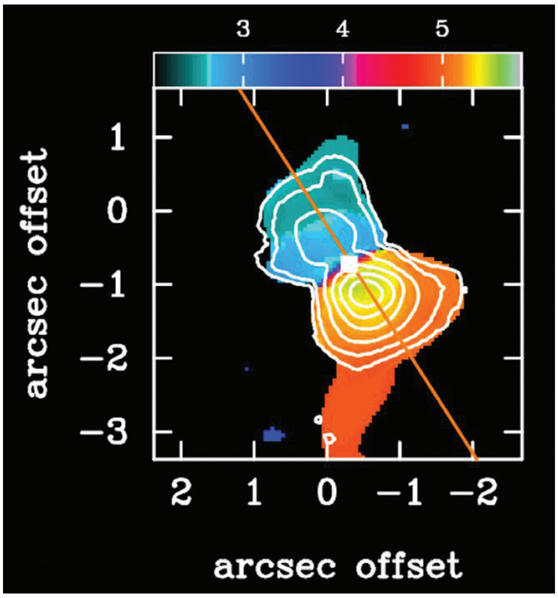

Fig. 2.9: *ALMA observations of C[18]O 2-1 emission from the low-mass protostar VLA 1623 A revealing a Keplerian disk circling a 0.2 M_{Sun} star in this deeply embedded stage. The disk mass is at most a few % of the envelope mass and size, emphasizing the need for high spatial resolution and high sensitivity observations opened up with ALMA (Murillo et al. 2013, A&A, 560, A103).*

Asymmetric dust trap in a transitional disk

The statistics of discovered exoplanets suggest that planets form efficiently. However, there are fundamental unsolved problems, such as excessive inward drift of particles in disks during planet(esimal) formation. Recent theories invoke dust traps to overcome this problem, but such traps had never been observed. Van der Marel (PhD), together with van Dishoeck, Pinilla (all Leiden) and collaborators found a surprisingly asymmetric structure in the disk around the star Oph IRS 48 with ALMA Band 9 data (Fig. 2.10). In collaboration with colleagues from Heidelberg, the structure has been modeled with a vortex-shaped dust trap triggered by a massive planet formed in the disk. In such dust traps, planetesimals and comets can form efficiently. This discovery of a 'comet factory' was highlighted in several ESO/ALMA/Dutch press releases and is the highest-cited ALMA paper to date.

To further constrain the origin of the dust cavities, deep ALMA observations of CO isotopologs (^{13}CO and $C^{18}O$) were obtained. The images clearly show that gas is still present inside the dust cavity, with a gas cavity that is significantly smaller than that of the dust. The overall gas surface density is determined using the physico-chemical model code DALI developed by Bruderer (MPE). The derived gas surface density profiles indicate drops up to three orders of magnitude pointing in all cases to a scenario in which the cavity is cleared by one or more companions, which trapped the millimeter-sized dust at the edge of the cavity.

Fast moving features in a young debris disk

Dominik (UvA) worked with collaborators from the VLT-SPHERE team on images obtained of the debris disk around the young M dwarf AU Mic (Fig. 2.11). The data were taken with the NOVA supported SPHERE/ZIMPOL instrument as well as with SPHERE/IRDIR. It shows a total of five wave-like structures on the eastern side of the disk. Comparison with recently re-reduced HST data from 2010 and 2011 shows that at least some of these features are moving radially with speeds of 4-10 km/s, above the local escape velocity in the disk. The structures are located at projected separations between 10 and 60 AU, persisting over intervals of 1-4 years. This is the first time that such a phenomenon has been discovered in a debris disk. While the features are not fully understood, they may be related to flares erupting from this highly active source.

Measuring the mass of a planet embedded in a disk from the shape of the disk rim

Mulders (PhD), Dominik (both UvA) and co-workers used the shape of the inner rim of a transitional disk to constrain the mass of the companion/planet that is creating the inner gap in the disk around HD 100546. That gap is known to extend to 13 AU from the star. In this work, mid-infrared interferometric measurements

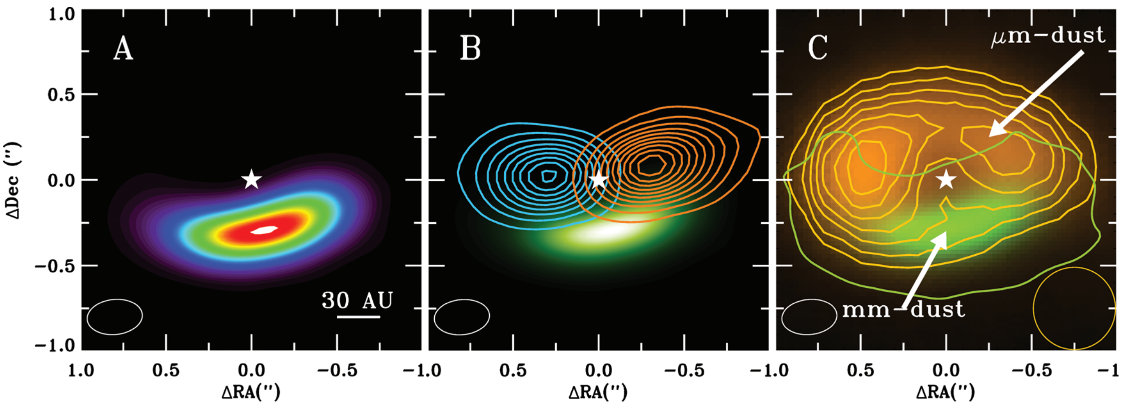

Fig. 2.10: *ALMA Band 9 observations of the IRS 48 transitional disk, revealing a major asymmetric dust trap and a ~60 AU radius hole, likely caused by a companion. Left: The 0.44 millimeter (685 GHz) continuum emission; the peak has 390s. Center: The integrated CO 6-5 emission over the highest velocities in contours showing a symmetric gas disk with Keplerian rotation. Right: The VLT VISIR 18.7 mu m emission in orange contours. The green background shows the 0.44 millimeter continuum (van der Marel et al. 2013, Science, 340, 1199).*

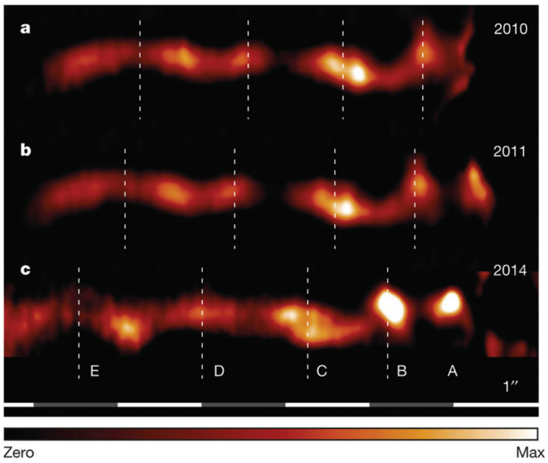

Fig. 2.11: Images of the AU Mic debris disk after unsharp masking, subtraction of the smooth main body of the disk, and stretching in the vertical direction by a factor of two. The same persistent pattern is recovered in all three epochs, though at shifted locations, implying motion away from the star (Boccaletti et al 2015, Nature, 526, 230).

at multiple baselines are interpreted by fitting the computed visibilities of a series of hydrodynamic computations of disks with embedded planets. The mass of the unseen planet is a key factor in the shape of the disk rim. While a sudden ramp-up of the surface density would lead to an oscillating shape of the visibility curve as a function, the smoother observed decline can be traced back to a high-mass companion of about 60 (+20 -40) Jupiter masses, in a disk with a viscosity parameter of at least $\alpha=2 \times 10^{-3}$ (Fig. 2.12). This high mass would put this object firmly into the brown dwarf range.

Direct imaging of gas giant exoplanets using new coronagraphs

Coronagraphs are telescope optics that can reduce the glare from bright stars and reveal the glow of

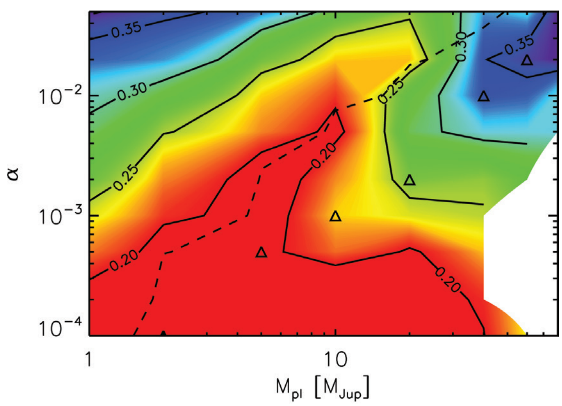

Fig. 2.12: Shape of the disk wall as a function of planet mass and disk viscosity. Solid contours and colors denote the rounding parameter w, required to be w ~0.33 to 0.40 for our best-fit radiative transfer models. The dashed line denotes a gap depth of 10^{-3}. In the region below, the gap is deep enough to be consistent with the observed visibilities. Blue colors indicate rounder walls, red colors more vertical walls. The solution consistent with all constraints requires high companion masses (upper right corner) (Mulders et al 2013, A&A, 557, 68).

extrasolar planets that are orbiting around them. Two such planets have been co-discovered by Kenworthy (Leiden) and collaborators using the Apodizing Phase Plate (APP) coronagraph designed by Kenworthy and installed at the VLT. HD 100546b is a young planet that is located in a gap at 53 AU within a disk that is showing signs of ongoing accretion (Fig. 2.13). This directly imaged planet is therefore at larger distances than that inferred by Mulders et al. above. More recently, a 5 Jupiter mass planet was discovered in a collaboration with Meshkat (PhD Leiden) and Kenworthy at the VLT, demonstrating the power of diffraction suppression in the process of direct imaging of gas giant exoplanets. Analysis shows that there is significant mixing within the upper atmospheres of these extrasolar planets.

Length of exoplanet day measured for first time

Snellen, Brandl, de Kok, Brogi (PhD), Birkby, and Schwarz (PhD) (all Leiden) have measured for the first time the spin rotation of an exoplanet (Fig. 2.14). Beta Pictoris b has been found to have a day that lasts only eight hours. Observations with VLT-CRIRES show it to spin with a velocity of 25 km/s. This is much faster than any planet in the Solar System. This new result extends the relation between mass and rotation seen in the Solar System to exoplanets. Beta Pictoris b is a very young planet, only about 20 million years old (compared to 4.5 billion years for the Earth). Over time, the exoplanet is expected to further cool and shrink, which will make it spin even faster.

Snellen and his team made use of high-dispersion spectroscopy combined with high-contrast imaging to spatially separate the planet from the star. By very carefully removing the effects of the much brighter parent star they were able to extract the rotation signal from the planet. Similar techniques will allow astronomers to map exoplanets in detail in the future with the E-ELT.

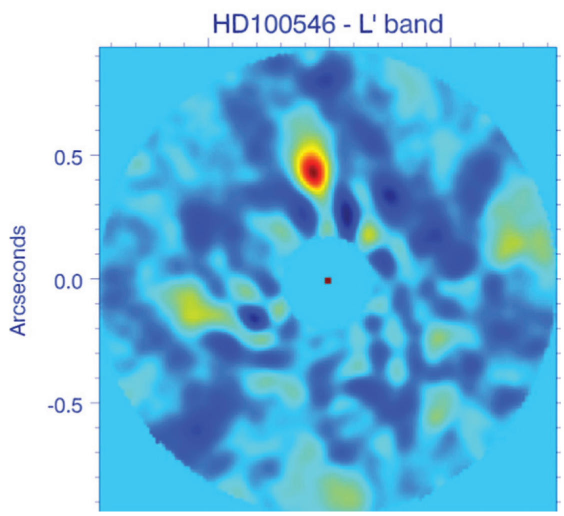

Fig. 2.13: PSF-subtracted image of the vicinity of HD 100546, showing the planet HD 100546b at the 12 o'clock position. These data were taken with Kenworthy's APP coronargaph on the VLT (Quanz et al. 2013, ApJ, 766, L1; 2015, ApJ, 807, 64)

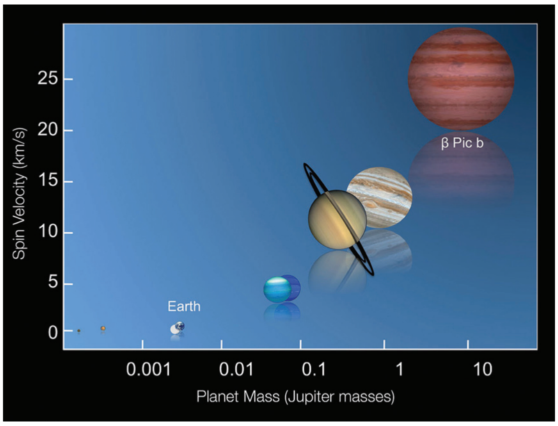

***Fig. 2.14:** Relation between planet mass and equatorial velocity due to rotation, for planets in the solar system and extended to β Pic b (Snellen et al 2014, Nature, 509, 63).*

Hunt for water on exoplanets

Using ESO VLT-CRIRES, Birbky, Brogi (PhD), Schwarz (PhD), Snellen, and collaborators have been able to detect the tell-tale spectral fingerprint of water molecules in the atmosphere of a planet in orbit around another star. The discovery endorses a new technique that will let astronomers efficiently search for water on hundreds of worlds without the need for space-based telescopes. The team studied the exoplanet HD 189733b, a world that orbits its star every 2.2 days and is heated to a temperature of over 1500 C. They measured the molecular absorption by tracing the Doppler shift of the water lines in the exoplanet's spectrum as it orbited the star at very high spectral resolution, allowing detection of the planet that is nearly a thousand times fainter than the star.

Discovery of an extrasolar ring system 200 times larger than Saturn's rings

Planets form in disks of material surrounding stars, and the planets themselves form circumplanetary disks, which eventually disperse, leaving a planet and attendant moons. In a series of papers, Kenworthy (Leiden) and collaborators show that the companion to a young star, called J1407, is substellar and contains a giant ring system with detailed structure, hinting at the presence of a Mars-sized exomoon, the first of its kind detected (Fig. 2.15). The star underwent a complex series of eclipses in May 2007. Kenworthy and collaborator van Werkhoven (PhD Leiden) and Mamajek (Rochester) hypothesize that we are witnessing the last stages of this circumplanetary disk dispersal and are seeing rings carved out by exomoons surrounding an unseen planetary companion next to J1407.

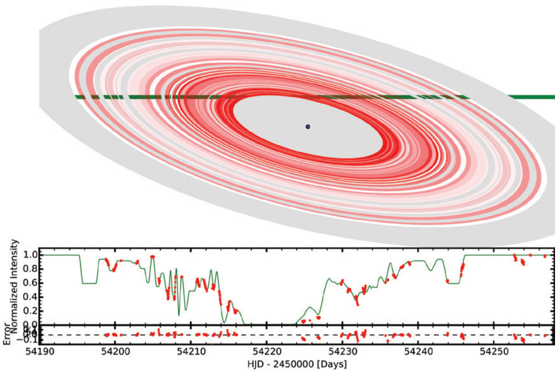

***Fig. 2.15:** Model ring fit to J1407 light curve. The image of the ring system around J1407b is shown as a series of nested red rings. The intensity of the color corresponds to the transmission of the ring. The green line shows the path and diameter of the star J1407 behind the ring system. The gray rings denote where no photometric data constrain the model fit. The lower graph shows the model transmitted intensity as a function of time (Kenworthy & Mamajek 2015, ApJ, 800, 126).*

The composition of evaporating exoplanets

One of the exciting discovery of the Kepler mission is the existence of small expolanets so close to their host star that they are evaporating, leading to transit events that are variable in depth and have a characteristic shape that point to a comet-like tail of dust emanating from the planet. Van Lieshout (PhD), Min, and Dominik (all UvA) studied the composition of the dust in these tails by constraining the properties of the material in the tail from the tail length. They found that corundum and iron-rich silicates are possible constituent materials, since these would produce a tail of the observed length (Fig. 2.16). Many other materials like metallic iron grains or carbon grains are excluded. While distillation processes on the planet itself may lead to selective evaporation of specific materials, this still provides a first peek into the internal composition of exoplanets – something that we cannot even do for the Earth.

Origin of surprisingly abundant O_2 in comets

Oxygen is the third most abundant element in the Universe, but the simplest molecular version of the gas, O_2, has proven surprisingly hard to track down, even in star-forming clouds with *Herschel*, because it is highly reactive and readily breaks apart to bind with other atoms and molecules. The announcement of abundant O_2 in comet 67P/Churyumov–Gerasimenko by Bieler (Michigan), Altwegg (Bern) and collaborators involving van Dishoeck and Walsh (both Leiden), therefore came as a big surprise. Comets are thought to contain the most primitive solar system material providing a direct link with the parent disc and interstellar cloud, and the Rosetta mission provides unprecedented information on the composition of the gases pouring from 67P's nucleus. High-resolution mass spectrometry allowed molecular oxygen (O_2) to be distinguished from other species with the same mass like sulphur (S) and methanol (CH_3OH) for the first time (Fig. 2.17). Its abundance of 4% with respect to H_2O makes it the fourth most abundant ice species in the comet, after H_2O, CO and CO_2. A similar O_2 abundance has been confirmed for comet Halley in re-analysis of the *Giotto* data. The team concluded that O_2 must be `primordial', i.e., originates in the cloud from which our Solar system formed and incorporated into the comet's ices. Models developed in Leiden to explain abundant O_2 ice show that the Solar system may have formed in an unusually

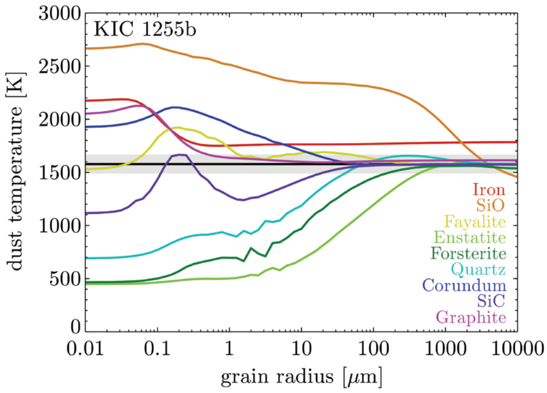

Fig. 2.16: *Characteristic angular tail length of an evaporating planet as a function of grain size for KIC 1255b with different colors for different materials. Dashed lines indicate that particles sublimate entirely before completing one orbit. Gaps (neither a solid nor a dashed line) appear where particles are unbound and will be ejected from the system. The horizontal black lines indicates the tail length as derived from the observation (van Lieshout et al. 2014, A&A, 572, A76).*

warm part of the prenatal cloud, at temperatures of 20-30 K rather than 10 K, which limits the conversion of O_2 to water demonstrated to be so efficient in the Sackler laboratory. This finding is also a 'wake up call' for exoplanets and the search for life since O_2 is the most prominent gas on the biosignature gas list.

Spectrum smallest aromatic molecule recorded

Zhao, Doney (PhD) and Linnartz (all Leiden) managed to record for the first time the laboratory infrared fingerprint spectrum of the cyclopropenyl cation, c-$C_3H_3^+$, the smallest aromatic molecule possible (Fig.

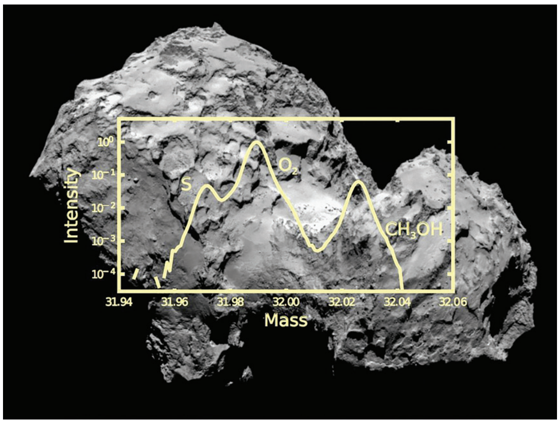

Fig. 2.17: *ROSINA mass spectrometer data superposed on an image of comet 67P/Churyumov-Gerasimenko. The strongest peak at mass 32 is due to O_2, the other peaks are due to sulfur and methanol (Bieler et al. 2015, Nature, 526, 678). Image credit: ESA Rosetta NAVCAM.*

2.18). They used supersonically expanding planar plasma to simulate 3 cm of interstellar cloud and cavity enhanced spectroscopy to measure more than 100 new transitions. This cyclic hydrocarbon molecule is considered to be a pivotal intermediate in ion-molecule reactions, but an astronomical identification has been prohibited so far, because of lacking gas phase spectroscopy. The resulting molecular parameters allow for an accurate comparison with high-level theoretical predictions, and provide the relevant spectroscopic information needed to search for this astrochemically relevant carbon-cation in space.

Top-down chemistry in the interstellar medium

For years, models explaining chemical complexity in space have been following bottom-up pathways, forming larger molecules by merging smaller ones. Recently Zhen, Castellanos (PhD), Linnartz and Tielens (all Leiden) and coworkers have shown that the opposite route offers interesting alternatives as well. In a new setup – iPoP (Instrument for the study of Photodynamics of PAHs) – large polycyclic aromatic hydrocarbon ions were irradiated in an ion trap and the resulting mass fragmentation pattern was recorded

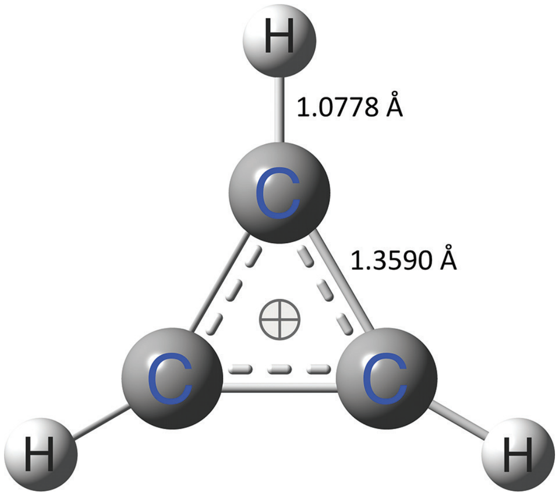

Fig. 2.18: *The equilibrium geometry of c-C_3H_3+. The type of CC bond is an intermediate between a typical double bond and single bond. The high symmetry prohibits a radio astronomical detection, but the recording of infrared transitions in the CH stretch region have made this molecule spectroscopically accessible (Zhao, Doney, & Linnartz 2014, ApJ, 791, L12).*

as function of wavelength and light intensity. The experiments show that PAHs are stripped, sequentially loosing H-atoms, and at a later stage C_2H_2 and C_2 units are kicked-out (Fig. 2.19). The resulting bare carbon skeleton transfers in fullerenes, carbon cages, rings and chains. This explains the recent detection of C_{60} and C_{70} in the interstellar medium, it also shows that chemical complexity may be much richer than anticipated so far.

Molecular complexity in dark interstellar clouds

Fedoseev (PhD), Chuang (PhD), van Dishoeck, Linnartz (all Leiden) and collaborators used laboratory experiments to show that complex molecules, like methyl formate (HC(O)OCH_3), glycolaldehyde (HC(O)CH_2OH) and ethylene glycol (H_2C(OH)CH_2OH), can be formed under dark interstellar cloud conditions by bombarding CO ice with H-atoms (Fig. 2.20). The experiments were performed in the Sackler laboratory

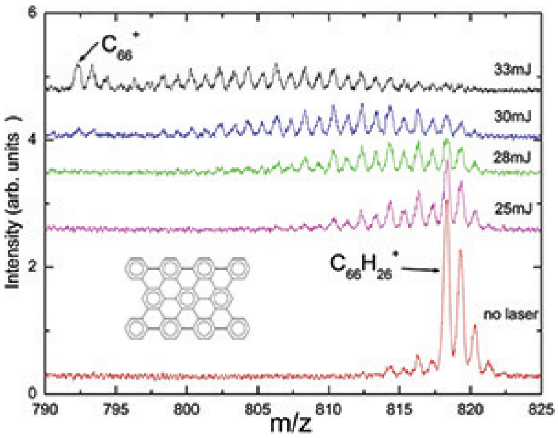

Fig. 2.19: *Fragmentation pattern of the fully benzenoid cation, $C_{66}H_{26}^+$, irradiated at 355 nm as a function of laser power. Additional peaks in the no-laser trace are isotopes and fragmentation produced by the electron gun. For higher energies C_{60}^+ is formed. Wavelength dependent experiments prove that this peak is largely due to a fullerene structure (Zhen, Castellanos, Paardekooper, Linnartz & Tielens 2014, ApJ, 797, L30).*

for astrophysics using a unique setup, SURFRESIDE2, capable of investigating atom addition reactions in interstellar ice analogues for astronomically relevant temperatures. It was already known that sequential hydrogenation of CO results in the formation of methanol. The study by Fedoseev et al shows for a first time that these reactions also result in the formation of larger organic molecules without the need for higher temperatures or UV radiation, fully in line with astronomical observations that recently identified such species in cold dark interstellar clouds.

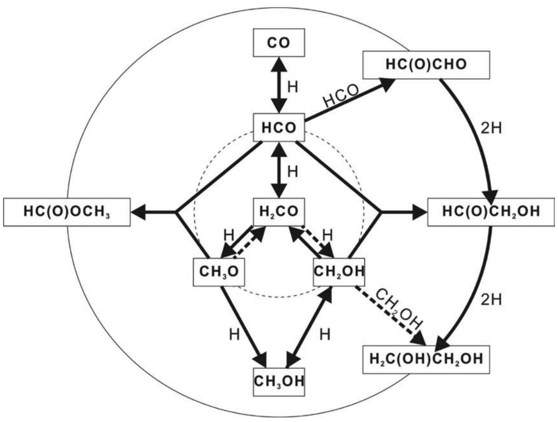

Fig. 2.20: *Extended interstellar ice formation network as obtained from CO, H_2CO, and CH_3OH hydrogenation and abstraction experiments. Solid arrows indicate the confirmed reaction pathways, dashed lines indicate the overall less efficient pathways (Fedoseev et al. 2015, MNRAS, 448, 1288).*

3.3 Astrophysics in extreme conditions

NW3 focuses on the physics of compact objects and the interaction with their environment. Stellar compact objects, such as white dwarfs, neutron stars, and stellar-mass black holes are the end products of stellar evolution and are often found in binaries. Super-massive black holes in the centers of galaxies, have very different formation history, but share very similar physics and allow the study of black holes on different scales. Compact objects manifest themselves as sources of high-energy radiation, non-thermal emission, highly energetic particles, gravitational waves, and high time variability. They are also natural sites to study the physics of strong gravity, dense matter, extremely high magnetic fields, accretion processes, and particle acceleration. The network changed gears in 2014 with the new NOVA phase 4 program and grouped its efforts in five themes: (1) Fast transients, (2) Accretion, ejection and feedback, (3) Physics of compact objects, (4) From binary star to high-energy phenomena and (5) Supernova remnants as particle accelerators.

The 2013-2015 period saw the completion of a number of projects, in particular LOFAR becoming operational and the AMUSE software framework for multi-physics simulations being finished. In the new NOVA phase 4 instrumentation program there is a strong NW3 involvement, with the development of ARTS, BlackGEM and CTA. The latter also features prominently in the new NWO Physical sciences astroparticle physics program.

LOFAR operations are now routine and a large number of papers have come out about topics ranging from AGN and radio galaxies, via transients and radio pulsars to the signals of cosmic rays interacting with the Earth atmosphere. The latter were even used to study the origin of lightning, a paper that in 2015 attracted international media attention.

Two topics that brought together different groups in the network are Tidal Disruption Events (TDEs), in which a star is disrupted around a black hole producing a sudden burst of accretion, and transitional millisecond pulsars, i.e., binary systems with a neutron star that switches between a state of accretion from the companion to being a radio pulsar and, unexpectedly, back. For both topics the focus is still on discovery and characterisation of these objects, but they promise to give a new view on (rapid) accretion and properties of black holes for the TDEs and on the evolutionary link between accreting neutron stars and radio pulsars, as well as the interaction between the pulsar and the companion star.

Not new, but the focus of much work in the past years has been on type Ia supernovae (NOVA PhDs Claeys, Chiotellis, Broersen, Toonen). A unique population synthesis code comparison was led by the students. Binary evolution studies of potential progenitors showed that there is a clear lack of understanding of the different paths that potentially lead to type Ia explosions and that they occur more often in nature that in the models. These studies were complemented by observational studies of potential pre-supernova X-ray emission potentially directly identifying progenitors (which was not found) and studies of the properties of type Ia supernova remnants (that suggested significant pre-supernova mass loss in the Kepler and possibly Tycho supernova systems). Finally, the Galactic center remains a focus of attention for the study of accretion onto super-massive black holes as detailed below.

NW3 routinely uses the full suite of radio telescopes and X-ray satellites and has been active in development of the instruments for the future. Unfortunately the LOFT mission was not selected for the ESA M3 launch slot, but the XIPE X-ray polarisation mission is one of the candidates for M4. The SKA effort is gearing up, and ESA has selected the Athena mission for its second large mission slot. Astro-H was unfortunately lost for science shortly after launch.
Also, the astroparticle physics efforts in the Netherlands have been consolidated. There is strong participation in the Auger Observatory, including new plans for expanding the radio detection capabilities after very successful detailed study of the radio signal of cosmic ray air showers with LOFAR (see below). The Radboud group became a member of the Virgo gravitational wave collaboration and is building the BlackGEM-array for follow-up of gravitational wave sources. The Netherlands is playing an increasing role in the development of CTA and some NW3 people are active members of the HESS collaboration. Furthermore the third ESA large mission was selected to be a space gravitational wave mission, again a theme with large interest from NW3 and plans are made to increase the Dutch involvement in this (long term future) mission. Finally, the European Pulsar Timing Array published new upper limits on gravitational wave background from super-massive black hole pair.

Synchronous X-ray and radio mode switches

Observations of the variable, mode-changing pulsar B0943+10 using a combination of the XMM-Newton and LOFAR telescopes produced perplexing results. Hermsen, Hessels and van Leeuwen (all UvA, SRON/ASTRON) led an international team of astronomers that carried out the simultaneous X-ray and radio monitoring. This revealed that the source, whose radio emission is known to switch from bright to quiet periodically in radio, behaves in reverse when observed at X-ray wavelengths (Fig. 3.1). These are the first X-ray emission switches ever detected in a pulsar, and the properties of this emission are unexpectedly puzzling. No current model can explain this switching behaviour, but it is clear that the global pulsar magnetosphere must change between different states within only a few seconds.

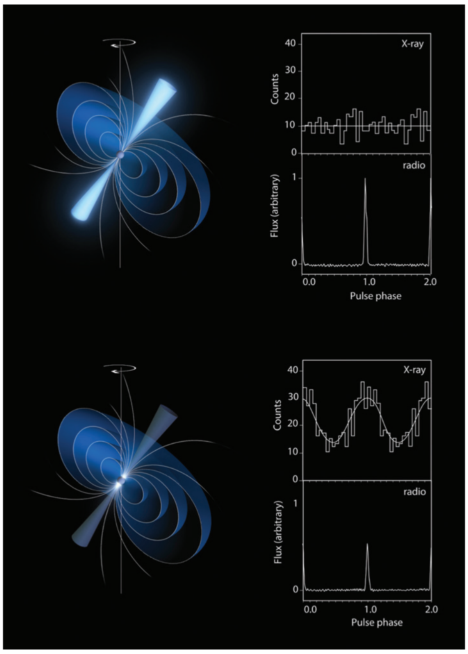

Fig. 3.1: *Artist impression and X-ray and radio signal showing the mode switching from X-ray faint, radio loud (top) to X-ray bright, radio quiet (bottom) modes (Hermsen et al. 2013, Science, 339, 436).*

Blitzar

Falcke with Rezolla (both Nijmegen), proposed that the origin of the newly discovered Fast Radio Bursts is the collapse of a supra-massive neutron star to a black hole. The process may originate in the merger of a double neutron star system. The spin down of the newly formed neutron star reduces the centrifugal force that supports the star and when it collapses to a black hole, the magnetosphere is suddenly decoupled and produces a coherent radio pulse (Fig. 3.2).

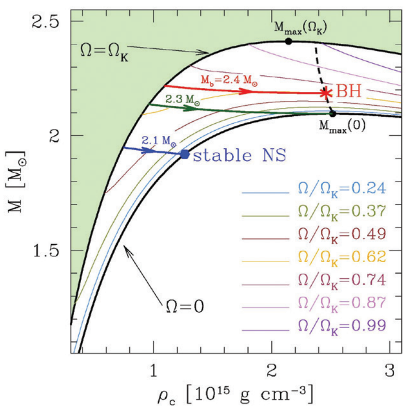

Fig. 3.2: *Mass – density diagram of rapidly rotating supra-massive neutron stars. The coloured arrows show spin down trajectories, the red one leading to collapse to a black hole and potentially emission of a fast radio burst (Falcke & Rezzolla 2014, A&A, 562, 137).*

X-ray transient: tidal disruption of white dwarf?

In 2013 Jonker, Nelemans (Nijmegen) and collaborators found a new kind of fast X-ray transient. The properties of this explosive event are well explained by an intermediate-mass black hole tidally disrupting a white dwarf. Over the last years more and more evidence is found for tidal disruption flares. When a star wanders too close to a black hole the tidal force, i.e. the difference between the gravitational pull on the side of the star that is close to the black hole and the gravitational pull on the side further away from the black hole, is so large that the star is torn apart (Fig. 3.3). When relatively compact stars like white dwarfs are involved, the tidal force has to be large, and perhaps counter-intuitively, such a large tidal force is achieved near intermediate-mass black holes and not near super-massive black holes. In the latter case white dwarfs will only be torn apart after they have crossed the event horizon and those events are thus not observable. The timescales for white dwarf tidal disruptions are short; they are minutes to hours and months for the aftermath. It is exactly these short timescales that coincide with the timescale of the new kind of explosive X-ray transient that has been found by Jonker and collaborators. The event was found in a directed search through the Chandra satellite archive. It was localized to come from close to the position of the large elliptical galaxy M86. The luminosity of a white dwarf tidal disruption at that distance agrees well with the Eddington luminosity for an intermediate-mass black hole. In 2014 and 2015 two additional events similar to the one found by Jonker and collaborators have been found.

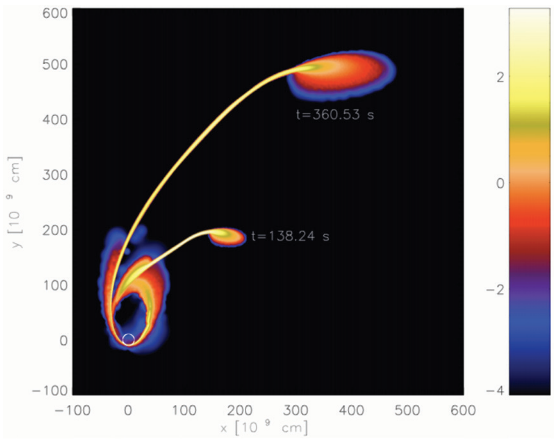

Fig 3.3: *This image is a composite of two stills from the simulation of the tidal disruption of a white dwarf by an intermediate-mass black hole by Rosswog et al. (2009, ApJ, 695, 404). The location of the black hole is indicated by the small white circle at position x,y=0,0. The times indicate the time in seconds since the start of the simulation where the disruption of the white dwarf is approximately at t=13.7 seconds, showing the short time scales involved. About half of the the white dwarf mass flies out and is lost to the system whereas the material of the other half circularizes and is accreted by the black hole. The colour indicates the density of the material in logarithmic units of gr per cubic cm. Observational evidence for this scenario has been found by Jonker et al. (2013, ApJ, 779, A14).*

The Galactic Center flaring

Sgr A* is the super-massive black hole in the center of the Galaxy, whose proximity makes it the ultimate test bed for theories of accretion. The Event Horizon Telescope (EHT) global VLBI project will image the inner few gravitational radii in the next few years. However in order to properly interpret the images, comparisons to general relativistic (GR)-MHD simulations are needed. Moscibrodzka, Falcke (Nijmegen) and collaborators developed new simulations showing that it is critical to understand the details of the radiating particle distributions, which are not included in the current simulations (Fig. 3.4).

Fig. 3.4: *GR-MHD simulation of the shadow of the black hole in the centre of the Galaxy at 1.3 mm wavelength. The image is 200 micro arcseconds across (Moscibrodzka et al. 2014, A&A, 570, 7).*

Important insights may come from the roughly daily flares in the X-ray with amplitudes from a few to hundreds of times the stable, quiescent X-ray flux. With the exquisite new multi-wavelength data acquired for Sgr A*'s flares during a 3 Msec Chandra X-ray Visionary Project (Markoff (UvA) was one of the three Co-PIs), the constraints are finally good enough to study not only details of the radiating particle evolution during flares, but also the statistics of flare distributions. For the former, a paper led by Dibi (PhD), with Markoff and collaborators, used a self-consistent treatment of the particle distributions for the first time within the innermost region of the accretion flow. By fitting the broadband flare data including the sub-millimeter, infrared and X-ray (including for the first time also simultaneous NuSTAR data), the authors showed that standard modelling assumptions such as "equilibrium" Maxwellian distributions may not be appropriate for the flares. The energetics of the flares are most consistent with magnetic reconnection events energizing the particles near the black hole, producing non-thermal synchrotron emission with a cooling break. These results set the stage for the next studies which extend these models to the entire population of flares in order to explore their statistical properties. Interestingly this treatment seems to favour a more complex scenario, which must be resolved in order to reach the eventual goal of devising optimal methods for assigning particle distributions to simulations of Sgr A* in time for the EHT results. In addition, one of the first radio/(sub)millimeter campaigns performed on Sgr A* including ALMA, involving Markoff, provided a completely independent study on the particle distributions and optical depth of the plasma near Sgr A*, also part of the puzzle for EHT preparation.

Furthermore, to accurately simulate the accretion flow around Sgr A*, it is also important to constrain the boundary conditions of this inflow from observations. Two key papers resulted from the above mentioned multi-wavelength program that shed light on these issues. First, a paper in Science, including Markoff presented the first (and only for any black hole) X-ray image of the accretion flow around Sgr A*, as well as high-resolution spectroscopy resolving the iron complex between 6-7 keV, and confirming that 99% of the inflowing material is lost to winds that are likely magnetized. These results were confirmed in a complementary VLBA campaign which resolved for the first time the two-dimensional structure of Sgr A* at 7mm.

An alternative origin of the flares was studied by Hamers (PhD) and Portegies Zwart, who investigated the idea that the energy source for these flares is the tidal disruption of planetesimals with radius 10 km or larger passing within one AU of the supermassive black hole. Two scenario's were explored (1) in a large-scale cloud bound to the black hole, and (2) in debris discs around stars. They conclude that the predicted flaring rate, of about 0.6 per day, is nearly independent of the distribution of perturbers. Moreover, it is insensitive to scenarios (1) or (2) . However, for scenario (1) some fine tuning is needed, so scenario (2) is the favoured explanation.

A magnetar close to Sgr A*

At a projected separation of 0.1 pc from the super-massive black hole Sgr A* at the center of the Milky Way, a transient magnetar SGR J1745-2900 was discovered in an effort which included Falcke (Nijmegen). It holds the record as the closest neutron star to a black hole ever observed. SGR J1745-2900 has been the object of an intensive monitoring campaign in the X-rays for about 1.5 years since the outburst onset, from April 2013 until September 2014. Detailed analysis by Coti Zelati (PhD), Rea (both UvA) and colleagues of these data revealed an extremely slow flux decay compared to the other known transient magnetars, making this source rather unique. The extremely slow cooling is currently challenging state-of-the art neutron star crustal cooling models. If the outburst evolution is indeed due to crustal cooling, as predicted and observed for all other magnetar outbursts in the past 10 years, then magnetic energy injection needs to be continuous over at least the first ~200 days, something so far never observed for sources of the class. Alternatively, heating of the star surface may result from strong magnetospheric currents confined within a gradually shrinking magnetic bundle which impact upon the surface. However detailed numerical simulations are needed to confirm this possibility.

Low level accretion onto NS/transitional pulsars

Significant progress has been made both observationally as well as theoretically on understanding low-level (<1% of the Eddington mass accretion rate) accretion onto weakly magnetized neutron stars. Armas Padilla (PhD), Degenaar, Wijnands (all UvA) and colleagues have shown that below 0.1% and down to 0.01% Eddington, the neutron star surface emission shows prominently in the observed X-ray spectra as a soft, low energetic component due to the release of potential energy of the accreted matter when it hits the neutron star surface. In addition, not only the soft spectral component but also the more energetic, hard component in the X-ray spectra of those systems is due to accretion of matter to the neutron star surface contrary to earlier assumptions. This conclusion is strengthened by the independent study of D'Angelo (PD, UvA) and colleagues who studied one particular system at very low accretion rate (~0.001 – 0.0001% Eddington). They suggested that the hard spectral component arises from the boundary layer (of likely just a few meters thick) just above the neutron star surface where the accreted matter goes from a super-sonic flow to a sub-sonic flow generating Bremsstrahlung (see Fig. 3.5). If true, then this should also be the case for those systems accreting slightly faster (0.01-0.1% Eddington). For this to work, it is assumed that the magnetic fields of the neutron stars in those systems are very low and they do not affect the accretion process significantly.

The last conclusion is strengthened by work led by Archibald (PD, UvA), on the transitional millisecond radio pulsar PSR J1023+0038, which shows that in that system the magnetic field is strong enough to influence the accretion alternating between distinct modes. This "mode switching" is not fully understood but it is likely due to the effect of the magnetic field that inhibits accretion during the low mode and only during the high and flare modes the neutron star accretes matter.

The exceptionally powerful TeV γ-ray emitters in the Large Magellanic Cloud

The HESS collaboration, with strong involvement of Vink (as corresponding author) and Berge (as Galactic Working group coordinator) (both UvA), reported the first detection of TeV gamma-ray emitters in the Large Magellanic Cloud (LMC) (Fig. 3.6). All three sources are exceptional in some way. The 30DorC super bubble is the first super bubble to be detected in gamma-rays. This is of large importance as it has been theorised that super bubbles may be the preferred ISM locations for acceleration of particles to energies in excess to 10^{15} eV. Although these high energies are not detected yet, the evidence points at least to super bubbles as sources of cosmic rays with energies of at least 10 TeV. The brightest TeV gamma-ray source in LMC is the pulsar wind nebula associated with PSR J0537−6910, the fastest spinning (16 ms) non-recycled pulsar. The energy loss rate of the pulsar is similar to the Crab nebula, but somehow the gamma-ray luminosity of the source is an order of magnitude larger than the Crab nebula. Finally, the detection is reported of the supernova remnant (SNR) N132D. The surprise for this source is that the SNR is 2000-3000 yr old, whereas TeV gamma-ray emitting SNRs are generally younger than 1500 yr. N132D may therefore be a transitional TeV gamma-ray source, which may be key in understanding when and why SNRs cease being TeV gamma-ray sources.

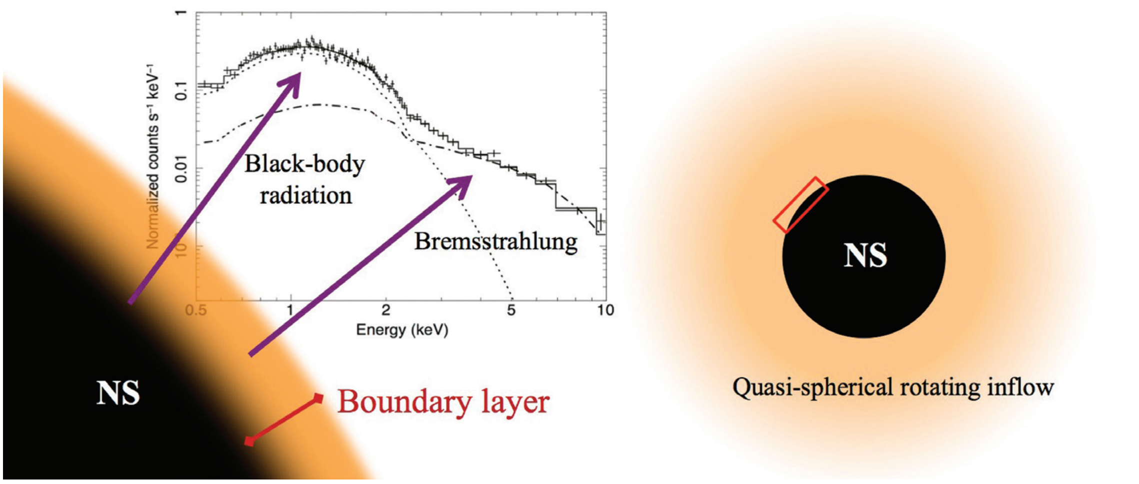

Fig. 3.5: Schematic overview of boundary layer accretion onto a very weakly or non-magnetized neutron star. It shows the neutron star surface with the boundary layer (only a few meters thick) that produces soft, black-body like emission from the surface and Bremsstrahlung emission from the boundary layer (Inset from Degenaar et al. 2013, ApJ, 767, L31; composite by Wijnands).

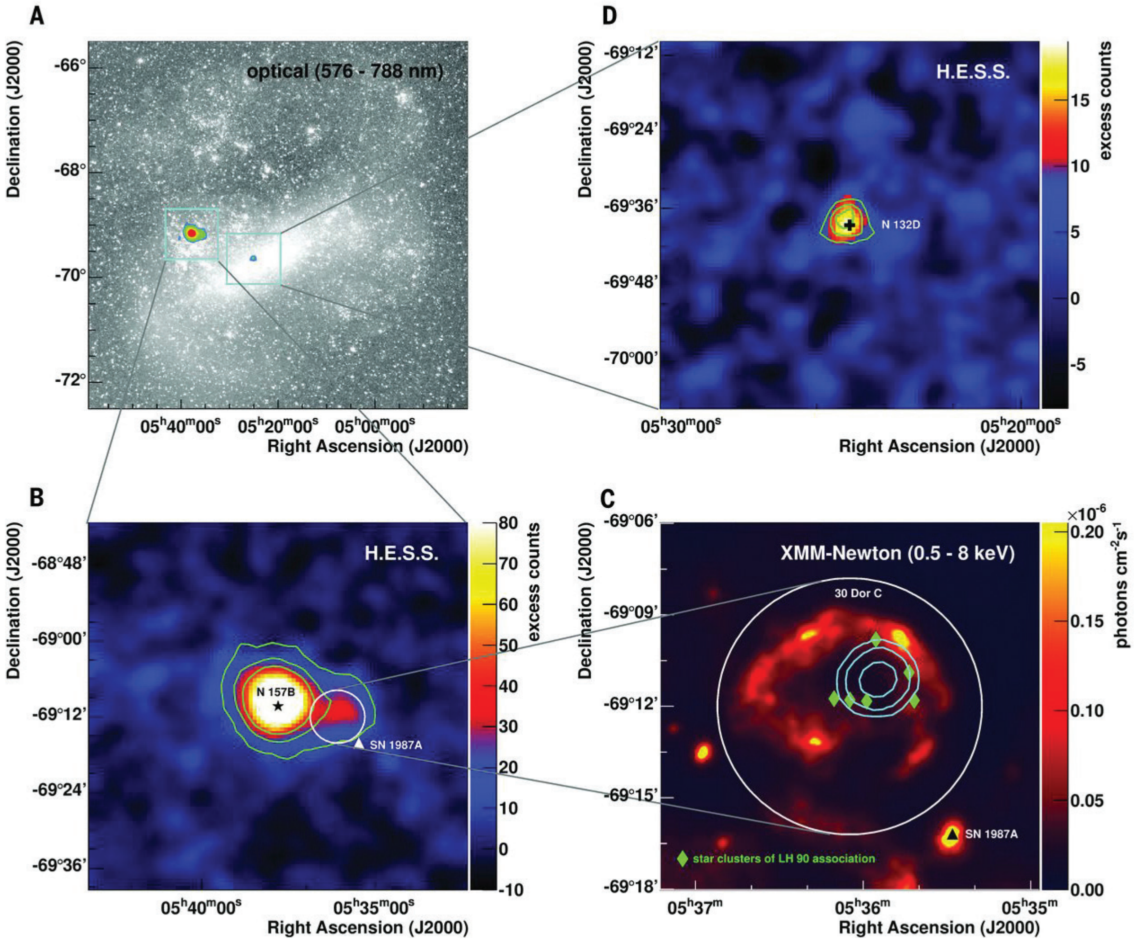

Fig. 3.6: *Sky maps of the LMC.(A) Optical image of the entire LMC. The boxes denote the regions of interest. Colors denote levels of 3, 5, 10, and 20 standard deviation (SD) statistical significance of the γ-ray signal. (B) VHE γ-ray emission in the region around N 157B. The green lines represent contours of 5, 10, and 15 SD statistical significance of the γ-ray signal. (C) XMM-Newton image of the region of 30 Dor C. The superimposed cyan lines represent contours of 68, 95, and 99% confidence level of the position of the γ-ray source. Diamonds denote the positions of the star clusters of the LH 90 association. (D) VHE γ-ray emission in the region around N 132D (The HESS Collaboration 2015, Science, 347, 406).*

Double white dwarfs and low-frequency gravitational wave sources

Double white dwarfs are the end product of the evolution of a large fraction of binary stars. In close orbits they emit gravitational waves and evolve towards shorter and shorter periods. At some point mass is transferred and either an interacting double white dwarf, known as an AM CVn system is formed, or the two stars merge, possibly accompanied by a type Ia supernova explosion. Rossi (Leiden) and collaborators studied this last aspect: the evolution of these compact binaries towards coalescence and possibly explosion. They developed a dynamical method to describe the effects of tides within neutron stars and white dwarfs. Specifically, they applied this method to white dwarfs and showed how it is theoretically possible to obtain constraints on the poorly known viscous forces inside the compact stars. They subsequently compared for the first time their predictions with observations of masses, radii and radial elongation of the ~12 min period binary SDSS J0651+2844 (Fig. 3.7) and estimated a viscous timescale that rules out the presence of both molecular and strong magnetic field viscosities. The knowledge of the strength of viscous forces is of paramount importance for predicting whether the two stars will merge (thus exploding as Type Ia supernova) or will start transferring mass from one to the other.

On the population of low-frequency gravitational wave sources great strides were made in a series of papers by Kupfer (PhD), Groot (both Nijmegen) and collaborators that uncovered and characterized the population of interacting double white dwarfs, known as AM CVn systems. The Palomar Transient Factory turned out to be a rich source of new discoveries, among others of the second-known eclipsing system and systems that brightened and faded a factor of ten in flux within a single night.

Carbon enhanced metal poor stars in the Milky Way halo

Abate (PhD), Pols (both Nijmegen) and collaborators studied the formation of binary carbon-enhanced metal-poor (CEMP) stars in the halo of our Milky Way, using models of asymptotic giant branch (AGB) nucleosynthesis combined with binary population synthesis. They showed that the observed abundances of heavy elements in CEMP stars require very efficient mass transfer by the wind of the AGB star, while the

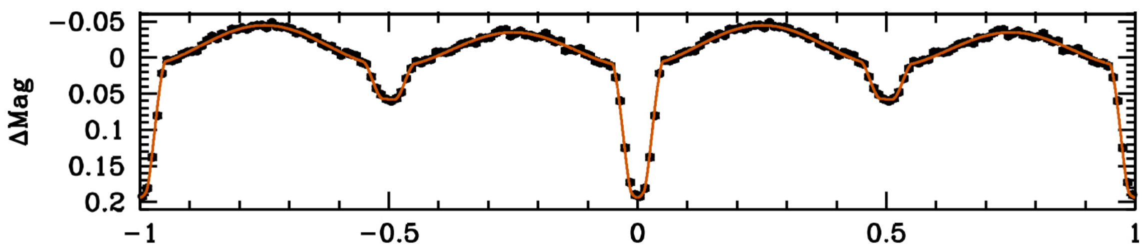

Fig. 3.7: Lightcurve of the 12 minute double white dwarf SDSS J0651+2844 showing eclipses but also two humps due to tidal heating of the larger white dwarf (Hermes et al. 2014., ApJ, 792, 39).

observed orbital periods indicate that the orbits shrink rather than expand during this process. Furthermore, their models show that the observed number of CEMP stars in the halo can be reproduced without requiring large modifications to the stellar initial mass function.

White dwarf companions of millisecond pulsars

Rivera-Sandoral (PhD), van den Berg, Wijnands (all UvA) and colleagues identified the counterparts to five millisecond pulsars in the globular cluster 47 Tuc using HST ultraviolet images (Fig. 3.8). They all turned out to be white dwarfs with orbital periods of about a day. The new work significantly increases the number of identified and characterised millisecond pulsar companions.

Black hole kicks

Black holes are the remnants of massive stars. When these collapse at the end of their nuclear evolution it is unclear if mass is ejected in a supernova and whether black holes receive natal kicks at birth like neutron stars. Repetto (PhD) and Nelemans (both Nijmegen) used the observed positions in the Galaxy of black-hole X-ray binaries to constrain the black hole natal kicks and find that in some cases there is evidence for high kicks (Fig. 3.9). In order to extrapolate from the current position back to the black-hole formation, a new simplified treatment of the preceding binary evolution

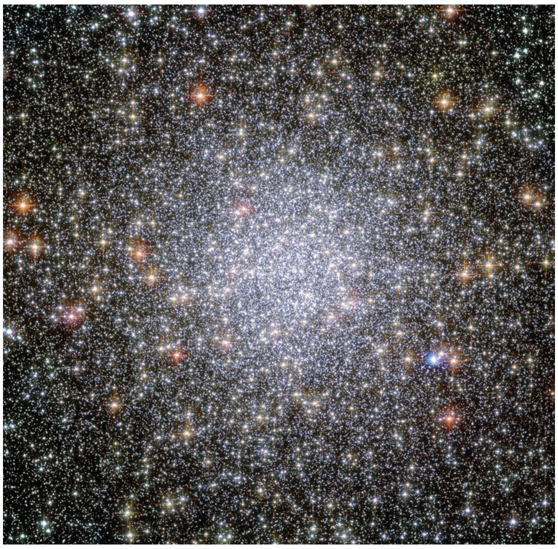

Fig. 3.8: Composite HST color image (2.8' x2.8') of the globular cluster 47 Tuc (based on Heyl et al. 2015, ApJ, 804, 53; credit HST/NASA/ESA).

and in particular the tidal interaction was developed.

Flame spread during thermonuclear explosions on neutron stars

Type I X-ray bursts are thermonuclear explosions triggered by unstable burning in the oceans of accreting neutron stars. The basic cause, an imbalance between nuclear heating and radiative cooling in settling material, can be explained using simple one-dimensional calculations. However major puzzles remain: in particular the precise conditions for ignition and flame spread, and how these sometimes result in the development of unusually bright formations known as burst oscillations on the burning surface.

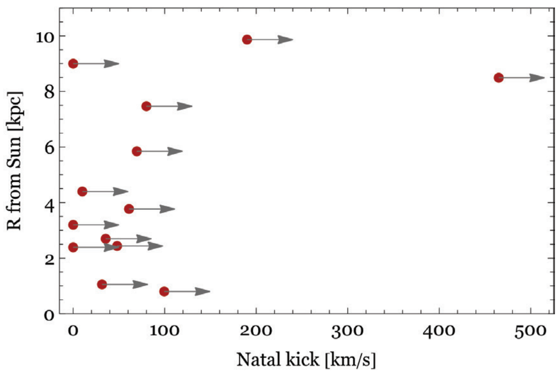

Fig. 3.9: Minimum natal kick for the black-hole X-ray binaries as function of the distance from the Sun, showing that at least some black holes receive significant kicks (Repetto & Nelemans, 2015, MNRAS, 453, 3341).

The hotspots that form in this fashion are extremely promising probes of the mass and radius of the neutron star, which in turn yield the dense matter equation of state, one of the major open questions in fundamental physics. Understanding their formation is crucial. Cavecchi (PhD), Watts (both UvA) and collaborators, developed the first hydrodynamical simulations of flame spread to incorporate all of the relevant physics. First they showed that the same effect that causes tornadoes on earth, the Coriolis force, causes fiery hurricanes on the neutron star. The flame is confined within the outer edge of the hurricane, and this 'ring of fire' keeps expanding under the action of conduction until it engulfs the whole star (Fig. 3.10). This is surprising since conduction is a slow process: but it is the hydrodynamical configuration imposed by the Coriolis force that accelerates the flame propagation to rates matching the observations. They subsequently

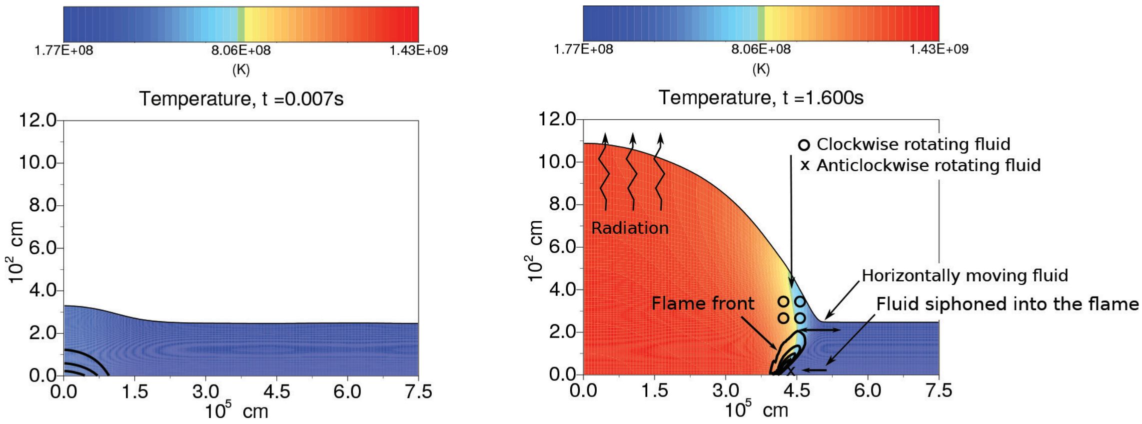

Fig. 3.10: *A section of the burning fluid on an accreting neutron star immediately after ignition (left) and shortly, 1.6 s, later (right). Colors: temperature. Black lines: contours of burning rate, indicating the location of the flame front. Also shown are the motion of the fluid on the plane and across it under the influence of pressure and Coriolis force. Conduction acts at the hot-cold fluid interface near the flame front (Cavechi et al. 2013, MNRAS, 434, 3526).*

showed that flames can cross the equator even though Coriolis confinement fails at this latitude, disproving a promising hypothesis for the phenomenon of double peaked bursts. They also found that the confinement associated rapid rotation is critical for burst ignition: otherwise, in the absence of dynamically important magnetic fields (likely the case for most bursters) the flame simply sputters out before it can spread any significant distance.

An exact analytic treatment of propagating mass accretion rate fluctuations in X-ray binaries

In a black hole binary system, a normal star circles around a black hole as the black hole's gravity pulls matter from the star. The process of spiralling towards the black hole heats the matter until it becomes a very hot plasma, glowing brightly with X-ray radiation. The propagation of density fluctuations in the plasma causes characteristic random variability in the X-ray emission, with bigger fluctuations created far from the hole fragmenting into smaller and smaller ones closer and closer to the black hole. Figure 3.11 (top) shows an illustration of plasma falling onto a black hole in an accretion disk. The plots on the bottom left show that, because of the fragmentation and the propagation time, density fluctuations in the plasma close to the black hole are faster and lag behind fluctuations in the plasma far from the black hole, which can be observed by measuring the time lag between hard and soft photons. The next step is to quantitatively compare this model to observations in order to learn about the distorted spacetime in the close surroundings of black holes. However, so far this has proved difficult since all previous treatments used a laborious calculation where the successive fragmentations of the fluctuations at different distances from the black hole were exp licitly simulated using computationally intensive Monte Carlo simulations. Ingram and van der Klis (both UvA) found a mathematical treatment of the model, which directly calculates the final outcome using only the properties of the fragmentation process at each distance from the black hole, without the need for any simulations. The figure (bottom right hand corner) shows the average variability amplitude of the X-ray brightness as a function of fluctuation speed calculated from a long simulation in black, and using the new analytic formulae in magenta. Not only is the new method exact, it also is much faster, achieving in one minute of computer time what previously took an entire week, thus making it possible for the first time to quantitatively compare propagating fluctuations models to large data sets.

New insights into the X-ray emitting region of neutron stars and black holes

Both the X-ray variability and spectrum encodes information about the structure of the innermost regions of accreting black holes and neutron stars. However, the systems vary in appearance over time and so comparing different systems can be difficult because it is not knows if the same intrinsic structure (e.g. inner disc radius) is compared or not. Heil (PD), Klein-Wolt (Nijmegen) and Uttley (UvA) developed a new way to describe the X-ray variability (called the 'power colour') which can be easily combined with the spectral information to identify systems with the same intrinsic structure, thus revealing the differences between systems due to other effects, such as whether they contain a neutron star or a black hole, or whether differences are due to viewing the system from a different angle. This latter effect may be indicated by the fact that accreting black hole X-ray binary systems which are more 'edge-on' (looking close to the edge of the large-scale flat disc of material feeding the black hole) produce X-rays with systematically higher average energies than those that are more 'face on'. This can be explained if the small and central hot 'corona' producing the X-rays also has a flattened shape, so that X-rays that come through a greater thickness of material (which scatters X-rays to higher energies) are seen when looking edge on.

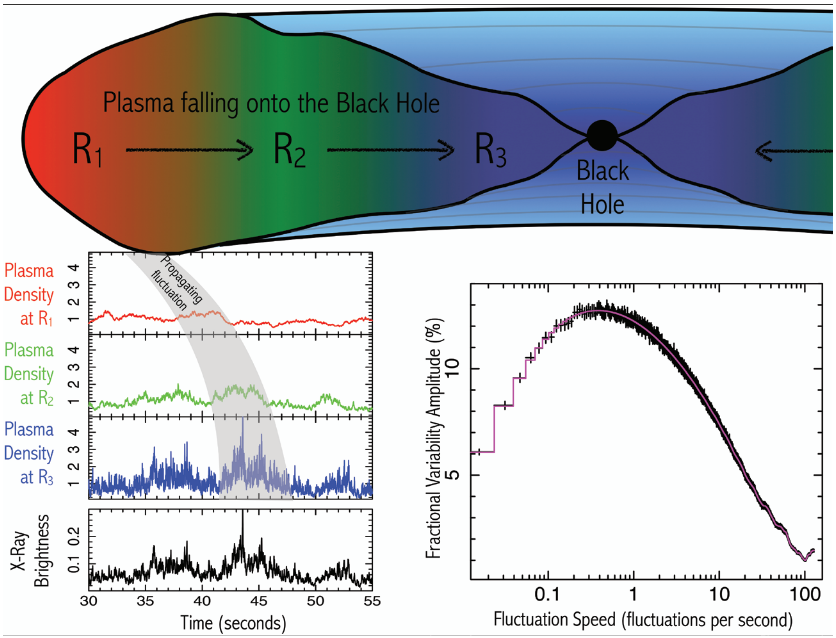

Fig. 3.11: ***Top:*** *Schematic of matter accreting onto a black hole. Random density fluctuations are stirred up throughout the accretion flow and propagate towards the black hole.* ***Left:*** *A simulation of the density as a function of time at three different radii of the accretion flow, where red, green and blue lines correspond respectively to R3, R2 and R1 in the schematic. The shaded area tracks a particular over-density in the matter propagating towards the black hole. These density fluctuations cause variability in the X-ray brightness (black).* ***Right:*** *Variability amplitude of the predicted X-ray brightness as a function of fluctuation speed. The black points are from the simulation, whereas the magenta line uses the exact analytic expression (Ingram & van der Klis 2013, MNRAS, 434, 1476)*

LOFAR unravels radio emission from cosmic-ray air showers

The LOFAR key science project Cosmic Rays (PI Hörandel, Nijmegen) is studying in detail the radio emission from extensive air showers with unprecedented precision. In particular, the shape of the radio wave front in air showers has been clarified: it is best approximated by a hyperboloid. The intensity pattern of the radio emission on the ground has been studied in the frequency ranges 30-80 and 120-240 MHz (Fig. 3.12).

A parametrization of the radio emission from cosmic-ray air showers developed by Nelles (PhD Nijmegen) and Hörandel allows for an universal description of the emission pattern. This is now also used at AERA at the Pierre Auger Observatory through Schulz (PhD Nijmegen) and Hörandel. Buitink, Hörandel, Falcke (all Nijmegen) and colleagues developed a method that is used to measure the composition of the cosmic-rays. The radio measurements of extensive air showers have been established as a new tool to measure the properties of cosmic rays. Now all relevant parameters, namely direction, energy and particle type/mass are routinely being reconstructed from the radio data. The methods developed at LOFAR have been successfully transferred to AERA (taskleader Hörandel) at the Pierre Auger Observatory. Radio detection of air showers went through a phase transition: before the understanding of the emission processes itself has been in the focus, now applying the new method and measuring the properties of cosmic rays is in the main focus. First analyses (and related publications) are under way. Of particular interest is the measurement of the mass composition of cosmic rays in the energy region between 10^{17} and 10^{18} eV. In this region a transition from a Galactic to an extragalactic origin of cosmic rays is expected. The radio data – with their good resolution – will allow to distinguish different astrophysical scenarios of the origin of high-energy cosmic rays.

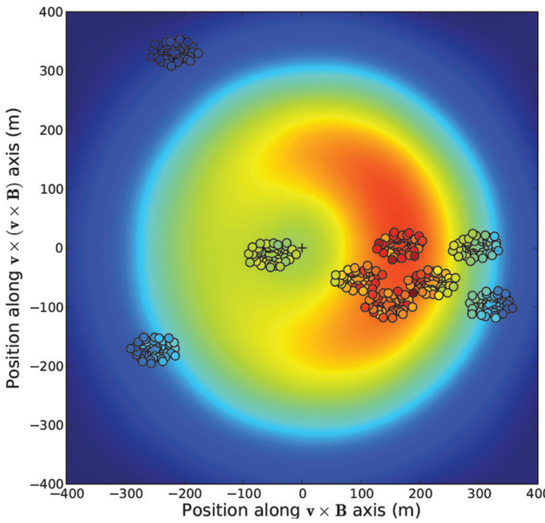

Fig. 3.12: Reconstruction of the cosmic-ray airshower induced radio emission (color map). Overplotted is the signal strength of the LOFAR stations on the same colour scale showing the good match between the model and the data (based on Buitink et al. 2014, Phys. Rev. D, 90, 2003).

4. PhD's in astronomy awarded in 2013, 2014, 2015

A total of 44 PhD's in astronomy were awarded in the Netherlands in 2013, 35 in 2014 and 43 in 2015. Of these 122 PhD's 40 were obtained through funding or co-funding from NOVA. The table below lists all PhD's over 2013-2015 specified for each university.

Name	PhD date	Funding	Promotor	Thesis title
UvA				
T. Bagnoli	04 12 2015	SRON	vd Klis co: in't Zand, Watts	The Rapid Burster and its X-ray bursts: extremes of accretion and thermonuclear burning
R. van Lieshout	27 11 2015	NOVA	Dominik co: Keller	Probing exoplanetary materials using sublimating dust
P.M. Bult	15 09 2015	NWO	vd Klis co: Patruno	Connecting the coherent and stochastic X-ray variability of accreting millisecond pulsars
O.H. Ramirez-Agudelo	04 09 2015	NOVA	de Koter, Kaper co: Sana	Properties of massive stars in the Tarantula Nebula
R. Andrassy	19 06 2015	Other	Spruit	Convective overshooting in stars
D. Antonopoulou	21 01 2015	NWO	vd Klis co: Watts	Rotational glitches in radio pulsars and magnetars
T. Chousinho Khouri	16 12 2014	NWO	de Koter, Waters co: Decin	Oxygen-rich AGB stars with low mass-loss rate observed with Herschel
O.E. Hartoog	10 12 2014	NOVA	Kaper, Wijers	Spectroscopy of the environments of long gamma-ray bursts and their progenitors
F. Tramper	28 11 2014	NOVA	de Koter, Kaper co: Sana	The properties of low-metallicity massive stars
D. Huppenkothen	14 10 2014	NWO	vd. Klis co: Watts	A New Statistical Toolbox for Studying Variability in Fast Transients
I. Thaler	11 09 2014	Other	Spruit	Solar Surface Magnetism: Selected Topics
S. Broersen	10 09 2014	NWO	Wijers, co: Vink	X-ray spectral analysis of non-equilibrium plasmas in supernova remnants
S. Dibi	01 07 2014	Other / NOVA	Wijers co: Markoff	Studying MHD and radiative processes in Sgr A*
L.E. Ellerbroek	14 03 2014	NOVA	Kaper	Star Formation History Written in Spectra
A. Chiotellis	16 12 2013	NOVA	Wijers co: Vink	The interaction of Type Ia supernovae with their circumstellar medium
M.N. Kalamkar	22 11 2013	NOVA	vd Klis	Probing accretion flow dynamics in X-ray binaries
T. Coenen	20 11 2013	NOVA	vd Klis co: van Leeuwen, Hessels	Searching for pulsars with LOFAR
M. Armas Padilla	01 11 2013	EC	vd Klis co: Wijnands	Subluminous X-ray binaries
Y.J. Yang	23 10 2013	Other / NOVA	vd Klis co: Wijnands	Accreting Black Holes
P. Polko	03 04 2013	NWO	Wijers co: Markoff	Exploring jet properties in magnetohydrodynamics with gravity
S. Drappeau	02 04 2013	NWO	Wijers co: Markoff	The Ins and Outs of Emission from Accreting Black Holes
G.D. Mulders	08 03 2013	NOVA	Dominik	Radiative Transfer Models of Protoplanetary Disks: Theory vs. Observations
K. Leventis	28 02 2013	NOVA	Wijers	The Many Phases of Gamma-Ray Burst Afterglows
E.M. Ratti	15 02 2013	Other	Hermsen, co: Jonker	Observations and dynamical studies of X-ray binaries in a low-accretion state
M. Kama	29 01 2013	NWO / NOVA	Dominik	Young Intermediate-Mass Stars: from a HIFI spectral survey to the physics of the disk inner rim
Y. Cavecchi	10 01 2013	NOVA	vd Klis co: Watts, Levin	Accreting Neutron Stars: Strong Gravity and Type I X-ray Bursts

Name	PhD date	Funding	Promotor	Thesis Title
UL				
C. Shneider	17 12 2015	NWO	Röttgering co: Haverkorn	Reconstructing Magnetic Fields of Spiral Galaxies from Radiopolarimetric Observations
W.L. Williams	10 12 2015	ASTRON / UL	Röttgering co: v.Weeren	Facets of radio-loud AGN evolution: a LOFAR surveys perspective
A. Elbers	10 12 2015	UL / NWO	v. Lunteren, Israel	Early Dutch Radio Astronomy (1940-1970): The People and the Politics.
A.J. Richings	08 12 2015	EC / UL	Schaye	Non-Equilibrium Chemistry and Cooling in Simulations of Galaxy Formation
M.L. Turner	12 11 2015	EC / UL	Schaye, Steidel	Metals in the diffuse gas around high-redshift galaxies
M. Velliscig	11 11 2015	EC / UL	Schaye co: Cacciato	Probing the darkness: The link between baryons and dark matter
P.R. Russo	10 11 2015	EC / UL	Miley, vd Broek	Design, Implementation and Evaluation of Transnational Collaborative Programmes in Astronomy Education and Public Outreach
T. Boekholt	10 11 2015	NWO	Portegies Zwart	Chaotic Dynamics in N-body systems
N. Marel, van der	29 09 2015	NOVA	v. Dishoeck, Dullemond	Mind the gap: gas and dust in planet-forming disk.
M. Fumagalli	08 09 2015	EC	Franx, van Dokkum	Star formation and aging at cosmic noon:the spectral evolution of galaxies from z=2
A. Stroe	02 09 2015	NWO	Röttgering co: Sobral	When Galaxy Clusters Collide: the impact of merger shocks on cluster gas and galaxy evolution
F.J. Salgado Cambiazo	02 09 2015	EC	Tielens co: Oonk	Studies of Dust and Gas in the Interstellar Medium of the Milky Way
B.B. Ochsendorf	01 09 2015	EC / NWO	Tielens, Kaper	Tales of Orion: The interplay of gas, dust, and stars in the interstellar medium
I. San Jose Garcia	18 06 2015	EC / UL	v. Dishoeck, vdTak co: Mottram	Paving the path between low- and high-mass star formation: Dynamics probed by Herschel far-infrared spectroscopy
B. Pila Diez	16 06 2015	NOVA / UL	Kuijken	Structure and substructure in the stellar halo of the Milky Way
T. Meshkat	11 06 2015	UL / Other	Snellen co: Kenworthy	Extrasolar Planet Detection Through Spatially Resolved Observations.
M. Kazandjian	03 06 2015	UL	Israel co: Meijerin	Diagnostics for Mechanical Heating in Star-Forming Galaxies.
A.L.M. Lamberts	20 05 2015	NWO	Linnartz co: Cuppens, Ioppolo	Unraveling the surface formation of regular and deuterated water in space
S. Krijt	29 04 2015	UL	Tielens, Dominik	From grains to planetesimals: the microphysics of dust coagulation
R. Smit	28 04 2015	NWO	Franx co: Bouwens	Star-forming galaxies at the Cosmic Dawn
X. Li	12 02 2015	NWO	v. Dishoeck co: Heays	Molecules during Stellar Formation and Death
S.H. Cuylle	29 01 2015	EC	Linnartz	Carbon in interstellar ice
D.P.C. Caputo	22 01 2015	NWO	Portegies Zwart	The Great Collapse
N. Clementel	18 12 2014	NWO	Icke co: Madura	Casting light on the ç Carinae puzzle
G.S. Fedoseev	10 12 2014	EU	Linnartz co: Ioppolo	Atom Addition Reactions in Interstellar Ice: new pathways towards molecular complexity in space
M.P. van Daalen	09 12 2014	UL/EC	Schaye, White	Galaxy formation and the structure of the Universe
G. van Harten	09 12 2014	UU	Keller co: Snik	Spectropolarimetry for planetary exploration
T.J.C. van Hengel	22 10 2014	buitenpromovendus	Gaastra, van Lunteren	The Diving Dutchman. Het Marien-Gravimetrisch Onderzoek van F.A.Vening Meinesz (1887 - 1966)

Name	PhD date	Funding	Promotor	Thesis Title
UL				
J. van de Sande	01 10 2014	NOVA	Franx, Kriek	Dawn of the Red and Dead Stellar Kinematics of Massive Quiescent Galaxies out to z = 2
A. Karska	24 09 2014	buitenpromovendus	v. Dishoeck co: Herczeg	Feedback from deeply embedded low- and high-mass protostars Surveying hot molecular gas with Herschel
D.S. Harsono	24 09 2014	SRON / NOVA / UL	v. Dishoeck co: Bruderer	Unveiling Protostellar Disk Formation around Low-Mass Stars
M.J. Rosenberg	18 09 2014	NOVA	Israel, van der Werf	Causing a stir: Radiative and mechanical feedback in starburst galaxies
J. Bédorf	02 09 2014	NWO	Portegies Zwart	The Gravitational Billion Body Problem
T.I.M. van Werkhoven	26 06 2014	STW/UL	Keller, Gerritsen	Lasers, lenses and light curves: adaptive optics microscopy and peculiar transiting exoplanets
K.M. Maaskant	23 06 2014	NOVA	Tielens, Waters, Dominik	Tracing the evolution of protoplanetary disks
M. Brogi	05 06 2014	NOVA	Snellen, Keller	Atmospheres of hot alien Worlds
R.F.J. van der Burg	14 05 2014	NWO	Kuijken co: Hoekstra	The Distribution of Stellar Mass in Galaxy Clusters over Cosmic Time
M. Iacobelli	25 02 2014	NWO / UL	Röttgering	Accreting Neutron Stars: Strong Gravity and Type I X-ray Bursts
S. Verdolini	20 02 2014	UL	Tielens	Modeling interstellar bubbles: near and far
M. de Juan Ovelar	12 12 2013	NOVA/ESFRI	Keller co: Snik	Imaging polarimetry for the characterisation of exoplanets and protoplanetary discs. Scientific and technical challenges.
K.S. Wang	10 12 2013	NOVA	van Dishoeck co: Hogerheijde	Small Scale Kinematics of Massive Star-Forming Cores
M. Weiss	27 11 2013	Other	v. Lunteren	The Masses and the Muses: A History of Teylers Museum in the Nineteenth Century
D. Szomoru	21 11 2013	EC	Franx, van Dokkum	The extraordinary structural evolution of massive galaxies
S. Rieder	30 10 2013	NWO	Portegies Zwart, de Laat	The Clustered Universe
M. Shirazi	15 10 2013	UL	Franx co: Brinchmann	Nearby and distant star-forming galaxies as seen through emission lines
A. Rahmati	15 10 2013	NOVA	Schaye	Simulating the cosmic distribution of neutral hydrogen and its connection with galaxies
E.C. Fayolle	01 10 2013	NOVA	Linnartz, Fillion co: Oberg	From Ice to Gas Constraining the Desorption Processes of Interstellar Ices
M. Mosleh	12 06 2013	EC / UL	Franx	The Stellar Mass - Size Evolution of Galaxies from z=7 to z=0
U. Yildiz	01 05 2013	UL	van Dishoeck co: Kristensen	Warm and Cold Gas in Low-Mass Protostars
Th. Karaldi	23 04 2013	SRON	Keller co:Stam	Broadband polarimetry of exoplanets : modelling signals of surfaces, hazes and clouds
B. Nefs	27 03 2013	NWO	Snellen, Fridlund	The Hunt for Red Dwarf Binaries and Hot Planets in the WFCAM Transit Survey
K. Isokoski	26 03 2013	NOVA / UL	Linnartz	Physics and Chemistry of Interstellar Ice
J.E. Bast	10 01 2013	NWO	van Dishoeck, Tielens	Hot chemistry and physics in the planet-forming zones of disks

Name	PhD date	Funding	Promotor	Thesis title
RUG				
P. Pranav	18 12 2015	RUG	Weygaert, Vegter Jones	Persistent holes in the Universe: A hierarchical topology of the cosmic mass distribution
Y. Choi	25 11 2015	NOVA / SRON	vd Tak, v. Dishoeck	Water vapor in high-mass star-forming regions and PDRs: Tracing the dynamics and chemistry with Herschel/HIFI
S. Meneses Goytia	20 11 2015	NOVA	Peletier, Trager	Stellar population models in the Near-Infrared
A. Gonneau	25 09 2015	RUG	Trager, Lançon	Joint optical and near-infrared spectroscopic studies of stars with X-shooter: An insight into carbon stars
J.T. Buist	11 09 2015	EC	Helmi	Dynamical modelling of stellar streams in a cosmological setting
H. Vedantham	26 06 2015	EC	Koopmans, de Bruyn	Opening the low frequency window to the high redshift Universe
W. Jellema	01 05 2015	SRON	Wild, Withington	Optical design and performance verification of Herschel-HIFI
R. Hein-Bertelsen	13 02 2015	NOVA	Kamp, Waters	CO ro-vibrational emission: Tracing the geometry of the inner protoplanetary disc
A. Shulevski	06 02 2015	RUG / ASTRON	Morganti, Barthel	AGN relics in the radio sky: a LOFAR look into spectral ageing and AGN duty cycles
G. Popping	14 11 2014	NOVA	Trager, Spaans, Somerville	The evolution of the atomic and molecular interstellar medium in star-forming galaxies
K Geréb	26 09 2014	RUG / ASTRON	Morganti	The Role of Neutral Hydrogen in the Life of Galaxies and AGN A Spectral Stacking Analysis
B. Beygu	26 09 2014	RUG	van de Weijgaert, van der Hulst, van Gorkom	The void galaxy survey: a study of the loneliest galaxies in the universe
G. Monari	19 09 2014	EC	Helmi, co Antoja Castelltort	The dynamical e!ects of the bar on the Galactic thin and thick disks
S.P.C. Peters	05 09 2014	RUG	Kruit, Freeman, Allen	A Closer Look at the Anatomy of Spiral Galaxies
M.C. Cautun	24 02 2014	RUG	Weygaert, Jones	The Cosmic Web and the Local Universe
F. Lelli	06 12 2013	RUG	Verheijen, Fraternali	Starbursts and gas dynamics in low-mass galaxies
S. Kazemi	22 11 2013	NWO	Zaroubi, de Bruyn co: Yatawatta	Efficient and accurate calibration for radio interferometers
Y.P. Chen	11 11 2013	RUG	Trager, Peletier	The X-Shooter spectral library and application to stellar population in galaxies
C. Spiniello	04 10 2013	RUG	Koopmans, Trager	The Initial Mass Function in Early-Type Galaxies
Z. Nagy	23 09 2013	RUG / SRON	vd Tak	Molecular line tracers of high-mass star forming regions
M.A. Breddels	01 07 2013	NOVA	Helmi	Orbit-based dynamical models of Local Group dwarf spheroidal galaxies
P. Noorishad	07 06 2013	RUG / ASTRON	vd Hulst, v Ardenne	Optimization for high fidelity imaging with aperture array telescopes
G. Chaparro	17 05 2013	RUG	Kamp	The Cosmic-Ray Dominated Midplane of Protoplanetary Disks : The Solar System Connection
K. George	29 04 2013	RUG	Trager	Recent star formation in cluster early-type galaxies : evidence from dynamics and stellar populations over the past 7 Gyr
E. Russell	19 04 2013	Other	van de Weygaert	Analytical exploration of large scale structure
A. Sanna	08 02 2013	NOVA	Mendez	Accretion flow properties in low-mass X-ray binaries
C.A. Vera-Ciro	21 01 2013	RUG	Helmi co: Sales	The Local Group in CDM : shapes and masses of dark halos

Name	PhD date	Funding	Promotor	Thesis title
RU				
M. Heida	09 12 2015	SRON	Nelemans co: Jonker, Torres	Red supergiant counterparts of ULXs : paving the way to dynamical mass measurements
S. Wykes	03 12 2015	NOVA / RU	Groot co: Hörandel	Mass entrainment and cosmic-ray energisation in Centaurus A
S. ter Veen	26 11 2015	ERC / Spinoza	Falcke	Searching for Fast Radio Transients with LOFAR
T. Kupfer	16 07 2015	NOVA	Groot	The population of ultracompact binaries and their progenitors
P. Schellart	02 03 2015	NOVA / EC / NWO	Falcke	Measuring radio emission from air showers with LOFAR
C. Abate	10 12 2014	NOVA	Verbunt co: Pols	Formation and evolution of carbon-enhanced metal-poor stars
S. Shah	24 11 2014	Other	Nelemans co: Sluys	The Synergy between Gravitational Wave and Electromagnetic Data of Compact Binaries
A.F. Nelles	01 10 2014	Other	de Jong co: Hörandel	Radio emission of air showers The perspective of LOFAR and AERA
S. van Velzen	02 09 2014	ERC / Spinoza	Falcke co: Körding	Jets from supermassive black holes: from cosmic to human timescales
O. Madej	08 07 2014	NOVA	Verbunt co: Jonker	Probing fundamental properties of accreting compact objects with X-ray and optical spectroscopy
J.S.W.A Claes	18 11 2013	NOVA	Verbunt co:Pols	The binary progenitor evolution of supernovae
M.T.B. Nielsen	15 11 2013	NWO	Nelemans, Dominik	X-Ray Emissions from Progenitors of Type Ia Supernovae
S.G.M. Toonen	07 10 2013	NOVA	Nelemans, Groot	The evolution of close binaries with white dwarf components
K. Verbeek	11 09 2013	NWO / NOVA	Groot	Evolved stars in Galactic Plane surveys
L. van Haaften	12 03 2013	NWO	Nelemans, Groot co: Voss	Ultracompact X-ray binary stars
C. Pinto	26 02 2013	SRON	Verbunt	The composition of the interstellar medium in the Galaxy as seen through X-rays

5. NOVA INSTRUMENTATION PROGRAM

The interrelated research and instrumentation programs are the two fundamental pillars under the NOVA collaboration. This is a significant change compared with 20 years ago before NOVA funding was available, when Dutch astronomy suffered from a lack of investment and expertise in optical astronomical instrumentation. The NOVA philosophy is that cutting-edge science is the product of training top scientific talent and providing them with access to state-of the art research facilities. The close connection between science and instrumentation has many advantages: Intimate knowledge of the instrument design and capabilities allows NOVA astronomers to maximize the scientific output. The instrumentation expertise also means that the community is aware of emerging technologies that will be needed to answer new scientific questions that are beyond the capabilities of today's astronomical instruments. Lastly, investing in instrumentation allow Dutch astronomers to be the first to use many new instruments through allocated guaranteed observing time.

NOVA concentrates on developing instruments for the optical and infrared wavelength ranges and sub-mm instruments for the Atacama Large Millimeter/submillimeter Array, ALMA. Strong collaborations are also maintained with the Dutch institutes ASTRON on instrumentation for radio astronomy and SRON for space instruments. ESO has been the focus of most NOVA instrumentation efforts, with NOVA acting as the Dutch national home base for ESO.

The NOVA instrument program is highly successful: to date, NOVA has delivered or made sizable contributions to six instruments for ESO's Very Large Telescope (VLT), with a seventh, MATISSE, currently undergoing final integration and testing at the PI institute in Nice. Four projects are currently underway for instruments for the future European Extremely Large Telescope (E-ELT) of which one, the mid-infrared imager and spectrometer METIS, has formally been approved for design and construction as one of the three first-light instruments. As the PI institute, NOVA is leading the development of this instrument. NOVA has played a leading role in the design and construction of the Band-9 receiver cartridges for ALMA and is currently leading the work on the Band-5 cartridges.

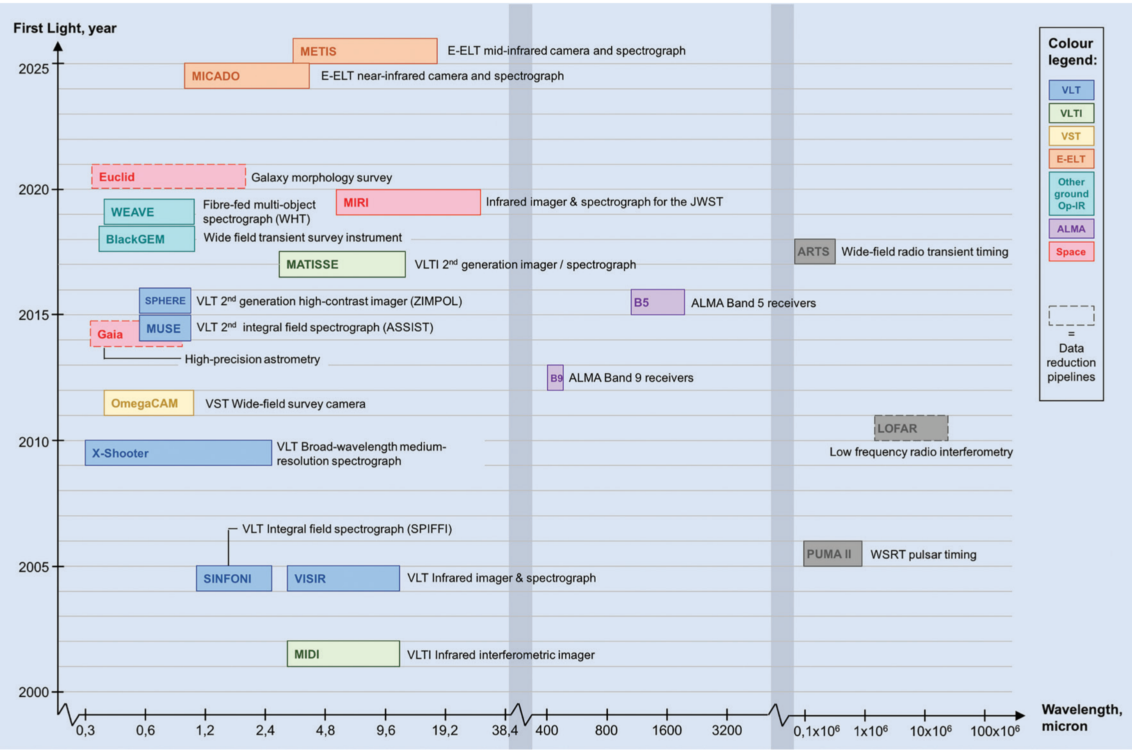

Fig. 5.1: Overview of astronomical instruments delivered or under development to which NOVA has made a significant hardware contribution.

Another measure of the success of the NOVA instrumentation program is the amount of leveraging resulting from the NOVA investments in instrumentation. The unique expertise built up in the design and manufacture of astronomical instruments has resulted in NOVA becoming a sought-after partner for international consortia in instrumentation projects. This financial turnover has allowed NOVA to seek and obtain additional funding from both national and international funding agencies. The turnover in the NOVA instrumentation program is significantly higher than the NOVA investment.

The NOVA instrumentation program is not limited to the design and construction of instrument hardware. Many NOVA projects emphasize the science exploitation phase and focus on the data reduction, calibration and astrophysical modelling. In this area, NOVA is active in the development and operation of science ground segments for astronomical space missions (e.g. GAIA, JWST, Euclid) and has in particular built up expertise in science exploitation of very large datasets. Examples are the OmegaCEN and MUSE-WISE data centers for the OmegaCAM and MUSE surveys. Furthermore the NOVA instrumentation program also includes science verification through modelling (e.g. AMUSE software) and laboratory experiments (the Sackler laboratory for astrophysics).

Fig. 5.2: Members of the NOVA Optical-Infrared instrumentation group.

NOVA optical-IR instrumentation group

The NOVA Op-IR group is responsible for most of the design and construction work on NOVA instruments operating at optical and infrared wavelengths. The group works under the leadership of NOVA, is co-located at the ASTRON radio astronomy institute for historical reasons and staff is employed by NWO. The hosting agreement between NOVA, ASTRON and NWO currently runs until end 2018.

The group consists of 16 experienced people (see chapter 6 for full list) and is led by Navarro. The combined expertise covers optical, mechanical, and cryogenic design, system engineering, CNC and optical production capabilities, instrument integration, and verification. Over the last decade the group has carried out the optical-IR instrumentation projects for which NOVA had final responsibility towards ESO, ESA, and international partners (Fig. 5.3).

In the reporting period the Op-IR group worked on the following major projects: the VLT 2nd generation instrument SPHERE-Zimpol, the VLTI 2nd generation instrument Matisse, the WEAVE multi-object spectrometer for the William Herschel telescope of the ING observatory on La Palma and the E-ELT instruments METIS and Micado. The group has also been involved in numerous (Phase-A) design studies for future instruments, both for the E-ELT and other telescopes. Some of the group's time is also spent on technical R&D and on collaboration with industry on technology spin-off.

Fig. 5.3: List of optical and infrared instruments for the VLT with a substantial NOVA participation.

The sub-millimeter group

A group of 6 specialists is working for NOVA on the development of sub-mm receiver cartridges for ALMA. This group is connected to the Kapteyn astronomical institute and located at the SRON institute in Groningen and builds on heritage that SRON has developed for HIFI sub-mm spectrometer for the Herschel Space Observatory.

The ALMA group has been responsible for the delivery of the ALMA Band-9 receivers and is now undertaking the final design, assembly and verification of the receivers for Band-5 in collaboration with GARD, a division of the Onsala Space Observatory connected to Chalmers University in Gothenburg, Sweden. Time is also invested in R&D on sub-mm technology for the next generation ALMA receivers and for a possible survey telescope at Chajnantor. The technology used in the receivers is very demanding: the superconducting heterodyne SIS mixers operate at deep cryogenic temperatures and the manufacturing tolerances for the wave guides and mixers are extremely exacting, in particular on the higher-frequency Band-9 receivers. One focus area in the R&D is the development of side-band separating (2SB) receivers for Band-9. When completion is achieved in 2017 this will be a world record for this type of receivers in the high-frequency range.

As the ALMA array consists of 66 dishes, 72 receiver cartridges, including spares, must be delivered for each band. The assembly and testing of the ALMA receivers therefore has an element of series production unknown to most other astronomical instrumentation projects. Over the last few years, the NOVA ALMA group has mastered the art of efficiently assembling and testing these receivers in a continuous flow. The series production was not suitable for transfer to industry because of the state-of-the-art technology and extreme demanding verification measurements.

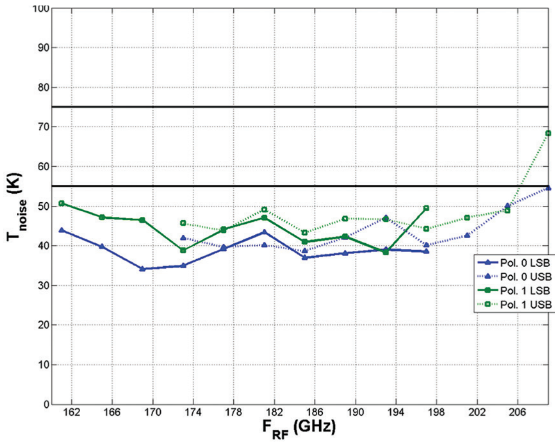

Fig. 5.4: *Left: NOVA sub-mm group member Jan Barkhof working on a Band-5 cartridge. Right: Band-5 receiver noise temperatures as measured during verifcation work in preparation for the Manufacturing Readiness Review. The measured noise is significant below the specifications, indicated with the black lines.*

5.1 Optical-Infrared Instrumentation

Project PI:
Brandl

NL Co-Is:
Caputi
van Dishoeck
Helmich
Hogerheijde
Jaffe
Kamp
Kaper
Keller
Kenworthy
De Koter
Dominik
Larsen
Peletier
Snellen
Spaans
Stam
Stuik
van der Tak
Tielens
Trager
Waters

NL team:
Agocs
Bettonvil (NL PM)
Doelman
Elswijk
Jager (Intern. PM)
Kenworthy
Koops
Kroes
Pauwels
Roelfsema
Stuik
Venema
Veninga

5.1.1 E-ELT METIS

The E-ELT, which is currently being built in northern Chile by ESO, will be the largest optical/near-infrared telescope in the world. With an aperture of 39 meters in diameter, it will gather 13 times more light than the largest optical telescopes existing today, sufficient to tackle challenging scientific questions concerning high redshift galaxies, star formation, exoplanets and protoplanetary systems. In December 2014, the ESO Council gave the green light for the construction of the E-ELT in two phases with first light of the telescope in 2024.

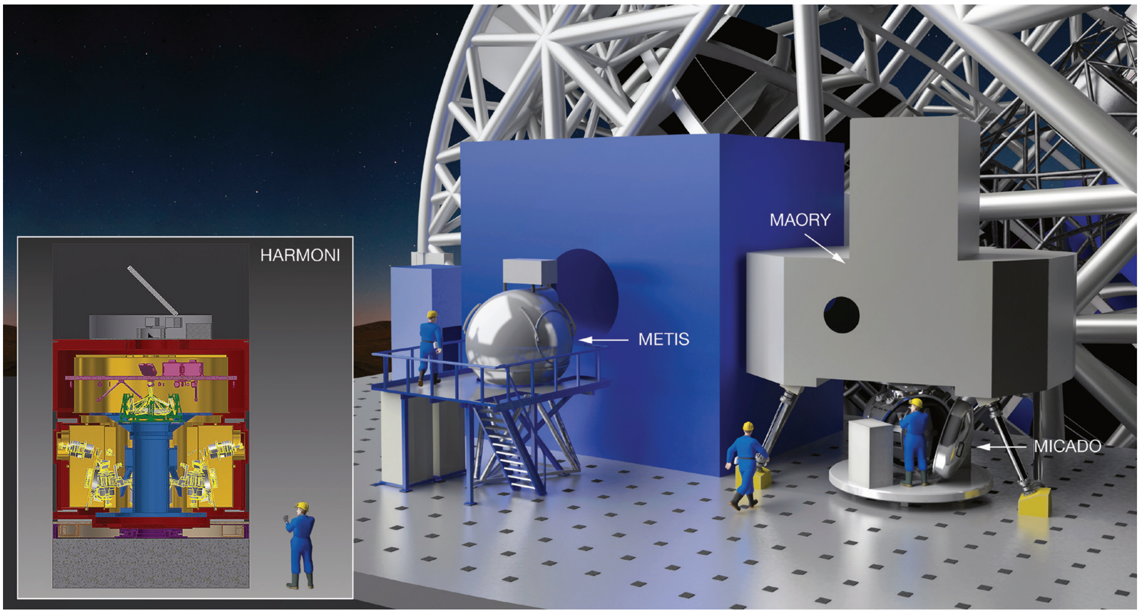

Fig. 5.5: *Figure accompanying the ESO accouncement on the selection of the first three scientific instruments for the E-ELT. Following the recommendations of its Finance Committee (FC) and Scientific Technical Committee (STC), the ESO Council authorized the Director General to sign the contracts for the first set of instruments for the E-ELT. These huge and innovative tools to analyse the light collected by the giant telescope will allow the E-ELT to address a wide range of astronomical questions soon after its completion.*

Following recommendations by the E-ELT Science Working Group, the E-ELT Project Science Team, and ESO's Scientific Technical Committee (STC) the three first science instruments have been identified. These are the NIR camera MICADO and its associated AO system MAORY, the NIR spectrograph HARMONI, and the Mid-infrared ELT Imager and Spectrometer (METIS). This selection was announced in July 2015 (Fig. 5.5).

METIS will be built by a consortium of seven institutes, led by NOVA (PI: Brandl, Leiden University). The other six partner institutes are MPIA Heidelberg (Germany), CEA-Saclay (France), UK-ATC (United Kingdom), KU Leuven (Belgium), ETH Zürich (Switzerland), and the A* Consortium, led by the University of Vienna (Austria). The consortium draws from its long-term successful experience with numerous ground- and space-based infrared instruments, including VISIR, NACO, CRIRES, ISO, Spitzer, Herschel, and most recently MIRI for the JWST.

The total cost of METIS is approximately 50 M€, of which approximately 15 M€ are for hardware, which is mostly covered by ESO. In return for the staff effort, the METIS consortium will receive 65 nights of guaranteed observing time (GTO) from ESO. With almost 40%, NOVA provides the largest contribution to the project, closely followed by MPIA. The main costs for NOVA are subdivided in consortium management (4.5 M€), systems engineering (3.5 M€) and other NOVA work packages, amounting to 7 M€ (including the fore optics, cold backbone structure, coronagraph, systems AIV, instrument simulator, and calibration plan). The planned efforts gradually increase during the upcoming design phases, and reach their maximum around the Final Design Review and the start of the manufacturing (2019/21), after which they will slowly decrease until acceptance in Chile in 2025.

Scientific Goals

With its unique combination of high angular and spectral resolution, METIS will open up a new parameter space for infrared astronomy, and enable observations which have never been possible before. METIS is a general purpose science instrument focusing on a wide range of targets from Solar System bodies, charaterization of exoplanets to distant starburst galaxies, in areas where METIS will be fully complementary to ALMA and JWST (Fig. 5.6).

Main science focus of METIS will be in two areas:

Proto-planetary disks: The initial conditions for planet formation within protoplanetary disks and the formation

***Fig. 5.6:** Overview of the main science drivers for METIS.*

of the planets themselves will be a main focus area for METIS. This includes measuring the composition and kinematics of gas and dust inside of 10 AU in young disks as well as looking for signs of dust and gas evolution when disks at different evolutionary stages are observed. METIS will also search for direct and indirect signs of forming planets embedded in the gas and dust rich disks of their host stars and may even be able to detect molecular line emission from circumplanetary disks. For more mature systems, METIS will search for and image exo-zodiacal dust disks around the nearest stars, which is particularly important for potential planet searches in these systems, and constrain the dust properties and radial extent of warm debris disk belts.

Exoplanets: METIS will have significant impact on both the detection and the characterization of extrasolar planets. In terms of exoplanet demographics METIS will be able to image, for the first time, a large sample of gas giant planets with an empirically determined mass and to reveal in large numbers long-period gas giant planets around nearby stars. Its high-dispersion spectroscopy mode will allow METIS to characterize dozens of hot Jupiters and hot Neptunes (transiting and non-transiting) and to investigate rotation periods and cloud coverage of more distant giant planets. Finally, around the nearest stars, METIS might be able to directly image small (Earth- or super-Earth-sized) planets under favorable conditions, leading the way to the characterization of such objects.

Instrument Description

METIS will be the only instrument covering the thermal/mid-infrared wavelength range on the E-ELT. It will provide diffraction limited performance in several modes:

- broad and narrow-band imaging from 3 – 19 μm,
- coronagraphy from 3 – 13 μm,
- low-medium resolution (R ~ few hundred - thousands) slit spectroscopy from 3 – 13 μm,
- high resolution (R ~ 100,000) IFU spectroscopy from 2.9 – 5.3 μm.

METIS offers a moderate field of view of at least 10" x10", which is corrected for atmospheric turbulence by a single conjugate (SC) – and later also a laser tomography (LT) – adaptive optics (AO) system. The design of the SCAO system is driven by the exoplanet science case, while the LTAO system is motivated by the lack of sufficiently bright guide sources in many science areas. METIS will be located at a lateral port on the Nasmyth platform (Fig. 5.5).

All subsystems and components of METIS will be built by either the NOVA Op-IR group or other partners. After initial local testing, these subsystems will be integrated, aligned and tested at system level at the AIV facility in the Netherlands, followed by thorough performance testing, and instrument calibration. The testing will involve personnel from all METIS partner institutions.

Recent progress

Although the work on METIS goes back to a non-committal phase A study in 2009, many milestones

***Fig. 5.7:** The METIS team applauds the signature of the METIS Agreement, signed by de Zeeuw (ESO, front, left) and te Beest (University Leiden, on behalf of NOVA, front, right). On the table to the left is the LEGO model of the E-ELT, developed by Snik*

were achieved between 2013 and 2015. By early 2015, the proposed METIS concept had been successfully reviewed by several internal and advisory committees of ESO, who provided valuable feedback. Within the so-called Interim Study, which started in late 2014, the Technical Specifications for METIS have been defined, the Statement of Work (SoW) was composed, and the Agreement between ESO and NOVA was prepared for signature, as well as updates to the science case and improved technical solutions. Finally, the agreement was signed on September 28th, 2015 in Leiden. The signing ceremony was performed by the ESO Director General, Tim de Zeeuw, and the Vice-President of the College van Bestuur of University Leiden, Willem te Beest, in the presence of NOVA representatives, and the key personnel of the METIS team (Fig. 5.7).

Essential to the selection of METIS was its technological readiness, which has been raised significantly by the national Roadmap funded technology development program. Most notably, two challenging key components of METIS have been developed in the past years: (1) an immersed silicon grating, a joint development between NOVA, SRON and MiPlaza/Philips, which provides a significant reduction in physical size of both grating and the surrounding optical system of the spectrometer, and (2) a fast, very precise, and cryogenic beam chopping mirror, which is essential in operations for the calibration of the thermal background in the science data. The chopper was a joint project between Janssen Precision Engineering, SRON and NOVA (Fig. 5.8).

During the period 2013 – 2015 the METIS project has also seen personnel changes in several key areas, most notably the appointments of Rieks Jager (NOVA, consortium project manager), Felix Bettonvil (NOVA, Dutch project manager), Sascha Quanz (ETH Zurich, project scientist) and Roy van Boekel (MPIA Heidelberg, instrument scientist). In addition, ESO appointed Ralf Siebenmorgen as the ESO science contact person and Christoph Haupt as management lead at ESO.

In the reporting period two PhD students successfully defended their theses on METIS related technical R&D: Wu (UT Twente) on sorption cooling, and Huisman (RUG/SRON) on the chopper control scheme.

Outlook

METIS is the largest Op-IR instrumentation project for NOVA. It provides excellent exposure of the high quality of astronomical instrumentation, and will offer unique scientific opportunities for the astronomical community. With PDR in 2018 and FDR in 2020, METIS is on track to its first light in 2025.

***Fig. 5.8:** Dutch Prime Minister Mark Rutte (left) visits Janssen Precision Engineering (JPE) in Maastricht and admires a prototype of the METIS beam chopper.*

5.1.2 E-ELT MICADO

MICADO is the first light instrument for the E-ELT providing an adaptive optics camera and slit spectrometer. The dramatically increased spatial resolution of a large aperture telescope is only enabled if it can work at or close to its diffraction limit. MICADO is designed to make use of both single conjugate (SCAO) and multi-conjugate (MCAO) adaptive optics facilities to regularly obtain diffraction limited images of unparalleled sensitivity straight away from the first light of the E-ELT. MICADO also includes a slit spectrometer for fast follow up of MICADO imaging.

MICADO Science

MICADO will allow breakthroughs in a broad range of scientific fields, including: black holes in the center of globular clusters and galaxies, including our own Galaxy; accurate proper motions for nearby galaxies and globular clusters; resolving individual Red Giant Branch stars in the central regions of distant elliptical galaxies; high resolution imaging and spectroscopy of individual star formation regions in high red-shift galaxies and strong gravitational lenses; discovery and characterization of Supernovae and Gamma ray burst explosions at high redshift. MICADO will be right from the start of operations at the forefront of high spatial resolution sensitive optical/infrared imaging and long wavelength coverage spectroscopy in the new era of ELTs.

NOVA Contribution to MICADO

The NOVA contribution to MICADO includes scientific support, and hardware contributions (Atmospheric Dispersion Corrector (ADC), focal plane unit & filter wheels) and software (data flow and pipelines). These contributions are carefully chosen to support the Dutch scientific and technical interests. It makes NOVA one of the major partners in the MICADO consortium. The PI (Ric Davies) is at MPE, which is an institute with a long history of developing and building successful Adaptive Optics instrumentation. MPE is making the major investment in this project, and other international partners include MPIA, Munich Observatory, Göttingen, LESIA at Paris Observatory and the A* consortium of Austrian Institutes (Vienna, Innsbruck & Linz).

Outlook

The MICADO project has been on hold since the end of the Phase A study in 2009/10 and had its restart with the signing of the design and construction agreement with ESO in September 2015 and the consortium Phase B kick-off in October 2015. Over the last few years the NOVA MICADO team has carried out two pre-studies to further develop the ADC concept and to determine the optimum functionality with respect to the location in the light path. Work at NOVA on the preliminary design of the ADC and the data flow system started in October 2015. The Consortium also started an update and expansion of the science case which had been untouched since the Phase A study from 2009.

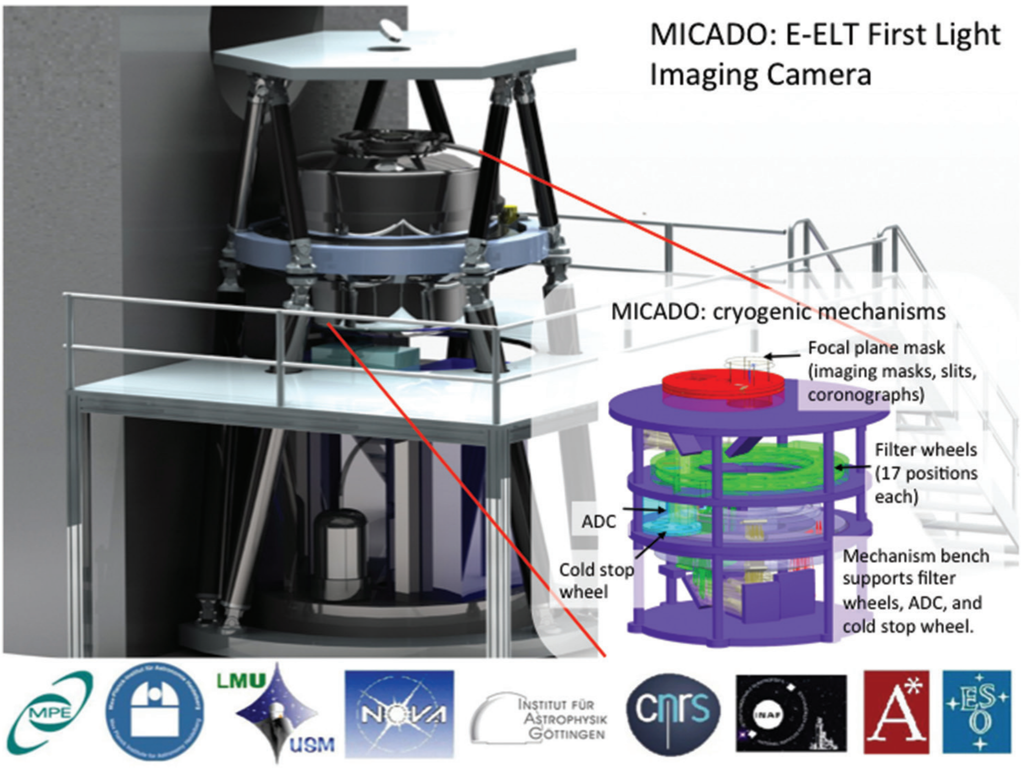

***Fig. 5.9:** Computer drawing of MICADO at its place on the Nasmyth platform of the E-ELT. The insert shows the cryogenic mechanisms section which will be delivered by NOVA.*

Project PI:
Davies (MPE, Garching)

NL PI:
Tolstoy

NL Co-Is:
Franx
Helmi
Koopmans
Kuijken
Larsen
Massari

NL team:
Agocs
Navarro (PM)
Stuik
Verdoes Kleijn

5.1.3 E-ELT MOSAIC

NL PI:
Kaper

NL Co-Is:
Caputi
De Koter
Groot
Labbe
Larsen
Lemasle

NL team:
Navarro (PM)
Roelfsema
Lemasle

MOSAIC will become the multi-object spectrometer for the E-ELT. It is expected to become the workhorse instrument for astrophysics, intergalactic medium studies and cosmology in the coming decades. MOSAIC will fully explore the large aperture and superb spatial resolution of the biggest eye on the sky. Key science cases involve searching for extra-galactic planets, resolving stellar populations in thousands of nearby galaxies, and studying high-redshift galaxies at the edge of the visible universe.

Instrument description

MOSAIC is envisaged as a fiber-fed spectrometer, covering the telescope's full field of view with several hundred fibers, and includes a dozen integral field units with adaptive optics capability delivering milli-arcsec spatial resolution, providing spectra ranging from the ultraviolet to the near infrared (380 – 2500 nm) at intermediate spectral resolution. It combines the flexibility and high multiplex of a fiber-fed spectrometer and the superb spatial resolution of AO assisted integral field units. These two concepts were evaluated during the phase A studies of, respectively, OPTIMOS-EVE (PI Hammer, NL-PI Kaper) and EAGLE (PI Cuby, no NL involvement). These phase A studies were successfully completed in 2010. Inspired by the common-focal plane approach of e.g. the Hubble Space Telescope, the OPTIMOS-EVE and EAGLE concepts were merged into one instrument concept called MOSAIC. In the period 2013-2015 Kaper (NL PI and Co-I of the international project Board, Navarro and Lemasle (NOVA postdoc funded from Roadmap program until August 2015) were actively involved in this merging process, preparing for a conceptual design study of the E-ELT/MOS starting in 2016.

The MOSAIC consortium

The MOSAIC consortium includes scientists from Brazil, France, The Netherlands, and the United Kingdom, as main partners. Another six European countries are associated with the consortium at different levels.

Status and outlook

In March 2015 Kaper and Navarro visited the University of Sao Paulo (USP) and the National Institute for Astrophysics (LNA) in Brazil during the workshop on Advanced Instrumentation organized by FAPESP and NWO in Sao Paulo. A direct result of that visit was the submission (and acceptance) of a proposal to NWO and FAPESP to study and develop the fibers to spectrometer interface (fiber-slit assembly). ESO released the Call for Proposals for the E-ELT/MOS phase A study in the summer of 2015, including top-level requirements with an almost perfect match to the E-ELT/MOS White Paper (Evans et al. 2015) prepared by the MOSAIC consortium. ESO has accepted the proposal of the MOSAIC consortium; the phase A study starts in Q1 2016 and will last 18 months. The Netherlands will be involved in the design and development of the optical spectrometers, the data reduction system, project science and project management.

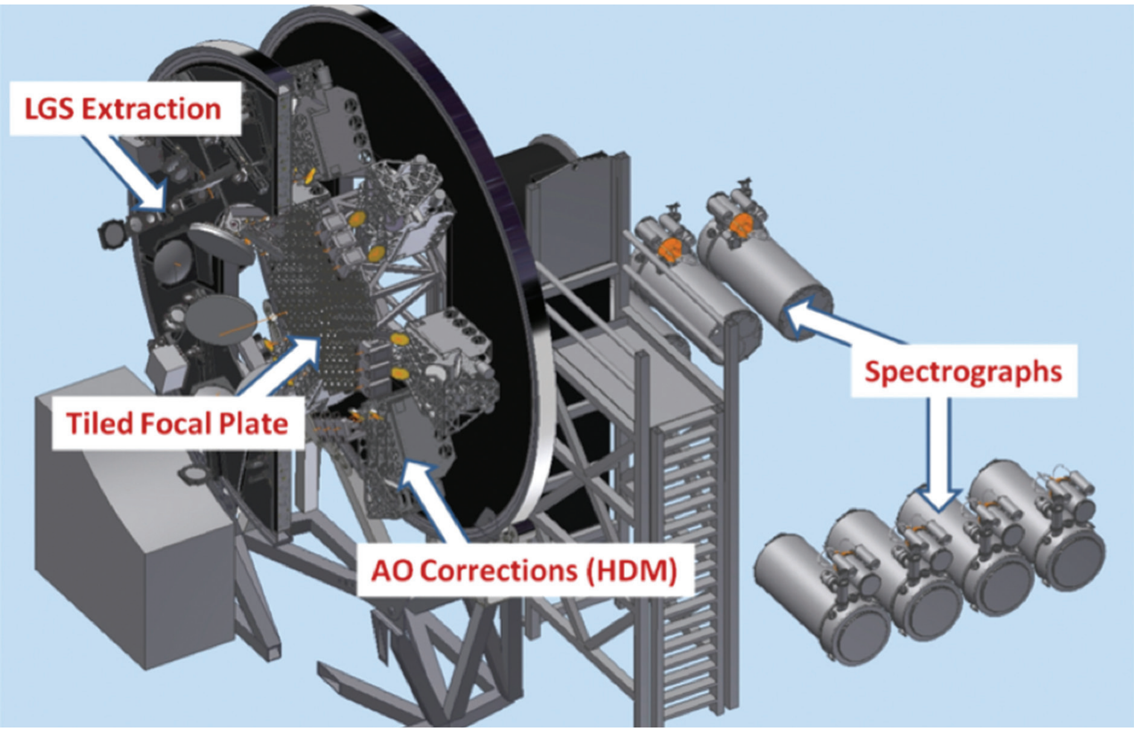

***Fig. 5.10:** Preliminary design of MOSAIC, the multi-object spectrometer for the E-ELT. During the phase A study, NOVA will be involved in the design and development of the spectrometer.*

5.1.4 E-ELT EPICS

EPICS is the E-ELT high-contrast imager for the characterization of exoplanets including rocky exoplanets in the habitable zone. Due to its importance for the scientific success of the E-ELT, EPICS has already been approved for construction. To bring the required technologies to a level where construction could begin, NOVA efforts on EPICS over the last three years have focused on developing key technologies and understanding systems aspects.

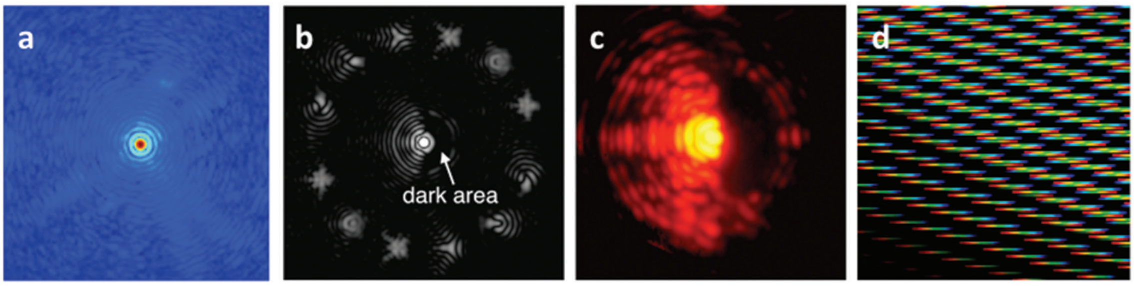

Fig. 5.11: *a) Laboratory wavefront correction with more than 50,000 actuators using the new Fast & Furious algorithm; b) Simulation of a combined coronagraph and focal-plane wavefront sensor using a single holographic element; c) On-sky image of a star with the new vAPP coronagraph at the MagAO facility; d) A part of Venus observed with the ExPo spectropolarimetric Integral Field Unit at the WHT.*

Scientific goals

EPICS will answer the following scientific questions: are planetary systems like the Solar System common? How frequently do rocky planets settle in habitable zones, where water is liquid on the surface? Do the atmospheres of exoplanets resemble those of the planets in the Solar System? How is pre-biotic material distributed in protoplanetary discs? Are there signs of life on any exoplanets?

Instrument description

To achieve its science goals, EPICS will combine: 1) *Extreme Adaptive Optics* to minimize wavefront aberrations; 2) *Advanced coronagraphy* to minimize diffracted starlight; 3) *Sensitive spectroscopy and polarimetry* to distinguish exoplanet light from starlight and detect methane, carbon monoxide, water vapor, liquid water and molecular oxygen; 4) *Data reduction methods* to provide additional separation of true exoplanet signals from remaining starlight.

During the Phase A effort in 2008-2010, a conceptual design was developed. This design will be updated during the coming years based on the experience gained with SPHERE at the VLT and other high-contrast imaging efforts.

Progress and results in 2013-2015

Over the last three years, major breakthroughs have been achieved in several of the key technologies that are needed for EPICS: 1) A new 'Fast & Furious' adaptive optics control algorithm that scales almost linearly with the number of actuators and can achieve Strehl ratios of >0.98 in laboratory testing; 2) The construction of broadband apodizing phase plate (APP) coronagraphs using self-aligning liquid-crystal patterns. These have been used on-sky at the Magellan and Large Binocular Telescopes, delivering record-breaking coronagraphic performance; 3) Combining APP coronagraphs with holograms allowing direct measurement of wavefront aberrations in the science focal plane; 4) Using the same liquid crystal technology to combine a grating and a polarizing beam-splitter in a single optical element. When combined with a micro-lens array, the first single-shot spectro-polarimetric images of planets and circumstellar disks were obtained at the William Herschel telescope on La Palma; 5) All polarimetric high-contrast imagers are far from reaching the photon noise close to the star. It has now been recognized that this is due to polarization aberrations that classical optical design codes neglect. With this new insight, it will be possible to design EPICS such as to minimize these effects and achieve much better performance.

Outlook

Research and development on key technologies and systems aspects will continue in the Netherlands over the coming years, followed by design Phase B, construction and ultimately operation at the E-ELT. The following R&D work packages for the Netherlands have been identified:

- Wavefront control at high spatial and temporal frequencies
- Sensing the wavefront at the science focal plane
- Understanding systematic polarimetric errors
- Developing broadband coronagraphic optics
- Developing broadband polarization measurements
- Implementing integral-field spectropolarimetry
- Integration of all optical techniques into an optimal system

EPICS technology spinoffs

The extreme optical technology requirements for EPICS lead to many innovative uses in other disciplines. Examples of these are shown in Fig. 5.12.

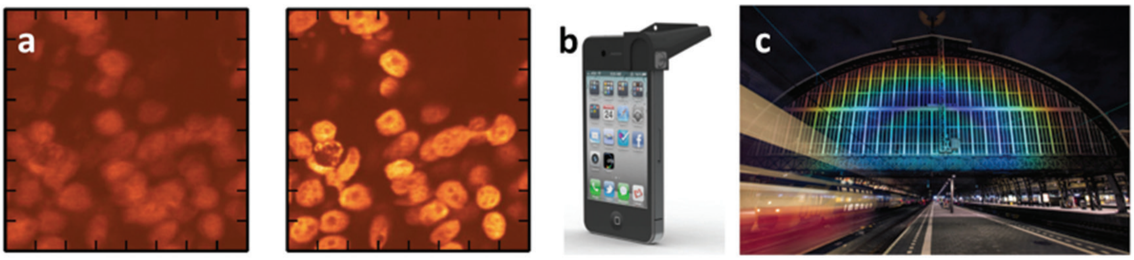

Fig. 5.12: *a) Two-photon microscope images of breast-cancer cells without (left) and with (right) astronomical adaptive optics technology. b) iSPEX spectro-polarimeter that allows smartphone owners to measure aerosols with plastic optics derived from astronomical polarimetry. c) Rainbow over Amsterdam Central station created with liquid-crystal elements that were developed for astronomical coronagraphs.*

NL PI:
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Doelman
Dominik
Fridlund (ESA)
Hogerheijde
Kamp
Kenworthy
Min
Rodenhuis
Snik
Stam
Verhaegen (Delft)
Waters (SRON)

NL team:
Bettonvil (PM)
Navarro
Roelfsema
Stuik
Venema

5.1.5 WEAVE

WEAVE is a multi-object spectrometer and multi-integral-field-unit (IFU) facility utilizing a large, new 2º-diameter prime focus corrector at the WHT with a pick-and-place fiber positioner system hosting 1000 multi-object fibers or 20 mini-IFUs (mIFUs) for each observation, or a single wide-field IFU (the large IFU, LIFU). The fibers are fed into a dual-beam spectrometer located in the GHRIL enclosure on the telescope's Nasmyth platform. The spectrometer measures nearly 1000 spectra simultaneously at a spectral resolution of R~5000 over an instantaneous wavelength range of 366–959 nm. In high-resolution mode this is R~20,000 over two more-limited wavelength regions. When WEAVE is complete in 2018, it will be the most capable (in terms of field size x number of fibers x resolution x wavelength coverage x system efficiency) wide-field multi-object spectrometer on any telescope and the only massively-multiplexed high-resolution spectrometer in the Northern Hemisphere. WEAVE is the instrument required for full scientific exploitation of the Gaia, LOFAR, and APERTIF surveys in the Northern Hemisphere, as recommended by the ASTRONET Roadmap from 2007. WEAVE will also be used to study the evolution of stars, the co-evolution of galaxies and their environments, and the structure of the Universe.

NL PI:
Trager (also WEAVE deputy PI & project scientist)

NL PM:
Pragt (also WEAVE deputy PM & spectrograph PM)

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Brown
Peletier
Tolstoy
Morganti
Kuijken
Groot
Larsen
Kaper
Koopman

NL team:
Elswijk
Hanenburg
Jasko
Kroes
Lesman
Stuik
Tromp

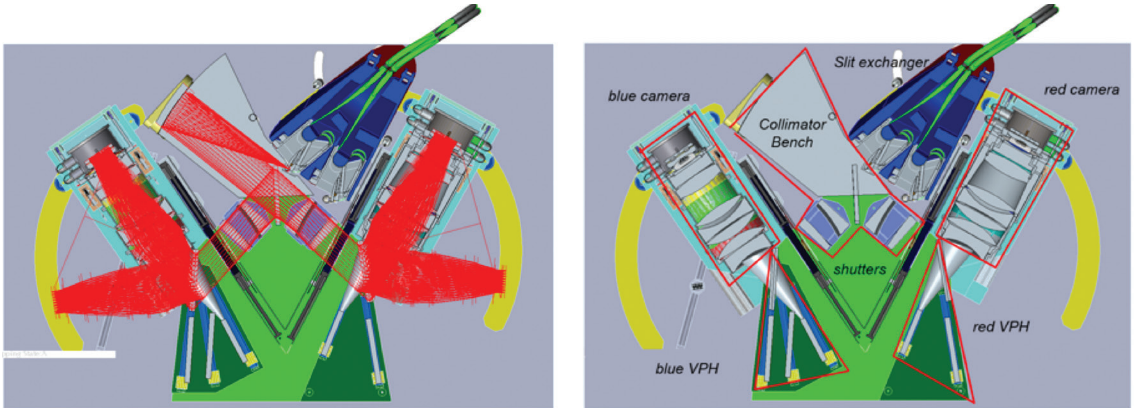

***Fig. 5.13:** Top view of the spectrometer, NOVA's primary contribution to WEAVE, showing both low-resolution and high-resolution optical paths (left) and the main units (right).*

Consortium & NOVA contribution

WEAVE is a collaboration between the UK (STFC RAL Space and Oxford, Liverpool John Moores, and Cambridge University), NOVA, Spain (IAC), the Isaac Newton Group of Telescopes, France (GEPI), Italy (INAF), Hungary (Konkoly Observatory), and Mexico (INAOE). RAL Space/Oxford University jointly has the PI role, and NOVA holds the Deputy PI role. It is responsible for the WEAVE spectrometer system. This includes management, design, manufacturing, assembly, integration, testing and commissioning.

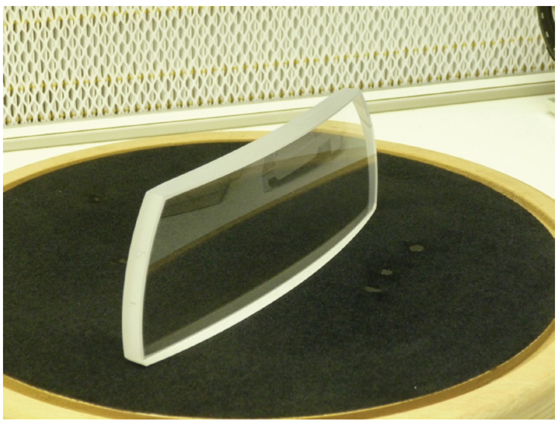

***Fig. 5.14:** One of the five slitlenses in the NOVA Op-IR lab (produced by FineOptix in Germany).*

Mechanical design, mechanisms, mechanics, and optics are provided by NOVA. The detector and cryostat subsystem is provided by Liverpool John Moores University (UK), and the VPH grating subsystem is provided by INAF. Optical design for the spectrograph system is provided by RAL (UK), optical procurement and alignment is handled by NOVA, and polishing and coating is done by INAOE (Mexico), as in-kind contribution to the project, with some pieces polished by TNO (NL). Instrument control is provided by the IAC (Spain), Padova (INAF), and the ING. Responsibility for this system is held by NOVA's Optical-IR instrumentation group. NOVA is also responsible for design of the LIFU and mIFU subsystems of the WEAVE fiber system, including management, optical design (for both IFU subsystems) and mechanical designs (for the LIFU subsystem only), as well as manufacturing, assembly, integration, and testing (MAIT) of the LIFU subsystem. The Netherlands is also responsible for the development of the science case and survey planning.

Progress and outlook

WEAVE has progressed substantially in the period 2013–2015, completing its preliminary design review in March 2013 and passing nearly all of its Final Design Reviews (FDRs, which have been held on a per-system basis) by the end of 2015. Regarding NOVA's responsibilities, the spectrometer passed its optical FDR in January 2014 and its system-level FDR in March 2015. NOVA's contribution to the WEAVE spectrometer is now in the MAIT phase, with final drawings nearly complete, optical blanks delivered (with some being sent on to manufacturing, including the slit-lenses, one of which can be seen in Fig. 5.14), mechanical production underway, and the slit exchange unit (the large blue unit just off the upper center of Fig. 5.13) under assembly, as seen in Fig. 5.15. Component testing is also in progress. Three of four CCDs have arrived at LJMU, and all are better than originally specified. Other systems and subsystems in the MAIT phase at the end of 2015 included the Prime Focus Corrector optics being figured and polished at KiwiStar (NZ); the Prime Focus Corrector rotator under construction at SENER (ES); the Fiber Positioner system at Oxford (UK); and two of the three data flow systems, the Core Processing System at Cambridge (UK) and the Advanced Processing System at IAC (ES).

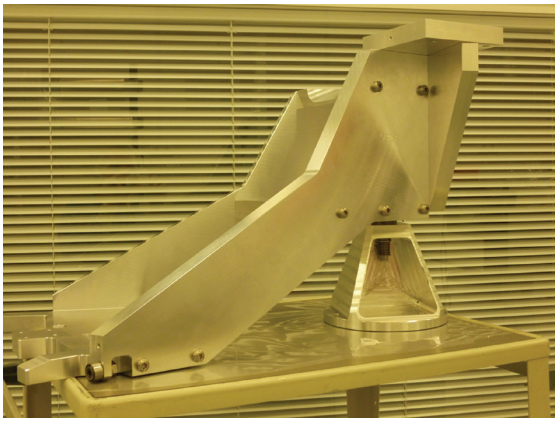

Fig. 5.15: *The slit translation mechanism in the NOVA Op-IR lab cleanroom.*

WEAVE's science case and survey strategy was very positively reviewed by an external panel of experts in late 2015, setting the stage for a refined and competitive science program. Three major science topics, the evolution of stars, galaxies, and the Universe, are represented by six proposed WEAVE surveys: Galactic archaeology and stellar, circumstellar, and interstellar physics, both exploiting Gaia's harvest; galaxy clusters; galaxy evolution, exploiting the new Westerbork front-ends APERTIF; WEAVE-LOFAR, providing optical properties of LOFAR sources; and WEAVE-QSOs, determining the size of the Universe at one-tenth its current age. Together, these surveys have been guaranteed 236 nights per year of WEAVE observations on the WHT for the five years after commissioning, currently expected for the middle of 2018.

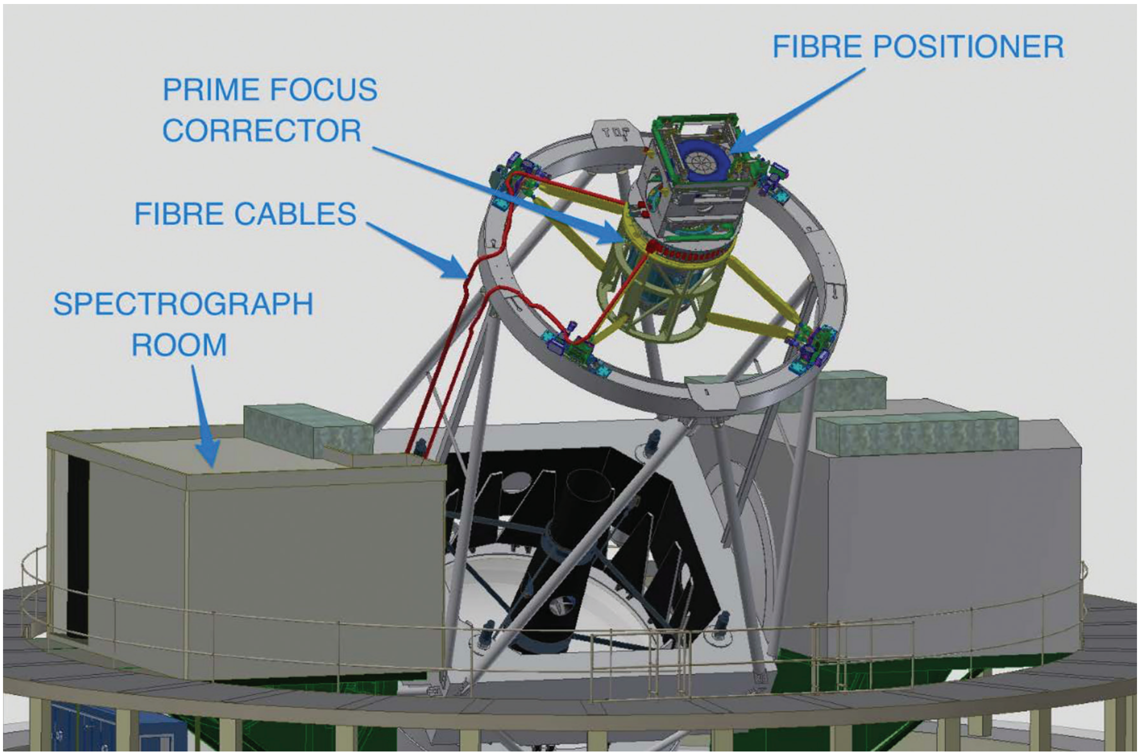

Fig. 5.16: *Image showing the new top end of the William Herschel Telescope with the WEAVE fibre positioner and prime focus corrector. The WEAVE spectrometer is installed in an enclosure on one of the Nasmyth platforms.*

NL PI:
Dominik

NL Co-Is:
Keller
Kenworthy
Min
Rodenhuis
Snik
Thalmann
Waters

NL team:
Elswijk
de Haan
Kragt
Roelfsema
Pragt (PM)

5.1.6 VLT SPHERE-ZIMPOL

SPHERE (Spectro-Polarimetric High-contrast Exoplanet Research) is the new high-contrast imaging instrument on the VLT. SPHERE was produced by a large international consortium with members from 12 institutes in 6 countries, including NOVA. The consortium was formed by a successful merger of two initially competing consortia. The result was a complex instrument that provides high-order corrected adaptive optics images to three science instruments at optical and infrared wavelengths. The complexity of the instrument has caused some delays on the way to Paranal, but the instrument now offers the currently worldwide best performance for high-contrast imaging.

Instrument description

SPHERE consists of an extreme adaptive optics system SAXO that uses a deformable mirror with 1681 actuators driven by a Shack-Hartmann wave front sensor to provide a highly stable PSF to the science instruments of SPHERE. The common path also offers a wide set of coronographs, including classical Lyot coronographs, 4 quadrant phase masks for Y, J, and H bands and an apodized pupil Lyot coronograph. All science instruments have pupil-imaging lenses. SPHERE contains three science instruments:

IRDIS (InfraRed Dual Imaging System) is a dual-band imager that can be used to simultaneously image an 11x12.5 arcsecond field of view at two different wavelength or two different polarization directions. IRDIS provides spectral and polarimetric differencing modes as a means of enhancing contrast. The wavelengths coverage of this imager ranges from 0.95 to 2.3 µm (Y to Ks bands).

IFS, the Integral Field Spectrometer images a small 1.77x1.77 arcsecond field into 145x145 spectra that cover the wavelength range from 0.95 to 1.35 µm with a spectral resolution of 54. IRDIS and IFS can be operated together in the default planet-searching mode IRDIFS where the central imaging with IFS is combined with dual band imaging near the methane bands in the H band. Those bands are common in warm giant planets.

ZIMPOL, the Zürich Imaging Polarimeter was built as a collaboration of the ETH in Zürich with API at the UvA and the NOVA Op-IR group. The basic design is a Zürich development, and the ETH also produced the special CCD cameras used in this system. The ZIMPOL instrument as a whole was built and integrated at the NOVA Op-IR group. ZIMPOL uses a special technique that allows measuring the different polarization directions on the same pixels of the CCD, using a custom CCD design in which every second row is covered and the incoming light is focused using a microlens array onto the uncovered pixels. A fast modulation pushes the electrons in each pixel up and down by one row while the modulated polarization signal is integrated. ZIMPOL operates from 600 to 900 nm with a 3.5x3.5 arcsecond field of view.

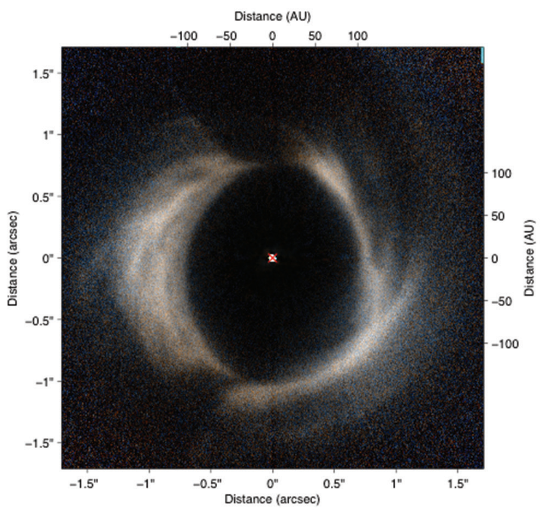

Fig. 5.17: A two-color (R and I bands) of the transitional disk around HD 142527, obtained with ZIMPOL. Clearly visible are the large 130 AU-sized gap, a family of spiral arms, and two dark shadow lanes caused by an invisible inner disk very close to the central star and projected onto the outer disk torus.

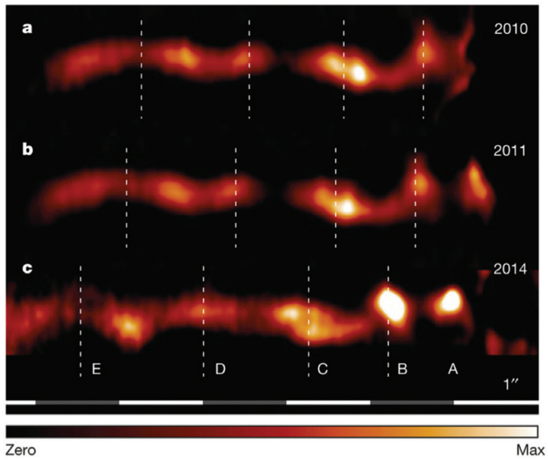

Fig. 5.18: Images of the AU Mic debris disk after unsharp masking, subtraction of the smooth main body of the disk, and stretching in the vertical direction by a factor of two. The same persistent pattern is recovered in all three epochs, though at shifted locations, implying motion away from the star (Boccaletti et al 2015, Nature 526, 230).

Results achieved in 2013-2015

After integration in Grenoble, SPHERE passed its acceptance tests in Europe in December 2013 and was then shipped to Paranal. The delicate reassembly was completed in May 2014 and the instrument is now mounted and in operation on the Nasmyth platform VLT Unit Telescope 3. After successful commissioning and science verification, SPHERE executes both guaranteed and open time programs since 2014. The pressure on the instrument is high. SPHERE is executing the GTO program at a rate of around 20 nights per semester, systematically going through the target list for planet searches. SPHERE has already provides stunning images of circumstellar disks (see Fig. 5.17 and Fig. 5.18 for examples) leading to a publication in Nature.

5.1.7 VLT MUSE-ASSIST

MUSE, the Multi Unit Spectroscopic Explorer, is a second generation instrument for the VLT. MUSE is an integral field spectrometer in the optical wavelength range. MUSE combines imaging and spectroscopy in a single instrument and is able to simultaneously take 90 thousand spectra, one for each 0.2 x 0.2 arcsecond pixel over the full 1x1 arcmin field of view. This makes MUSE highly suitable for studies of galaxy evolution and dynamics, both for high-redshift Lyman alpha emitters and for more nearby galaxies. Fig. 5.19 provides an example of how the combination of spatial and spectral resolution gives insight in the kinematics of a galaxy. For resolved stellar populations within our galaxy, MUSE can be used to perform massive parallel spectroscopic studies of stellar evolution.

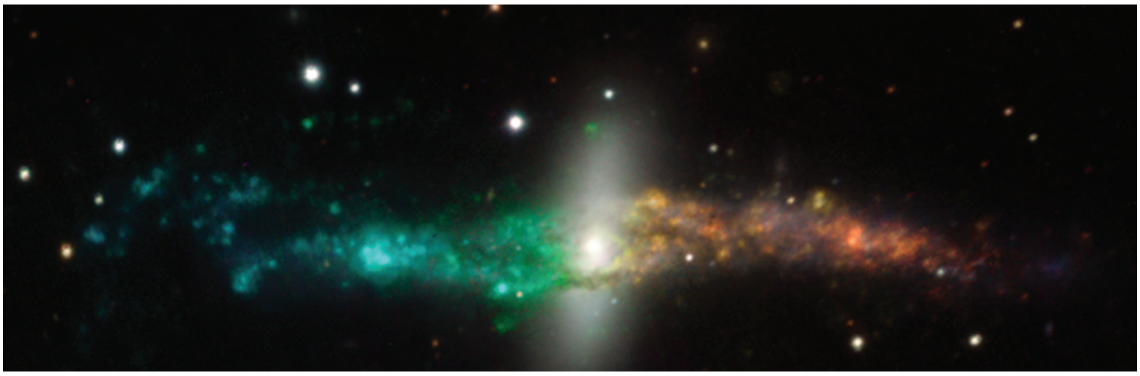

Fig. 5.19: *MUSE 3-D image of the polar ring galaxy NGC 4650A. The white parts are dominated by stellar light. The color encodes the velocity relative to the galaxy of a star-forming gaseous disk, where blue and red regions are rotating towards and away from us, respectively. Credit: ESO/MUSE consortium / R. Bacon.*

Instrument description

The instrument consists of 24 identical high performance integral field units, each one composed of an *advanced image slicer*, a spectrometer and a 4kx4k pixel detector. The simultaneous wavelength range is 460-940 nm, at a resolution of R~3000. The combination of the large field of view, the large wavelength range, and the high spatial and spectral resolution give MUSE huge discovery potential.

MUSE was built by a consortium of 6 institutes, including NOVA. The NOVA PI is Schaye, while the overall project is led by Bacon at Lyon. NOVA's contributions include ASSIST, a test bench for parts of ESO's adaptive optics facility for the VLT led by Stuik, the interface control documents for the interface between MUSE and its adaptive optics module GALACSI, the signal-to-noise calculator, and MUSE-WISE, an adaption of the Astrowise system specifically designed to handle the complex MUSE data, coordinated by Brinchmann and developed in Groningen.

Progress and status

ASSIST was integrated with GRAAL, the adaptive optics module for HAWK-I, and the operation of GRAAL with the deformable secondary mirror was verified in 2013 and 2014. GALACSI was the last adaptive optics system to be tested in Europe and spent most of 2015 on ASSIST.

The years 2013-2015 were filled with important milestones, including the preliminary acceptance in Europe (Sep 2013), the re-integration in Paranal, Chile (Dec 2013), first light (Jan 2014), commissioning (Feb-Aug 2014), science verification (Jun-Aug 2014), and the start of guest observing (Oct. 2014). MUSE is performing extremely well and is already among the most in demand instruments on the 4 VLT telescopes, spanning science from star-forming regions in the Milky Way to z>6 galaxies.

In return for its investments, ESO awarded the consortium 255 nights of guaranteed time observations (GTO), which is used for common large programs. GTO started in Sep 2014 and consists of a number of projects, including a series of deep fields. One of the large programs is led by Schaye and targets quasars with the aim of detecting the galaxies that are responsible for the absorption seen in the quasar spectra.

Among the exciting results that have come out of the analysis of the commissioning data by the consortium are 3-D images of emission from gas around individual, low-mass high-redshift galaxies (Wisotzki et al. 2016), which could previously only be detected statistically by averaging data from many galaxies.

Outlook

In 2016 GALACSI will be shipped to Paranal and integration of the adaptive optics facility on the telescope UT4 will commence. This will clear the path for two major upgrades for MUSE. The current wide-field mode will be enhanced with ground-layer adaptive optics and later a narrow-field mode will become available, which will provide 25 milli-arcsec sampling over a 7.5x7.5 arcsec field of view.

NL PI:
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NL Co-Is:
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Franx

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de Haan
ter Horst
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Stuik (PM, ASSIST)

NL PI:

Jaffe

NL Co-Is:

Hogerheijde
Dominik
Snellen

NL team:

Agocs
Bettonvil (PM)
Elswijk
de Haan
ter Horst
Jasko (Hungary)
Kragt
Kroes
Navarro
Schuil
Tromp
Venema

5.1.8 VLT MATISSE

MATISSE (Multi-AperTure mid-Infrared SpectroScopic Experiment) is one of the second-generation instruments for the ESO/VLTI, and is a successor to AMBER and MIDI. For the latter NOVA also contributed the cryogenic beam combiner. MIDI was decommissioned in 2015. MATISSE is being built by a consortium consisting of Observatoire de Cote de Azur (Nice), MPIA (Heidelberg), MPIfR (Bonn) and NOVA. MATISSE will coherently combine the light of all four 8-m VLT telescopes, synthesizing a telescope with an aperture of up to 130-m. Spatial resolutions of 2 milliarcsec, similar to ALMA, are within reach. MATISSE can also make use of the mobile 1.8-m auxiliary telescopes (ATs), all relocatable in position, and capable of adding more baselines and thus improving the filling of the synthetic aperture and extending it to 200 meters.

Fig. 5.20: *At the Hannover Messe in 2014, the LM-band Cold Optical Bench of MATISSE was handed over to consortium partner MPIA during a ceremony attended by Dutch secretary of state OCW Dekker, OCW Directeur Onderzoek en Wetenschapsbeleid Van der Wenden, NOVA director Boland, NOVA Board chair Groot, MPIA Scientific Coordinator Jäger, Dutch MATISSE project manager Bettonvil and lead engineer Kroes, for a large audience including many of the Dutch industrial contributors.*

MATISSE science

MATISSE will measure coherent flux, visibilities, closure- and differential phases, as a function of wavelength in selected spectral bands and spectral resolutions. The multi-baseline capability will allow high dynamic range imaging in the mid-Infrared. No other instrument in the world will offer similar capabilities, placing MATISSE at the forefront of infrared interferometry.

MATISSE can observe in the L, M, and N bands (resp. 3-4, 4.6-5 and 8-13 micron) and therefore well suited for study of Active Galactic Nuclei (AGNs), protoplanetary discs (e.g. T Tauri, Herbig AeBe stars), planetary debris disks (beta Pic types), the formation and evolution of planetary systems (e.g. young giant planets, hot Jupiter-like planets), the birth of massive stars, hot and evolved stars, as well as minor bodies of our solar system (asteroids, comets). There is major scientific interest from the universities of Leiden and Amsterdam. Scientific operations at the VLTI will begin in mid-2018. The initial high priority projects for Dutch astronomers will be: mapping the angular/spiral structures in protoplanetary discs at scales comparable to the Earth's orbit, both in thermal dust and in molecular gas emission; mapping the chaotic obscuring dust structures in AGNs and emission lines from molecules and shock-heated gas; possible direct detection of emission from hot Jupiter-like planets.

The NOVA contribution: Cold Optical Bench

The NOVA-Op-IR group is responsible for the so-called Cold Optical Bench (COB), being the most complex part of MATISSE. It accommodates ~280 optical components, located into two boxes of roughly 70x70x40cm size, with in total over 56m(!) optical path length. There are 2 COBs, one for LM-band, the other for the N-band, allowing for simultaneous observation in both bands.

Each COB handles 4 telescope beams. All beams travel individually through the system and are only combined at the very end. The beams first are spatially filtered, then split up in an interferometric and photometric beam (for flux determination) and then anamorphically magnified (for reaching a different image scale in spectral and spatial direction). Thereafter the 8 beams are sent altogether to a filter-, polarizer and disperser unit. At the end the beams are combined by a camera system and focused on the detector, where the fringes are formed. MATISSE allows for dispersions between R=30 and 5000, the latter to observe in detail the Br-alpha line and CO band centered around 4.05 and 4.8 micron.

The small envelope together with the complex functionality (each COB contains 17 mechanisms for configuration selection and alignment) required an unusual design approach: from the very beginning systems-, optical and mechanical engineers worked closely together, including suppliers, to define the concept, analyze the performance and finalize the design. For this instrument the philosophy of alignment

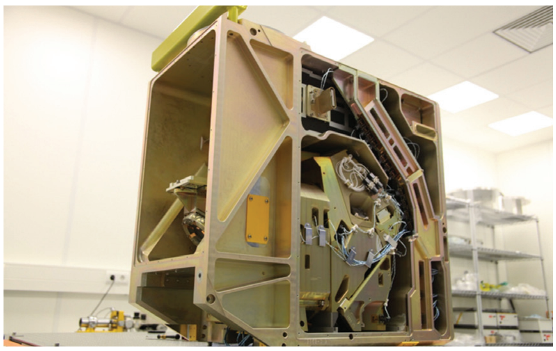

Fig. 5.21: *One of the two Cold Optics Benches, nearing completion at the NOVA Op-IR instrumentation group in Dwingeloo.*

by design was chosen, which required an extremely detailed Monte Carlo analysis and lead to a design with only one active alignment mirror per beam, avoiding

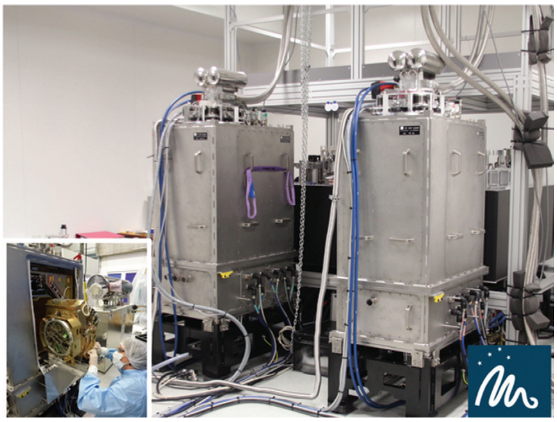

Fig. 5.22: *The two cryostats of MATISSE in the cleanroom at OCA for verification. Inset: NOVA lead engineer Kroes assembles the disperser wheel in one the cold optics benches.*

the need of a time consuming and difficult alignment phase, and at the same time resulting in a very stable instrument. Without any doubt, MATISSE is the most challenging instrument built at the NOVA Op-IR group so far.

Progress & outlook

The Op-IR Group designed and built the two cold optical benches, one for M-L and one for N band, that were delivered to our partner MPIA. After integration into the cryostat the combination was shipped to the Observatoire de la Côte d'Azur (OCA) in Nice, where the final assembly and verification of the entire instrument takes place, before shipment to Paranal. First light at the VLTI is foreseen in 2018.

Achieved milestones 2013 – 2015

- Manufacturing, integration and verification of the M-L band and N band Cold Optical Benches at the NOVA Op-IR Group.
- Shipment to Max Planck Institut für Astronomie in Heidelberg for integration into the cryostats and test at infrared wavelengths.
- Shipment of the two cryostats with the optical benches to Observatoire de la Côte d'Azur in Nice for final integration together with the fore optics. Complete alignment of MATISSE. Registration of first fringes.

Future milestones up to preliminary acceptance

- Completion of the integration and full verification at OCA (early 2017)
- Preliminary Acceptance in Europe by ESO (mid 2017)
- Shipment to Paranal – Chile (July 2017)
- Final integration, alignment and verification (end 2017)
- Commissioning, Provisional Acceptance Chile (First half 2018)

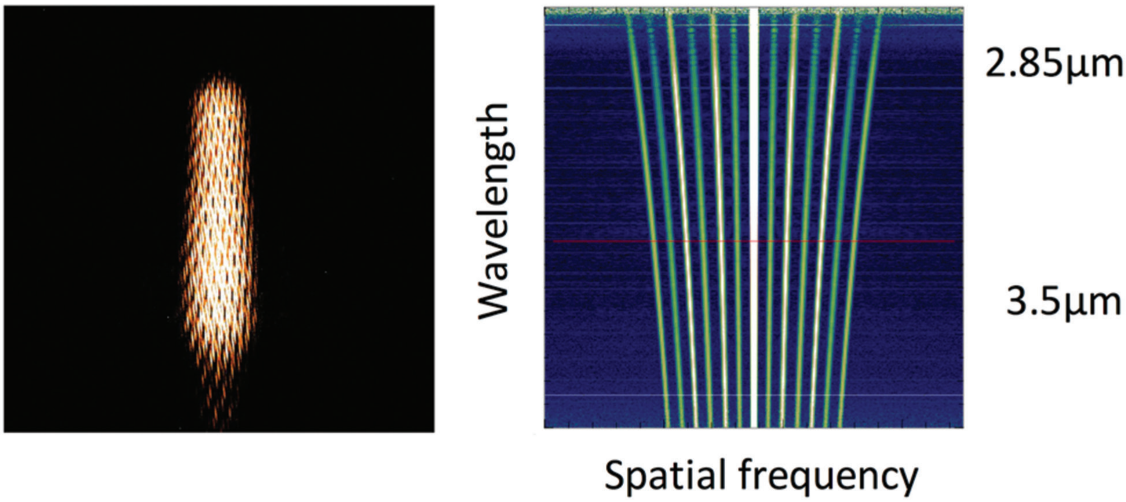

Fig. 5.23: *First fringes with MATISSE in the laboratory. Left: interferometric light spot on the detector, being the projection of all four parallel telescope beams on top of each other. As in a Michelson's interferometer the beams produce a fringe pattern, with each fringe period defined by the distance between two telescope beams. In MATISSE its four beams have all unique distances which give 6 unique fringe periods. When transformed in the frequency domain (right picture), these 6 frequencies evidently become visible. The vertical axis is the wavelength. As in radio synthesis, from the fringe pattern finally an image of the astronomical object can be obtained.*

NL PI:
Groot

NL PM:
Klein-Wolt
Bloemen

NL Co-Is:
Nelemans
Raskin
Scheers
Wijnands

NL team:
Engels
Balster
Dolron
Bettonvil
ter Horst
Kragt
Lesman
Roelfsema

5.1.9 BlackGEM

The aim of the BlackGEM project is to detect the optical light emitted by the remnants of a black hole – neutron star merger or a neutron star – neutron star merger. These events themselves herald their occurrence by the arrival of a burst of gravitational waves, to be detected by the Advanced LIGO & Virgo laser-interferometer systems. The first such direct detection of gravitational waves has been accomplished by LIGO in 2015 in the event GW150914. After the actual merger of the neutron star and black hole, a mass as large as ~1% of a Solar mass is ejected from the event after being heated up to ~5 billion degrees. The radiation from this ejected mass peaks in the optical-infrared regime and is termed a 'kilonova'.

Scientific motivation

The added value of also detecting these merger events in the optical is that it allows a clear positioning in the sky and identifying the system in which the event has happened: in a galaxy? Outside a galaxy? In a star-forming region or perhaps in a globular cluster? From the time evolution of the optical event (fading and reddening and detailed spectra) it can be deduced which elements are synthesized in the ejecta.

Finding these optical signals is a major challenge for multiple reasons:

1. Gravitational detectors can pinpoint the location of these merger events only with an accuracy of ~400 times the size of the full Moon. To know exactly where it happened the localization accuracy needs to be increased by a factor of a billion! Any optical system must therefore be able to scan this complete area on the sky quickly.
2. The kilonova signals are expected to be faint: 2.5 million times fainter than the faintest object visible to the naked eye.
3. The kilonova signals are expected to fade quickly: modelling shows that they should be visible for hours - days only.

The research into these gravitational wave merger events is one of the key science drivers of NOVA Network 3, whose aim is to understand the (astro) physics of neutron stars, black holes and the binary star systems and stellar populations in which they occur. No telescope system available to NOVA researchers is able to meet the above three challenges, and therefore the BlackGEM project was initiated to design and build such a system. Once a signal is detected with BlackGEM it will be followed in detail with larger telescopes, primarily those of ESO.

The BlackGEM project will deliver three major science products:

- The optical counterparts to gravitational wave mergers;
- A six-band multi-color survey of the complete Southern Sky ('a southern Sloan Survey');
- A fast synoptic survey to characterize the variability of faint sources in the night sky on the time scales of minutes to hours.

The combination of an array approach to wide-field synoptic surveys makes BlackGEM completely unique and highly flexible: the telescopes can be 'spread wide', they can be all co-stare at the same point in the sky ('drilling mode'), or they can be co-staring in different filter bands. In this way, the BlackGEM project is not only the required project for identifying gravitational wave counterparts but also the next step in transient astronomy and synoptic surveys.

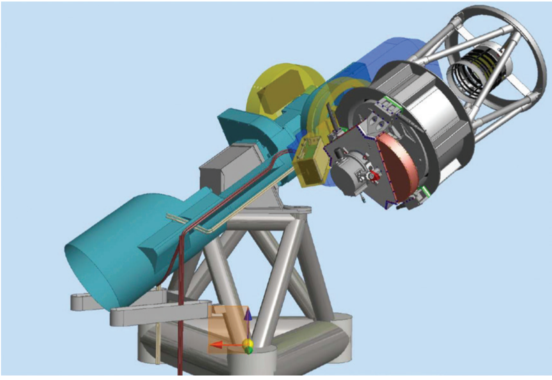

__Fig. 5.24:__ Design drawing of the BlackGEM telescope, on its Fornax 202 mount and pyramidal pier. Credit: RU/Tech-noCenter and NOVA Op-IR Group.

The project

The BlackGEM project is a two-phased project, where in the first phase a prototype system (MeerLICHT) and the first three BlackGEM telescopes will be designed, built and operated. In the second phase the BlackGEM array will be expanded to 15 telescopes. The BlackGEM array will be located at ESO's La Silla Observatory in Chile. The NOVA Op-IR Group, the TechnoCenter at Radboud University, the Institute of Astronomy at the KU Leuven, the University of Cape Town and the NWO Center for Mathematics and Computer Sciences (CWI) are designing and building the full array, including the telescopes, the cameras, the housing, the data reduction pipeline and the database system. Groot (NOVA) is the PI of the BlackGEM project.
The optical system of each BlackGEM telescope consists of a 65 cm primary mirror, a 23 cm secondary mirror, a triplet lens system, the last of which acts as an atmospheric dispersion corrector. After passing through a filter, this creates a focal plane that is flat and achromatic and is imaged by a single 110 Megapixel detector, the largest available single detector in the world. The optical elements are held in place in an 'optical telescope assembly' made of carbon-fiber, co-designed between NOVA and Airborne Composites BV. The telescope is pointed in the sky on a mount

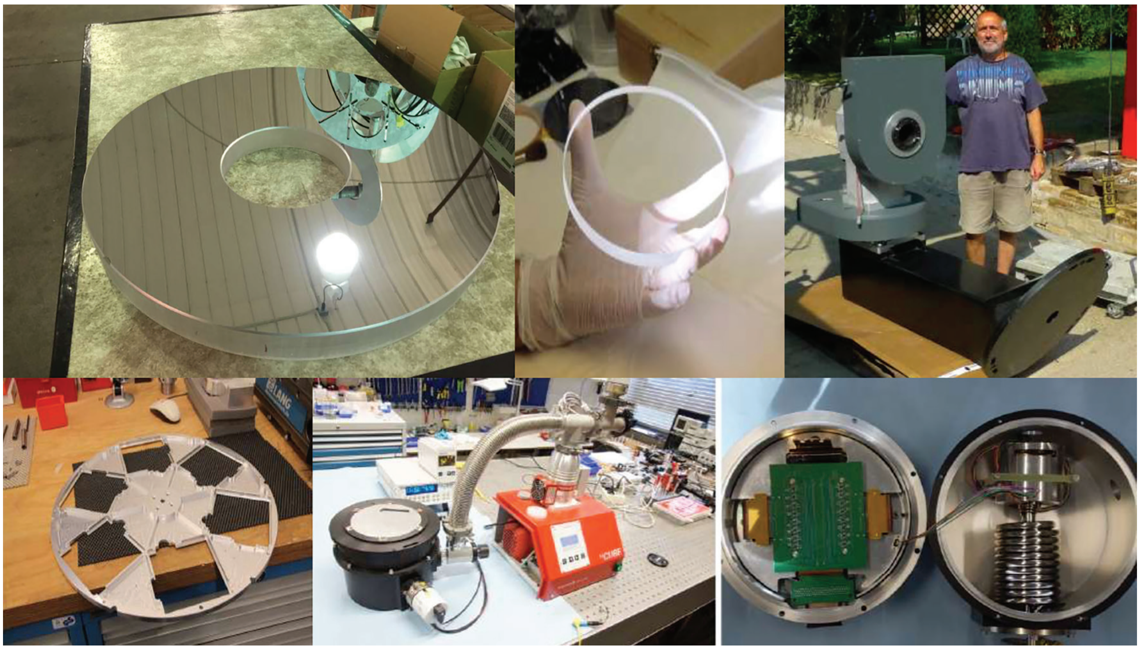

Fig 5.25: *Finished components of the BlackGEM prototype. From top left, clockwise: The main mirror, the cryostat window, the mount, the open cryostat, the closed cryostat under vacuum and the filterwheel.*

that is co-designed by the TechnoCenter and Fornax Mounts. Each telescope is housed inside a clam-shell dome and placed on top of a completely open tower structure, to minimize any air turbulence created by the structure itself.

Current status and outlook

The BlackGEM prototype system MeerLICHT is currently under construction: the CCD detector and cryostat system has been successfully completed; the main mirror has been polished and coated, the lenses have been delivered and the mount is undergoing factory testing. All other major parts are under construction. The prototype telescope will be assembled at the NOVA Op-IR Group in summer 2016, then moved to Radboud University and united with the mount which will be tested first in the dome on top of the Huygens building. After a complete system verification and operation test in Fall 2016, the prototype will be shipped to South Africa where it will be installed at the Sutherland Observatory as a stand-alone project: to co-observe with the MeerKAT radio array.

Construction of the first three BlackGEM telescope will commence after successful testing of the MeerLICHT prototype in The Netherlands. Shipment to Chile is foreseen for the end of 2017, with first light on La Silla in the first quarter of 2018. Phase II depends on future funding, but can commence as soon as funding becomes available.

Fig. 5.26: *The spot on the ESO La Silla Observatory where BlackGEM will be installed. The middle (full white) building is the GPO-Marly telescope building. It will be removed by ESO and the BlackGEM array will take its place.*

5.2 ALMA related projects

NL team:
Adema (PM)
Barkhof
Bekema
de Haan
Hesper
Koops

The Atacama Large Millimeter/submillimeter Array (ALMA) is located in Northern Chile at the Chajnantor altiplano in the Andes at an altitude of 5,000 meter. Science operations started in 2011. ALMA's primary function is to observe and image with unprecedented clarity the enigmatic cold regions of the Universe, which are optically dark, yet shine brightly in the millimeter part of the electromagnetic spectrum. When complete, ALMA will observe in 10 frequency bands between 30 and 950 GHz, with a maximum baseline of up to 18 km. The array consists of 66 telescopes. By moving them to different platforms it will be able to observe in a wider field of view mode or in a close up mode with highest angular resolution in the range of milliarcseconds.
ALMA is a partnership of Europe, North America and East Asia in cooperation with the Republic of Chile. ALMA is funded in Europe by ESO, in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC) and the National Science Council of Taiwan (NSC) and in East Asia by the National Institutes of Natural Sciences (NINS) of Japan in cooperation with the Academia Sinica (AS) in Taiwan. The Joint ALMA Observatory (JAO) provides the unified leadership and management of the facility.

NOVA involvement

NOVA contributed in various ways to the worldwide ALMA program. In the 2000-2012 period, under contract with ESO, NOVA designed, prototyped and constructed the Band-9 receivers covering the 600-720 GHz frequency range. Starting in 2012 NOVA in collaboration with GARD started a new contract with ESO for the final-design and production of the Band-5 receivers covering the 163-211 GHz frequency band. Through ALLEGRO (next section) contributions are made to the European Regional Center for ALMA providing scientific support to the users from preparing observing proposals through assisting with data reduction and interpretation of the observations. NOVA researchers also contributed to ALMA as members of advisory committees and the ALMA Board.

5.2.1 ALMA Band 5 receivers

Fig. 5.27: *Colliding Antennae galaxies. Composition of ALMA and Hubble observations. Credit: ESO*

Building on the experience gained with the production of the ALMA Band-9 receivers, NOVA together with GARD (the Group for Advanced Receiver Development at Onsala Space Observatory, which is part of Chalmers University in Gothenburg, Sweden) formed a consortium to final design and build the ALMA receivers for Band-5 (163-211 GHz). The contract for the work between ESO, NOVA and Chalmers University was signed in 1st February 2013. It was for delivering 67 receivers plus spare for the first two years of operations. In 2015 ESO ordered six additional receivers that will replace the pre-production ones and additional spare parts to secure 20-year operations. In the collaboration GARD will produce the detectors based on SIS heterodyne mixers and will deliver sideband separating mixer assemblies to NOVA. The latter is responsible for the manufacturing of the receiver and verification of the specifications through measurements. NRAO, formally via ESO, will provide the local oscillators including the electronics to operate them.

The wavelength range of the Band-5 receivers allows observations of dense molecular gas through the thermally excited emission line of water vapor at 183 GHz. The receiver will become the workhorse to study water in a wide range of environments, from comets and planetary atmospheres in our solar system to protoplanetary disks and star forming regions. It will also study water masers in both circumstellar envelopes and starburst galaxies. For high-redshifted galaxies, emission from CO and CII lines lies in the band. Complicating factor is that emission of water vapor in the Earth's atmosphere will also be received. Therefore the receiver has to meet stringent specifications on the sideband separation to avoid disturbances.

The design of the Band-5 receivers builds on an earlier study by GARD together with RAL (Rutherford Appleton Laboratory, UK) and managed by ESO under a grant from the EC. The study resulted in a final design and production of six prototype receivers which were tested at ALMA. Final conclusion of this study was that the design meets the technical specifications except for the local oscillators developed at RAL. Therefore it was decided to initiate collaboration with NRAO to design and fabricate the LO's for the Band-5 receiver following the concept as used in ALMA receivers for the other frequency bands.

Progress in 2013-2015

The official kick-off meeting of the NOVA-GARD project was held in January 2013. The initial phase of the project was used to consolidate and verify the specifications. The design of the cartridge lay-out was upgraded compared to the pre-production units to (1) create space to locate the cryogenic parts of the LO, to (2) achieve a robust structure for the chain of cryo-amplifiers, IF components and isolators, and (3) to optimize the structure for series production and maintenance. In parallel three technical specifications were upgraded to allow for better astronomical performances.

This culminated in the Manufacturing Readiness review, held in June 2014. This was about one year later than initially anticipated because the project wanted to be sure that the upgraded specifications can easily be met. Procurement of 3rd party supplies started thereafter for 17 components varying from cryo amplifiers, RF hybrid blocks, cartridge bodies, precision machined parts to temperature sensors. First three receiver cartridges were shipped to ALMA on 17 April 2015 (Fig. 5.28).

After an initial good start 7 receivers were delivered to ALMA between April and July 2015 using RF-Hybrid blocks produced by GARD. Thereafter the production slowed down because industry was unable to deliver these blocks according specifications. Three parallel paths were followed to resolve the problem: (1) use of RH-Hybrid blocks from the pre-production cartridges, (2) support the company with quality control recommendations, and (3) search for a second supplier for the production of the RF-Hybrid blocks. By the end of 2015 12 receiver cartridges were delivered to ALMA. The problem was finally solved in early 2016 by cancelling the contract with the initial supplier and moving to a new one.

Outlook

Once the supply of components are all according contractual arrangements NOVA-GARD will produce and deliver three receiver cartridges per month leading to completion of work by end of 2017 or early 2018.

Fig. 5.28: *First three Band-5 receivers of the production series.*

NL PI:
Hogerheijde

NL Co-Is:
Barthel
van Dishoeck
Dominik
van Langevelde
Oosterlo
Roelfsema

NL project team:
Juhasz
van Kempen
Klassen
Schmalzl
Tilanus

5.2.2 Allegro

Allegro is one of the nodes of the European ALMA Regional Center, the regional support facility for ALMA. Allegro assists ALMA users with proposal preparation and calibration, reduction, and analysis of their ALMA data. Furthermore, it is an expertise center on high-frequency observing with ALMA, millimeter Very Long Baseline Interferometry (mmVLBI), and the use of advanced science-analysis software. Allegro staff is actively involved in enhancement and development activities of the observatory in Chile and provides direct operational support for the calibration of scheduled high-frequency observations. Allegro staff has been conducting a detailed study of the atmospheric condition above ALMA, the distortions it introduces, and techniques to counter those. As part of a larger NOVA project, Allegro is investigating the potential benefits of introducing a dual-frequency capability for ALMA, which will allow for simultaneous observations at two frequencies.

ALMA is the world's most powerful mm/submm observatory to study the universe, including some of the most distant, ancient galaxies ever seen, and gas and dust disks around young stars where planets are in the process of forming. NOVA's ALMA instrumentation group at the Kapteyn Institute of the University of Groningen had built one of its highest frequency receivers. Once its full suite of receivers is completed, ALMA will observe at wavelengths in the range 10 - 0.3 mm (frequencies 30 - 950 GHz). In spite of it being located in thin air and at one of the driest locations on Earth observations at wavelengths shorter than ~0.6 mm (ν > 500 GHz) are challenging due to water vapor in and turbulence of the atmosphere.

Allegro staff is conducting dedicated observations and detailed analyses in order to characterize and counter these atmospheric distortions. Ultimately these will determine the circumstances under which high-frequency and high-spatial-resolution observations are feasible. Important parameters are the amount of water vapor and wind turbulence present. Equally important is designing techniques to counter their detrimental effects. One of these techniques successfully measures and subtracts distortions caused by the varying amount water vapor in the column of air through which each telescope observes. Compensating for water vapor is less effective though at the higher observing frequencies that already require the driest conditions possible.

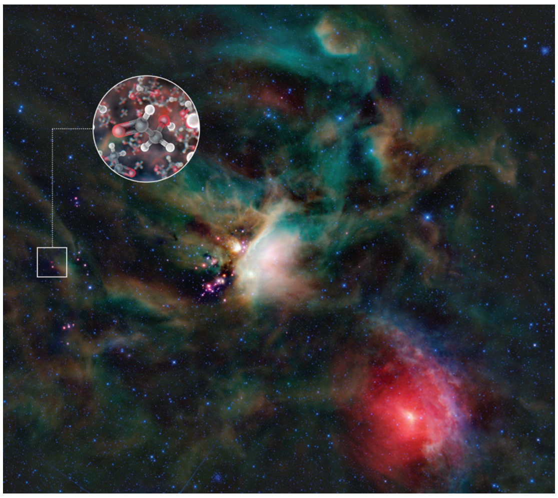

Fig. 5.29: *Artist impression of the discovery of glycolaldehyde, a molecular simple form of sugar in the source IRAS 16293-2422 observed by Jørgensen. Image credit: ESO*

For those an alternative is to observe simultaneously at two distinct frequencies and to use the less-affected lower-frequency observation to correct the higher-frequency one. As part of the NOVA project, Allegro staff started researching special techniques for future dual-frequency receivers. In many respects this is similar to stopping stars from twinkling at optical wavelengths and ALMA recently awarded proof-of-concept time for test observations. These observations will attempt to use neighboring dishes at different frequencies as a substitute for dual-frequency. If successful, this may also result in a new observing mode that will improve current high-frequency observations, which is another key objective of Allegro's research, when ALMA is in its compact array configuration.

Allegro is also involved in the creation of the Event Horizon Telescope (EHT), a Very Long Baseline Interferometry (VLBI) network of millimeter telescopes spanning four continents, from Europe, the South Pole, and the Americas, to Hawaii and that includes ALMA as its most sensitive contributor. The EHT will be active during several observing blocks in the year at which time it will form a 'virtual' earth-sized telescope of more than 10,000 km in size capable of resolving smaller structures than any other observatory on Earth. A primary science goal is to directly image Sgr A*, the supermassive black hole at the center of the Milky Way galaxy, on scales that will show the 'shadow' of its event horizon.

NOVA's ALMA instrumentation group, in collaboration with the BlackHoleCam (BHC) project of the Astrophysics Department of the Radboud University, Allegro, and MIT/Haystack Observatory have built frequency downconverters that are a critical part of EHT's next-generation VLBI equipment and that prepare the astronomical signals for digitization and recording. Assembled and delivered in record-pace time, the downconverters have successfully been used in preliminary EHT observations that have cleared the way for first observations with the full network and ALMA expected in 2017.

5.2.3 ALMA R&D

NL PI:
Baryshev

NL Co-Is:
Tilanus

NL project team:
Hesper
Khudchenko
Montofre

Part of the activities of the NOVA submillimeter group is technical R&D for next generation receivers for ALMA and maybe a large survey telescope. Prototype equipment is tested at the Atacama Pathfinder EXperiment (APEX) located at 3 km distance from ALMA. Focus points for R&D are (1) development of technology to carry out observations in the ALMA Bands 9 and 6 exploring possibilities to improve calibrations of ALMA observations at highest frequencies through finding relations between phase calibrations at Band-6 and Band-9 frequencies and their dependencies on the water vaper content in the atmosphere and (2) R&D on multi-pixel receivers through integrating as many parts as possible on one chip. This work will start in 2016.

Development of dual frequency receivers

Objective of the project is to develop a dual frequency Band-9/6 observing mode for ALMA through starting with three telescopes at the ALMA site to verify a new calibration scheme by measurements. The NL project is co-led by Baryshev (technical R&D) and Tilanus (calibration scheme) with support of Hesper (instrument physicist). The theoretical work at ALLEGRO (section 5.2.1) aims to develop an ALMA calibration scheme linking water vapor optical depth and frequency dependence.

Feasibility and technical solutions of the dual frequency observations were discussed between Baryshev and Whyborn (ALMA) leading to the conclusion that the approach is feasible. Montofre (PhD student (50% Chile and 50% EC grant) completed the optical design and tolerance analysis. He started the mechanical design of beam combining optics. It will have adjusters in order to be able to align the beam of Band-6 with respect to Band-9 on the sky as well as on the telescope secondary mirror. This work is done in collaboration with the University of Chile.

Band-9 receiver for LLAMA

In 2015 a collaboration between astronomers and instrumentation groups in the Netherlands and the state of São Paulo have been started structured around the Long Latin American Millimeter Array (LLAMA) which will start scientific observations in early 2018. The collaboration is led by Boland for the Netherlands and Lepine for São Paulo. The activities include joint observations with LLAMA in the submillimeter wavelength range, data analysis and publications, a joint submillimeter instrumentation project and NOVA providing a Band-9 receiver and integrating a Band-5 and a Band-9 receiver into a cryostat for use on LLAMA. In December 2015 the collaboration received funding from a joint NWO-FAPESP call for proposals. NOVA got 495 k€ from NWO and the Brazilian partner at the Universidade de São Paulo a yet unknown amount from FAPESP. First a Double Side-Band (DSB) Band-9 receiver will be delivered. Once development at NOVA is completed the receiver will be upgraded to a single side-band 2SB receiver providing 8 GHz bandwidth in upper and lower sideband as well as in each polarization. In total observations with this receiver cover 32 GHz IF bandwidth if other parts in the telescope equipment (IF system and correlator) are capable to handle such an amount of data. This would be worldwide the first 2SB system operating at 650 GHz frequencies.

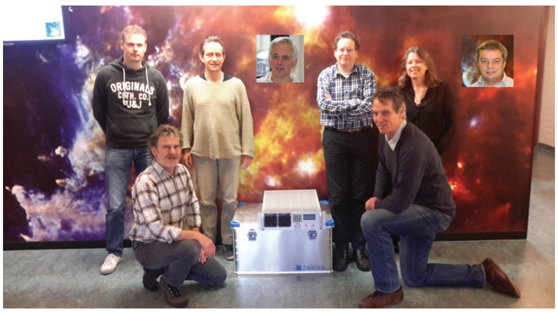

***Fig. 5.30:** Members of NOVA's submillimeter instrumentation group (employed by Kapteyn Astronomical Institute, RUG, based at the SRON institute in Groningen) with the first downconverter assembled for the BlackHoleCam project.*

Band-9 receiver for APEX

In 2015 NOVA, Onsala Observatory and ESO started a collaboration to equip the Swedish-ESO SEPIA receiver at APEX with a ALMA-type Band-9 receiver in return for 70 hours guaranteed observing time with this receiver on APEX under good weather conditions for observing at 650 GHz conditions. The MoU was signed in January 2016 and the receiver was installed at APEX in the same month. Plan is to replace the DSB Band-9 receiver at APEX with a 2SB system once technology is demonstrated.

Down-convertors for BlackholeCam project

In 2014-2015 the NOVA submillimeter group produced and tested 6 down-convertors for the BlackholeCam project in which NOVA astronomers at the Radboud University are active players to enable millimeter VLBI interferometry observations of event horizons of black holes (Fig. 5.30).

5.3 Space projects

5.3.1 MIRI

NL PI:
Van Dishoeck

NL Co-Is:
Brandl
Caputi
Kamp
Waters
van der Werf

NL team:
Kroes
Lahuis (PM)
Mueller
Bailey

During 2002-2009, the Netherlands constructed the Spectrometer Main Optics (SMO) of the Mid-InfraRed Instrument (MIRI) for the James Webb Space Telescope (JWST). In 2010-2012, the Flight Module (FM) has been integrated, tested and delivered to ESA and NASA. After instrument delivery in May 2012, the MIRI European Consortium (EC) continues to be responsible for the instrument and is contractually required to deliver major parts of the instrument characterization and calibration, support Integrated Science Instrument Module (ISIM) testing, and co-lead software development and mission preparation. The Dutch MIRI team has played an important role in the MIRI consortium during all of the project phases, from making the initial science case and conception of the instrument to the design and development of the SMO by the NOVA Op-IR instrumentation Group, support of the instrument tests at Rutherford Appleton Laboratory and the analysis of the test data, to leading the MIRI EC software development and supporting mission preparation at STScI (the JWST operations center). During the design phase the Dutch team has been instrumental in safeguarding the spectroscopic capabilities of MIRI and is now the driving force in exploiting the unique science potential of the integral field unit (IFU) spectrometer within the EC. The Dutch MIRI team aims to maintain its strong role in the continued MIRI EC activities. In particular, the NL co-leads the EC software developments and IFU characterization and is heavily involved in the preparation of the MIRI GTO science program.

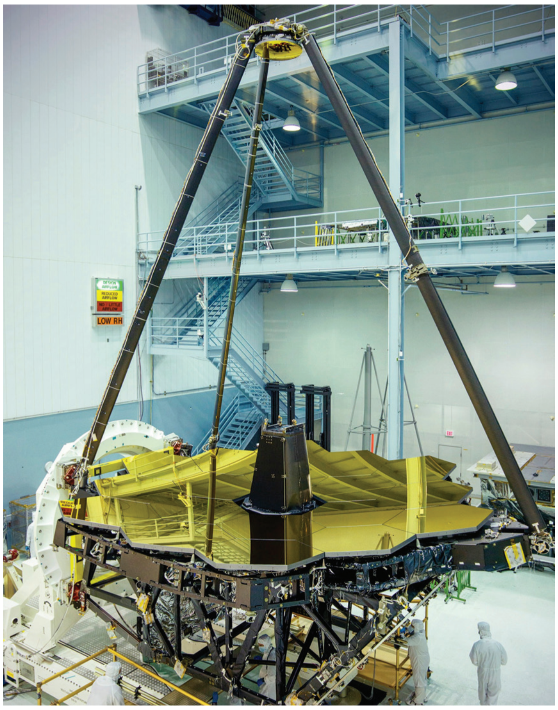

Fig. 5.31: *The recently completed main mirror of the James Webb Space Telescope.*

Scientific goals

The main science drivers are: (i) high redshift galaxies: MIRI is the key instrument for distinguishing true 'first light' galaxies from galaxies with more evolved stellar populations and to quantify the stellar mass density-star formation relation at high redshifts; (ii) protostars: MIRI will probe the physics of shocks and disk formation close to the growing star and will make an inventory of ices, including the more complex species for the first time; (iii) protoplanetary disks: MIRI will uniquely probe the chemistry and physics in the inner terrestrial planet-forming zones of disks; (iv) exoplanetary atmospheres: all JWST instruments, including MIRI, will highlight observations of exoplanetary atmospheres (transit, eclipse) down to the super-Earth masses.

MIRI will be three orders of magnitude more sensitive than any existing ground-based instrument in the 5−30 μm range, a large part of which (>50 %) is completely blocked by atmospheric features from the ground. Compared with Spitzer (85 cm space telescope), MIRI will have more than an order of magnitude increase in sensitivity and almost an order of magnitude increase in spatial resolution. Moreover, its R~3000 spectral resolving power is much higher than that of Spitzer. MIRI complements Herschel and ALMA, which observe(d) at wavelengths >50 μm.

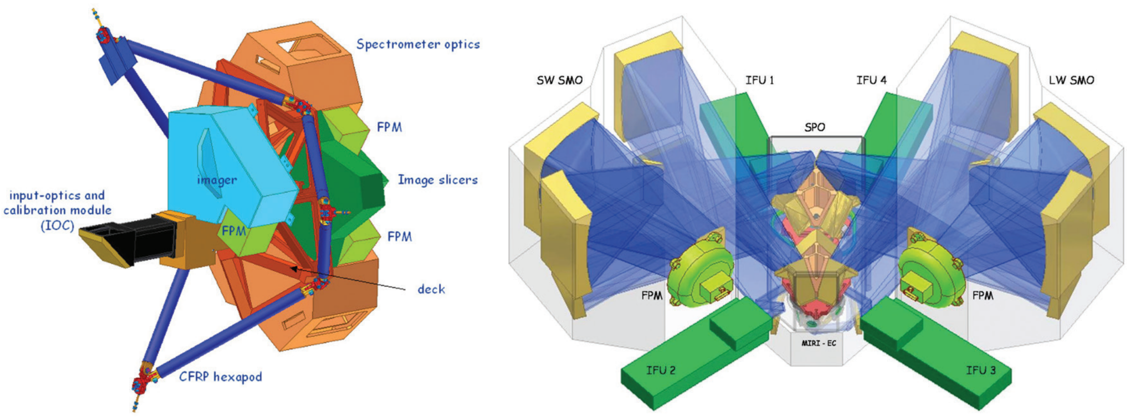

Fig. 5.32: *Graphical overview of the MIRI instrument (left) and the MIRI spectrometer (right).*

Instrument description

MIRI (European Consortium PI Wright) is a collaborative effort between NASA and ESA to provide mid-infrared imaging and spectroscopy on JWST. MIRI consists of a camera and an R ~3000 IFU spectrometer that will operate in the 5−28.5 μm wavelength range. Light from the JWST focal plane is collimated and then split spectrally into four paths by sets of dichroic filters mounted in a wheel. The resulting four passbands are fed into four IFUs 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 Si:As 1024x1024 detector arrays. By arranging two spectral ranges onto each detector simultaneously the efficiency of the spectrometer is doubled. This results in a division of the full 5-28.5 μm range into four equal channels. Full wavelength coverage is obtained in three grating moves using a single grating wheel mechanism.

NOVA participation

After delivery, the NOVA participation in MIRI consists of:

- Ensuring that MIRI has an excellent and well characterized high resolution integral field spectrometer;
- Gaining intimate knowledge of the instrument characteristics and data reduction, essential for the science harvest;
- Having leading roles in the MIRI guaranteed time program;
- Retaining mid-infrared scientific and technical expertise in the Netherlands, relevant for the E-ELT METIS instrument.

MIRI progress in 2013-2015

The 2013-2015 period was marked by ISIM test campaigns at NASA Goddard, MIRI detector characterization tests at JPL and various JWST mission preparation activities.

In 2013, 2014 and 2015 three ISIM cryo-vacuum (CV) test campaigns took place with a duration of two to three months each. During each test campaign fulltime on-site support was provided by the MIRI test team. Dutch support was provided on-site and for the analysis of the ISIM test data. MIRI performance was consistent from campaign to campaign and the MIRI instrument remains in good health to date, proof of the high quality of its design and manufacturing. JPL performed detailed tests on a flight representative MIRI focal plane system for detailed characterization, testing a MIRI electronics upgrade and optimizing flight detector settings. Both the ISIM and JPL test results complement the full instrument characterization performed by the MIRI consortium at RAL prior to instrument delivery in 2012. Together these will enable an optimal operation and scientific exploitation of the MIRI instrument.

During the 2013-2015 period the MIRI team provided five deliveries of calibration data products, pipeline architecture descriptions and data reduction algorithms. These deliveries were all reviewed and are essential for the STScI in developing the JWST operational pipeline. Other areas of MIRI support to STScI include input for operations and supporting commissioning preparation activities.

Outlook

With JWST launch planned for late 2018, science preparations are in full swing. The MIRI science team is revising the GTO proposals, started detailed science instrument modelling and are working toward a final target selection. The Dutch science team has representatives and lead roles in all large MIRI GTO programs. Interactions between the MIRI team and other Dutch scientists have been established in anticipation of the JWST call for open time proposals in 2017, to maximize JWST observing opportunities for the Dutch community.

The MIRI consortium will remain actively organized up to launch and into the JWST commissioning phase, and maintain links with the NASA and STScI teams at all levels of the project. Mission preparation, i.p. instrument calibration, (pipeline) software development and commissioning, will form the main activities.

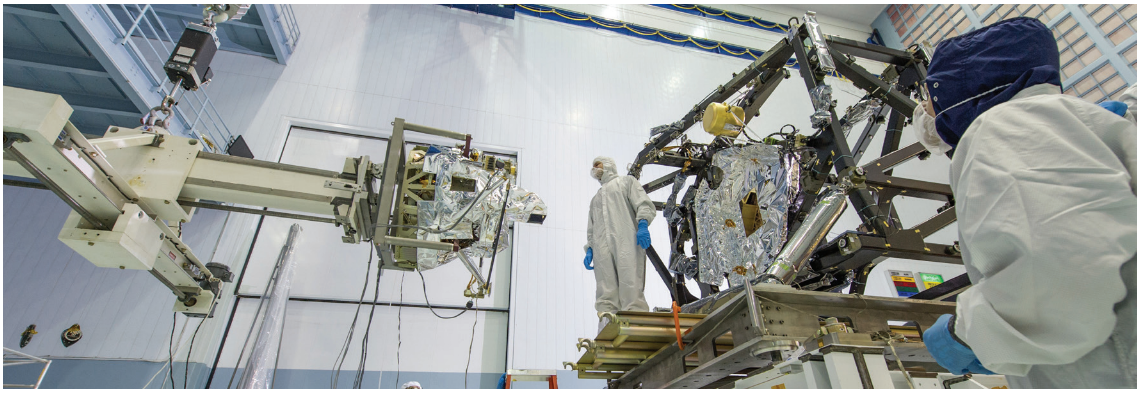

Fig. 5.33: *MIRI optical module being mounted in the Integrated Science Instrument Module (ISIM). Credits: NASA*

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5.3.2 GAIA

ESA's Gaia mission represents the next European breakthrough in astrophysics, a cornerstone mission launched in December 2013 aimed at producing the most accurate 3D map of the Milky Way to date. The resulting stereoscopic census of our Galaxy will represent a giant leap in astrometric accuracy complemented by the only full sky homogeneous photometric survey with an angular resolution comparable to that of the Hubble Space Telescope, as well as the largest spectroscopic survey ever undertaken.

Fig. 5.34: *Launch of GAIA from Kourou, French Guyana on 19th of December 2013.*

GAIA Science

The primary scientific aim of the mission is to map the structure of our Galaxy and unravel its formation history and subsequent evolution. This 'Galactic archaeology' 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 parallaxes), space velocities (through proper motions and radial velocities) and astrophysical characterization (through multi-color photometry) for massive numbers of stars throughout most of the Galaxy. However, Gaia is not simply a 'Milky Way mission' but is truly a multi-faceted astrophysics mission which will enable all three of NOVA's science networks to obtain exciting scientific results covering many topics: fundamental stellar data across the Hertzsprung-Russell diagram, the characterization of tens of millions of binary stars, unique samples of variable stars of nearly all types (including key cosmological distance calibrators), detection and orbital classification of thousands of extra-solar planetary systems, a comprehensive survey of objects ranging from huge numbers of minor bodies in our Solar System, through galaxies in the nearby Universe, to some 500,000 distant quasars. Gaia will also provide a number of stringent tests of general relativity. Last but not least, a massive survey such as Gaia will uncover many surprises that the Universe still holds in store for us.

NOVA Contributions

Gaia will measure positions, parallaxes and proper motions with accuracies ranging from ~10 to ~300 micro-arcsecond per year for over 1 billion stars to 20th magnitude. Multi-color photometry will be obtained for all stars and radial velocities, ranging in accuracy from 1 to 15 km/s, will be collected for stars brighter than 16th magnitude. This NOVA instrumentation project is aimed at enhancing the scientific exploitation of Gaia data in The Netherlands by participating in the photometric data analysis and in the scientific validation of the Gaia data products. The photometric data analysis encompasses all steps from the treatment of the raw photometric data coming directly from the satellite to the delivery of the final mission-averaged photometry for each observed object. Gaia's photometric instrument consists of two low-resolution fused-silica prisms dispersing all the light entering the telescopes. One disperser — called BP for Blue Photometer — operates in the wavelength range 330–680 nm; the other — called RP for Red Photometer— covers the wavelength range 640–1050 nm.

The data processing for Gaia is undertaken by the Gaia Data Processing and Analysis Consortium (DPAC). The funding is provided by the national funding agencies through a multilateral agreement (MLA) with ESA. Each partner commits to delivering a specific contribution to the overall data processing system for Gaia. The NOVA deliverable is specified as the 'definition, design, development, validation, provision and maintenance of a complete software package for the flux extraction, color estimation, initial data treatment, and PSF/LSF calibration for the Blue and Red Photometers (BP/RP) of Gaia' and 'the definition, design, development, validation, provision and maintenance of a complete software package for clustering and advanced data selection for multi-Dimensional visualization'.

The overall DPAC photometric data processing effort is led from the United Kingdom and includes partners from Italy, Spain, and the Netherlands. The work on the NOVA contributions is carried out by a team at Leiden University, consisting of Brown and van Elteren. The work on the multi-dimensional visualization is carried out by Helmi and Breddels at the University of Groningen.

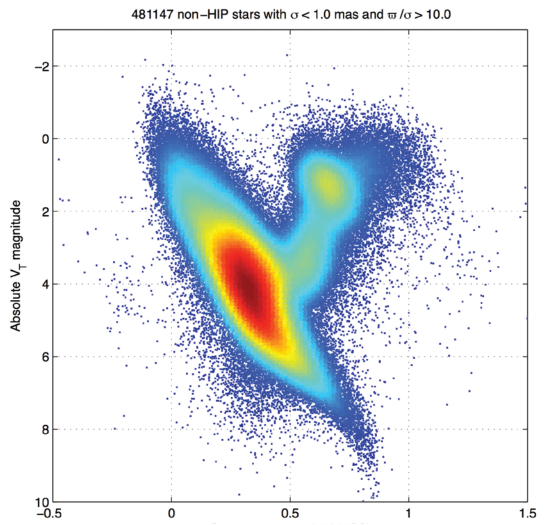

Fig. 5.35: *Hertzsprung-Russell diagram based on provisional absolute parallaxes determined by the first Tycho-Gaia Astrometric Solution. Distances for stars with less than 10% relative parallax uncertainty (formal standard errors) were used to convert the apparent Tycho-2 magnitudes into the absolute magnitudes on the y-axis. Stars in the Hipparcos catalogue and stars with formal parallax uncertainties larger than 1 milli-arcsecond were omitted. Awaiting Gaia's own extensive photometric survey, the color indices J-K on the x-axis were taken from the ground-based 2MASS catalogue. The absolute magnitudes and color indices have not been corrected for interstellar extinction. Credits: ESA/Gaia/DPAC/IDT/FL/DPCE/AGIS*

Progress and achievements in 2013 – 2015
Launch, commissioning and early operations

The Gaia commissioning period started two weeks later after the successful insertion of the spacecraft into its orbit around the L2 Lagrange point, 1.5 million km from Earth. During the entire commissioning period, which lasted 6 months, the DPAC data processing systems were running without major problems. This includes modules that were contributed by NOVA to the initial data treatment system. Prior to launch Brown had a leading role in the international working groups that prepared the commissioning phase. The plans were all successfully executed and the support from DPAC for the Gaia payload commissioning proved essential, in particular through quick scientific analyses of the incoming telemetry.
The nominal science mission started on July 25 2014 and since then the DPAC has continuously processed the incoming Gaia data while steadily bringing online more and more of the advanced processing systems, in particular the astrometric, photometric, and radial velocity spectrograph pipelines. In the summer of 2015 preliminary results from the astrometric solution were presented to the community, based on the so-called Tycho-Gaia Astrometric Solution which allowed for the derivation of 2 million new parallaxes and proper motions already at this early stage of the mission. This exciting result is illustrated in Fig. 5.35.

The data processing production runs for the first Gaia data release started at the end of 2015 and the release itself is expected during the summer of 2016.

Photometric instrument algorithms and multi-dimensional visualization

The teams in Leiden, Cambridge, Rome, and Teramo continued to develop the photometric instrument algorithms for which NOVA is responsible. The team in Leiden focused on the real-time algorithms running in the initial data treatment pipeline, while the other teams continued the development of the complex pre-processing steps that are needed to get from the raw Gaia telemetry to photometric measurements that can be reduced to the same instrument system and then flux and wavelength calibrated.

The Gaia observations will lead to a high dimensional and very large catalogue. Accessing and visualizing a catalogue of this size is not a trivial task. To address this challenge the team in Groningen is developing an application which ranks the large number of lower dimensional (1D, 2D, 3D) sub-spaces of the Gaia data according to their information content. The researcher can thus focus on the most interesting of these sub-spaces and accelerate the discovery process within the Gaia data. The tool is capable of handling large (billions of rows) data sets, and comes with an integrated graphical user interface for the visualization of the results. This application will be used for the validation of the Gaia data products prior to a data release and will also be offered to the community as a general research tool.

Role in international coordination

Since 2012 Brown is the chair of the Gaia Data Processing and Analysis Consortium Executive (DPACE) and as such is in charge of overall coordination of DPAC. Specific responsibilities include convening, preparing, and chairing the DPACE meetings; monitoring the overall progress of the DPAC; acting as the main contact point between DPAC and ESA. The DPACE chair is a member of the Gaia Science Team.

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5.3.3 Euclid

The Euclid satellite, due for launch in 2020, will measure the expansion of the universe and the growth of structure within it over an unprecedented fraction of its history. This will provide a fundamental test of our cosmological world model by probing the nature of the dark matter and dark energy. Euclid will map 15000 square degrees of sky with sharp visible and near-infrared images of over a billion galaxies as well as measure emission-line redshifts for tens of millions of faint galaxies in the near-infrared. The Euclid data will be complemented with color measurements from large ground-based imaging surveys. All these data will be provided to scientists via the Euclid Archive System. It enables a wide range of legacy science opportunities for those able to handle the large volumes of data, in addition to the cosmology science.

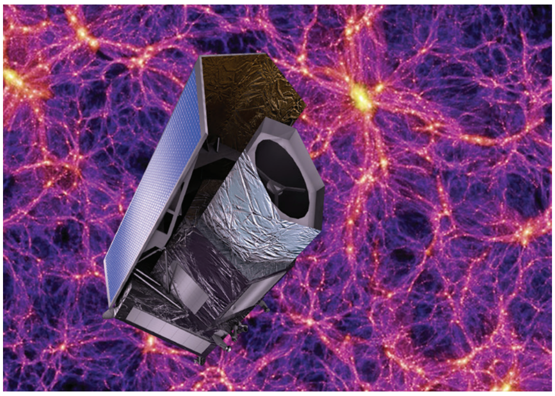

Fig. 5.36: *Artists impression of the Euclid spacecraft.*

NOVA Contribution

The Dutch in-kind contribution to the Euclid mission, supported by NOVA funding for 2014-2018, consists of the workpackages that center around the *Netherlands Euclid Science Data Center* which is the Dutch node in the *Euclid Science Ground Segment*. The Netherlands has responsibility for the following tasks:

- Develop, prototype, build and maintain the *Euclid Archive System* in collaboration with ESA,
- Develop the pipelines and data handling system to process and combine the large ground-based surveys and populate the *Euclid Archive System* with it, jointly with Euclid-Germany.
- Develop a data reduction and calibration pipeline for the near-infrared Euclid imaging data in collaboration with Euclid-Italy,
- Develop the Netherlands *Euclid Science Data Center* that will implement the above pipelines and provides data processing and storage facilities. It will also host one of two mirrors of the metadata database of the *Euclid Archive System*.

Progress 2013-2015

During the period 2013-2015 considerable progress has been made. Extensive documentation was prepared for the *Science Ground Segment Preliminary Design Review*, which was passed in May 2015.

A major effort to gather and refine the requirements on the *Euclid Archive System* was undertaken. This has led to an architectural design which divides the system into three sub-systems: The *Euclid Archive Data Processing System*, the *Euclid Archive Distributed Storage System* and the *Euclid Archive Science Archive System*. Early versions of the *Data Processing System* and the *Distributed Storage System* have been rolled out and are already providing services to the Euclid consortium.

An analysis of the requirements for external data showed the need for four processing functions to provide the following data: 1) Ground-based survey imaging data required for combination with the Euclid data; 2) Space-based imaging data that are needed for calibration and validation of Euclid data; 3) Spectroscopic ground based survey datasets, needed for photometric redshift calibration; 4) External catalogue data needed for or combination with higher level Euclid data products.

Efforts have so far been concentrated on the first of these functions. A prototype system has been developed and has been used to process KiDS data. These data have been ingested into the *Euclid Archive System.*

For the processing of Euclid infrared data, the following tasks are the responsibility of NOVA:

- Developing and validating algorithms and code for pre-processing of the raw data (stage 1)
- Prototyping and validating the algorithms and code needed to do the relative and absolute photometric calibration for Euclid

To date efforts have concentrated on algorithm development. A programmer has recently been recruited to start the creation of production ready code.

The Netherlands Euclid Science Data Center has been established, currently using the existing infrastructure from the Target project. This currently hosts the *Euclid Archive System* and a system supporting the submission and monitoring of Euclid jobs in a distributed environment.

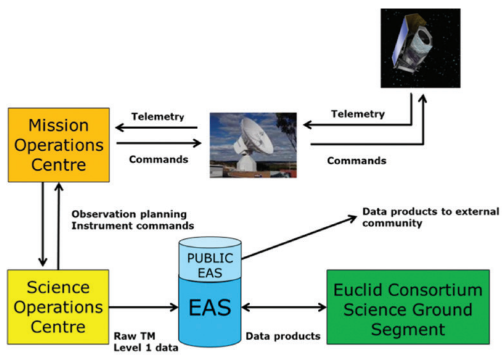

Fig. 5.37: *Top-level view of the Euclid Ground System showing the central role of the Archive, as it connects the Science Ground Segment (containing the Science Data Centers) to the Operations Centers.*

5.4 Miscellaneous Projects

5.4.1 ARTS

APERTIF is a highly innovative receiver system that is currently being constructed for the Westerbork Synthesis Radio Telescope. Its factor 30 increase in field-of-view allows astronomers to survey the entire sky at 1.4 GHz with an unprecedented combination of sensitivity and speed. ARTS, the APERTIF Radio Transient System, extends this wide-field APERTIF system to high time resolution, enabling unique searches for millisecond transients, as well as nanosecond neutron-star timing. ARTS also allows for a wholly new approach to Very Long Baseline Interferometry (VLBI) that produces sensitive, wide-area images at milliarcsecond angular resolution.

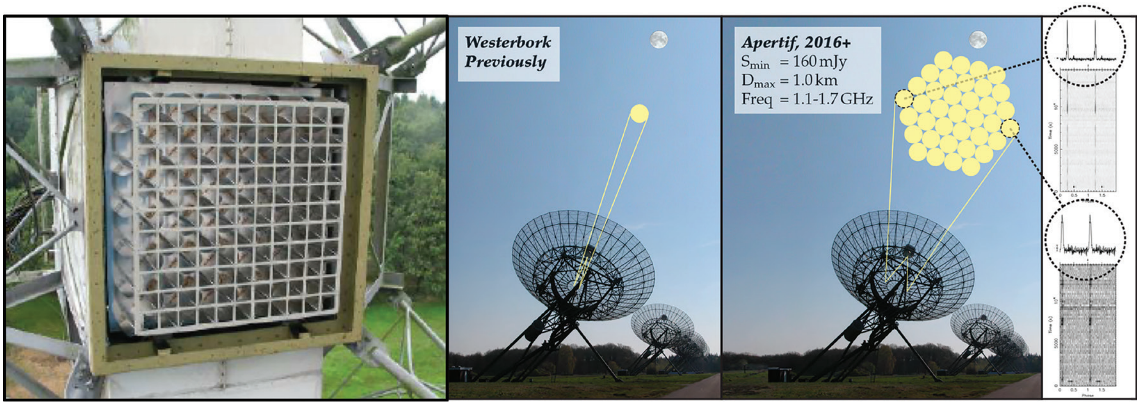

***Fig. 5.38:** The APERTIF system increases the field of view of the original WSRT (left) by a factor 30 (right). ARTS builds on the APERTIF receivers to create an ultra-high time resolution, wide-field transient survey telescope. Shown fully right is the ARTS test detection of two pulsars at the edge of the 8.7 sq. deg. field.*

Science motivation

The ARTS team represents all three NOVA science networks for research on radio transients and their likely origin: supernovae, neutron stars, and stellar-mass or supermassive black holes. The extreme energies, densities and gravity in these sources far exceed what can be produced in terrestrial laboratories. Their study is thus imperative for fundamentally understanding mass and energy. Through ARTS, we aim to understand how dense, hot matter is attracted and expelled in extreme gravity, to precisely measure stellar kinematics, and to determine supermassive black-hole energetics.

The ARTS system

The I/O demands and computing power required for ARTS are extraordinary. The ARTS instrument algorithms, however, map exceedingly well on Graphics Processing Units (GPUs). ARTS is therefore being implemented as a GPU-based supercomputing instrument that will serve as a unique wide-field VLBI backend; as a pulsar timing machine much more powerful than PuMa II; and finally, as a next-generation fast-transient survey instrument. ARTS is an order of magnitude more sensitive to extragalactic radio bursts than any other experiment currently operating world-wide, including the Parkes telescope that recently found and confirmed these bursts. ARTS also provides much better localization, essential for discovering the nature of these enigmatic, powerful cosmological events.

NOVA contribution

The NOVA Instrumentation program funds part of a 500-TFLOPS GPU cluster for transient searching, pulsar timing, and wide-field VLBI. The NOVA funding also covers the salaries for a post-doctoral fellow plus 2 technical PhD students to develop and implement the GPU transient-search and pulsar-timing pipelines, and the program coordinator to oversee this effort at UvA. Thanks to the enabling funding provided by NOVA, significant external investment in ARTS has been secured.

Progress 2013-2015

The ARTS project successfully passed its PDR in July 2015. In November of that year, the ASTRON management approved the full roll-out of the APERTIF receivers for all 12 WSRT dishes and approved the detailed ARTS budget. Since the PDR, the design of the ARTS H/W and pipeline algorithms has been detailed and the required procurement plan and costing made. These have been approved by a 7-member panel of international experts at the successful CDR meeting in March 2016. In the meantime, the ARTS demonstrator systems have already successfully detected real-life transients.

Outlook

The APERTIF Radio Transient System will offer a unique combination of wide-field detection and high-precision radio characterization, for unprecedented and potentially transformative studies of the nature of matter, space and time. Pulsar timing measurements with ARTS will commence in late 2016 with the full system being handed over to the VLBI science teams by mid-2017.

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5.4.2 Lab Astrophysics

In 2013-2015 three NOVA funded ultra-high vacuum cryogenic setups have been used to study solid state processes in interstellar ice analogues for astronomically relevant conditions. CRYOPAD2 has been completely upgraded and is fully operational since summer 2015, SURFRESIDE2 and MATRI2CES have been continuously producing data.

Scientific goals

CRYOPAD2 has been designed and constructed with the aim to quantitatively derive parameters that characterize the photodesorption and photodissociation in interstellar ice analogues and to derive the resulting photochemical pathways that explain the molecular complexity as observed by e.g. ALMA. Wavelength dependent photodesorption rates using the SOLEIL synchrotron facility have been obtained in close collaboration with UPMC Paris. SURFRESIDE2 is suited to study atom addition reactions under dense cloud conditions where UV light is less important and experiments have shown how both smaller (H_2O, CH_3OH and CO_2) as well as more complex species, like glycolaldehyde ($HC(O)CH_2OH$) and ethylene glycol ($H_2C(OH)CH_2OH$) form. MATRI2CES, based on a new approach to study interstellar ices, aims for lifting ice processing studies into the prebiotic domain where astrochemistry and astrobiology meet. Experiments in 2014 and 2015 showed that molecular complexity extends beyond the borders accessible with standard techniques.

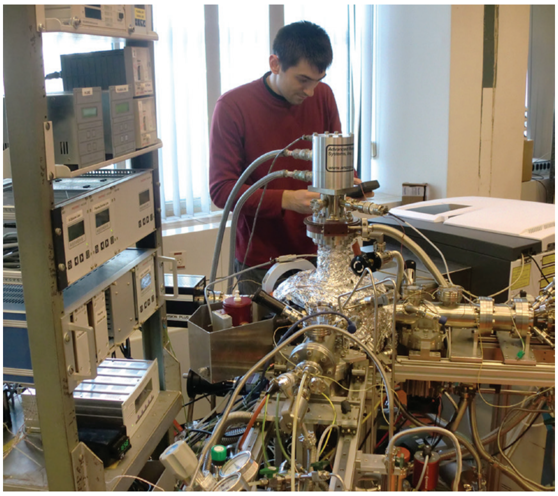

Fig. 5.39: *SURFRESIDE2, an UHV setup to study molecule formation on icy dust grains for dense interstellar cloud conditions.*

Instrument description

The setups are all used at ultra-high vacuum (better than 10^{-12} mbar). Mixed or layered ices, compact or porous, are grown with monolayer precision. Physical (i.e., photodesorption and photodissociation) and chemical (molecule formation) processes are initiated using calibrated microwave driven H_2 discharge lamps as well as atomic beam lines (H, D, N, O and also OH) that simulate interstellar radiation fields or particles impacting onto icy dust grains in space. The detection is realized spectroscopically, using reflection spectroscopy (FTIR RAIRS) or mass spectrometrically, using QMS or TOF based methods.

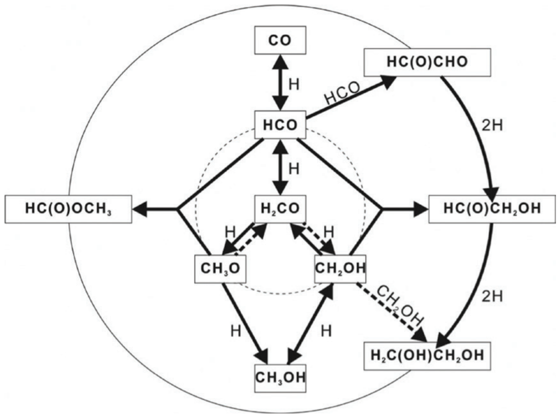

Fig. 5.40: *Solid state reaction scheme, derived from experiments performed with SURFRESIDE2, that shows how dense interstellar cloud chemistry can result in the formation of complex organic molecules. [Fedoseev et al. 2015 , MNRAS 448, 1288]*

Results achieved in 2013-2015

In 2013 the full potential of the SURFRESIDE2 experiment was described in Reviews Scientific Instruments. A new indirect photodesorption mechanism was discovered, hinting for a new way to evaporate interstellar ice constituents. For the first time evidence was found for wavelength dependent photochemistry in ice and discussed during the Faraday Discussions 168, organized by the Sackler Laboratory for Astrophysics. Also for the first time it was shown that COMs (complex organic molecules) can be formed under cold dense cloud conditions. Many of the highlights realized with the Leiden ice setups were summarized in the International Reviews for Physical Chemistry and as a book chapter in 'Laboratory Astrochemistry' (Wiley, 2014).

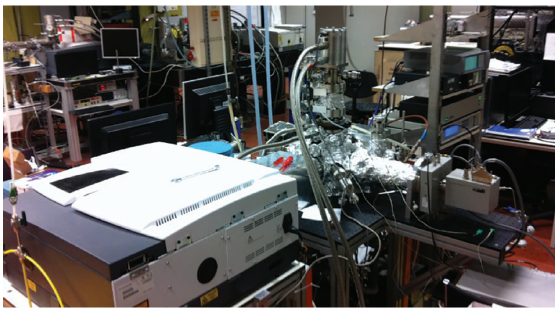

Fig. 5.41: *The upgraded CRYOPAD2; a new ultra-high vacuum chamber, evacuated by a larger turbo pump, and coupled to a recently purchased highly sensitive quadrupole mass spectrometer and UV discharge lamp that is monitored by a new visible-UV spectrometer. An adapted cold head allows to perform in situ calibration measurements and the spectral features are measured using a new Fourier-transform IR spectrograph.*

5.4.3 AMUSE

The Astronomical Multipurpose Software Environment (AMUSE) is a component library for simulating astronomical phenomena. It is composed of some 50 high-level production quality numerical codes packed together in a homogeneous and unique framework. The individual codes are written in highly optimized and often parallelized or GPU enabled source code, whereas the interfaces that enable the communication between the codes are written in the high level scripting language Python.

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Description and usage

AMUSE has the best of two worlds: Python enables rapid prototyping of production quality astronomically motivated experiments, and the underlying optimized solvers warrant a quick execution, even on large parallel supercomputers.

Another major advantage of AMUSE is the unified unit conversion between dimensionless code units and astrophysically motivated units. This allows even novice users to be able to set up their experiments quickly and interpret the results. As a consequence, AMUSE is extremely suitable for education of astronomy at all levels.

The hundreds of example and scientific production scripts enable any users (even the inexperienced programmers) to setup a simple experiment in a matter of minutes. More complicated experiments can include any combination of hydrodynamics, stellar evolution, gravitational dynamics and radiative transport.

AMUSE is used for more than 20 papers and 6 PhD theses. More than 30 people are using the framework, half of them outside the Netherlands. Topics vary from the study of planetary dynamics, the evolution of millisecond pulsars, to triple star dynamics, supernova remnants, star cluster formation, galaxy evolution and cosmology. Many studies adopt one or two physical domains, even though the framework allows for much more complicated studies. Those complicated studies have so far not been carried out because there is already so much to explore with relatively simple code couplings. In that sense, AMUSE is a revolution in computational astrophysics.

Results

Two notable results include the curious evolution of the triple star system Xi Taurus, by a combination of high-precision gravitational dynamics, stellar evolution and hydrodynamics. In Fig. 5.42 we present a snapshot of a simulation of this notorious triple system.

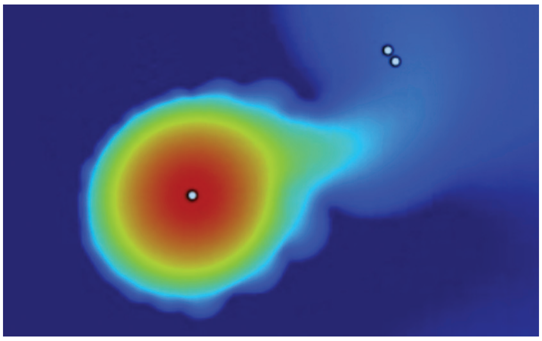

Fig. 5.42: *Snapshot of a simulation of the triple star system Xi Tau in the constellation Taurus. The blob to the left is the primary star, filling its Roche lobe to a lower mass binary system.*

The evolution of Xi Tau was never studied before because the complication of the gravitational dynamics of the triple system together with the complicated stellar evolution and the hydrodynamics of the gas from the primary star to the lower-mass binary star was too complicated to simulate. With the AMUSE framework we have been able to unravel the complicated and rich evolution of this triple star system.

Another important breakthrough achieved with the AMUSE framework was the simulation of a young embedded star cluster, in order to study how the gas was expelled from the cluster. In Fig. 5.43 two images of this simulation are presented that show two time frames of the evolution of a cluster of 1000 stars and with about 1000 $M_\odot$ in interacluster gas.

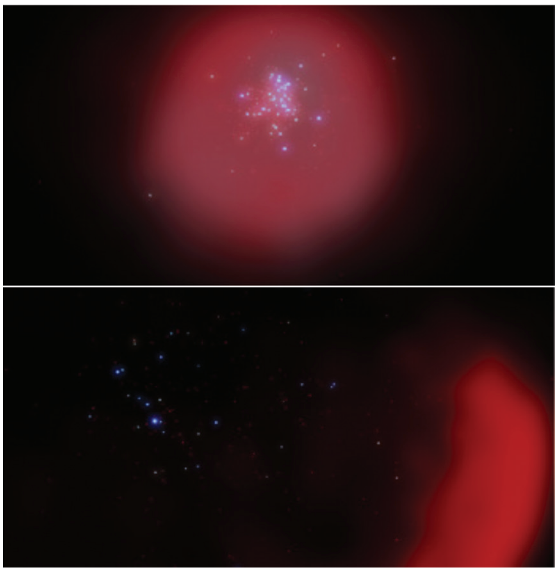

Fig. 5.43: *Top: snapshot of a simulation of an embedded star cluster at the moment that all stars have arrived on the zero-age main sequence (by construction). This cluster consist of 300 $M_\odot$ in stars distributed in a Plummer sphere with a Salpeter IMF, and 1000$M_\odot$ in ambient gas (with the same spatial distribution as the stars). Bottom: snapshot of the same embedded cluster as middle panel, but now after the majority of the gas has been expelled (at an age of about 8 Myr, the first supernova in this cluster occurs at about 10 Myr.)*

The authors demonstrated with this simulation, for the first time, how it is possible to combine high-precision gravitational dynamics, stellar evolution and hydrodynamics, all in one code and running concurrently on 4 computers distributed over the Netherlands.

Outlook

AMUSE has great potential for science, educational purposes and outreach. In addition, it is rather straightforward to expand the framework to other research fields. At the moment a spin-off for the study of long-term weather prediction has been initiated, the first results of which are expected to be published in 2016.

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5.4.4 Data-centric astronomy

NOVA has invested heavily in a suite of survey instruments that produce very large data streams. This provides the Dutch astronomical community with state-of-art raw data to be used for many science cases. OmegaCEN is NOVA's survey datacenter plus expertise center for astronomical information technology. The team has its primary base at the Kapteyn Astronomical Institute and also includes members from Leiden Observatory. Its aim is to provide the environment and infrastructure in which the science teams together with their international partners can efficiently generate their science-grade data, embed their ever changing smart algorithms and thereby perform scientific analyses. OmegaCEN's strategy is to be efficient by pooling its expertise, software and hardware across the NOVA projects.

Fig. 5.44: *Using observations made with the OmegaCAM survey instrument at the VST, astronomers from the Kilo-Degree Survey (KiDS) were able to infer the distribution of Dark Matter in the observed region (colored magenta in the right-hand image) from its aberration of light of galaxies in the background. To do this, light from some 2 million galaxies at distances of around 5,5 billion light-years had to be analysed. This was done by OmegaCEN using the WISE technology. Image credit: Kilo-Degree Survey Collaboration/A. Tudorica & C. Heymans/ESO*

Science motivation

The scientific goals of projects supported by OmegaCEN include Solar System studies, Galaxy and Local Group dwarfs (OmegaCAM, MICADO), the evolution of galaxies, dark matter and dark energy (OmegaCAM, MUSE, Euclid) and the early Universe (OmegaCAM, MICADO, MUSE, Euclid). We refer to the instrument specific sections in this report and the 2010-2012 tri-annual report for a more in depth science discussion for each instrument.

OmegaCEN description

In 2013-2015 OmegaCEN supported the data handling for NOVA's share in following ESO projects:

1. the OmegaCAM wide-field imager, leading the handling of its Dutch-led Kilo-Degree Survey and many GTO projects;
2. leading the handling of GTO surveys with the MUSE multi-unit IFU spectrograph and
3. leading the design for dataflow and pipelines for E-ELT's First Light imager and spectrograph MICADO. For the Science Ground Segment of ESA's Euclid Mission, OmegaCEN leads NOVA's share: hosting the national Science Data Center, co-leading with ESA the Euclid Archive System and co-leading with Germany the handling of all auxiliary ground- and space-based data. OmegaCEN also continued support for the LOFAR Long-Term Archive which it delivered in 2011.

OmegaCEN's "instrument" is its in-house developed WISE technology. WISE allows to build "Living Archives", which are information systems for massive data that integrate survey calibration, quality assessment, science analysis and data mining with archiving. This is achieved by integrating databases, storage and computing resources in a single system. WISE allows to connect heterogeneous hardware and software which are geographically distributed across dozen locations. In 2013-2015, OmegaCEN operated Astro-WISE for OmegaCAM and dozen other wide-field imagers, MuseWise for MUSE and has used WISE technology for Euclid and MICADO dataflow design activities.

Progress and results in 2013-2015

In 2013-2015, OmegaCEN led with Astro-WISE the survey calibration and data processing for the Kilo-Degree Survey for all public data releases to ESO and internal releases to the science consortium. OmegaCEN supported seven OmegaCAM GTO projects, hosting the survey data and managing the pipelines and tuning and expanding algorithms with the science teams. At the end of 2015 Astro-WISE had over 300 users, ~150 Terabytes of pixel data and ~100 million source extractions.

OmegaCEN led the development of MuseWise survey system. It was commissioned together with the MUSE instrument in February 2014. Its role progressed from being an archive system for raw data to calibration production system to science-grade spectral-cube production system for the GTO projects by the end of 2015. MuseWise user community grew to 80 persons. It stores ~100 Terabyte of data including several million files.

For MICADO, OmegaCEN led the top-level design of its dataflow and pipelines on behalf of the consortium. This was part of the delivery which led eventually to the acceptance of the MICADO concept by ESO, signed as an agreement in September 2015.

The Target program was a significant contributor to hardware and expertise for OmegaCEN's activities for NOVA. Target was an OmegaCEN-led multi-disciplinary project at the University of Groningen involving also ASTRON, IBM and Oracle among others. The OmegaCEN's Groningen datacenter was hosted in full on the Target hardware park and maintained by Target personnel at the University's Computing Center together with OmegaCEN.

Status and outlook

OmegaCEN has developed into an internationally operating data and expertise center which on behalf of NOVA is the main Dutch partner for data handling for both the European Southern Observatory and the European Space Agency.

OmegaCEN capabilities are being expanded to handle multi-dimensional data such as integral-field spectrograph datacubes, and collaboration also continues with ASTRON on archiving and access of radio interferometry data. With these continuing developments, OmegaCEN will be in an excellent position to archive and exploit data from future instruments and missions such as MICADO and Euclid.

Fig. 5.45: *The staff of NOVA's eScience expertise center OmegaCEN*

5.5 Co-operation with Industry

The ambitions of Dutch astronomers do not only significantly advance our knowledge of the universe, but they also push the limits of our technology. NOVA therefore collaborates intensively with Dutch industrial partners, both to develop instrumentation to observe planets, stars, and galaxies with breakthrough performance, but also to apply innovative astronomical technologies to address urgent challenges here on earth.

In 1608, the telescope was invented in the Dutch town of Middelburg. Nowadays, the Netherlands is a major partner in the development of the 39-m European Extremely Large Telescope, which will have a larger light-collecting area than all telescopes ever built combined. Dutch astronomers are therefore teaming up with Dutch industry partners to develop key components of both the telescope and several E-ELT instruments. A consortium consisting of TNO (Delft) and VDL-ETG (Eindhoven) with support from NOVA aims to deliver the support actuators and associated control of the 798 hexagonal segments that together make up the primary mirror of the E-ELT.

An ESFRI roadmap grant was awarded to NOVA and a consortium of industrial partners to develop the required technology for E-ELT instruments. Most of this funding has been dedicated to the METIS instrument (for which NOVA is the PI). Janssen Precision Engineering (Maastricht) has, together with NOVA and SRON, designed and prototyped a high-speed “chopper” mirror that is essential to distinguish astronomical signals from the thermal emission of the telescope. To enable a compact and efficient implementation of spectroscopy within METIS, a consortium consisting of SRON, TNO, and Philips (Eindhoven) has developed an “immersed grating” based on silicon technology. To provide vibration-free cooling of the METIS instrument, a collaboration with Airbus Defense and Space (Leiden) and the University of Twente is developing novel “sorption-coolers” that are based on active carbon. The company Airborne (Den Haag) is leading the development of new lightweight composite materials for, for instance, the METIS cryostat.

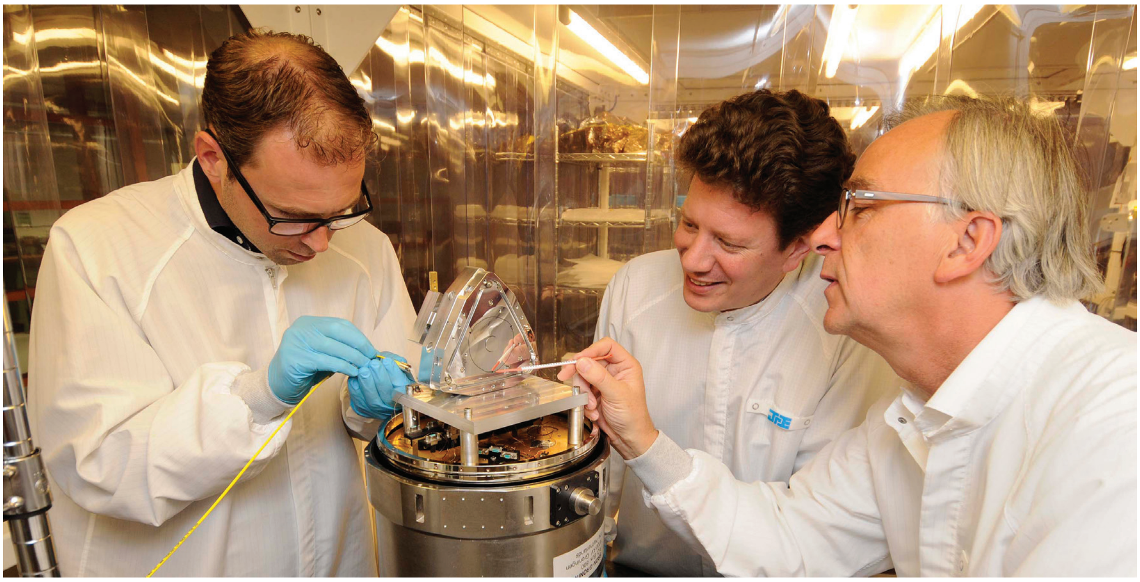

Fig. 5.46: *Janssen Precision Engineering personnel at work testing the METIS cold chopper. Credit: JPE*

The development by NOVA astronomers of advanced adaptive optics (AO), coronagraphic, and polarimetric techniques for current telescopes and for the E-ELT has already led to significant spin-off. In collaboration with Nikon Europe (Amsterdam) and Utrecht University (and supported by an STW grant), Leiden astronomers have developed an AO system in a microscope to enable sharp imaging and in-vivo diagnostics of, e.g., cancer cells. Leiden astronomers also collaborated with TNO (also supported by an STW grant) to apply wavefront-correction techniques to long-range imaging. The development of polarimetric techniques to study the atmospheres of exoplanets has led to a suite of SPEX instruments to study the effects of particles in the earth’s atmosphere on our health and climate. A consortium of Dutch institutes (SRON, Leiden University, NOVA) and industry (TNO, Airbus, Cosine, Mecon) has built a SPEX instrument for operation on an earth-observing satellite platform. This instrument has already passed all crucial qualifications, most notably in terms of the stringent polarimetric requirements, and has been installed in NASA’s ER-2 research plane for flight campaigns at 21 km altitude.

The SPEX polarimetric technology has also be adapted for use on smartphones in the iSPEX project, led by Leiden/NOVA, in collaboration with RIVM, SRON and KNMI. The mass-produced iSPEX add-on was developed by Bright LED Solutions (Veldhoven), and the iSPEX app was developed by DDQ (Valkenburg). Supported by societal partners like Longfonds, Avantes, and KIJK magazine, the iSPEX consortium organized a

Fig. 5.47: NOVA-developed technology forms the basis of the SPEX instrument used to perform aerosol measurements from the NASA ER-2 high-altitude research plane (pictured). Credit: NASA.

large-scale citizen science experiment throughout the Netherlands (2013) and in 11 major European cities (2015) to provide a unique measurement network of air pollution. The Leiden team is currently commercializing the SPEX technology for ground-based air pollution measurements in the FlySPEX project (supported by an STW Demonstrator grant), together with the engineering company Tegema (Eindhoven). The Leiden team also delivered a polarimetric unit for the HAWKEYE hyperspectral camera (developed by AMC Amsterdam, Avantes, and Cosine) for non-invasive crime scene investigation and biomedical imaging.

In 2014 a very special collaboration was established between Snik, Rodenhuis and Studio Roosegaarde, an art studio of worldwide renown. The developed an installation that projected a rainbow in true color onto the main arch of the Amsterdam Central train station. As conventional technology did not fulfil the artistic requirements, the astronomers found a solution with brand-new liquid-crystal technology that are already using for building high-performance “coronagraphs” to directly image exoplanets. The liquid-crystal technology itself was adopted as a “spin-in” from developments of e.g. computer displays. Together with the US-based company, the NOVA/Leiden astronomers developed a so-called polarization grating that produced a rainbow of the correct shape, and with a very high efficiency throughout the visible spectrum. After the opening ceremony in December 2014, the Rainbow Station installation has produced its rainbow at the Amsterdam Central train every day in 2015.

***Fig. 5.48:** Train passing underneath the light-artwork “Rainbow Station” by Studio Roosegaarde, projected on the 125-year old Amsterdam Central Station train shed. The art installation was made possible thanks to advanced optical technology developed for astronomy. Credit: Studio Roosegaarde*

6. NOVA-funded research and instrumentation positions

The tables in the chapter list all research and instrumentation positions whose employment was - partially - funded through NOVA in 2013-2014-2015.

Project	Title	Project leader	Univ	Researcher	Yrs	Start	End	Notes
Network 1								
10.1.3.2	Ly-α emission around galaxies	Schaye	UL	Drs. Alireza Rahmati	4,00	Sep 1, 2009	Aug 31, 2013	
10.1.3.3	Galaxy evolution at z=3	Franx	UL	Drs. Jesse van de Sande	4,00	Nov 1, 2009	Oct 31, 2013	
10.1.3.4	Evolution of gas in galaxies	Trager	RUG	Drs. Gergo Popping	4,00	Sep 1, 2010	Aug 30, 214	
10.1.3.7	Galaxies in the cosmic web	Van de Weijgaard	RUG	Drs. Patrick Bos	4,00	Sep 1, 2010	Aug 30, 2104	
10.1.3.8	Resolved stellar populations	Peletier	RUG	Drs. Sofia Meneses-Goytie	4,00	Dec 1, 2009	Nov 30,2013	
10.1.3.9	Galaxy centers	Israel	UL	Drs. Marissa Rosenberg	4,00	Sep 27, 2010	Sep 30, 2014	
10.1.3.10	Gaia in the galaxy	Helmi	RUG	Drs. Maarten Breddels	4,00	Feb 1, 2009	Jan 31, 2013	
10.1.3.11	Stars in the KIDS survey	Kuijken	UL	Drs. Pila Diez	2,00	Oct 11, 2010	Jul 31, 2013	a
10.1.3.12	The connection between gas and magnetic fields in spiral galaxies	Van der Hulst	RUG	Dr. Sarrvesh Seetapuram Sridhar	1,00	Jan 1, 2013	Dec 31, 2013	
10.1.4.1	Growth of Galaxies in the Early Universe	Franx	UL	MSc. Daniel Lam	4,00	Oct 15, 2015		
10.1.4.4	Onset of the Red Sequence	Franx	UL	MSc. Allison Hill	3,00	Oct 15, 2013		a
10.1.4.6	Characterizing the low-mass stellar IMF in galaxies	Trager	RUG	Dr. Mariya Luybenova	3,00	Jan 1, 2014		
10.1.4.7	Probing feedback in the nuclei of (U)LIRGs using water lines	Van der Werf	UL	MSc. Saskia van den Broek (80%)	3,00	Sep 1, 2014		a
10.1.4.8	Galaxy halo masses, shapes, and sizes from KiDS+VIKING+GAMA	Kuijken	UL	MSc. Margot Brouwer	4,00	Oct 1, 2013		
10.1.4.10	Star formation at ultra-low levels	Brinchmann	UL	MSc. Mieke Paalvast	4,00	Jan 1, 2015		
10.1.4.11	Chemical composition of stellar populations beyond the Local Group	Larsen	RU	MSc. Svea Hernandez Orta	4,00	Jan 1, 2015		
10.1.4.12	Hypervelocity stars as a powerful new tool to investigate the Galaxy	Brown/Rossi	UL	MSc. Clement Bonnerot	3,00	Jan 1, 2014		a
10.1.4.13	Structures and substructures in the Milky Way using Gaia	Helmi	RUG	Dr. Jovan Veljanoski	3,00	Sep 15, 2014		
10.1.4.14	NOVA fellowship 1	Schaye	UL	Dr. Tiago Costa	2,00	Sep 1, 2015		
10.1.4.15	NOVA fellowship 2	Schaye	UL	Dr. Michael Maseda	2,00	Sep 1, 2015		

Project	Title	Project leader	Univ	Researcher	Yrs	Start	End	Notes
10.1.4.15	NOVA fellowship 3	Helmi	RUG	Dr. Manolis Papastergis	3,33	Sep 1, 2013		
Network 2								
10.2.3.1	Water in star-forming regions	Van Dishoeck	UL	Drs. Daniel Harsono (25%)	4,00	Sep 1, 2010	Dec 31, 2013	a, b
10.2.3.2	Water in high mass SF regions	Van der Tak	RUG	Drs. Yunhee Choi	4,00	Sep 1, 2010	Aug 31, 2014	b
10.2.3.3	Molecular complexity	Dominik	UvA	Drs. Gijs Mulders (50%)	4,00	Feb 1, 2009	Jan 31, 2013	b
10.2.3.4	HIFI, ALMA laboratory studies	Linnartz	UL	Drs. Edith Fayolle	4,00	Sep 1, 2009	Aug 31, 2013	
10.2.3.5	From dust to planets	Spaans	RUG	Dr. Rowin Meijerink	2,50	Nov 1, 2011	Apr 30, 2014	
10.2.3.7	Inner disk gas models	Kamp	RUG	Drs. Rosina Bertelsen	4,00	Oct 1, 2010	Sep 30, 2014	
10.2.3.9	Disks around embedded YSOs	Hogerheijde	UL	Drs. Kuo-Song Wang	4,00	Sep 15, 2009	Sep 14, 2013	
10.2.3.10	Youngest massive stars	Kaper	UvA	Drs. Lucas Ellerbroek	4,00	Mar 1, 2010	Feb 28, 2014	
10.2.3.11	Massive starts in LMC	de koter	UvA	Drs. Frank Tramper	4,00	Nov 15, 2010	Nov 14, 2014	
10.2.3.12	Red dwarf transients	Snellen	UL	Drs. Matteo Brogi	4,00	Jun 1, 2010	May 31, 2014	
10.2.3.13	Exo-planets with Corot and Sphere	Dominik	UvA	Drs. Rik van Lieshout	4,00	Oct 15, 2011	Oct 14, 2015	
10.2.3.15	Tracing the evolution of protoplanetary disks	Tielens	UL	Msc. Koen Maaskant	2,50	Jul 1, 2010	Jun 30, 2014	
10.2.4.1	Disk structure and planet formation across spectral types	Kamp	RUG	MSc. Aaron Greenwood	4,00	Apr 15, 2014		
10.2.4.4	PAH evolution in disks	Tielens	UL	MSc. Cornelia Pabst (80%)	5,00	Sep 1, 2015		
10.2.4.5	Transport in disks with Freeze-out	Dominik	UvA	MSc. Lucia Klarmann	4,00	Jun 1, 2014		
10.2.4.6	Planet formation	Spaans	RUG	Dr. Gisela Bano Esplugues	1,00	Jan 1, 2015	Dec 31, 2015	a
10.2.4.7	Observing disk Structure with evolving dust	Hogerheijde	UL	MSc. Nico Salinas Poblete	4,00	Nov 1, 2013		
10.2.4.8	The brightest transiting planets	Snellen	UL	MSc. Geert Jan Talens	4,00	Sep 1, 2014		
10.2.4.10	Direct imaging techniques with SPHERE-ZIMPOL	Keller/ Kenworthy	UL	Dr. Christian Ginski	2,50	May 1, 2014		
10.2.4.11	Modelling disks and planets in reflected light	Dominik/Keller	UvA	MSc. Tomas Stolker	2,00	Sep 1, 2015		a
10.2.4.12	High mass star formation from Herschel to ALMA	Van der Tak	RUG	MSc. Veronica Allen	4,00	Jan 1, 2014		b
10.2.4.13	Formation and early evolution of the most massive stars	Kaper	UvA	MSc. Maria Ramirez Tannus	4,00	Sep 15, 2014		
10.2.4.14.1	Multiplicity properties of massive stars	de Koter	UvA	Dr. Sana Hugues	0,26	Jan 1, 2013	Aug 15, 2013	

Project	Title	Project leader	Univ	Researcher	Yrs	Start	End	Notes
10.2.4.14.2	Episodic mass-loss by massive stars in low metallicity environments	de Koter	UvA	Dr. Frank Tramper	1,74	Nov 15, 2014		
10.2.4.15	Star formation history in the Gould Belt	Brown/Kaper	UvA/ UL	MSc. Difeng Guo	4,00	Oct 1, 2014		
10.2.4.16	Population synthesis of star forming galaxies	de Koter	UvA	MSc. Emmanouil Zapartas (50%)	2,00	Oct 1, 2014		a
10.2.4.18	Diffuse emission in the Galactic plane	Haverkorn	RU	Msc. Irene Polderman	4,00	Oct 1, 2014		
Network 3								
10.3.3.3	High-energy follow-up observations of radio transients	Wijnands	UvA	Msc. Yi-Jung Yang	1,00	Jul 1, 2012	Jun 30, 2013	
10.3.3.5	X-ray timing of stellar mass black holes	Van der Klis	UvA	Drs. Maithili Kalamkar	4,00	Aug 1, 2009	Jul 31, 2013	
10.3.3.7	Jet evolution during accretion outbursts	Markoff/ Falcke	UvA	Msc. Salomé Dibi-Rousselle	1,00	Jan 1, 2013	Dec 31, 2013	
10.3.3.9	X-ray spectra of binaries with ultra-short periods	Verbunt	UU/ RU	Drs. Oliwia Madej	4,00	Sep 1, 2009	Aug 15, 2013	b
10.3.3.11	Galactic plane compact binary population	Groot	RU	Drs. Thomas Kupfer	4,00	May 1, 2011	Apr 30, 2015	
10.3.3.12	Galactic budge population of x-ray binaries	Nelemans	RU	Drs. Serena Repetto	2,00	Oct 1, 2011	Sep 30, 2013	
10.3.3.14	Stellar populations in dense systems	Portegies Zwart	UL	MSc. Edwin van der Helm	4,00	Sep 1, 2012		
10.3.3.15	Progenitors of Type Ia supernovae 2 + 20	Pols	UU/ RU	Drs. Joke Claeys	2,00	Sep 1, 2011	Aug 15, 2013	
10.3.3.17	Particle acceleration in intermediate power jets	Achterberg	UU/ RU	Drs. Sander Walg	4,00	Mar 1, 2010	Feb 28, 2014	
10.3.3.18	Ultra-high energy cosmic rays with AUGER	Hörandel	RU	Drs. Johannes Schulz	2,00	Feb 15, 2012	Feb 14, 2014	
10.3.4.1	LOTAAS: The LOFAR Tied-Array All-Sky Survey for pulsars and fast transients	Hessels	UvA	MSc. Nina Gusinskaia (50%)	2,00	Sep 1, 2015		c
10.3.4.2	Fast optical and radio intranight variables and transients	Groot/ Nelemans	RU	MSc. Jan van Roestel	4,00	Sep 1, 2013		
10.3.4.3	Fast Gaia transients: a treasure trove to be explored	Nelemans	RU	MSc. Thomas Wevers	4,00	Sep 1, 2013		
10.3.4.5	Detecting the epoch of reionization and transients with AARTFAAC/LOFAR	Koopmans	RUG	MSc. Bharat Gehlot	2,00	Nov 1, 2014		
10.3.4.6	How does Sgr A* relate to other Black Holes?	Markoff/ Wijers	UvA	MSc. Riley Connors	4,00	Sep 1, 2013		
10.3.4.7	Black-hole ejecta physics: studying tidal disruption events	Wijers	UvA	MSc. Adam Jakub Ciesielski	4,00	Oct 1, 2014		

Project	Title	Project leader	Univ	Researcher	Yrs	Start	End	Notes
10.3.4.8	AGN fedback and super-massive Black Hole growth with LOFAR	Wise	UvA	MSc. Georgi Kokotanekov (50%)	2,00	Dec, 1, 2013		c
10.3.4.9	Revealing the clockwork: The physical origin of low-frequency quasi-periodic oscillations in Black Holes and neutron stars	Uttley/Mendez	UvA	MSc. Abigail Stevens	4,00	Sep 1, 2013		
10.3.4.10	Outflows from supermassive Black Holes	Constantini	UvA/ SRON	MSc. Catia Vanessa Silva	4,00	Oct 1, 2013		b
10.3.4.12	Black Hole masses in Galactic Black Hole X-Ray binaries and ultra-luminous X-ray sources	Jonker	RU/ SRON	Dr. Manuel Torres	2,50	Jul 1, 2014		b
10.3.4.13	Q(ED)music: radio bursts from magnetars	Watts	UvA	MSc. Chris Elenbaas (50%)	2,00	Oct 1, 2013		a
10.3.4.14	Imaging the event horizon of a Black Hole with radio telescopes	Falcke	RU	MSc. Raquel Fraga-Encinas	2,00	Sep 1, 2013		Spinoza
10.3.4.15	Understanding binary mass transfer with AMUSE	Pols	RU	MSc. Martha Irene Saladino	4,00	Oct 1, 2014		
10.3.4.16	From star/binary population synthesis to single/binary neutron stars	Verbunt	RU	MSc. Andrei Igoshev	4,00	Oct 1, 2013		
10.3.4.17	Formation and evolution of young stellar clusters	Portegies Zwart	UL	Dr. Silvia Toonen	1,00	Jan 1, 2015	Dec 31, 2015	
10.3.4.18	Faint X-Ray source populations in different environments: from the Galactic plane to the cores of dense star clusters	Van de Berg	UvA	MSc. Liliana Rivera Sandoral (50%)	2,00	Oct 1, 2013		a
10.3.4.19	Galactic propagation of energetic cosmic rays and interactions with the interstellar molecular gas	Achterberg/ Hörandel	RU	MSc. Ala'a Al-Zetoun	4,00	Jun 1, 2015		
10.3.4.20	Supernova remnants and pulsar wind nebulae observations with LOFAR	Vink/Haverkorn	UvA	MSc. Maria Arias de Saavedra Benitez	4,00	Oct 1, 2015		
Cross Network								
10.CN.3.1	Stellar clusters in the local universe		RU	Drs. Tjibaria Pijloo	4,00	Jul 1, 2012		
10.CN.3.2	Illuminating high redshift matter with GRBs		UvA	Drs. Olga Hartoog	4,00	Dec 1, 2010	Nov 30, 2014	
10.CN.3.3	The Galactic Halo in the Gaia era	Nelemans	RU	Drs. Peter van Oirschot	4,00	Sep 1, 2011	Aug 31, 2015	
10.CN.3.4	Massive Stars after the FLAMES Survey	de Koter	UvA	Drs. Oscar Ramirez Aguledo	4,00	Mar 1, 2011	Feb 28, 2015	

Project	Title	Project leader	Univ	Researcher	Yrs	Start	End	Notes
Science Support								
10.SS.3.1	Early Science with ALMA	Hogerheijde	UL	Dr. Markus Schmalzl	2,00	Apr 1, 2011	Mar 31, 2014	
10.SS.3.2	SPHERE Science Support	Dominik	UvA	Dr. Christian Thalmann	2,50	Jan 1, 2011	Jun 30, 2013	
10.SS.3.5	OmegaCEN, database	Valentijn	RUG	Dr. Danny Boxhoorn	5,00	Apr 1, 1999	Dec 31, 2013	
10.SS.3.5	OmegaCEN, Photometry	Valentijn	RUG	Dr. Gijs Verdoes Kleijn (0.8)	5,75	Dec 1, 2006	Dec 31, 2013	
Overlap appointments								
10.OA.3.1	Protoplanetary disks	Wijers	UvA	Prof.dr. Carsten Dominik	5,00	Jan, 1, 2009	Dec 31, 2013	
10.OA.3.2		Peletier	RUG	Prof.dr. Mariano Mendez	4,08	Nov 1, 2009	Jan 31, 2013	
10.OA.3.3.4		Kuijken	UL	Dr. Matthew Kenworthy	2,50	Jan 1, 2011	Jun 30, 2013	
10.OA.3.6		Groot	RU	Dr. Elmar Körding	2,50	Jan 1, 2012		
10.OA.4.2	Pulsar research	Wijers	UvA	Dr. Selma de Mink (20%)	1,10	Jan 1, 2014	Dec 31, 2015	
10.OA.4.5	LOFAR, radio astronomy	Peletier	RUG	Dr. J.P. McKean (50%)	2,50	Jan 1, 2014		
10.OA.4.7		Groot	RU	Dr. Soren Larsen	3,50	Jan 1, 2014		
10.OA.4.8		Groot	RU	Dr. Onno Pols	3,50	Jan 1, 2014		
10.OA.4.9		Groot	RU	Dr. Elmar Körding	0,50	Jan 1, 2014	Jun 30, 2014	
Transfer Phase 3 continuation Research & Instrumentation								
UU	Transfer UU to UvA		UvA	Dr. Jacco Vink	2,50	Jan 1, 2013	Jun 30, 2015	
UU	Transfer UU to UvA		UvA	Dr. Maureen van den Berg	3,92	Feb 1, 2012	Dec 31, 2015	
UU	Transfer UU to UvA		UvA	MSc. Smriti Vats	3,00	Jan 1, 2013	Dec 31, 2014	
UU	Transfer UU to UL		UL	Prof.dr. Christoph Keller	2,00	Jan 1, 2012	Dec 31, 2013	
Seed funding	Early science with ALMA Band 9 receiver	van Dishoeck	UL	Msc. Nienke van der Marel	4,00	May 1, 2011	Apr 30, 2015	
	Postdoc NW 3.1/LOFAR COS-02/COS-09		RU	Dr. David Cseh	1,50	Jan 1, 2014	Jun 30, 2015	
	Postdoc NW 3.1/LOFAR COS-02/COS-09		RU	Dr. Monika Moscibrodzka	1,50	Jan 1, 2014	Jun 30, 2015	
Notes								
a	Additional funding up to 4 year in total is covered by the university							
b	Co-funded by SRON							
c	Co-funded by ASTRON							

Instrumentation Program

Project/job description	Project leader	Inst	Researcher	Yrs	Starting date	Ending date	Notes
Allegro							
Technical postdoc	Hogerheijde	UL	Dr. Tim van Kempen	3,00	Jul 1, 2010	Jun 15, 2014	
ALMA Band-5 final design and production							
Head of Group; project manager	Boland	RUG	Ir. Joost Adema	Pw	Mar 1, 2003		
Front-End scientist	Adema	RUG	Dr. Ronald Hesper (30%)	Pw	Sep 1, 2000		
Verification measurements	Adema	RUG	Jan Barkhof	Pw	Mar 16, 2004		
Test Engineer	Adema	RUG	Rob de Haan	Pw	Nov 1, 2009		
Documentalist	Adema	RUG	Albert Koops	Pw	Dec 1, 2004		
Assembly technician	Adema	RUG	Marielle Bekema	Pw	Jan 1, 2005		
Submillimeter technical R&D							
Receiver scientist	Baryshev	RUG	Dr. Ronald Hesper (70%)	Pw	Sep 1, 2000		
Technical postdoc	Baryshev	SRON	Dr. Andrey Khudchenko (50%)	3,00	Jan 1, 2013		
Technical postdoc	Tilanus	UL	Dr. Ilsang Yoon (50%)	1,00	Sep 1, 2014		
ARTS							
Technical postdoc	van Leeuwen	UvA	MSc. Samayra Straal (50%)	2,00	Sep 1, 2014		
Technical postdoc	van Leeuwen	UvA	MSc. Klim Mikhailov	4,00	Sep 1, 2014		
CTA							
Instrument scientist	Berge	UvA	Dr. Arnim Balzer	3,00	Jan 1, 2014		
Instrument scientist	Hörandel	RU	Dr. Antonio Bonardi	3,00	Jan 1, 2014		
EPICS							
PhD student	Keller	UL	MSc. Michael Wilby	4,00	Sep 1, 2014		
EUCLID							
Database expert	Verdoes Kleijn	RUG	Drs. Danny Boxhoorn (80%)	4,00	Jan 1, 2015		
System Engineer	Verdoes Kleijn	RUG	MSc. Bertrand Delforge	3,70	May 15, 2015		
OU-NIR software designer	Bouwens	UL	Dr. Mher Kazandjian	4,00	Jun 1 , 2015		
OU external ground-based data	Valentijn	RUG	Dr. Gijs Verdoes Kleijn (50%)	3,00	Jan 1, 2015		
Technical postdoc	Valentijn	RUG	Dr. John McFarland	4,00	Jan 1, 2015		
Gaia							
Software scientist	Brown	RU	Dr. Arjen van Elteren	1,00	Jan 1, 2013	Jan 1, 2014	

Project/job description	Project leader	Inst	Researcher	Yrs	Starting date	Ending date	Notes
Laboratory astrophysics							
Technical Postdoc	Linnartz	UL	Dr. Gleb Fedoseev (80%)	1,00	Oct 15, 2014	Oct 14, 2015	
Technical Postdoc	Linnartz	UL	Dr. Cruz Diaz	0,71	Sep 1, 2014	May 14, 2015	
LOFAR for astronomy							
SRV-2 P3 cont postdoc	Röttgering	UL	Dr. Bas van der Tol	2,25	Apr 15, 2011	Jul 15, 2013	
TRA-09 postdoc	Wijers	UvA	Dr. Bart Scheers (50%)	1,00	Feb 1, 2012	Dec 31, 2013	
Long-term archive & data mining							
MUSE-OmegaCAM-GTO support	Verdoes Kleijn	RUG	Various people (total 80%)	5,00	Jan 1, 2014		
MUSE-OmegaCAM-GTO support	Valentijn	RUG	Dr. Gijs Verdoes Kleijn (20%)	5,00	Jan 1, 2014		
METIS							
International project manager	Brandl	SRON	Drs. Ing. Rieks Jager		Jun 1, 2014		
Postdoc instrument modelling	Brandl	UL	Dr. Eva Meyer	1,61	Jun 15, 2011	Jul 31, 2013	
Postdoc	Brandl	UL	Dr. Jeff Meisner	0,55	Sep 1, 2012		
MIRI							
Instrument science support	van Dishoeck	UL	Dr. Fred Lahuis (80%)	4,72	Jan 1, 2010		
ESA bridging support	Lahuis	RUG	Dr. Michael Müller	3,00	Jan 1, 2015		
MUSE							
Postdoc system support	Schaye	UL	Dr. Thomas Martinsson	2,00	Nov 1 , 2011	Dec 31, 2014	
Optical-Infrared Instrumentation Group							
Head of group; project manager		NOVA	Dr. Ramon Navarro				
Project manager; system engineer		NOVA	Johan Pragt (70%)				
System engineer/cryogenic engineer		NOVA	Ronald Roelfsema				
System engineer/project manager		NOVA	Ir. Felix Betonvil				
System engineer/mechanical designer		NOVA	Niels Tromp				
Optical designer		NOVA	Rik ter Horst (84%)				
Optical designer		NOVA	Tibor Agocs				
Senior mechanical designer		NOVA	Gabby Kroes (90%)				
Mechanical designer		NOVA	Jan Kragt				
MAIT engineer		NOVA	Eddy Elswijk				
Mechanical fabrication		NOVA	Menno Schuil				
Optical fabrication and AIT		NOVA	Menno de Haan				
Instrument physisist - Liaison		UL	Dr. Remko Stuik (80%)				a

Project/job description	Project leader	Inst	Researcher	Yrs	Starting date	Ending date	Notes
Various							
ALMA Band-9 early science harvesting	Van Dishoeck	UL	Drs. Nienke van der Marel	4,00	May 1, 2011	April 30, 2015	
EPICS, NL Roadmap program							
Polarimetry system engineering	Keller	UL	Dr. Frans Snik	4,00	Jul 1, 2009	Nov 30, 2014	
EPICS integral field unit development	Keller	UL	Dr. Michiel Rodenhuis	2,00	Jan 1, 2011	Aug 31, 2014	
Polarization performance prediction	Keller	UL	Drs. Maria de Juan Ovelar	4,00	Feb 15, 2010	Feb 14, 2014	
High contrast adaptive optics testbed	Keller, Kenworthy	UL	Drs. Gilles Otten	4,00	Nov 1, 2011	Oct 31, 2015	
METIS, NL Roadmap program							
Background calibration	Brandl, Keller	UL	MSc. Stephanie Heikamp	3,00	Oct 15. 2012	Oct 14, 2015	
Various, NL Roadmap program							
MOSAIC trade-off studies	Kaper	UvA	Dr. Bertrand Lemasle	3,00	Jun 1 , 2012	May 30, 2015	
Upscaling sorption cooling performance	Ter Brake	UT Twente	Drs. Wu	4,00	Jan 1, 2011	Jun 30, 2015	

Notes

a Additional funding by the university

Pw Permanent contract with warning

Office & Outreach

Project/job description	Name	Inst	Yrs	Starting date	Ending date
Outreach					
Public Outreach officer	Drs. Marieke Baan (70%)	NIC-A'dam			
Education officer	Jaap Vreeling (60%)	NIC-A'dam			
Support staff	Franka Buurmeijer (60%)	NIC-A'dam		Aug 1, 2012	Dec 31, 2014
Support staff	David Redeker (40%)	NIC-A'dam		Jan 15, 2015	
Office					
Scientific Director	Prof.dr. Ewine van Dishoeck	NOVA/UL			
Executive Director	Dr. Wilfried Boland	NOVA/UL			
Finance & Control	Kirsten Groen	NOVA/UL			
Management Assistant	Jacqueline Quist	NOVA/UL			
Instrumentation Coordinator	Dr. Michiel Rodenhuis (40%)	NOVA/UL		Feb 1, 2015	Oct 30, 2015
Instrumentation Coordinator	Dr. Michiel Rodenhuis (100%)	NOVA/UL		Nov 1, 2015	

7. Workshops & Visitors

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

7.1. Workshops in 2013-2014-2015

The table below lists the workshops which received financial support from NOVA. The table is followed by a description of each meeting. In addition the university astronomical departments in Amsterdam, Groningen, Leiden, Nijmegen and Utrecht received NOVA funding up to 3400 € per institute per year to strengthen the local colloquium program by inviting more foreign speakers. A 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.

Nr.	1st Date	Applicant	Event	University	# days
W-179	14-1-2013	H. Röttgering	Imaging the low frequency radio sky with LOFAR	UL/LC	5
W-183	6-10-2013	H. Röttgering	Astronomy , Radio Sources and Society; The Wonderful Century	UL	3
W-184	20-5-2013	H. Linnartz	IAU297 'The Diffuse Interstellar Bands'	UL	4
W-185	22-4-2013	M. Franx	What regulates Galaxy Evolution?	UL/LC	4
W-186	2-4-2013	S. Portegies Zwart	Hands-on Workshop on Computational Astrophysics	UL/LC	4
W-188	25-2-2013	K. Kuijken	The PNS: future projects and ideas	UL/LC	5
W-189	7-1-2013	O. Pols	Steps towards a new generation of stellar models	RU/LC	5
W-190	15-5-2013	C. Waelkens	68th Dutch Astronomy Conference (NAC)	KUL	5
W-192	27-3-2013	R. vd Weygaert	3rd Quantum Universe Symposium	RuG	2
W-193	17-6-2013	R. vd Weygaert	The Antikythera Mechanism: Science and Innovation in the Ancient World	RuG/LC	5
W-194	5-6-2013	H. Bloemen	Latest results from the neutron star lab	SRON	5
W-195	19-6-2013	B. Oppenheimer	Leiden Summer CGM-Galaxy Interface	UL/LC	3
W-196	23-9-2013	G. Nelemans	Observational signatures of Type Ia supernova progenitors II	Ru/LC	5
W-197	5-6-2013	M. Franx	Galaxy Evolution from z=5 to z=0	UL/LC	5
W-198	29-7-2013	X. Tielens	Oort Workshop The Molecular Physics of Interstellar PAHs	UL/LC	5
W-199	11-4-2013	S. Zaroubi	The radio universe: at Ger's Wavelength	RuG	4
W-200	25-9-2013	J. Vink	The Anisotropic Universe	UvA	3
W-201	10-12-2013	B. Brandl	KINGFISH meeting	UL	3
W-202	12-9-2013	L. Kaper	Astrospheres: From the Sun to Red Super Giants	UvA/LC	5
W-203	31-3-2014	P. Jonker	ULXs – Implications for our View of the Universe	RU/LC	5
W-204	27-1-2014	J. Brinchmann	Astrostatistics	UL/LC	5
W-205	12-1-2014	P. Barthel	Congres Ster van Bethlehem	RuG	1
W-206	4-7-2014	R. Peletier	Star Formation and Galactic Structure	RuG	2
W-207	22-1-2014	J. Schaye	Virgo and Eagle workshops	UL	3
W-208	16-4-2014	R. vd Weygaert	4th Quantum Universe Symposium	RuG	2
W-209	19-5-2014	J. Brinchmann	69th Dutch Astronomy Conference (NAC)	UL	3
W-210	17-2-2014	R. vd Weygaert	Tracing the Cosmic Web	UL/LC	5
W-211	17-3-2014	T. vd Hulst	PHISCC	RuG	3
W-212	30-6-2014	R. Peletier	Nuclear Clusters in Galaxies, and the Role of the Environment	RuG/LC	5
W-213	13-5-2014	E. van Dishoeck	Episodic Accretion in young stars	UL	3

Nr.	1st Date	Applicant	Event	University	# days
W-214	17-9-2014	L. Kaper	Magnetism and variability in O stars	UvA	3
W-215	1-5-2015	J. Vink	Shock Accerleration: from the Solar System to Cosmology	UvA	5
W-216	3-2-2015	P. Pinilla	Transition disks and planet formation	UL/LC	5
W-217	15-1-2015	P.vd Kruit	The Born Investigator of the Heavens	RuG	1
W-218	30-7-2015	J. Vink	International Cosmic Ray Conference	UvA	30
W-219	15-6-2015	S. Zaroubi	First stars, Galaxies and Black Holes: now and then	RuG	5
W-220	4-1-2015	R. vd Weygaert	5th Quantum Universe Symposium	RuG	2
W-221	20-5-2015	J. van Leeuwen	70th Dutch Astronomy Conference (NAC)	ASTRON	3
W-222	5-11-2015	X. Tielens	Energetic Prcessing of Large Interstellar Molecules	UL/LC	3
W-223	29-6-2015	S. de Mink	The Impact of Massive Binaries Troughout the Universe	UvA/LC	5
W-226	10-7-2015	E. Valentijn	The Information Universe	RuG	3
W-227	10-7-2015	KNVWS	Water between heaven and Earth	KNVWS	1
W-228	14-12-2015	J. Schaye	Computational cosmology	UL/LC	4
W-230	16-11-2015	A. Brown	DPAC consortium meeting	UL	5

7.2. Visitors in 2013-2014-2015

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.

Nr.	1st Date	Applicant	Event	University	# days
V-211	2-5 Apr 2013	P. Barthel	Academy Colloquium FIRSED2013 - the FIR-submm SEDs of galaxies with and without active nucleus	RuG	4 dg
V-217	2013	S. Trager	Visiting Blaauw Professor Daniela Calzetti, University of Massachusetts	RuG	3 visits
V-218	24 Apr-5 June 2013	H. Henrichs	Natallia Sudnik, St. Petersburg, Russia	UvA	1.5month
V-220	1 Sept 2013 - 1 Sept 2014	H. Hoekstra	Michael Balogh, University of Waterloo, Canada	UL	12 months
V-221	1 Sept- 1 Oct 2013	H. Röttgering	Bill Cotton, National Radio Astronomy Observatory, USA	UL	1 month
V-222	Nov-Dec 2013	H. Henrichs	Natallia Sudnik, St. Petersburg, Russia	UvA	2 months
V-223	9-13 Dec 2013	R. Weygaert	Jacques Delabrouille, APC laboratory, Paris	RuG	5 days
V-224	18-22 nov 2013	E. Rossi	Shiho Kobayshi, Liverpool University	UL	5 days
V-225	spring 2014	E. vd Heuvel	visit KITP Santa Barbara	UvA	3 weeks
V-228	1-30 June 2014	K. Kuijken	Nick Kaiser, Hawaii	UL	3 weeks
V-229	1-30 June 2014	H. Henrichs	Natallia Sudnik, St. Petersburg, Russia	UvA	1 month
V-230	aug-sept 2014	H. Henrichs	Natallia Sudnik, St. Petersburg, Russia	UvA	1 month
V-231	23-29 Nov 2014	E. Rossi	Davide Fiacconi, Center for Theoretical Astrophyscis and Cosmology and Institute for Computational Science, University of Zurich	UL	6 days
V-234	Summer 2015	J. in 't Zand	Duncan Galloway, Monash University	SRON U	4 weeks
V-237	jun-15	H. Henrichs	Natallia Sudnik, St. Petersburg, Russia	UvA	3 weeks

8. Public Outreach and Education

NOVA feels a compelling obligation to communicate its frontline research in the widest sense and considers public outreach and communication as a high priority. The NOVA Information Center (NIC) has been established for this purpose and organizes and coordinates press and public outreach activities on behalf of the four university astronomical institutes in the Netherlands. Over the years the NIC has developed in an expertise center for communicating astronomy and an information point for press, broadcasters, schools, festivals and the general public. The NIC is also the Dutch national communication and press hub for the ESO. The main focus areas of the NIC are (1) press & media, (2) students & educators, and (3) the general public.

The head of the NIC is Marieke Baan (0.73 fte), who was honored for her contributions to astronomy outreach by having an asteroid named after her in 2013. David Redeker (0.4 fte) is the Press and Information officer (PIO) and Jaap Vreeling (0.6 fte) the Education and Outreach Officer (EPO). On a project by project basis, the NIC calls in the services of about 15 freelancers. The NIC office is located at the Anton Pannekoek Institute of the University of Amsterdam. The NOVA outreach activities are monitored by the Minnaert Committee, chaired by Alex de Koter.

NOVA strategy for Outreach and Communication

Prime goals of the NIC outreach efforts are to (1) inform and involve the public about and in astronomy, (2) identify and engage with societal developments where astronomy can contribute, and (3) contribute to the teaching of the astronomy curriculum in schools. It aims to reach these goals by communicating to selected target groups using those media and platforms that are most efficient in reaching these groups.

The sizes of such target groups range from very large (e.g. the general public) to small (e.g. engineers specialized in detector technology). Communication to specific groups is both direct and indirect. Examples of the former are public events, science fairs, and school visits with the mobile planetaria. Examples of the latter are outreach via the press, a presence on social media, and school books.

Press & Media

The NIC issues about 50 press releases and announcements annually, communicating Dutch science results of (inter-)national importance. A similar number of ESO press releases is translated and disclosed to the public in the Netherlands. These efforts contribute to the many hundreds of astronomy news items and features that are reported on in regional and national newspapers, internet sites, radio, television and social media every year. Press releases are issued in close collaboration with the four academic NOVA institutes and ESA, ESO, SRON, ASTRON, NWO, JIVE, NSO and UNAWE, when appropriate.

In collaboration with partners, the NIC initiated and coordinated prime time national TV shows on astronomy as well as science documentaries and children programs. These programs reached millions of viewers. Highlights are two shows of Heel Nederland Kijkt Sterren, the Dutch counterpart of the BBC show Stargazing Life; the Rosetta comet landing, and a series of episodes for De Kennis van Nu, a science show for a broad audience, and Het Klokhuis, aimed at young children.

__Fig. 8.1:__ ESA-Astronaut André Kuipers and school children in front of one of the mobile planetaria celebrating their Techniekpact certificates. The participation in Techniekpact is one of the NOVA initiatives to promote science & technology in schools.

Online public outreach

The online and communication landscape is changing fast, which requires the NIC to be an agile and flexible organization and to continuously monitor and adjust its communication strategy. The period 2013-2015 is characterized by the maturity of the (mobile) internet as a mass media and news platform, a development that demands a much more visual presentation of results and brought us apps. For children in the age of 4-8 the NIC launched the successful and prize winning iPad-app 'Planet Challenge'. The NICstarted to develop the concept of an even more ambitious educational game on astronomy (ages 12 up) in 2015.

The astronomy news produced and distributed by the NOVA Information Center is also published on the NOVA's popular public website 'astronomie.nl', under the editorship of the NIC. This website generated half a million visitors in the period 2013-2015. In the case of special celestial events, such as solar and lunar eclipses and planetary transits for the Sun, the NIC produces animations for TV programs and internet sites and communicates those directly to the public via a YouTube-channel. On social media the NIC has a follower base of thousands of interested people.

Education

Major developments occurred as well in the educational landscape. The physics curriculum in the Netherlands for secondary schools has been redefined. The NIC initiated a collaboration with the largest educational publisher in the Netherlands to produce the astronomy chapters in their new senior-level textbook series, with the support of De Koter, Lamers, and Van den Heuvel. Together with the NOVA astronomy institutes, the NIC organized a teacher training program to familiarize high-school physics teachers with the new materials, offer them additional educational tools and materials, and to bring them into direct contact with NOVA astronomers. In 2015, the first year of the training, over 100 teachers participated in this program.

From 2010 the NIC operates three mobile planetaria as one of their strategies to transfer astronomical knowledge in schools. These inflatable domes travel to primary and secondary schools, and are frequently hired by kids-, science-, and film festivals. The project is very successful. At the end of 2015 about 175.000 children visited an interactive planetarium show since the start of the project, which converts to 1/6th of the total annual cohort of students in the Netherlands. Schools pay a minimum contribution for covering transport and personnel costs.

Fig. 8.2: *Screenshot from the NOVA prize-winning iPad app Planetenreis (Planet challenge) for primary school children. This app was considered one of the three best apps for the primary school curriculum in the 2013 Meester App contest organized by the Ministry of Education, Culture, & Science.*

Societal Relevance

Astronomy impacts our world view and plays an important role in the way society regards its place in space and time. Alongside to its cultural and philosophical impact, astronomy is at the frontier of science and technology.

Astronomers also push developments, technologically as well as economically, because they require instruments and software beyond the current possibilities. As part of this process, they train young people in logical and quantitative reasoning. These skills are indispensable for both students that pursue scientific and technical careers and those that ultimately take up positions elsewhere in society.

The third way in which astronomy demonstrates its relevance to society is via citizen science. Examples of such outreach in the period 2013-2015 that transcend the NIC's outreach & education programs are:

- The citizen science project iSPEX. This project is unique in its kind, because the public was not asked to classify objects or already collected data, but was asked to help atmospheric researchers to collect new data on aerosols in cities and the countryside through measurements using a set-up piece on their iPhones. These data are important for people coping with lung diseases. The project also shows that astronomers develop innovative technologies that have applications in other disciplines and have the power to engage tens of thousands of people in scientific practice. The iSPEX technology (polarimetry) will also be used in future E-ELT instrumentation.
- NOVA's mobile planetarium program enthuses and engages children in science in general and astronomy in particular. The program is supported by the Dutch government that runs the project Techniekpact to motivate youngsters to choose science & technology as a career path. In the Techniekpact concept, space and astronomy are considered main attractors for these paths. Spearheaded by ESA-astronaut André Kuipers, college-tours are organized for both primary and secondary school pupils of which the NOVA mobile planetaria are a structural part.

The NIC Expertise in a broader perspective

During the reporting period the NIC has further developed as a center of expertise for astronomy in the Netherlands, as evidenced by invitations in boards and advisory committees in science communication. Both Baan and Redeker are board members of the Platform Wetenschapscommunicatie; Vreeling is the chairman of the Dutch & Belgian planetarium society Planed, and Baan is a member of the editorial board of the popular website natuurkunde.nl.

9. Organization

9.1 Board

Prof.dr. P. Groot (chair)	RU, (chair)
Prof.dr. H.J.A. Röttgering	UL
Prof.dr. R.A.M.J. Wijers	UvA
Prof.dr. R.F. Peletier	RUG

9.2 International Board (visit 2014)

Prof.dr. R.C. Kennicutt (Chair)	University of Cambridge, UK
Prof.dr. R.D. Blandford	Stanford University, California, USA
Prof.dr. H-A. Rix	MPIA, Heidelberg, Germany
Prof.dr. A. Sargent	Caltech, Pasadena, California, USA
Prof. dr. B.P. Schmidt	Australian National University, Australia
Prof. dr. D.N. Spergel	Princeton University, USA

9.3 NOVA Research Network 1, 2 and 3

Network 1: Galaxies	*Network 2: Star/planet formation*	*Network 3: Extreme physics*
University staff	*University staff*	*University staff*
Helmi, chair, RUG	Dominik, chair, UvA	Nelemans, chair, RU
Barthel, RUG	Desert, UvA	Achterberg, RU
Bouwens, UL	Brown, UL (nw1+nw2)	Berge, UvA
Brandl, UL	de Koter, UvA	de Mink, UvA (nw2+nw3)
Brinchman, UL	de Mink, UvA (nw2+nw3)	Falcke, RU
Brown, UL (nw1+nw2)	Haverkorn, RU (nw1+nw2)	Groot, RU
Caputi, RUG	Hogerheijde, UL	Hessels, UvA
Dayal, RUG	Kamp, RUG	Hörandel, RU
Franx, UL	Kaper, UvA	Körding, RU
Haverkorn, RU (nw1+nw2)	Keller, UL	Markoff, UvA
Hodge, UL	Kenworthy, UL	Mendez, RUG
Hoekstra, UL	Linnartz, UL	Nissanke, RU
Koopmans, RUG	Snellen, UL	Pols, RU
Kuijken, UL	Spaans, RUG	Portegies Zwart, UL
Larsen, RU	Tielens, UL	Rossi, UL (nw1+nw3)
McKean, RUG	van Dishoeck, UL	Rowlinson, UvA
Peletier, RUG		Uttley, UvA
Rossi, UL (nw1+nw3)		van der Klis, UvA
Röttgering, UL		Verbunt, RU
Schaye, UL		Vink, UvA
Tolstoy, RUG		Watts, UvA
Trager, RUG		Wijers, UvA
Valentijn, RUG		Wijnands, UvA
van der Weygaert, RUG		
van der Werf, UL		
Verheijen, RUG		
Zaroubi, RUG		

Network 1: Galaxies	Network 2: Star/planet formation	Network 3: Extreme physics
Long-term postdocs	**Long-term postdocs**	**Long-term postdocs**
Holwerda, UL	Aleman, UL	van den Berg, UvA
Labbé, UL	Cazaux, RUG	Rea, UvA
Meijerink, UL		Patruno, UL
Oonk, UL/ASTRON		
Verdoes-Kleijn, RUG		
Co-workers	**Co-workers**	**Co-workers**
Costantini, SRON/UvA (nw1-2-3)	Aerts, RU/Leuven	Costantini, SRON/UvA (nw1-2-3)
de Blok, ASTRON/RUG	Baryshev, SRON/RUG	Jonker, SRON/RU
Garrett, ASTRON/UL	Costantini, SRON/UvA (nw1-2-3)	Kaastra, SRON/UL (nw1+nw3)
Fraternali, Bologna/RUG	Helmich, SRON/RUG	Janssen, ASTRON/RU
Heald, ASTRON/RUG	Fridlund, ESTEC/UL	van Leeuwen, ASTRON/UvA
Kaastra, SRON/UL (nw1+nw3)	van Langevelde, JIVE/UL	Wise, ASTRON/UvA
Morganti, ASTRON/RUG	Min, SRON/UvA	In 't Zand, SRON/UvA
Oosterloo, ASTRON/RUG	Roelfsema, SRON/RUG	
Wang, SRON/RUG (nw1+nw2)	Shipman, SRON/RUG	
Wise, ASTRON/UvA	Snik, NOVA/UL	
	van der Tak, SRON/RUG	
	Wang, SRON/RUG (nw1+nw2)	
	Waters, SRON/UvA	
Emeriti, still active researchers	**Emeriti, still active researchers**	**Emeriti, still active researchers**
de Bruijn, RUG		Hermsen, SRON/UvA
van der Hulst, RUG		van den Heuvel, UvA
Israel, UL		Kuijpers, RU
Jaffe, UL		
van der Kruit, RUG		
Miley, UL		
Le Poole, UL		
Sanders, RUG		

9.4 Coordinators research networks

Prof.dr. M. Franx	UL	Network 1, until March 2013
Prof.dr. A. Helmi	RUG	Network 1, since March 2013
Prof.dr. C. Dominik	UvA / RU	Network 2
Prof.dr. G. Nelemans	RU	Network 3

9.5 Instrument Steering Committee

Prof.dr. T. de Graauw (chair)	Chili, since April 2013
Prof.dr. P. Roche (chair)	Oxford, until April 2013
Dr. T. Augusteijn	NOT, La Palma, since May 2013
Prof.dr. R. Bacon	Univ. Lyon, until April 2013
Ing. F. Bettonvil	UL
Dr. B. Brandl	UL
Dr. F. Helmich	SRON, since May 2013
Dr. T. Herbst	MPIA, since May 2013
Dr. J. Hörandel	RU
Prof.dr. L. Kaper	UvA
Dr. G. Kruithof	ASTRON, since September 2014
Prof.dr. H.J. van Langevelde	JIVE, until April 2013
Dr. D. Martin	ESTEC, until March 2014
Dr. Verdoes Klein	RUG, since October 2014
Prof.dr. M. Verheijen	RUG, until December 2013
Dr. M. de Vos	ASTRON, until October 2014
Prof.dr. W. Wild	ESO

9.6 Education Committee

Prof.dr. M. Mendez (chair)	RUG, from July 2014
Prof.dr. F. Verbunt (chair)	RU, until July 2014
L.Boschman	RUG, until December 2014
Dr. M. Brentjens	ASTRON
Drs. T. Coenen	UvA, until September 2014
Mr. M. Dries	RUG, since December 2014
Mr. J.Hoeijmakers	UL, since January 2015
Mr. M.Janssen	RU, since September 2015
Prof.dr. I.E.E. Kamp	RUG
Dr. S. Larsen	RU, since July 2014
MSc N. van Marel	UL, until January 2015
Ms. S. Vats	UvA, since September 2014
Dr. A.L. Watts	UvA
Prof.dr. P.van der Werf	UL
MSc S. Wykes	RU, until September 2015

9.7 Minnaert Committee

Prof.dr. A. de Koter (chair)	UvA
Prof.dr. P.D. Barthel	RUG
Dr. W. Boland (observer)	NOVA
Dr. M. Klein Wolt	RU, since February 2013
Prof. dr. G. Nelemans	RU, until February 2013
Prof. dr. I. Snellen	UL

9.8 Instrument Principal Investigators (PI or NL-PI on international projects)

Prof.dr. A. Baryshev	SRON, RUG	ALMA R&D
Dr. D. Berge	UvA	CTA
Prof.dr. B. Brandl	UL	E-ELT METIS
Dr. A.G.A. Brown	UL	Gaia
Prof.dr. E.F. van Dishoeck	UL	MIRI
Prof.dr. C. Dominik	UvA	SPHERE-Zimpol
Prof.dr. P. Groot	RU	BlackGEM
Prof.dr. A. Helmi	RUG	4MOST
Dr. M. Hogerheijde	UL	ALLEGRO
Prof.dr. W. Jaffe	UL	MATISSE
Prof.dr. L. Kaper	UvA	Moons
Prof.dr. L. Kaper	UvA	E-ELT MOSAIC
Prof.dr. C.U. Keller	UL	E-ELT EPICS
Prof.dr. Kuijken / Prof.dr. Valentijn	UL / RUG	EUCLID
Prof.dr. K.H. Kuijken	UL	OmegaCAM
Dr. J. van Leeuwen	ASTRON, UvA	ARTS
Prof.dr. H.V.J. Linnartz	UL	Laboratory for astrophysics
Prof.dr. S.F. Portegies Zwart	UL	AMUSE
Prof.dr. R. Röttgering	UL	LOFAR / DCLA
Prof.dr. J. Schaye	UL	MUSE
Prof.dr. E. Tolstoy	RUG	E-ELT MICADO
Prof.dr. S.C. Trager	RUG	WEAVE
Prof.dr. E.A. Valentijn	RUG	OmegaCEN

Seed funding

Prof.dr. H. Falcke	RU	AUGER-radio
Prof.dr. I. Snellen	UL	Mascara
Dr. J. Vink	UvA	CTA pilot study

9.9 NOVA Information Center (NIC, located at UvA)

Drs. M. Baan (0.7)	
Msc. F. Buurmeijer (0,2)	until January 2015
Drs. D. Redeker (0,4)	since January 2015
Dhr. J Vreeling (0,6)	

9.10 Office (located at UL)

Prof.dr. E.F. van Dishoeck (scientific director)
Dr. W.H.W.M. Boland (executive director)
Dr.ir. M. Rodenhuis (instrumentation coordinator), since March 2015
C.W.M. Groen (finance and control)
J.T.Quist (management assistant)

10. Financial report 2013 - 2014 - 2015

in k€	*2013*	*2014*	*2015*
ASTRONOMICAL RESEARCH			
EXPENDITURES			
Overlap Appointments	*256*	*370*	*323*
Research Networks			
Departure of astronomy from Utrecht	372		
Network 1: Formation and Evolution of Galaxies	371	506	601
Network 2: Formation of Stars and Planetary Systems	547	507	758
Network 3: Astrophysics of Black Holes, Neutron Stars and White Dwarfs	532	595	802
Miscelleneous research projects and master fellows	328	642	355
Science Support	239		
Workshops & Visitors	60	59	39
TOTAL ASTRONOMICAL RESEARCH	**2.704**	**2.678**	**2.878**
INSTRUMENTATION (NOVA administrated projects)			
ALMA			
ALMA-ALLEGRO	72		
ALMA Technical R&D Band 9	32	46	142
ALMA Band 5 final design and production	636	1.093	2.079
ALMA Band 9 Production	1.872		
E-ELT instrumentation			
METIS	71	337	430
MICADO	3	41	38
EPICS		27	65
MOSAIC		8	20
Other Op-IR instrumentation			
4MOST			10
LTA & Datamining		83	80
BlackGEM		345	279
MATISSE	635	447	89
WEAVE		758	1.004
Optical-IR group	1.637	145	23
Participation in space missions			
MIRI	60	69	137
Gaia	152	15	11
Euclid		14	324
Other projects			
ARTS		27	72
CTA		171	316
EHT - Down Converter		101	18
Laboratory Astrophysics	13	117	129
LOFAR astronomy preparations	76		
MUSE	68		
Seed funding / Miscelleneous projects	153	564	121
Completion Phase 3 projects		33	
TOTAL INSTRUMENTATION	**5.480**	**4.443**	**5.386**

in k€	*2013*	*2014*	*2015*
SUPPORT			
NOVA Office	251	290	312
Outreach	152	274	258
Reservation Wachtgeld	632		
TOTAL Management/Outreach	**1.035**	**564**	**570**
TOTAL EXPENDITURES	**9.219**	**7.685**	**8.833**
REVENUES			
OCW grant NOVA	5.184	5.197	5.227
Interest	141	170	111
Contributions NOVA institutes	10	73	205
Contributions NOVA projects	209		
External funding	200	53	427
National Roadmap Large Research infrastructures	744	5	30
ESO	645	1.645	1.650
SRON	45		
ASTRON	14		
NWO grants for instrumentation projects	1.765	845	
NOVA REVENUES	**8.956**	**7.988**	**7.651**

11. List of abbreviations

2SB	Sideband Separating
A&A	Astronomy & Astrophysics
AAS	American Astronomical Society
ACS	Advanced Camera for Surveys (instrument on HST)
ADC	Atmospheric Dispersion Compensator
AGB	Asymptotic Giant Branch
AGN	Active Galactic Nuclei
AIO	Assistant-in-onderzoek - PhD student
AIP	Astrophysical Institute Postdam (Germany)
AIV	Assembly, Integration & Verification
AJ	Astronomical Journal
ALLEGRO	ALMA Local Expertise GROup
ALMA	Atacama Large Millimeter/submillimeter Array
AMUSE	Astrophysical Multipurpose Software Environment (NOVA project)
AO	Adaptive Optics
AOF	Adaptive Optics Facility
APERTIF	APERture Tile in Focus (Multi-beam receiver for WSRT)
APEX	ALMA Pathfinder Experiment
API	Astronomical Institute Anton Pannekoek (UvA)
ApJ	Astrophysical Journal
APP	Apodized Phase Plate (type of coronagraph)
ARC	ALMA Regional Center
ARTS	APERTIEF Radio Transient Survey
ASSIST	Adaptive Secondary Setup and Instrument Simulator (NOVA project)
ASTRON	ASTRON - Netherlands Institute for Radio Astronomy (NWO institute
ASTRONET	European group coordinating strategic planning for astronomy
ASTRO-WISE	Astronomical Wide-field Imaging System for Europe (EU-funded network involving NOVA-RuG)
ATLAS3D	Galaxy survey (not an acronym)
AU	Astronomical Unit
Auger	see PAO
Band-5	ALMA receiver for the atmospheric window between 163 and 211 GHz
Band-9	ALMA receiver for the atmospheric window between 610 and 720 GHz
BHC	Black Hole Cam
Caltech	California Institute of Technology
CANDELS	Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey
CCD	Charge-Coupled Device
CDF	Chandra Deep Field
CDM	Cold Dark Matter
CEA Saclay	Commissariat à l' Energie Atomique (institute at Saclay, France)
CEMP	Carbon-Enhanced Metal-Poor
Cen A	Centaurus A (galaxy)
CERN	European Organization for Nuclear Research
CfA	Center for Astrophysics (Harvard, USA)
CFHT	Canada France Hawaii Telescope
CFHTLenS	CFHT Lensing Survey
CHAMP+	CHAMP+ is a dual-frequency heterodyne submillimeter array receiver built by MPIfR and NOVA/SRON/TuD for APEX
Chandra	NASA's X-ray space observatory
CMB	Cosmic Microwave Background
CNC	Computer Numerical Control (automated manufacturing process)
CNO	Carbon-Nitrogen-Oxygen (cycle)
COB	Cold Optical Bench
COROT	French led astronomical space observatory to search for extrasolar planets and stellar seismology
COSMOGrid	Worldwide super-computer collaboration for astrophysical simulations
COSMOS	Cosmic Evolution Survey (HST survey project)
CRAL	Centre de Recherche Astronomique de Lyon (Fr)
CRLL	Carbon Radio Recombination Lines
CRIRES	Cryogenic high-Resolution InfraRed Echelle Spectrograph (instrument on VLT)
CRs	Cosmic Rays
CRYOPAD	CRYOgenic Photoproduct Analysis Device (set-up at Sackler Laboratory at Leiden Obdervatory)
CSO	Caltech Submillimeter Observatory
CTA	Cherenkov Telescope Array
DCLA	Development and Commissioning of LOFAR for Astronomy
DDT	Director's Discretionary Time
DTFE	Delaunay Tessellation Field Estimator
DPAC	Data Processing and Analysis Consortium (on development data processing software for Gaia)
DSM	Deformable Secondary Mirror (for one of the VLT telescopes)
DTFE	Delaunay Tessellation Field Estimator
DUEL	Dark Universe through Extragalactic Lensing (EU Network)
EAGLE	Evolution and Assembly of GaLaxies and their Environments (cosmological simulation project)
E-ELT	European Extremely Large Telescope
EC	European Commission
ECDFS	Extended Chandra Deep Field-South
EHT	Event-Horizon Telescope
EoR	Epoch of Reionization
EPICS	Exo-Planet Imaging Camera and Spectrograph (Instrument in study for the E-ELT)
EPOL	EPICS Polarometer
ESA	European Space Agency
ESFRI	European Strategy Forum on Research Infrastructures
eSMA	extended SMA
ESO	European Southern Observatory
ETH	Eidgenössische Technische Hochschule (Zürich)
EU	European Union
EU FP7	EU Framework Program 7
EUCLID	Possible ESA Cosmic Vision mission to map the geometry of the dark universe
EUV	Extreme Ultra Violet
eV	electron Volt
EVN	European VLBI Network
ExPo	Extreme Polarimeter (instrument on WHT)

FAPESP	Fundação de Amparo à Pesquisa do Estado de São Paulo (São Paulo Research Organisation)
FDR	Final Design Review
Fermi	Fermi Space Telescope for gamma ray wavelengths (NASA)
FIR	Far InfraRed
FIRES	Faint Infrared Survey (large program at the VLT)
FLAMES	Fibre Large Array Multi Element Spectrograph (instrument on VLT)
FLOP	FLOating Point Operation
FOM	Fundamenteel Onderzoek der Materie (NWO institute for physics)
FP	"Framework Program (EU) Fundamental Plane"
Gaia	Gaia - ESA's astrometric cornerstone mission
GALACSI	Ground Atmospheric Layer Adaptive Corrector for Spectroscopic Imaging (for MUSE)
GALEX	Galaxy Evolution Explorer (NASA satellite for UV wavelengths)
GAMA	Galaxy And Mass Assembly survey (galaxy survey project)
GARD	Group Advanced Receiver Development at Onsala Space Observatory, Sweden
GASPS	GAS in Protoplanetary Systems (observing program with Herschel space telescope)
GC	Globular Cluster
GEPI	Galaxies Etoiles Physique et Instrumentation (Division of Observatoire de Paris, France)
GHz	Giga Herz
GMRT	Giant Meterwave Radio Telescope
GPU	Graphics Processing Unit
GRAAL	Ground layer Adaptive optics Assisted by Lasers (ESO facility for instrument tests)
GRAPPA	Astroparticle physics and gravitation initiative (at UvA)
GRB	Gamma Ray Burst
GTC	Gran Telescopio CANARIAS
GTO	Guaranteed Time Observations
GZK	Greisen-Zatsepin-Kuzmin limit (energy cut-off for cosmic rays)
H/W	Hardware
HARMONI	High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph (E-ELT instrument)
HAWK-I	High Acuity Wide field K-band Imager (instrument on VLT)
HerCULES	Herschel Comprehensive ULIRG Emission Survey
Herschel	Herschel - Far infrared space observatory (ESA)
HESS	High-Energy Stereoscopic System
HI	Hydrogen 21 cm line
HIFI	Heterodyne Instrument for the Far-Infrared for Herschel
HST	Hubble Space Telescope
HV-setup	High Vacuum setup (at Sackler Laboratory at Leiden Observatory)
HzRGs	High-redshift Radio Galaxies
I/O	Input/Output
IAC	Institudo Astrofisica de Canarias
IAP	Institut d'Astrophysique de Paris
IAU	International Astronomical Union
IceCube	Neutrino telescope at South Pole
ICM	Inter-Cluster Medium
IFS	near-IR integral Field unit (part of SPHERE)
IFU	Integral Field Unit
IGM	Inter-Galactic Medium
IMF	Initial Mass Function
INAF	Instituto Nazionale di Astro-Fisica (Italy)
INAOE	Instituto Nacional de Astrofísica, Óptica y Electrónica (National Institute of Astrophysics, Optics and Electronics, Mexico)
ING	Isaac Newton Group of the Roque de los Muchachos Observatory on La Palma
INSU/CNRS	Institut National des Sciences de l'Universe du Centre National de la Recherche Scientifique (funding agency, Fr)
INT	Isaac Newton Telescope (part of ING)
IPoP	Instrument for the study of Photodynamics in PAHs
IR	Infra-Red
IRAM(-PdBI)	Institut de Radio Astronomie Millimétrique (Grenoble, Fr) - Plateau de Bure Interferometer
IRAS	InfraRed Astronomical Satellite
IRDIS	InfraRed Dual Imaging Spectrograph (part of SPHERE)
IRS	InfraRed Spectrometer (instrument on Spitzer Space Telescope)
ISAAC	Infrared Spectrometer And Array Camera (instrument on VLT)
ISC	Instrument Steering Committee (NOVA)
ISIM	Integrated Science Instrument Module (on JWST)
ISM	InterStellar Medium
ISO	Infrared Space Observatory (ESA)
IXO	International X-ray Observatory (under consideration, ESA, NASA, JAXA)
JAXA	Japan Aerospace Exploration Agency
JCMT	James Clerk Maxwell Telescope (on Mauna Kea, Hawaii)
JIVE	Joint Institute for VLBI in Europe
JPL	Jet Propulsion Laboratory, Pasadena, USA
JWST	James Webb Space Telescope (successor of Hubble Space Telescope)
KiDS	Kilo-Degree Survey (planned for VST/OmegaCAM)
KIPAC	Kavli Institute for Particle Astrophysics and Cosmology
KM3NeT	Neutrino telescope in Mediterranean Sea; successor of ANTARES
KNAW	Koninklijke Nederlandse Akademie van Wetenschappen (Royal Academy of Arts and Sciences)
KNMI	Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorology Institute)
KRP	Key Research Project
KRs	Key Researchers (leaders of the NOVA research networks)
LABOCA	Large APEX Bolometer Camera
LAM	L'Observatoire Astronomique de Marseille-Provence (Fr)
LAOG	Laboratoire d'Astrophysique de l'Observatoire de Grenoble (France)
LAOMP	Laboratoire d'Astrophysique Observatoire Midi-Pyrénées (Fr)
LERMA	Laboratoire d'Etude du Rayonnement et de la Matière en Astropysique (part of Observatoire de Paris)
LESIA	Laboratoire d'études spatiales et d'instrumentation en astrophysique (part of Observatoire de Paris)

LGS	Laser Guide Star
LIGO	Laser Interferometer Gravitational-Wave Observatory (USA)
LIFU	Large Integral Field Unit (on the WEAVE instrument)
LIRG	Luminous InfraRed Galaxy
LISA	Laser Interferometer Space Antenna (possible ESA mission to detect gravitational waves)
LJMU	Liverpool John Moores University (Liverpool, UK)
LLAGN	Low Luminosity Active Galactic Nucleus
LMC	Large Magellanic Cloud
LOFAR	LOw Frequency ARray - new radio observatory managed by ASTRON in collaboration with European partners
LOFT	Large Observatory For x-ray Timing (a proposed ESA mission)
LOPES	LOFAR PrototypE Station (at Karlsruhe, Germany)
LRIS	Low Resolution Imaging Spectrometer (Keck Instrument)
LSS	Large Scale Structure Survey (by XMM)
LUAN	Laboratoire Univeritaire d'Astrophysique de Nice (Fr)
M2-unit	Secundary mirror in telescope
MAGPHYS	Multi-wavelength Analysis of Galaxy Physical Properties (simulation)
MAIT	Manufacturing, Assembly, Integration & Test
MAORY	Multi-conjugate Adaptive Optics RelaY (on E-ELT)
mas	milli-arcsec
MATISSE	Multi AperTure Mid-Infrared Spectroscopic Experiment (2nd generation VLTI instrument)
MATRI2CES	Mass Analytical Tool of Reactions in Interstellar ICES (set-up at Sackler laboratory at Leiden Observatory)
MCAO	Multi-Conjugate Adaptive Optics
METIS	Mid-infrared ELT Imager and Spectrograph for E-ELT
MICADO	Near-infrared wide-field imager for E-ELT
MIDI	MID-Infrared instrument (instrument on VLTI)
Mid-IR	Mid-InfraRed
mIFU	mini-Integral Field Unit (on the WEAVE instrument)
MIRI	Mid Infra-Red Instrument (under construction for JWST)
MIT	Massachusetts Institute of Technology
MNRAS	Monthly Notices of the Royal Astronomical Society
MOS	Multi-Object Spectrograph
MOSAIC	Multi Object Spectrograph instrument concept for E-ELT
Mpc	Megaparsec
MPE	Max-Planck-Institut für Extraterrestrische Physik (Garching, Germany)
MPIA	Max-Planck-Institut für Astronomie (Heidelberg, Germany)
MPIfR	Max-Planck Institut für Radioastronomie (Bonn, Germanny)
MUSE	Multi Unit Spectroscopic Explorer (instrument under construction for VLT)
NAC	Nederlandse Astronomen Club
NACO	NAOS-CONICA (instrument on VLT)
NASA	National Aeronautics and Space Administration (USA)
NAVCAM	Navigation Cameras (instrument on Rosetta spacecraft)
NGC	New General Catalogue (1888 star catalogue)
NIC	NOVA Information Center
NIKHEF	Nationaal Instituut voor Kernfysica en Hoge-Energiefysica (institute of FOM)
NL	Netherlands
nm	nanometer
NOVA	Nederlandse Onderzoekschool Voor Astronomie (Netherlands Research School for Astronomy)
NRAO	National Radio Astronomical Observatory (USA)
NRL	Naval Research Laboratory (USA)
NSF	National Science Foundation (USA)
NW	NOVA research network
NWO	Nederlandse organisatie voor Wetenschappelijk Onderzoek (Netherlands Organization for Scientific Research)
OCA	Observatoire de la Côte d'Azur (Nice, France)
OCW	Dutch ministry for Education, Culture and Science
OmegaCAM	Wide-field camera for the VLT Survey Telescope
OmegaCEN	OmegaCAM data center (at RuG)
ONERA	Office National d'Etudes et de Recherches Aérospatiales (Fr)
OP/IR	Optical to InfraRed
OSO	Onsala Space Observatory (in Sweden)
PACS	Photodetector Array Camera and Spectrometer (instrument on Herschel)
PAH	Polycyclic Aromatic Hydrocarbon molecule
PAO	Pierre Auger Observatory (international cosmic ray observatory in Argentina)
pc	parsec
PD	Postdoc
PDF	Probability Density Function
PDR	Preliminary Design Review
PDR	Photon-Dominated Region
Ph	Phase
PhD	Philosophiae Doctor
PI	Principal Investigator
PSF	Point Spread Function
PuMa	Pulsar Machine (instrument on WSRT)
Q1/Q2/Q3/Q4	First quarter / second quarter / third quarter / fourth quarter
QMS	Quadrupole Mass Spectrometer
QSO	Quasi-Stellar Object (quasar)
QSR	Quasar
R&D	Research and Development
RadioNet	EU-funded network for radio astronomy
RAL	Rutherford Appleton Laboratory (Didcot, UK)
RF	Radio Frequency
RG	Radio Galaxy
RIVM	Rijksinstituut voor Volksgezondheid en Milieu
RLL	Radio Recombination Line
RM	Rotation Measure
ROSINA	Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (Instrument on Rosetta probe)
RU	Radboud Universiteit, Nijmegen
RUG	Rijksuniversiteit Groningen
S5T	Small Synoptic Second Solar Spectrum Telescope (NOVA project)
SAFARI	SpicA FAR-infrared Instrument (instrument on Japanese-European SPICA mission)
SAURON	Spectrographic Areal Unit for Research on Optical Nebulae (instrument on WHT)
SCAO	Single Conjugate Adaptive Optics
SDSS	Sloan Digital Sky Survey

SED	Spectral Energy Distribution
SINFONI	Spectrograph for INtegral Field Observations in the Near Infrared (instrument on VLT)
SIS	Superconductor Insulator Superconductor; detector technology for (sub)-mm and far-IR
SKA	Square Kilometer Array
SLACS	Sloan Lens ACS Survey
SMA	SubMillimeter Array (on Mauna Kea, Hawaii)
SMASH+	Southern Massive Stars at High Angular resolution Survey
SMC	Small Magellanic Cloud
SMG	SubMillimeter Galaxies
SMO	Spectrometer Main Optics (MIRI)
SNN	Samenwerkingsverband Noord Nederland
SOFIA-GREAT	Spectroscopic Observatory For Infrared Astronomy - German Receiver for Astronomy at Teraherz frequencies
SPEX	Spectrometer for Planetary Exploration
SPHERE	Spectro-Polarimetric High-contrast Exoplanet Research (instrument under construction for VLT)
SPICA	SPace Infrared telescope for Cosmology and Astrophysics (likely Japanese mission with European participation)
SRON	SRON - Netherlands Institute for Space Research
STC	Science & Technology Committee (ESO committee)
STFC	Science & Technology Facilities Council
STScI	Space Telescope Science Institute
SURFRESIDE	SURFace Reactions Simulation Device (setup for Sackler Laboratory at Leiden Observatory)
TDE	Tidal Disruption Event
TFLOPS	Tera Floating-Point Operations
TNO	Research Institute for applied physics in the Netherlands
TOF	Time-of flight (e.g. In TOF mass spectroscopy)
TUD	Technical University Delft
UD	Assistant professor
UGCA	Uppsala General Catalogue of Galaxies
UHD	Associate professor
UHE	Ultra-High Energy
UHECR	Ultra-High Energy Cosmic Rays
UK	United Kingdom
UK-ADC	United Kingdom Astronomy Technology Center
UKIRT	United Kingdom Infrared Telescope
UL	Universiteit Leiden
ULIRG	Ultra Luminous Infra-Red Galaxy
UltraVISTA	Ultra deep near-IR imaging program with VISTA
UNAWE	Universe Awareness (international outreach activity aimed at kids of 4-10 years)
UNESCO	United Nations Educational, Scientific and Cultural Organization
univ	university
USM	Universität-Sternwarte München (Germany)
UU	Universiteit Utrecht
UV	ultra violet
UvA	Universiteit van Amsterdam
UVES	Ultra-violet and Visual Echelle Spectrograph (instrument on VLT)
vAPP	Vector-Apodized Phase Plate (type of coronagraph)
VIKING	Vista Kilo-degree Infrared Galaxy survey
VIMOS	Visible Multi-Object Spectrograph (VLT instrument)
VISIR	VLT-Imager and Spectrometer for mid InfraRed (instrument on VLT)
VISTA	Visible and Infrared Survey Telescope for Astronomy (ESO)
VLA	Very Large Array
VLBI	Very Long Baseline Interferometry
VLT	Very Large Telescope (ESO)
VLTI	Very Large Telescope Interferometer (ESO)
VO	Virtual Observatory
VST	VLT Survey Telescope
WC	Type of Wolf-Rayet star with dominant lines of ionised Oxygen
WEAVE	Multi-object & multi-IFU spectrographic instrument for the WHT
WFC3	Wide-Field Camera 3 (instrument on HST)
WFI	Wide-Field Imager (ESO 2.2m instrument)
WISE	Wide-field Infrared Survey Explorer (NASA spacecraft)
WISH	Water In Star-forming regions with Herschel (observing program with Herschel space telescope)
WLM	Wolf-Lundmark-Melotte (galaxy)
WFPC	Wide-Field Planetary Camera (instrument on HST)
WHT	William Herschel Telescope (part of ING)
WN	Type of Wolf-Rayet star with dominant lines of ionised Nitrogen
WO	Type of Wolf-Rayet star with dominant lines of ionised Oxygen, hotter than WC
WSRT	Westerbork Synthesis Radio Telescope
XIPE	X-ray Imaging Polarimetry Explorer (proposed ESA mission)
XMM-Newton	X-Ray Multiple Mirror (ESA's X-ray observatory)
XRB	X-Ray Binary
X-Shooter	Single target optical and near-IR spectrometer (instrument on VLT)
XSL	X-Shooter Spectral Library
YSO	Young Stellar Object
ZIMPOL	Zurich IMaging POLarimeter - part of SPHERE

NOVA