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ASTRONOMY IN THE NETHERLANDS

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Abstract. We describe the state of astronomical research in the Netherlands per early 2012. We add some notes on its history of this research and on the strategic choices for the future. Compared to the size of the country (16 million people) the Netherlands is maintaining a high profile in astronomical research over a period of more than one century. The professional research community consists of about 650 people. This includes research staff, postdocs, PhD students, technical staff working on instrumentation projects and people involved in the operations of ground-based telescopes and astronomical space missions. We do not take into account staff working for international organizations based in the Netherlands. Astronomical research in the Netherlands is carried out at four university institutes and two national research institutes that fall under the umbrella of the national funding agency NWO. The Netherlands is the host of two international organizations: ESTEC, the technology division of the European Space Agency (ESA), and the Joint Institute for VLBI in Europe (JIVE). The Netherlands are one of the founding members of the European Southern Observatory (ESO) and of ESA. This paper will address a number of significant multilateral collaborations.

1. Organization

1.1. NOVA AND UNIVERSITY ASTRONOMY

The four university astronomical institutes are federated in the Netherlands Research School for Astronomy (NOVA, Nederlandse Onderzoekschool Voor Astronomie). NOVA started in 1992 as a national 'research school' recognized as such by the Royal Academy of Science (KNAW). E.P.J. van den Heuvel was chairman of the board of NOVA and P.T. de Zeeuw became director. NOVA consisted then of the astronomical institutes of the Universities of Amsterdam, Groningen, Leiden and Utrecht, with some participation by the Free University (VU) at Amsterdam. In 1998 the VU terminated astronomical education and left NOVA.

Recognition by the KNAW brought very few funding and the main achievements of NOVA were the harmonization of the astronomical education programs at the four universities and the introduction of a monitor of the progress of PhD projects.

In 1997 the Dutch government initiated a ten-year research program to allocate considerable grants for Research Schools that compared favourably with the best research institutes elsewhere. The training of outstanding young scientists was one of the objectives of the program. NOVA submitted an innovative research program entitled 'The Life-Cycle of Stars and Galaxies'. In April 1998 six proposals were selected out of the 34 proposals covering all academic disciplines and NOVA was ranked highest among the six. The six schools all received a grant from the Minister of Education, Culture and Science (OCW) in order to carry out its proposed programme. The NOVA programme combines key investments in permanent and temporary personnel at the participating universities in three related areas of research interlinked with a strong program of instrumentation development.

After an extensive review in 2003 the grants for the six top-research schools were continued for another period of five years up to and inclusive 2008 and in 2006 the funding was extended for five more years. The six schools were reviewed again in 2010. The review panel qualified four schools as excellent and two, including NOVA, as "exemplary", to be understood as 'better than excellent'! As a result of this process the funding for NOVA was extended up to and inclusive 2018.

In 2002 the Radboud University Nijmegen (RUN) started an astronomy programme and joined the NOVA federation. Unfortunately the Utrecht University decided to close down its astronomy institute by late 2011 and to leave the NOVA collaboration.

1.1.1. *University of Amsterdam (UvA)*

The Astronomical Institute Anton Pannekoek (API) is one of the research institutes within the Faculty of Science of the University of Amsterdam (UvA). It has been founded by Anton Pannekoek in 1921; in recent decades the institute was led by E.P.J. van den Heuvel (1974-2005), M. van der Klis (2005-2011) and R.A.M.J. Wijers (2011-present). API executes astronomical research and carries out the PhD program. It is responsible for the astronomical components in the bachelor program and for the master program in astronomy and astrophysics. API's research program is concentrated in two areas, (1) high energy astrophysics, neutron stars and black holes; and (2) low energy astrophysics, star formation and exoplanets.

In 2011 the Science Faculty of the UvA established the GRAPPA Institute (Gravitation Astro-Particle Physics Amsterdam) as a collaboration between the institutes for Theoretical Physics, Astronomy and High Energy Physics. In total six new staff members are or will be appointed. Their research interests include dark matter, dark energy, neutrinos, and cosmic rays, with a focus on both theoretical modeling of astrophysical source physics as well as (in)direct detection. In addition, there are about 15 affiliated staff members from the collaborating institutes, who are involved in experimental work at various physics and astrophysics projects, as well as theory.

1.1.2. *University of Groningen (RuG)*

The Kapteyn Astronomical Institute is part of the Faculty of Mathematics and Natural Sciences of the University of Groningen (RuG). It is founded by J.C. Kapteyn in 1878, a leader of Milky Way research. He was succeeded in the early 1920s by P.J. van Rhijn who continued the work of Kapteyn. In 1956 A. Blaauw succeeded van Rhijn and began a modernization of the institute's program. In recent decades the institute was led by H. van Woerden until 1998, and subsequently by P.C. van der Kruit (1998-2006), J.M. van der Hulst (2006-2011) and R.F. Peletier (2011-present). At the RuG, the Kapteyn Institute is responsible for the astronomical components in the bachelor education in physics and astronomy, for the master study in astronomy and for the PhD education. The focus of the research is in cosmology, in the study of galaxies and in the formation of stars and planets. Charting of the Epoch of Reionization (EoR) with LOFAR is one such item; 'Galactic archaeology', *i.e.* probing evolving structures in the Milky Way and in nearby galaxies is another.

One of the two laboratories of SRON, the Space Research Organisation of the Netherlands, is located in Groningen in the same building as the Kapteyn Astronomical Institute. This has stimulated strategic alliances in the area of far-infrared and submm astronomy. One example is the SIS heterodyne detector successfully developed for Herschel/HIFI by SRON and the University of Delft and now used in the Atacama Large Millimeter-submillimeter Array (ALMA).

The Kapteyn Institute has similar strategic alliances with ASTRON for the scientific exploitation of the WSRT and LOFAR and for the development of new instrumentation for these facilities. The central computer facility for the correlation of the LOFAR data is located at the Donald Smits Center for Information Technology of the RuG. A long term aim is the participation in SKA.

1.1.3. *University Leiden (UL)*

Leiden Observatory (Sterrewacht Leiden) was established in 1633 to house the quadrant of Snellius. It is part of the faculty of mathematics and natural sciences of University Leiden (UL). It is the oldest university observatory still in operation in the world and has a rich tradition built around important figures such as F. Kaiser, W. de Sitter, E. Hertzsprung, J.H. Oort and H.C. van de Hulst. These men were not only formidable scientists, but they have also been very much involved in shaping Dutch and international astronomy into what it is today. In recent decades Leiden Observatory was led in succession by H. van der Laan, H.J. Habing, G.K. Miley, P.T. de Zeeuw, K.H. Kuijken and H. Röttgering (since mid 2012). The Sterrewacht is responsible for the astronomical components in the bachelor education in physics and astronomy, for the master program in astronomy and astrophysics and for the PhD program. The research at the Sterrewacht spans a wide range of closely interlinked areas, focusing on understanding the universe as seen today. Astronomy world-wide is undergoing a tremendous technological evolution, leading to ever more sensitive, sharper, and broader multi-wavelength views of the sky. The staff of the Sterrewacht is using many new observing facilities to study the formation and evolution of galaxies in the early phases of the Universe, regions around massive black holes at the centers of nearby galaxies, the formation of complex molecules in nearby star forming regions and the formation and evolution of proto-planetary systems. In recent years exoplanets were included as a new research area. The development of new instruments has gained in importance, in part by the influx of technical astronomers from the University of Utrecht when that closed the astronomy department in late 2011.

1.1.4. *Radboud University Nijmegen (RUN)*

The Department of Astrophysics of the Radboud University Nijmegen (RUN) is a young group that started in 2001. It has grown quickly over the years since, from two scientific staff at the start to 10 staff members from February 2012 onwards. The Department has been led in the first years by J.M.E. Kuijpers (2001-2006), and thereafter led by P.J. Groot (2006-present). The Department of Astrophysics is part of the Institute of Mathematics, Astrophysics and Particle Physics (IMAPP). The Astronomy Department is responsible and for the astronomical components in the bachelor education, for the master astronomy and astrophysics and for the PhD program. The Department focuses its research activities on high energy astrophysics (in particular on compact objects and in binaries), on the radio detection of high energy cosmic rays and on gravitational waves. It participates in new facilities such as LOFAR, the Pierre Auger Observatory (PAO) and the X-Shooter spectrograph on the VLT. The Department is a leader in the fields of ultra-compact binaries and in radio detection of high energy cosmic rays. In early 2012 the Department of Astrophysics saw a major expansion from 6 to 10 staff members when four staff and their research groups moved from Utrecht to Nijmegen.

1.1.5. *Utrecht: Utrecht University (UU)*

The Astronomical Institute (Sterrekundig Instituut Utrecht, SIU) in Utrecht was founded by the university in 1642. The SIU has been part of the Department of Physics and Astronomy of the Faculty of Science. It was led by A. Achterberg (1998-2002), N. Langer (2002-2008) and C.U. Keller (2008-2011). At the UU, the SIU was responsible for the astronomical components of the bachelor education, for the master in astronomy and astrophysics and for a PhD program. The subjects of research at the SIU were various, ranging from stellar and binary evolution, theoretical high-energy astrophysics, and instrumentation for both ground and space-based facilities.

SIU and SRON's High Energy Astrophysics and Earth and Planetary Science divisions – both located next to each other at the university campus – collaborated on leading research in high-energy astrophysics and exoplanetary and planetary atmospheres. The proximity of SRON provided an excellent environment also for PhD and MSc students as they could participate in the latest space research and mission developments carried out at SRON.

On 16 June 2011, the Faculty of Science of the UU announced its plan to restructure its efforts in research and education. This decision effectively led to the termination of the 370-year old tradition of education and research in astronomy and astrophysics in Utrecht, which not only has produced eminent scientists such as M. Minnaert, H.C. van de Hulst, C. de Jager and E.P.J. van den Heuvel, but in recent times also promising scientists who received major national research grants and international prestigious fellowships. The formal closing ceremony took place on 5 April 2012 after the symposium to celebrate 370-years of astronomy in Utrecht. Staff and their research groups have moved to other NOVA institutes in Nijmegen (A. Achterberg, S. Larsen, O. Pols and F. Verbunt), Amsterdam (J. Vink and M. van den Berg) and Leiden (C.U. Keller).

1.1.6. *NOVA organization*

The NOVA Board consists of the directors of the participating university astronomy institutes. The chair was held by E.P.J. van den Heuvel (1992-2003), P.C. van der Kruit (2003-2007), M. van der Klis (2007-2011) and K.H. Kuijken (2011-present). The Board has the overall responsibility for the NOVA program, chooses the overall strategy and decides on the distribution of the funding to the several programmes.

The NOVA directorate is responsible for the execution of the program, preparation of policy decisions and of strategic issues, not only with the participating universities but also with external (international) institutes and agencies. The directorate is supported by a small office that carries out the secretariat, the financial administration and control of spending. P.T. de Zeeuw was the scientific director of NOVA between 1992 and 2007. W. Boland was deputy director from 1999 to 2007. From 2007 until present the NOVA directorate consists of E.F. van Dishoeck (scientific) and W. Boland (executive).

The legal representation of NOVA has rotated between the participating universities in five year cycles. Accordingly, University Leiden (1992-1997), University of Amsterdam (1997-2002), University of Groningen (2002-2007) and University Utrecht (2007-2011) held this role. Since 2012 NOVA is legally represented by University Leiden for an indefinite period.

Further information about the NOVA organization and program can be found online[1] as well as about the NOVA public outreach activities[2].

1.2. ASTRON, NETHERLANDS INSTITUTE FOR RADIO ASTRONOMY

ASTRON is a foundation under the umbrella of NWO. Its mission is to develop novel and innovative technologies for radio telescopes and to pursue fundamental astronomical research. The ASTRON institute employs approximately 160 staff. In addition, it hosts JIVE and the NOVA laboratory for Optical-IR instrumentation. ASTRON has been led by H. van der Laan (1970-1987), W.N. Brouw (1987-1990), H.R. Butcher (1991-2006) and M.A. Garrett (2007-present). Further information can be found on the web[3]. An overview of the development of radio astronomy in the Netherlands is provided in Sect. 3.1.

[1] http://www.strw.leidenuniv.nl/nova
[2] http://www.astronomie.nl/
[3] http://www.astron.nl/

Figure 1. Six of the 73 ALMA Band-9 cartridges, a main part of the Dutch contribution to the ALMA project, designed and produced in a collaboration between NOVA, SRON and TuD. (Courtesy NOVA)

ASTRON has initiated the successful fund-raising for the LOFAR telescope and is now responsible for LOFARs construction and operations. In addition it has to keep the Westerbork Synthesis Radio Telescope (WSRT) up to date and to explore new technologies for radio astronomy. ASTRON is actively participating in discussions of and research for the future of radio astronomy. It is involved in the developments for SKA, the Square Kilometer Array, contributing its experiences with LOFAR, the prototype for SKA. ASTRON collaborates with international organizations, with major national industries and it is involved in the transfer of knowledge to national and regional/local businesses.

1.3. SRON, NETHERLANDS INSTITUTE FOR SPACE RESEARCH

SRON's mission is to conceive and develop innovative space instruments for astrophysical and earth-oriented research, and to analyze the data provided by these instruments, in collaboration with astronomers and other scientists, for example, those in atmospheric research. SRON has two laboratories; one at the University of Groningen for low-energy astrophysics and the other at Utrecht University for high-energy astrophysics. SRON advises the Dutch government on participation in international space research programs, in particular those of ESA, and supports the economy by making its knowledge and expertise available. SRON has been led by J.A.M. Bleeker

(1983-2002), K. Wakker (2003-2009) and R. Waters (2010-present).

Research at SRON is concentrated on harvesting the scientific results obtained with the X-ray spectrometers on the Chandra and XMM space observatories, for which it provided the gratings, and with the HIFI instrument on board of the Herschel Space Observatory. SRON has been the PI institute for these instruments. For the next decade, SRON has the ambition to become PI of the far-infrared SAFARI instrument on the Japanese SPICA mission and contributes to the JAXA-ESA ASTRO-H X-ray mission. In the long term, SRON aims for a (co-)PI role in an international consortium for building one of the instruments on the next generation international or European X-ray space mission. At its institutes in Utrecht and Groningen together, SRON employs about 200 staff. Further information is available on the web[4]. An overview of the development of astronomical space research in the Netherlands is provided in Sect. 3.2.

1.4. JOINT INSTITUTE FOR VLBI IN EUROPE (JIVE)

JIVE, the Joint Institute for VLBI in Europe, was established in 1993 by the Consortium for VLBI in Europe. The Institute is governed by a Board nominated by the research councils and national radio astronomy facilities of the Netherlands (NWO and ASTRON), CNRS (France), MPIfR (Germany), INAF (Italy), NAOC (PR China), IGN (Spain), OSO (Sweden) and STFC (United Kingdom). JIVE is located in Dwingeloo, the Netherlands, and hosted by ASTRON. JIVE has been led by R.T. Schilizzi (1993-2003), M.A. Garrett (2003-2007) and H.J. van Langevelde (2007-present).

The mission of JIVE is to operate and further develop the VLBI data processor and to support EVN users and operations of the EVN facility. The Institute carries out a broad range of technical research and development activities in VLBI related fields. JIVE staff, consisting of about 20 scientists, also carries out research in various fields of galactic and extragalactic radio astronomy, planetary and space sciences. The Institute is actively involved in several large international projects, among which there is SKA. JIVE acts as a coordinator in several projects funded by the European Commission.

Further information can be found at the web[5].

1.5. THE NETHERLANDS ORGANIZATION FOR SCIENTIFIC RESEARCH (NWO)

NWO is the national funding agency for scientific research in the Netherlands. Science policy within NWO is determined by discipline-oriented re-

[4] `http://www.sron.nl/`
[5] `http://www.jive.nl/`

search councils. Astronomy together with mathematics and computer sciences is part of the NWO Council for Physical Sciences (EW). NWO-EW acts as the policy and granting organization for NWO-supported astronomical research. It funds individual research grant applications without any thematic boundary conditions (free competition grants that cover a single PhD or postdoc position) as well as positions in thematic (interdisciplinary) research programs. NWO-EW also has a budget line for medium sized instrumentation projects up to 900 kEuros. Competitions are held twice per year; oversubscription factors are typically 3 to 5. NWO-EW provides access to the Isaac Newton Group (ING) of optical telescopes on La Palma and, until March 2013, the submillimeter-wave telescope JCMT on Mauna Kea, Hawaii. It supports JIVE and the ALMA regional expertise center ALLEGRO based at Leiden Observatory.

NWO finances a very successful programme called VENI-VIDI-VICI through which personal grants are awarded to university staff. Of particular relevance are the VIDI (experienced researchers; maximum 8 years after PhD, up to 800 kEuros) and VICI (researchers of professorial quality; maximum 15 years after PhD, up to 1.5 MEuros). VIDI and VICI allow new staff to build up their own independent groups. Oversubscription is typically a factor of 5-10. In recent years on average 3 astronomers per year received a VENI grant, 2 a VIDI grant and 0.5 per year a VICI grant.

NWO finances the organisations ASTRON and SRON, and funds additionally large national instrumentation projects. New funds are made available every 2 years with awards typically between 2 and 6 MEuros. Recent astronomy awards include the grant for the Dutch contribution to JWST-MIRI in 2002 and the grants to ASTRON to develop and build the new wide field imager APERTIF for the WSRT in 2006 and 2010.

NWO carries out the evaluation and selection procedure for the 'Roadmap program' for Dutch participation in large-scale European research infrastructures; it acts on behalf of the Ministry of OCW. So far three astronomy programs were selected: in 2008 18.8 MEuros was granted to NOVA and its collaborators for the participation in the design and construction of instrumentation for the E-ELT; in 2012 18 MEuros was allocated to SRON for their PI role in the Spica-SAFARI instrument. The ASTRON participation in SKA was identified as a 'Roadmap program' with a possible funding allocation in the coming years.

NWO awards the most prestigious prizes for scientific research in the Netherlands, the Spinoza prize. Since its introduction in 1995 the price has been awarded to six astronomers: E.P.J. van den Heuvel (1995), E.F. van Dishoeck (2000), M. van der Klis (2004), M. Franx (2009), H. Falcke (2011) and A. Tielens (2012).

1.6. MINISTRY OF EDUCATION, CULTURE AND SCIENCE (OCW)

The Dutch universities and NWO receive their funding directly from the Ministry of OCW. The funds for NOVA come directly from OCW. The Ministry is the national representative in the treaty organization of the European Southern Observatory (ESO). The national contribution to ESO is administered at the Ministry level. The Ministry of Economic Affairs, Agriculture and Innovation (EL&I) is the national representative of the European Space Agency (ESA). OCW provides the funding for the science program of ESA. The national funding for de construction of LOFAR of order 70 MEuros was provided by OCW through a special program for investment in knowledge based infrastructures.

1.7. THE ROYAL DUTCH ACADEMY OF SCIENCE (KNAW) AND THE EUROPEAN UNION (EU)

The Royal Netherlands Academy of Arts and Sciences (KNAW) donates yearly a prestigious KNAW academy professorship. This is an award typical 1 MEuros in total for senior scientists and allows them to concentrate fully on teaching and research. Astronomers who received such an award are G.K. Miley (2003), M. van der Klis (2010) and E.F. van Dishoeck (2012).

The European Union (EU) is a growing source of funding. Every 4 to 7 years a new Framework Program (FP) is developed which defines the strategy and programs for that period. The initial training networks (ITN) have been an important component of most FP cycles; they typically fund teams of 6-12 institutes across Europe to carry out a collaborative program. Recent changes include a shift from funding of postdocs to mostly PhD student positions and a stronger emphasis on links with industry. The latter requirement makes it more difficult for astronomy projects to get funding. A new prestigious program to promote individual investigator-driven frontier research was launched in 2008 by the European Research Council (ERC). It has a budget line for young investigators (starting-ERC grant, typically 1.5 MEuros) and for established scientists (advanced ERC grant, typically 2.5 MEuros). Oversubscriptions for all EU programs are typically a factor of 20. Advanced ERC grants (see also Fig. 2) were awarded to the following astronomers in the Netherlands: H. Falcke (2008), M. Franx (2008), A. Tielens (2009), R. Wijers (2009), E.F. van Dishoeck (2011) and J.M. van der Hulst (2011).

1.8. RELATIONS WITH ESA AND ESO

Dutch astronomers have contributed to ESA and ESO as official representative for the governing bodies of these organisations and also, on the basis of personal merit, as adviser to the various special committees of these organisations. The foundation of ESA owes much to the Dutch astrophysicists H.C. van de Hulst and C. de Jager. J.H. Oort took the first decisive steps toward the foundation of ESO. Four Dutch astronomers (A. Blaauw, J. Woltjer, H. van der Laan and P.T. de Zeeuw) have been or are Director-General of ESO.

A special case is ESTEC, the large international development and testing facility of ESA and located in Noordwijk, the Netherlands. Approximately 2000 employees are involved in typically a dozen projects at any time. In recent years ESA has moved most of the scientists to its science centre in Vilspa near Madrid, with the exception of the project scientists and their teams. There are contacts with Dutch universities, ASTRON and SRON at the individual project level. The space sector has an intrinsic value, offering unique economic and societal benefits for the Netherlands; the location of ESTEC reinforces those benefits manifold. Dutch companies and research institutes have direct and easy access to ESTEC's unique knowledge and facilities, with direct and indirect benefits for their technical capabilities.

1.9. RELATIONS BETWEEN OCW, NWO, NOVA, ASTRON, SRON AND NCA

ASTRON, NOVA, NWO, and SRON share together the responsibility for the finances for research in astronomy. The university institutes combined in NOVA are funded by their universities. In 2007-2008, a major policy change occurred when OCW transferred about 100 MEuros from the universities to NWO to strengthen the international reputation of Dutch scientific research though the VENI-VIDI-VICI scheme but without any significant extra investment in scientific research. As a result, university funding of PhD students has now almost completely disappeared. This reduces the flexibility of the staffs at the universities in accepting new PhD students.

To summarize, the main responsibilities are

- NOVA: research and education, granting of PhDs; home base for ESO
- ASTRON: national institute for radio astronomy
- SRON: national institute for space research; home base for ESA
- NWO-EW: various research grants; ING, JCMT and JIVE
- OCW: funding of the universities, funding of NWO, funding special, large projects (*e.g.* LOFAR)

The joint national strategy for astronomy is set at the Netherlands Committee for Astronomy (NCA), an informal body of representatives from the university institutes and from ASTRON and SRON. ASTRON, SRON, NWO and NOVA plan the strategy for the future of astronomy in the

Netherlands. The latest strategic plan dates from June 2012 and is available from the NOVA website. The NCA represents the Netherlands in the International Astronomical Union and constitutes the astronomy 'chamber' of the Association of Universities in the Netherlands (VSNU), but does not itself fund any scientific research.

The interactions between NOVA, ASTRON and SRON are many. First, several ASTRON and SRON scientific staff members have partial appointments (0.5-1 day per week) at one of the universities. There they participate in teaching at master level and in PhD supervision. Second, university and ASTRON/SRON scientists work closely together to develop and exploit scientific instruments. Many university scientists are fortunate to have (had) privileged access to the world class instruments to which SRON or ASTRON contributed, such as WSRT, IRAS, Beppo-SAX, ISO-SWS, Herschel-HIFI, JIVE, and LOFAR, or built with NOVA contributions for use on ESO's VLT, VLTI and VST and the ALMA observatory. Conversely, university astronomers support ASTRON and SRON in building these instruments. This includes conception of the instruments, the writing of science cases, performing simulations, promoting and lobbying for the projects (inter)nationally, etc. It typically takes 20-25 yr from conception to science, emphasizing the long term commitments that all parties need to be able to make.

Since 2007, NWO has been implementing a new governance model for its institutes. The board of the institute has been placed 'more at a distance' and contains no or a few stakeholders. The scientific advisory council of each of these institutes is largely international. This results in longer lines between university astronomers and the upper management. One wonders whether this governance model is efficient from the point of view of the united future planning and coordination of astronomical research in the Netherlands.

2. Access to Observing Facilities

Astronomy is among the science disciplines that require large and expensive observing facilities that are nowadays affordable only in international and even world-wide collaborations. Astronomers in the Netherlands are successful users of the observing facilities made available through the European organizations ESO and ESA. ESO provides access to the Very Large Telescope (VLT), the VLT Interferometer (VLTI), the survey telescopes VISTA and VST, the two 3.6m-class telescopes at La Silla (Chile), the Atacama Pathfinder Experiment (APEX) and the Atacama Large Millimeter/submillimeter Array (ALMA). Through ESO, Dutch astronomers expect to have access to the European Extremely Large Telescope (E-ELT, with an effective diameter of 39.3m) that will become operational in 2022. ESA provides access to the Hubble Space Telescope (HST), the X-ray observatory XMM-Newton, the gamma ray mission INTEGRAL, the far-IR Herschel Space Observatory, and in the future the James Webb Space Telescope (JWST), Gaia (astrometric mission) and Euclid (test for dark matter and dark energy models). Through the national funding agency NWO astronomers in the Netherlands have access to the optical telescopes in the northern hemisphere of the Isaac Newton Group (ING) on La Palma (UK-NL-Spain). Because ALMA became operational the Dutch access to the submillimeter James Clerk Maxwell Telescope (JCMT) on Hawaii will be ended in March 2013. The radio domain is well covered with access to the WSRT, LOFAR and the EVN-JIVE interferometer; there are good prospects on participation in the future Square Kilometer Array (SKA). Dutch astronomers either as individuals or through collaborations have been successful in getting time on a wide variety of telescopes funded by other agencies across the world, both on the ground (*e.g.*, ATCA, Gemini, SMA, GranTeCan) and in space (*e.g.*, Chandra, RXTE, Spitzer, Fermi, Swift). For all of these facilities, observing time is obtained only through a competitive proposal process, with oversubscription factors of more than a factor of 5 for the most powerful telescopes.

Dutch astronomers collaborate with physicists through the Committee for Astroparticle physics in the Netherlands (CAN) to develop opportunities at the interface of these fields in furthering our understanding of extreme processes by detecting neutrinos, cosmic rays, gravitational waves, and high-energy gamma rays.

2.1. RADIO ASTRONOMY IN THE NETHERLANDS

Following the discovery of radio radiation from the Milky Way by Jansky (1932) and Reber (1940) J.H. Oort wondered whether line radiation in the radio spectrum would make it possible to map the structure of the Galaxy. He asked H.C. van de Hulst, then a PhD student at Utrecht, if such lines might exist. At a colloquium on 15 April 1944, Van de Hulst showed that hydrogen atoms in the ground state should have a hyperfine transition at 21cm wavelength. In 1945 the Netherlands were much impoverished by WW II and plans for significant new investments for science were not easy to find. But Oort followed a ministerial suggestion and in 1946, together with M. Minnaert from Utrecht, he founded the 'Stichting Radiostraling van Zon en Melkweg' (Netherlands Foundation for Radio Astronomy, NFRA) under the umbrella of ZWO (precursor of NWO), to investigate radiation at radio wavelengths from the Sun and the Milky Way. The electronic firm of Philips, the Post and Telecom Service (PTT), and The Royal Meteorological Institute (KNMI) joined the Leiden and Utrecht observatories in NFRA. At PTT's Kootwijk Radio Station the director, A.H. de Voogt, made a German 7.5m Wrzburg radar dish available, and in the fall of 1950 a promising young engineer, C.A. Muller, was appointed to develop a suitable receiver. Muller's receiver detected the 21cm line in May 1951. Technically supported by Muller, a group of Leiden astronomers, lead by Oort and van de Hulst, measured the Galactic rotation curve (1954), mapped the distribution of atomic hydrogen in the Galaxy and demonstrated its spiral structure (1954-1958). Further information about the early development of radio astronomy in the Netherlands is provided by Van Woerden and Strom (2006).

After the success of the 21-cm line map of the Galaxy, funds for a 25m diameter radio telescope were made available by ZWO. The 25m Dwingeloo Telescope was inaugurated in 1956, and over a period of forty years it made many major contributions to radio astronomy. These included: a catalogue of radio-continuum sources at 22cm wavelength; discovery of strong radial motions of hydrogen around the Galactic Centre; measurement of the atomic hydrogen distribution and rotation in the Andromeda Nebula; demonstration of systematic non-circular motions of atomic hydrogen in the Galaxy; mapping of the distribution, spectrum and polarization of the radio continuum radiation at several wavelengths; studies of interstellar OH molecules; discovery and mapping of hydrogen clouds at highly anomalous velocities; and in the 1990's a high-quality, full-sky map of galactic atomic hydrogen which also lead to the discovery of 'Dwingeloo 1' and 'Dwingeloo 2', nearby galaxies hidden behind the absorbing Milky Way. For a summary of the instrumental developments and scientific achievements of the Dwingeloo Telescope see Van Woerden and Strom (2007).

Plans for a still larger radio telescope were developed soon after 1956. The first plan was for the so-called 'Benelux Cross Antenna Project' a joint project of the Netherlands and Belgium for a telescope on the principles of a successful 'cross antenna' in Australia. The project stranded in 1964 and that led to a major change of direction. Now plans were made for a telescope-array using the earth-rotation aperture-synthesis principle developed by Ryle at Cambridge. The Westerbork Synthesis Radio Telescope (WSRT), consisting of twelve 25m dishes on a 1.6km east-west baseline, was inaugurated in 1970, and extended in 1980 to 14 dishes (10 fixed and 4 movable) on a 3km baseline. H. van der Laan played a key role in the adaptation of the structure and management of NFRA to the requirements set by this new, large instrument.

Several upgrades of the dishes, frontends, backends and software have kept the WSRT at the international forefront. These developments have been documented in a series of papers: Allen, Hamaker & Wellington (1974);

Baars & Hooghoudt (1974); Casse & Muller (1974); Högbom and Brouw (1974); Van Someren Greve (1981), Noordam & De Bruyn (1982). Highlights of WSRT research have been described by Allen & Ekers (1980) and by Strom (1996).

Since the early experiments in the 1980's the WSRT was an active partner in the first VLBI experiments in Europe leading to the founding of the European VLBI Network (EVN) and the Joint Institute for VLBI in Europe (JIVE). For the Netherlands the initiatives were led and coordinated by R.T. Schilizzi who became the first director of JIVE; the present director is H.J. van Langevelde. The VLBI initiatives were motivated to obtain the sharpest and most detailed images possible in astronomy.

To keep the WSRT at the forefront of its technical capabilities the telescope's Multi-Frequency-Frontends were replaced (in 2010-2012) by the APERTIF focal plane arrays. This new receiver system increased the field of view by a factor of 25 and will enable the WSRT to conduct fast surveys of the radio sky with the spatial resolution typical of a radio interferometer. With the experiences made in the operation of such systems and in the scientific exploitation of large radio surveys, the WSRT will play a crucial role in the preparation of the SKA.

In the early 1990's the concept of the Square Kilometer Array (SKA) emerged with the realization that the study of the formation and evolution of galaxies in the early universe requires a next generation radio telescope facility with a collecting area at least 100 times larger than what was available at existing telescopes. In the Netherlands the early developments were led by H.R. Butcher and A. van Ardenne. It was realized that such a project required innovative software and hardware techniques that were not yet available but should be developed. A worldwide collaboration appeared to be required.

In the 1990s G.K. Miley realized that the existing experience and technical means in the Netherlands would be sufficient to build a prototype for SKA for measurements at the lowest radio frequencies for which the Earth atmosphere is still fully transparent. This inspired ASTRONs director, H.R. Butcher and his deputy, E. de Geus, to start fund-raising for such a telescope, named LOFAR (Low Frequency Array). It was a hard and long way, but they found the support that they needed: funding by the Dutch government and by the Northern provinces of the Netherlands. The telescope is operational although it has not yet reached completion; its first paper with scientific results has been published. At present the key LOFAR science projects are: (1) epoch of reionization, (2) deep extragalactic surveys, (3) transient sources, and (4) cosmic rays.

LOFAR is being developed by a consortium of knowledge institutes, universities and industrial parties, led by ASTRON. All participating institutes provide as well in-kind contributions to the development of LOFAR. International partners including Germany, the UK, Sweden and France joined during the construction of the project, providing in kind contributions, mainly through remote LOFAR stations in their countries. Together they constitute the International LOFAR Telescope (ILT). LOFAR consists of two distinct antenna types: the Low Band Antenna (LBA) operating at frequencies between 10 and 90 MHz and the High Band Antenna (HBA) operating between 110 and 250 MHz. In total 36 stations have been constructed in the Netherlands; these are distributed over an area about one hundred kilometres in diameter (located in the North-East of the Netherlands). Half the stations in the Netherlands are located in a 2×3 km^2 core area near the village of Exloo. The remaining stations are distributed around this core at distances of up to 50km. The largest baselines across Europe will be of the order of 1500km.

2.2. ASTRONOMICAL SPACE RESEARCH IN THE NETHERLANDS

Astrophysical space research started around 1960 at the universities of Utrecht, Leiden and Groningen, through special government funding. In 1983 these three groups were formally brought together in a research institute under the umbrella of ZWO (now NWO). Since then SRON has been the national institute for scientific space research. In its advisory role to government ministries and the Netherlands Space Office (NSO) SRON has been contributed to the developments in national and international space policies. As a consequence SRON became engaged in new fields of space research, notably in earth observation. By participation in continued series of both high-energy (X-rays and gamma-rays) and infrared missions of ESA and NASA (commitments that often have exceeded 20 or more years) SRON has built space instruments for high-resolution spectroscopy, specifically through the development of gratings, heterodyne technology and more recently cryogenic direct detectors in ESA and NASA satellites.

In the 1960s many small rocket and balloon-borne experiments were conducted, but a major step was the A stronomische Nederlandse Satelliet (ANS; active 1974-1977), initiated by J. Borgman from Groningen and built by a Dutch industrial consortium and the space research institutes in Groningen, Utrecht and Leiden. While ANS had a UV camera from Groningen, under the leadership of Borgmans successor, R.J. van Duinen, the Groningen laboratory further specialized in infrared science and technology. Van Duinen led also the successful fund raising for an infrared satellite that was done in collaboration with NASA: IRAS, the InfraRed Astronomical Satellite. In 1981 van Duinen left astronomy and his role in IRAS was taken over by H.J. Habing. IRAS was launched in 1983 with an American built set of photon detectors and with an additional low-resolution spectrograph (LRS) built in Groningen. IRAS provided the breakthrough for science in the infrared with a.o. the discovery of ultraluminous IR-galaxies. IRAS was immensely successful and made ESA to select the Infrared Space Observatory (ISO) as one of its next missions. SRON became PI for the Short Wavelength Spectrometer (SWS). ISO was active between 1995 and 1998. The SWS revealed many molecular lines in a variety of objects and uncovered for the first time spectral bands of crystalline dust and ices. The SWS experience was later used in the VLT-instrument VISIR and in the concepts of the Dutch contribution to the JWST-MIRI instrument.

After the ANS project SRON/Utrecht and SRON/Leiden developed new X-ray spectrographs with became important contributions to NASA's Einstein observatory (1978-1981) and ESA's EXOSAT satellite (1983-1986). It also delivered the novel Coded Mask Imaging Spectrometer COMIS to the Russian KVANT-module of the MIR station. Since 1990 SRON participated in parallel in the development of three X-ray satellite missions: BeppoSAX (operational: 1996-2002), Chandra (operational since 1999) and XMM-Newton (also operational since 1999). For all three, SRON was the PI for the development and construction of an instrument. Additionally, SRON contributed to ESA's pioneering gamma-ray satellite COS-B (1975-1982) that opened the high-energy gamma-ray window above 100 MeV. SRON was involved in the operation of the ESA's gamma-ray satellite INTEGRAL. In all of these missions SRON was also active in the processing and interpretation of the data that the instruments provided. In the 1990s SRON built the imaging Compton telescope COMPTEL aboard NASA's Compton Gamma-Ray Observatory (CGRO; 1991-2000). On the Dutch-Italian satellite BeppoSAX there were two wide-field X-ray cameras that SRON had developed to image variable X-ray sources over a longer period of time. These cameras had a particularly large field of view of 40 by 40 degrees and under the leadership of J.A. van Paradijs it played a key role in ascertaining the origin of Gamma Ray Bursts and understanding their cosmological origin.

For future X-ray missions SRON develops a new type of detector for X-ray spectroscopic studies, the microcalorimeter. The detector is able to precisely determine the energy of each photon captured with a spectral resolution matching that achieved with gratings. An array of microcalorimeters has the advantage over a grating spectrometer that it can simultaneously produce images. For the eventual flight instrument, the aim is to place more than one thousand microcalorimeters in an array. In the SPICA/SAFARI project these developments for an imaging X-ray spectrometer are transferred to extremely sensitive far-IR detectors.

SRON participates in the Japanese-European ASTRO-H mission with a launch planned for 2014. This mission shall use observations of cosmic X-rays to study collapsing material in the vicinity of black holes, turbulences in clusters of galaxies, the shockwaves caused by supernova explosions and large-scale structures in the universe. Dark matter and the acceleration of cosmic particles to high energies shall also be investigated during the mission. SRON is supplying technology for the Soft X-ray Spectrometer (SXS) of ASTRO-H. This spectrometer shall be the first instrument to simultaneously provide maps and extremely accurate spectra of clusters of galaxies and the remains of supernovas.

From 2009 onwards, astronomers throughout the world use HIFI (Heterodyne Instrument for the Far-Infrared), a very-high resolution spectrograph onboard of ESA's Herschel space telescope that was launched and operated by ESA. M. de Graauw (SRON/Groningen) led the international consortium of 25 institutes that actually built HIFI. Through ultra-high spectral resolution HIFI combines high spectral resolution in a wide wavelength range using partially in a up to then inaccessible part of the infrared spectrum. This became possible by new cryogenic detector technology developed by T. Klapwijk at the Technical University of Delft. HIFI provides access to details of hundreds of thousands of molecular, atomic and ionic spectral lines thus probing physical and chemical conditions in molecular clouds, star-forming regions and galaxy cores. Herschel carries out the observations from the L2 Lagrange point at a distance of 1.5 million km from Earth. It is expected that the helium in the cryostat of Herschel will be boiled off in 2013 and then the instruments will stop functioning. Even at the time of writing it is clear that Herschel and its three instruments are a major scientific success.

Based on the instrument end-to-end development necessary for the PI-ships on ISO and Herschel SRON became the Principal Investigator Institute for the long wavelength spectrometer (SAFARI) on the next big far-infrared mission SPICA, led by the Japanese Space Agency (JAXA). SRON successfully applied to the national committee for the roadmap on large scale research infrastructures and is now able to contribute about a third of the SAFARI instrument including some of the most challenging detector arrays. A final go ahead decision from JAXA is expected in the middle of 2013. SAFARI will be able to map galaxies in large volumes of space and to characterize these galaxies spectroscopically.

2.3. UK/NL COLLABORATION IN ASTRONOMY

In 1981 the British Science and Engineering Research Council (SERC, now STFC) and the Nederlandse Organisatie voor Zuiver-Wetenschappelijk onderzoek (ZWO, now NWO) signed the protocol on the collaboration in astronomical research. The initial agreement was for 30 years starting in 1979. The basis of the collaboration was the recognition that astronomers in the UK and The Netherlands need to have access to first-class telescopes on good sites in the Northern Hemisphere and that these telescopes will need to the developed and updated throughout their useful life. The protocol covered four telescopes with their associated equipment and buildings: the 1.0m Jacobus Kapteyn Telescope, the 2.5m Isaac Newton Telescope and the 4.2m William Herschel Telescope, sited on the Roque de los Muchachos on the Canary Island La Palma, Spain, becoming the Isaac Newton Group (ING). The fourth telescope is the 15m diameter James Clerk Maxwell Telescope located on Mauna Kea, Hawaii, optimized for observations at millimetre and submillimetre wavelengths. The INT and JKT began scheduled use by the astronomical community in 1984 and the WHT and JCMT in 1987.

In the Netherlands the UK/NL collaboration was initiated by H. van der Laan. His UK counterpart was H. Atkinson. Both recognized that multi wavelengths observations were needed to obtain further insight in astrophysical processes and objects. The radio observations obtained with the WSRT require follow-up observations in the optical and (sub)millimetre wavelength regime and the X-ray and IR observations from space need groundbased follow-up as well with ESO in the south and ING in the north.

At RZM in Dwingeloo, coordinated by J.L. Casse and W.N. Brouw, the laboratory for the development of radio receivers broadened its scope to become involved in work for optical telescopes and its instrumentation (CCD controllers, database and archiving system) and equipment for the JCMT (345 GHz receiver system, telescope thermal analysis).

At the KSW in Roden, coordinated by H.R. Butcher and J.W. Pel, the group contributed the development and construction of two instruments and one facility tool: TAURUS II, an imaging Fabry-Pert spectrometer on the WHT, the Multi Purpose Photometer on the JKT, and the Nasmyth acquisition and guiding system for the WHT.

At UU R. Hoekstra and J. van Nieuwkoop developed and constructed the High Dispersion Spectrograph for the WHT and H. van de Stadt coordinated the design and construction of the chopping secondary mirror for the JCMT. The antenna structure of the JCMT was built by a company in the Netherlands, Genius Fabricage BV in IJmuiden.

The UL/NL collaboration required that Dutch staff was seconded to RGO and RAL in the UK to participate in various joint work packages. Staff was also seconded to La Palma en Hawaii to contribute to commissioning of the telescopes and its instrumentation and thereafter to regular telescope operations. The ING was led twice by a Dutchman, J. Lub and R.G.M. Rutten.

A Steering Committee was set up to coordinate the Dutch part of the UK/NL coordination. It was chaired by H. van der Laan and P.C. van der Kruit. H. Weijma represented NWO in the Steering Committee. He was the key-person to coordinate the role of NWO. In the early years these three people represented the Netherlands in the governing boards that were set-up of the ING and JCMT, respectively.

In 1987 Canada jointed the JCMT collaboration. From that year onwards the share and observing time were distributed as follows over the partners: UK-Cnd-NL 55-25-20%. For the further development of the JCMT the Netherlands contributed an upgraded spectral line receiver for the 320-370 GHz band, SIS junctions for the HARP B-band array receiver and parts for SCUBA-II array camera.

In 2002 the Instituto de Astrofsica de Canarias (IAC) jointed the ING as an official partner. From that year onwards the observing time was distributed as follows over the partners: UK-Es-NL $\sim$ 48-32-20%. In 2009 the three partners decided to extend their collaboration for a period of three years. Now discussions regarding the future of the ING are ongoing. One likely option is that the WHT will be upgraded with a wide-field fibre-fed survey instruments capable to take hundreds of spectra simultaneously to study the dynamics and evolution of our Galaxy and the role of dark matter and dark energy in the evolution of galaxies and the universe as a whole.

3. NOVA and University Strategy Towards Research

NOVA is a collaborative and coherent research effort at all astronomy departments at Dutch universities. Its program is centred on the theme 'The lifecycle of stars and galaxies: from high redshift to the present'. There are three interconnected programs each executed by a national network of researchers and lead by researchers with a strong scientific record. Dutch astronomy is very productive and its research is internationally well appreciated. Its quality, as measured through various citation analyses and other indicators of leadership, is at the level of the leading countries worldwide. Dutch PhD students compete successfully for the most prestigious fellowships worldwide and find good jobs in astronomy (Fig. 2) and elsewhere in society.

NOVA's objectives are: 1) to continue scientific innovation in the three main lines of NOVA's coherent research program while maintaining its high quality; 2) to further strengthen its instrumentation program by having a leading role in designing and realizing cutting-edge instrumentation for the E-ELT; 3) to keep attracting very talented PhD students and educating them to levels where they compete successfully for the best positions in science and elsewhere; and 4) to share our increased understanding of the

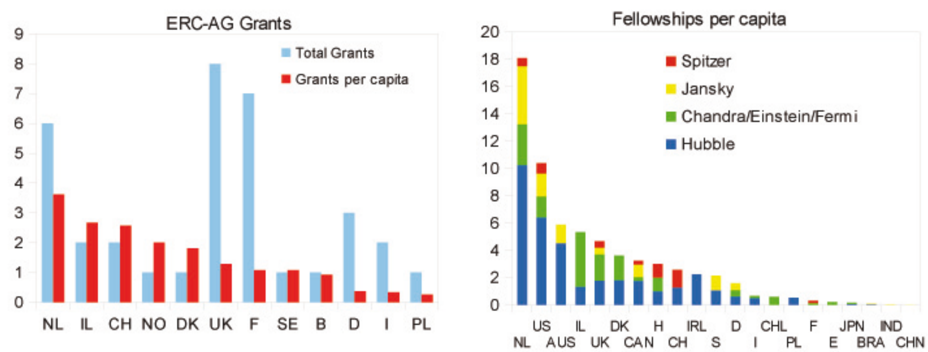

Figure 2. Performance indicators of Dutch astronomy. Left: the total number of ERC Advanced Grants in astronomy per country in 2008-2011 (light blue), and normalized per inhabitant (red). Credit P. Groot. Right: a similar plot of the total number of (highly competitive) US fellowships awarded by NASA to PhD graduates of different countries. In both cases the Netherlands can be seen to be leading the field, illustrating the high level and visibility of its astronomy programme. The USA itself is off-scale. (Courtesy J. Brinchmann)

Universe with the general public.

The research program carried out by NOVA is organized along the following three interconnected thematic programs:

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

The NOVA Grant from the Ministry of OCW helps funding an equivalent of about 40 fulltime people per year of PhD and postdoc positions and through the so-called 'overlap' appointments for permanent staff, which makes it possible to appoint successors to retiring faculty staff several years before retirement. It also stimulates astronomers at the universities to undertake the design and building of instruments for use at telescopes or satellites provided by ESO, ESA or ASTRON, to carry out technical research and development for the next generation of instruments, and to develop specialized software pipelines for data calibration and analyzes. The integrated research and instrumentation program enables Dutch astronomers to obtain a rich harvest of results from ground-based and space-based facilities, in conjunction with strong theory, numerical modeling, and laboratory astrophysics efforts. Over the last decade NOVA has revitalized optical-infrared astronomical instrument-building in the Netherlands involving many university astronomers and has positioned itself well for participation in future major projects.

3.1. STAFF INVOLVED IN NOVA'S PROGRAM

The NOVA program involves about 290 fte[6] scientific staff members spread over the participating universities: 60 fte senior staff in permanent and tenure-track positions, 55 fte postdoctoral fellows, 140 fte PhD students, and 35 fte staff working on instrumentation projects. These numbers are for 2009. The permanent staff includes full professors, associate professors and assistant professors (often on tenure-track positions). The ratio of permanent to temporary staff is about 1:5 at each of the institutes. 95% of the permanent scientific staff carries out research in one or more of the NOVA networks. The staff working on instrumentation projects includes postdoctoral fellows with technical and scientific programming expertise. Over the period 2003-2009 the research staff numbers increased from about 200 to 290, mainly in the categories PhD students, postdocs and staff working on instrumentation projects.

The staff positions at the university institutes are funded by the universities (43%), NOVA Grant (18%), grants from NWO, KNAW and ERC (total 25%), ESO contracts (6%), and other contractual work including EU network funding (8%). These figures are averaged over the period 2003-2009. It is a clear trend that grants from NWO and the European Commission increase over the years whereas direct funding by the universities decreases.

Each of the three national research networks is led by the network coordinator and contains 6-10 senior researchers. With input from the other university astronomers these senior researchers determine the research plans within and across the networks. NOVA-funded research positions have a second supervisor or mentor from another university or from ASTRON or SRON, stimulating collaboration between the institutes. In total, there are 27 permanent staff members associated with Network 1, 12 with Network 2 and 19 with Network 3. There are also cross network projects and several staff members participate in the activities of more than one network. These activities include regular 1-day scientific meetings.

The NOVA instrumentation program is monitored by the Instrument Steering Committee (ISC). All PIs of instrumentation projects submit detailed progress reports to the ISC twice per year, which are discussed in a 1-day face-to-face meeting. The ISC monitors ongoing developments and project risks, reviews intermediate milestones, and, if necessary, recommends corrective actions, including use of contingency funds. One of the major tasks of the NOVA executive director (at present: W. Boland) is

[6]Full-time equivalent.

Figure 3. Top left: The Westerbork Radio Synthesis Telescope (WSRT). Top right: The LOFAR core station. Bottom: the three astronomy projects on the National Road Map Large-scale Research Facilities. Left: the E-ELT on a Chilean mountain top above the clouds, middle: the SKA high-band dishes in a desert setting, right: the SPICA satellite in space. (Courtesy top: ASTRON, bottom: ESO/SKA/ESA-JAXA)

to oversee and guide the instrumentation program on a daily basis, represent its organization in international steering committees for the projects to which NOVA is making contributions and, where necessary, renegotiate existing contractual arrangements. This strict oversight has proven to be essential in keeping the NOVA projects within budget and time.

In 2008 NOVA took over the responsibility for the optical-infrared instrumentation group based at ASTRON in Dwingeloo and employed by NWO. The expert group of optical and mechanical designers and instrument engineers and technicians of about ten people have to be added to the staff members specified above. Over the last decade this group, largely financed by NOVA projects, carried out most of the optical-IR instrumentation projects for which NOVA had the final responsibility toward ESO, ESA, and international partners.

3.2. NOVA'S RESEARCH STRATEGY

The three NOVA research networks address many of the main questions of modern astronomy. Network 1 is concerned with the biggest structures: how did galaxies and galaxy clusters evolve out of the tiny quantum fluctuations observed in the microwave background? How did our own Milky Way galaxy form and what is the feedback of stars onto their host galaxies? Network 2 focuses on the early life of stars and planets. How do stars – high- and low-mass – form from large, tenuous clouds of gas and dust? How are planets such as the Earth made out of the submicron-sized dust grains circling these stars? Network 3 probes the most extreme physical conditions in and around compact objects: white dwarfs, neutron stars and black holes, where the extremes of gravity, density, energy and radiation occur. How are these objects formed and in which environment, what is their internal structure and the relevant physics?

All these questions cannot be studied in isolation but are intimately linked. Galaxies and galaxy clusters are ecologies in which stars, gas and dust, stellar remnants and supermassive black holes all interact with each other, thus linking the subject matter of all three networks. The galaxies and galaxy clusters themselves are descendents from a hot Universe dominated by the laws of quantum mechanics and general relativity (Networks 1 and 3). Massive star formation, evolution and death combine topics in Networks 2 and 3. The interstellar medium in galaxies connects Networks 1 and 2 and it is probed at high redshift through bright gamma ray bursts, a topic in Network 3.

Given the size of the Netherlands and its astronomical community, it is clear that choices have to be made and that not every topic in astronomy can be pursued in depth. For example, the Netherlands has had no or little involvement in solar system and cosmic microwave background research, and has only recently entered the exoplanet research field.

The networks typically organize 1-2 one-day meetings per year with typically 30-50 people attending. Presentations of on-going research are mostly by PhD students with sometimes a guest speaker from abroad. There are also smaller meetings of other groups. For example, a cross-network group on stellar populations and stellar evolution in galaxies meets regularly, as does a group on exoplanet research. Here the Netherlands truly benefits from its small physical size: all universities can easily participate in one-day meetings (no flights or overnight stays needed).

In the past several years innovative research plans have emerged from all three science networks including plans for newly emerging research fields such as exoplanet atmospheres and the transient radio sky Dutch astronomers are deeply involved in national and international multi-disciplinary programs on astroparticle physics, computational astrophysics and astrochemistry. They have made important contributions to the building of some of the major new facilities of the next decade. They are confident to be scientifically well prepared for the exploitation of these instrumental developments. NOVA also has the ambition to lead some instrumentation projects for the E-ELT, the next European flagship, and significant national funding for this ambition has been secured.

New discoveries in astronomy are often made possible by new observational facilities; instrumental developments, in turn, are driven by astrophysical questions. Access to world-class telescopes across the electromagnetic spectrum is vital to Dutch astronomy, and astronomers in the Netherlands are fortunate to have access to major telescopes (VLT, ALMA, HST, XMM-Newton, Gaia, Herschel, JCMT, WSRT, LOFAR) through government funding lines. In the present system NOVA and the universities, the NWO-funded institutes ASTRON and SRON, NWO and the Ministry of OCW each have complementary roles in realizing, running and providing access to these facilities.

Astronomy inspires the general public, and Dutch astronomers take their responsibility very seriously to share their excitement and knowledge about the Universe with a wide audience through hundreds of lectures, newspaper and magazine articles, television and radio appearances, as well as educational programs for school children. Astronomy also stimulates the 'knowledge society' by driving technology, interacting with industry, and training PhD students in a variety of transferable skills related to mining of large volumes of data, software development, high-performance computing, project management, grant writing and strategic thinking.

Figure 4. The MIRI spectrometer main optics for the JWST satellite in the NOVA Op-IR instrumentation group located at ASTRON. (Courtesy NOVA)

3.3. NOVA'S APPROACH TO INSTRUMENTATION

There are various reasons for NOVA to be actively involved in building instruments. The first is to ensure that instruments are built with the required capabilities to address the major scientific questions of great interest to astronomers in the Netherlands. All instruments are designed with specific science goals in mind. For some instruments only participation in the design and construction can ensure that they become reality. An example is the design and construction of the near-IR spectroscopic arm on the second generation VLT instrument X-Shooter. The second reason is to gain expert knowledge of the increasingly complex instruments, necessary to be among the first to harvest the scientific results and, ultimately, to get the most out of the data. Third, and very importantly, the guaranteed time: participating institutes have privileged early access to the telescopes. This makes it possible to carry out large coherent programs with exclusive data as well as smaller seed programs that prepare for the use of subsequent open time. NOVA policy is to make guaranteed time for NOVA-funded projects available to the entire Dutch community.

Building instrumentation is also an excellent way to capitalize on the Dutch investments in the world-wide facilities provided by ESO and ESA. In fact, both organizations expect the member countries to design, build and finance the instruments that go on the billion-euro telescopes. Thus, a relatively small investment of 1-10 MEuros can still have a large impact. An example is the contribution of the spectrometer main optics and the collimator-grating camera optics for the mid-infrared instrument (MIRI) for the James Webb Space Telescope (JWST). Finally, NOVA's involvement in instrumentation strengthens the technical expertise at the universities and provides 'hands-on' experience with the technical intricacies and project management of instrument building and training of a new generation of instrumentalists. Collaboration with nearby physics groups provides fertile ground for technical innovation. In 1996 an astronomy foreign evaluation committee judged a lack of involvement of university staff in instrument to be a weakness that needed to be addressed. The NOVA Grant gave the opportunity to do so starting in 1999 and the program is now in full swing.

Another example of the integrated research-instrumentation approach is OmegaCAM, the wide-field camera for optical wavelengths for ESO's VLT Survey Telescope (VST). NOVA astronomers contributed the data archiving and reduction software. In parallel OmegaCEN was developed to become the national datacenter for wide-field imaging and the expertise center for astronomical information technology. It is situated at the Kapteyn Astronomical Institute of the RUG. The center brings together astronomers and astronomical IT experts. It is partner in various optical and radio wide field surveys, conducted by international collaborations. The largest of these is the Kilo Degree Survey (KiDS).

The knowledge obtained with the development of SIS heterodyne detectors for HIFI at SRON and TuD allowed NOVA astronomers to take a pro-active role in the development of the so called Band-9 receivers for ALMA covering the frequency range between 610-720 GHz, the highest frequency band of the initial set of receivers for ALMA. After the initial design, verification and prototyping phases (2000-2007) 73 Band-9 receiver cartridges were constructed and delivered by the NOVA-ALMA team at the RuG by end 2011.

3.4. OPTICAL-INFRARED INSTRUMENTATION

There is a clear division in technical focus between NOVA, ASTRON and SRON. NOVA has grown into the national 'home base' for instrumentation on the ESO telescopes including the VLT, VLTI, VST, ALMA and in the future the E-ELT. The NOVA-funded program is the long-desired national complement for the ESO program, similar to what has existed for decades with respect to ESA and CERN. The NOVA Optical-Infrared instrumentation group has built up a solid reputation in various areas of optical and infrared instrument design (especially the optical-mechanical design of components that have to operate in cryogenic conditions). This group started as instrumentation workshops at the universities in Groningen, Leiden and Utrecht. In 1982 the university instrumentation workshops in Leiden and Groningen were merged into the Kapteyn Sterrenwacht Werkgroep (KSW) based in Roden and operating under the leadership of H.R. Butcher and J.W. Pel. They gained experience with optical instrumentation for the Dutch Telescope at La Silla, for the UK/NL Isaac Newton Group of telescopes of the Observatorio del Roque de los Muchachos on La Palma, and for the ESO's VLT.

With the advent of 8-10 meter class telescopes the scale and complexity of instrumentation projects increased significantly and it became mandatory to embed the optical instrumentation work in a broader technological environment. In 1996 the optical group moved to Dwingeloo where it became part of ASTRON. The first large instrumentation project was the mid-infrared instrument for the VLT together with the Service d'Astrophysique (Saclay, France). Thereafter (1999-2004) NOVA, ASTRON, and the Max Planck Institute for Astronomy (MPIA) together designed and built the first two-beam combiner, MIDI, for the VLT Interferometer. NOVA and ASTRON were responsible for the design and construction of the cold optics including the beam combiner. In addition NOVA staff at Leiden made a significant contribution to the data reduction software for MIDI.

Engineering state-of-the-art instrumentation is only possible when improved and novel techniques can be applied. The group has built up a reputation in achieving excellent solutions in opto-mechanical engineering, and inventing new solutions to meet the stringent requirements. Examples are the innovative cryogenic lens mounts for the Spiffi camera (for the Sinfoni instrument on the VLT); development of the Adaptive Secondary Setup and Instrument Stimulator (ASSIST), the primary test-bench for ESO's Deformable Secondary Mirror (DSM) for the VLT, used for verifying control algorithms and hardware, functional validation of the adaptive optics facility needed for the 2nd generation instruments such as MUSE and ensuring the DSM operates at specification before being deployed at the VLT; development together with ETH in Zurich of the ZIMPOL system for the SPHERE instrument for ESO's VLT, which is a sensitive imaging polarimeter to detect the faint reflected light signal from extrasolar gas planets in wide orbits in exo-solar planetary systems.

The Netherlands is one of the ten European countries making contributions to the Mid-Infrared camera/spectrometer Instrument (MIRI) for the James Webb Space Telescope (JWST) covering the wavelength range between 5-28 μm. The spectrometer input/pre-optics (SPO) with the dichroics and IFU's are provided by the UK whereas the actual spectrometer main optics (SMO) with collimator-grating camera optics are the responsibility of the Netherlands. The gratings mechanism is contributed by Germany and the detector units are US responsibility. The Dutch contributions organized through NOVA were initiated by E.F. van Dishoeck, R. Waters and J.W. Pel and were designed and constructed by the optical-infrared instrumentation at ASTRON. The work was completed and delivered to the European MIRI consortium in early 2009.

At the same time (2003-2008) the Optical-IR instrumentation group together with NOVA astronomers (L. Kaper and P. Groot) and technical staff at the Radboud University Nijmegen designed and manufactured the near-infrared spectroscopic arm of X-Shooter, the first second generation instrument at the VLT in operation since 2010. X-shooter is a powerful optical and near-infrared medium-resolution spectrograph, with a unique spectral coverage from 300 to 2500 nm in one shot.

From January 2008, NOVA took over the leadership and responsibility of the optical-IR instrument group located at ASTRON. The group together with a number of university astronomers made significant contributions to the Phase A studies for four E-ELT instruments: EPICS (C.U. Keller), METIS (B. Brandl), Micado (K.H. Kuijken succeeded in 2012 by E. Tolstoy) and Optimos-EVE (Kaper). The study work was completed in early 2010. The involvement in the Phase-A studies led to the role of NOVA in two of the three first instruments for the E-ELT (Micado and METIS).

The national funding for the Dutch contributions to the E-ELT instrumentation was partly secured in 2008 through a national Roadmap grant in a collaborative proposal by NOVA, ASTRON, SRON, TNO (organisation for industrial technology development) and several industrial partners. Under the supervision of W. Boland the partners in the collaboration started a program to distinguish areas in which readiness still had to be demonstrated or further improved. Ongoing technical R&D projects include the advanced chopper, immersed gratings and sorption cooling technology for METIS, and polarimetry system engineering and high-speed computer systems and algorithms for adaptive optics corrections for EPICS.

3.5. UNIVERSITY ASTRONOMY EDUCATION

All graduate astronomy education in the Netherlands is concentrated in NOVA, *i.e.*, all PhD students in the Netherlands are part of NOVA even if funded from other sources. The NOVA educational program has three aims (1) Broadening of the astronomical knowledge of the PhD students; this is accomplished through courses at the annual NOVA fall school as well as attendance of colloquia at the home institution; (2) Deepening of insight in topics related to the thesis project; this is mostly done through literature studies and courses at the home institution, the NOVA network meetings, as well as international summer schools. (3) Presentation: opportunities and training in presenting scientific results are provided at the NOVA school, home institution, the annual Netherlands Astronomy Conference and international conferences. The progress of each PhD student is monitored annually by the NOVA PhD review committee at each institution.

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TABLE 1. **Some Institutional Links**

ASTRON Netherlands Institute for Radio astronomy	http://www.astron.nl/
JIVE – Joint Institute for VLBI in Europe	http://www.jive.nl/
NOVA – Netherlands Research School for Astronomy:	http://www.strw.leidenuniv.nl/nova
SRON Netherlands for Space Research	http://www.sron.nl/
European VLBI Network	http://www.evlbi.org/
Astronomical Institute Anton Pannekoek	http://www.astro.uva.nl/
Kapteyn Astronomical Institute	http://www.rug.nl/sterrenkunde
Leiden Observatory	http://www.strw.leidenuniv.nl/
Astronomy Department Radboud University Nijmegen	http://www.astro.ru.nl/

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