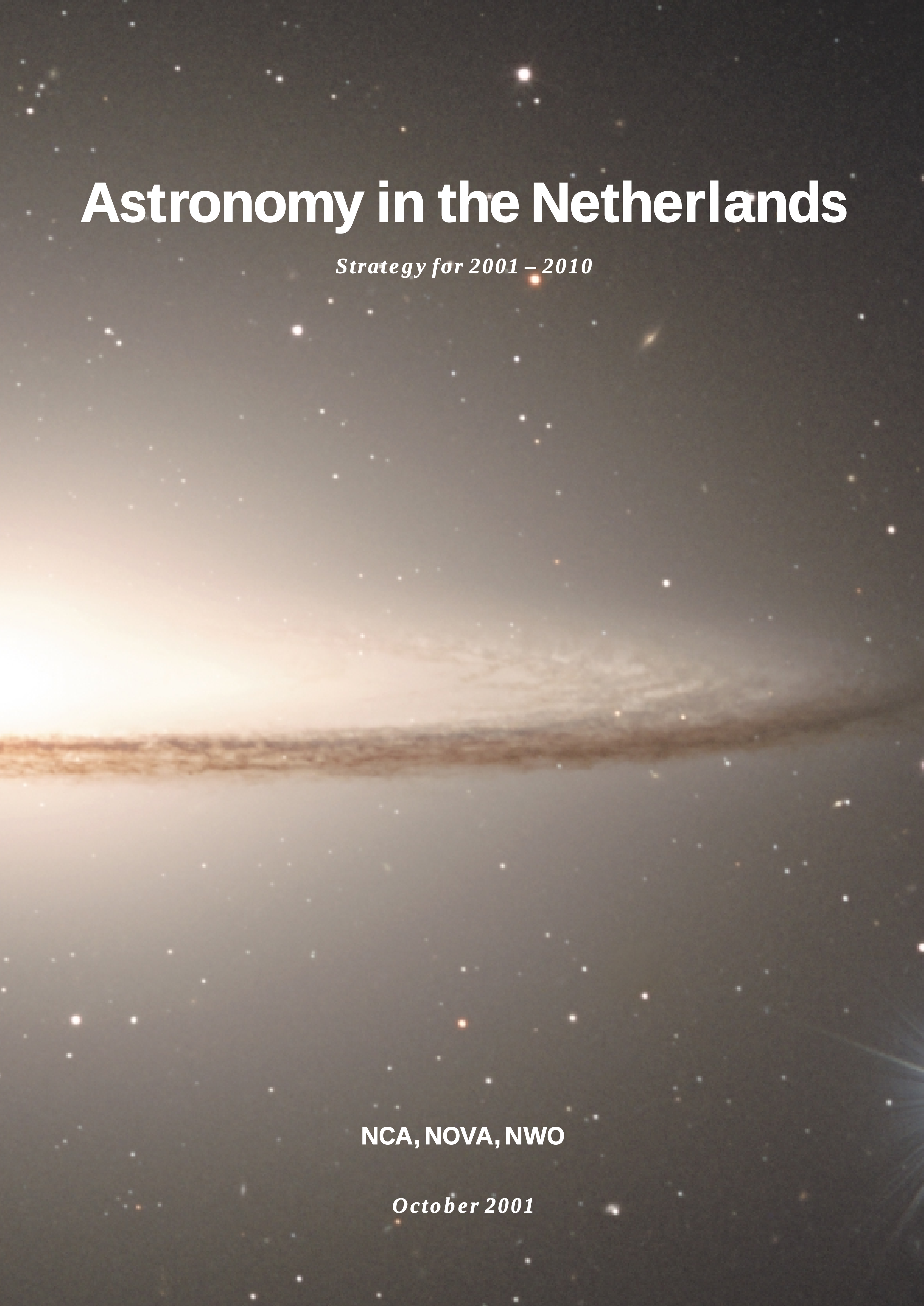
Astronomy in the Netherlands

Strategy for 2001 – 2010



NCA, NOVA, NWO

October 2001

Astronomy in the Netherlands

Strategy for 2001 – 2010

Nederlands Comité Astronomie (NCA)
Nederlandse Onderzoekschool Voor Astronomie (NOVA)
Nederlandse organisatie voor Wetenschappelijk Onderzoek (NWO) – Gebied Exacte Wetenschappen

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Executive summary

Astronomy

The ultimate goal of astronomical research is to understand the Universe and the objects within it in terms of the laws of physics. The structure of the Universe and its development over the course of time, the nature, formation, and evolution of planets, stars, galaxies, clusters and superclusters of galaxies, and the properties of the medium in which these are embedded, are all important objects for study. Cosmological questions concerning the nature and evolution of the Universe are profound. They relate directly to such questions as the geometry of space-time, the nature of the dark matter which constitutes over 90% of the gravitating mass in the Universe but leaves no trace in the form of electromagnetic radiation, the formation of the elements and, ultimately, the origin of the Earth and of life. Furthermore, the Universe provides a unique laboratory for investigating and testing the laws of chemistry and physics under conditions far more extreme than can be reached in laboratories on Earth. Astrophysicists study phenomena involving enormous scales of length and mass (the Universe as a whole), huge densities (e.g., neutron stars, black holes), extreme vacua (interstellar and intergalactic media), immense energies (explosive phenomena such as supernovae and quasars), and intense fluxes of particles and radiation (neutrinos, gamma-ray bursts).

Research focus

Throughout much of the 20th century, the Netherlands has held a strong international position in astronomy and astrophysics, particularly in the fields of radio astronomy, the interstellar medium, structure and dynamics of the Milky Way and other galaxies, stellar and solar physics, and, more recently, plasma and high-energy astrophysics. In order to maintain and strengthen this pre-eminent position during the coming decade, the astronomical community in the Netherlands has decided to concentrate on the following three research areas:

– Formation and evolution of galaxies: from high redshift to the present
– Birth and death of stars: the life-cycle of gas and dust
– Final stages of stellar evolution: physics of neutron stars and black holes

Each area addresses deep physical questions as highlighted in part I. Together they constitute the overall theme of the NOVA research strategy: The Life Cycle of Stars and Galaxies.

The ambition to maintain a top ranking in the quality of astronomical research carried out in the Netherlands requires (1) access to state-of-the-art observing facilities on the ground and in space that cover the entire electromagnetic spectrum, and (2) the ability to attract and keep the most brilliant researchers, by supporting them with sufficient human resources and computing facilities.

Computational astrophysics

The ongoing increase in computing power allows the computation of astrophysical problems of increasing complexity. The physics required to tackle these problems usually involves the combination of different fields of expertise, and a variety of computational methods. Mastering these methods, and writing the computer programs to apply them, requires a long-term investment, both in the computers themselves and in manpower needed to manage these programs. A number of collaborations in this field are already in place, which often transcend the boundaries of astrophysics, involving scientists from related disciplines in physics and applied mathematics. The various applications often require different pieces of highly specialized theory, and they profit mutually from an intense exchange of views and knowledge between them.

Observatories and instruments

Astronomy differs from most other sciences, in that it cannot make in situ measurements of the objects and physical processes under study. For this reason it is critical to make observations covering the full electromagnetic spectrum – from gamma- and X-rays to long radio waves – with the greatest sensitivity, the sharpest details in images and in spectral features. This multi-spectral approach also makes it possible to probe physical conditions at various depths into objects.

Astronomers in the Netherlands have access to the international observing facilities made available through ESO and ESA (in particular the Very Large Telescope and the space observatories Hubble, Chandra and XMM-Newton), to the UK/NL optical telescopes of the ING at La Palma, the UK/CND/NL submillimeter JCMT on Mauna Kea, and to the fully Dutch-owned WSRT and the multilateral EVN-JIVE facility. Together, these facilities deliver an outstanding scientific program as judged by international review committees. Participation in these facilities will be supported as long as they continue to deliver the highest quality science.

Several revolutionary new observatories will become available in the next decade. On the ground, new techniques are being developed that will routinely correct for the blurring motions of the atmosphere so that objects can be imaged at ever increasing resolution from the ground. This also opens the way to the construction of optical telescopes with diameters between 30 and 100m. At longer wavelengths, a global collaboration between Europe (ESO), the USA and Japan aims to construct the very large millimeter interferometer ALMA. New facilities at much longer wavelengths (cm to meters) such as LOFAR and SKA are being planned. In space, NASA, ESA and their Japanese and Russian partners expect to launch a new generation of space observatories. These include SIRTF, Herschel Space Observatory (formerly FIRST), NGST, and GAIA. Finally, astronomical databases all over the world are being connected so that they can be exploited in conjunction as a world-wide `virtual observatory', available to anyone who can access the internet.

Technical Research and Development

In the past decades, the Netherlands had a significant role in planning of new international facilities because the NWO institutes ASTRON and SRON offered key technologies and expertise to strengthen the science potential and exploitation of these new observatories. In-depth investments in four areas of technical R&D are required to allow continuation of this active participation also in the next generation of observatories.
At SRON, the astronomy related technical research is focused on the next generation of detectors for X-rays, and on possibilities for infrared interferometry from space. ASTRON maintains its cutting edge expertise in long wavelength radio astronomy correlator design and phased-array technology, and has added a program in optical/infrared instrumentation and R&D, which includes participation in first generation ESO VLT and VLTI instrumentation projects.

The time-scales for the development of major next generation observing facilities are long, typically 15-20 yr. The four-pronged national R&D effort is in harmony with the strategy where each NWO institute has two major thematic lines, so that at any time, each institute has one program in the development phase and the other in the construction phase. Continuation of this successfull approach requires an increase of the structural funding of both SRON and ASTRON in order to be able to compete effectively with other European institutes. In particular, the optical/IR program at ASTRON needs strengthening to allow participation in the ESO VLT and VLTI second generation instrumentation programs, and - on longer time-scales - in the development of the 100m telescope OWL.

A coordinated approach

It is essential that the research and instrumentation development programs at the universities carried out by NOVA on the one hand, and the major instrumental development and R&D initiatives at the NWO institutes ASTRON and SRON on the other hand, are fully complementary, well-coordinated, and have sufficient critical mass. For this reason, astronomers in the Netherlands have chosen to make a few major investments in well-selected new initiatives rather than taking part in many projects in a ratio of gross national product of the partners.

Top priorities for new observing facilities for the coming decade are

1. Participation in ALMA through ESO
2. ESO VLT-VLTI instrumentation
3. NGST mid-infrared camera/spectrograph
4. LOFAR/SKA preparation
5. JIVE real time VLBI

The intent is to terminate participation in the JCMT when ALMA comes into operation, and to substantially reduce support for the WSRT when the next generation radio facility starts operations. Access to groundbased optical telescopes in the northern hemisphere remains a priority especially for follow-up work of new discoveries from space observatories. For the ING the resources should be concentrated on the 4m WHT to continue to equip this telescope with state-of-the-art instrumentation. The ultimate goal for La Palma is to establish a European collaboration to guarantee access to the next generation groundbased optical telescopes in the northern hemisphere.

Human resources and research funding

A key objective for the coming decade is to make sure that Dutch astronomy can attract and keep the most brilliant researchers. To be able to compete in the global arena, access to world-class observing facilities and a vigorous instrumentation program must be complemented by sufficient means to support the top scientists with PhD and postdoctoral positions as well as state-of-the-art computational infrastructure. This general research support has been under pressure for the past two decades, and significant investments in human resources and infrastructure are required to reverse this trend.

A first step in this direction was taken in the ten-year NOVA program which started in 1999. It provides funding for overlap appointments for future vacancies on the permanent university staff, dedicated support staff for reduction and handling of large data streams, and graduate students and postdocs. Funding of this program beyond the first phase which ends in mid 2005 is critical.

Part I. Present situation and its time derivative: in which direction are we heading ?

1. Research Infrastructure

The Netherlands has a strong international position in astronomical research, particularly in the fields of radio astronomy, the interstellar medium, structure and dynamics of the Milky Way and other galaxies, stellar and solar physics, and plasma and high-energy astrophysics. This prominent position is strongly linked to the quality of the research education, to which traditionally much care is devoted. Many of the astronomy graduates gain postdoctoral and staff positions at premier institutions abroad, or obtain good research positions outside of astronomy.

1.1. Structure and organizations

At a national level, three organizations have their own area of responsibility: the research school NOVA, in which the four university astronomical institutes of Amsterdam, Groningen, Leiden and Utrecht (and in the future also Nijmegen) collaborate, and the NWO institutes ASTRON and SRON, respectively.

The Netherlands Organization for Scientific Research (NWO) is a semi-governmental organization that functions as a national research council. It was set up by an act of parliament as an independent organization, and relies for its funding almost entirely on the Ministry of Education, Culture and Science. The NWO institutes receive their baseline funding from the NWO General Board. Science policy within NWO is determined through its discipline oriented research councils. Astronomy resides under the Council of Physical Sciences (GBE, physics, mathematics, computer sciences and astronomy). The GBE also acts as granting organization for NWO supported astronomical research in the Netherlands.

Intergovernmental organizations like the European Space Agency (ESA) and the European Southern Observatory (ESO) determine, in broad outline, the long-term opportunities for astronomical research in the Netherlands, in the fields of space research and ground-based optical-infrared and millimeter astronomy, respectively. Dutch researchers do have influence on the choices ESA and ESO make, but this influence is rarely decisive. There is no equivalent of ESO or ESA in radio astronomy, but ASTRON and JIVE (the Joint Institute for VLBI in Europe) in Dwingeloo play a leading part in organizing European radio astronomy.

1.1.1. NOVA and universities

Most of the astronomical research in the Netherlands is carried out at the astronomical institutes of the universities of Amsterdam, Groningen, Leiden and Utrecht. In 1992, these institutes decided to collaborate in the Netherlands Research School for Astronomy (Nederlandse Onderzoekschool Voor Astronomie, NOVA).

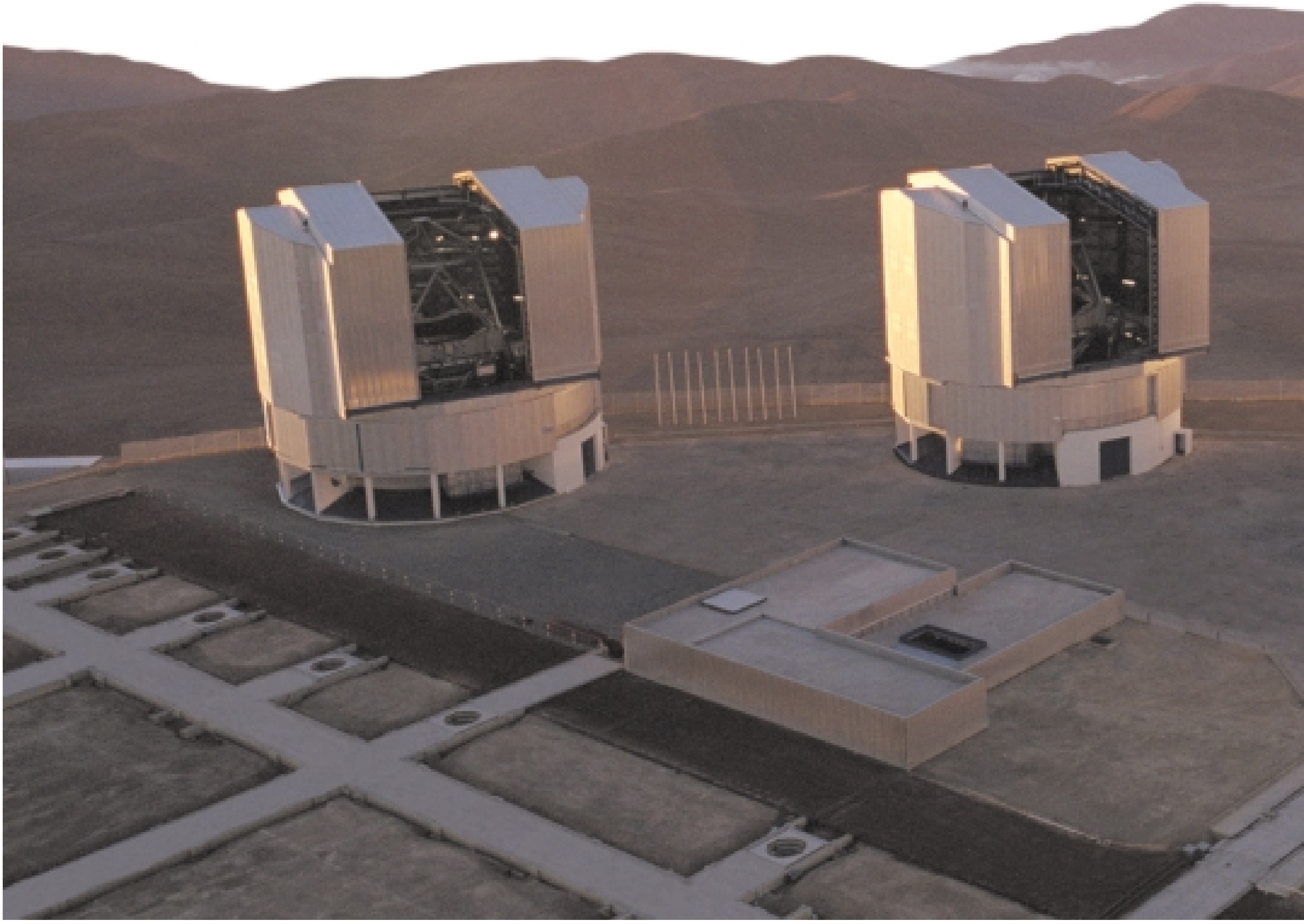
NOVA's mission is to carry out frontline astronomical research in the Netherlands, and to train young astronomers at the highest international level. Graduate astronomy education in the Netherlands is concentrated in NOVA.

In 1998, the Dutch government initiated a research program, the so-called `In-Depth Strategy' to identify and stimulate national focus areas of world-class scientific research. Six national research schools were selected by the NWO, from 34 applications covering all academic disciplines. NOVA was ranked highest among these, and received a grant of 21 million Euro for the period 1999-2005 to carry out an innovative program on the overall scientific theme: The Life-Cycle of Stars and Galaxies. This program focuses on the formation and evolution of galaxies, on the formation of stars and planetary systems, and on the high-energy phenomena which occur in the stellar populations and in galactic nuclei. It combines three key areas of astrophysical research where Dutch astronomy has a strong international reputation. The program has technical, observational, interpretative and theoretical components, which are carried out in interuniversity networks, and which maximize the scientific exploitation of the available ground-based and space-based observatories. It also provides excellent training for future generations of astronomers.

Discoveries with large international telescopes are often made by groups which have built a novel auxiliary instrument, such as a special purpose spectrograph or a new detector system. NOVA initiated Dutch involvement in several instrumentation programs for the ESO Very Large Telescope (VLT), the VLT Interferometer (VLTI) and ALMA, as well as in an upgrade of the PUMA pulsar facility on the WSRT and support of Laboratory Astrophysics. This strategic effort is carried out in cooperation with the instrumentation groups at ASTRON and SRON, capitalizes on the Dutch investments in ESO, and provides an excellent complement to the planned ESA Herschel Space Observatory, the planned NASA-ESA Next Generation Space Telescope, and the initiative for the Square Kilometer Array. NOVA astronomers are also involved in the construction of the Advanced Camera for the Hubble Space Telescope. A key part of the NOVA instrumental effort is the development of a university curriculum for technical astronomy, which includes hands-on experience with instrumentation, special-purpose computing, and data analysis.

1.1.2. ASTRON

ASTRON, the Netherlands Foundation for Research in Astronomy, is the technical arm of Dutch ground-based astronomy. Its mission is to provide front-line research facilities in support of the community's research programs, with particular emphasis on long-term research infrastructure. ASTRON strives to ensure that the community has access to forefront ground-based observing facilities across the electromagnetic spectrum. The present program consists of two main activities: (1) operation and continued enhancement of the Westerbork Synthesis Radio Observatory



The Very Large Telescope on Cerro Paranal, Chile. The four 8.2 meter telescopes can be used separately, or as an interferometer with superior resolution. In that case the light from their mirrors is guided through tunnels to a common focus in the central buildin (courtesy ESO).

(WSRT) which is again one of the world's most sensitive instruments of its kind after the completion of its major upgrade program; and (2) development of innovative instrumentation in the radio and the optical-infrared wavelength regions at its technical laboratory in Dwingeloo. In addition, ASTRON plays a central role in determining the future of radio astronomy internationally by hosting the Joint Institute for VLBI in Europe (JIVE), by participating through ESO in the design and development program of ALMA, by taking the lead in the technical design of LOFAR (Low Frequency ARray) and of the international organization of the Square Kilometer Array (SKA) project.

1.1.3. SRON - astronomy activities

SRON, the Space Research Organization of the Netherlands, is an expertise center of international repute for the development and scientific exploitation of instrumentation for space observatories for astrophysics and earth observations. For astronomy, the main focus is on (1) X- and gamma-ray astronomy (high-energy), and (2) infrared and sub-millimeter astronomy (low-energy). These two areas are prominent in ESA's long-range plan Horizon 2000 plus.

The program for the coming decade includes diagnostics of high-energy transients such as X- and gamma-ray bursts (BeppoSAX), X-ray spectroscopy of nearly all known classes of cosmic X-ray sources (Chandra and XMM-Newton, operations planned until 2010), gamma-ray spectroscopy (Compton GRO, Integral), high-reso-

lution spectroscopy of the cool universe in the mid-IR wavebands (ISO), and ultra-high resolution spectroscopy of very cold matter (Herschel Space Observatory, HSO, 2007-2012). In nearly all these missions SRON has Principal Investigator (PI) status for its contribution to the scientific payload.
SRON is actively involved in European preparatory instrument studies for a possible future 10 meter X-ray telescope, XEUS, which will require in-orbit build-up with the aid of the International Space Station. SRON has also begun to make investments to participate in future initiatives for space-based interferometry (IRSI/Darwin).

1.2. Existing observing facilities

This section describes existing observing facilities with a major Dutch financial contribution. Dutch astronomers also frequently use the Hubble Space Telescope, the X-ray observatories RXTE, XMM-Newton and Chandra, the gamma-ray satellite BeppoSax, and many of the world's groundbased telescopes, including AAT, ATNF, BIMA, CFHT, CSO, CTIO, GMRT, IRAM, Keck, KPNO and VLA (see list of acronyms for further information).

In astronomy it is common practice to offer colleagues worldwide access to each others' observing facilities through open telescope time allocation procedures based on a proposal judged on scientific merit only. Use of each others' facilities is in principle free of charge. The overall quality of astronomical research has greatly benefited from this open-minded approach.

1.2.1. European Southern Observatory (ESO)

ESO is an intergovernmental organization set up in 1962 to establish and operate an astronomical observatory in the Southern Hemisphere and to promote and organize co-ordination in astronomical research in Europe. The Netherlands is one of the nine (soon ten) members of ESO. Its annual contribution is 5.5 million Euro per year. In return, Dutch astronomers receive about 6.5% of the observing time on the ESO telescopes on La Silla and on the VLT at Paranal, in Chile, and are regular users of the Swedish-ESO Submm Telescope on La Silla.

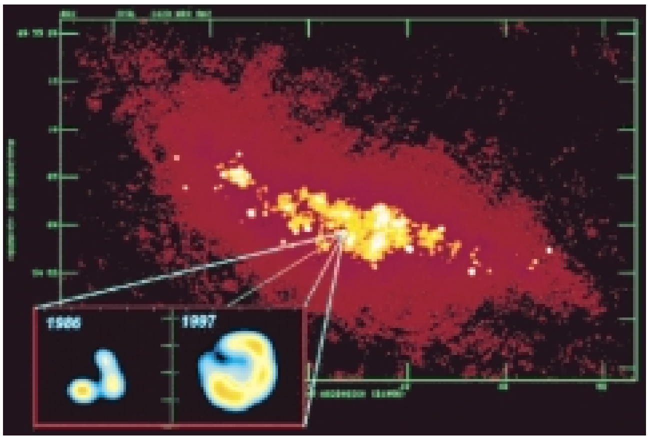
The VLT consists of an array of four 8m diameter optical telescopes equipped with eleven different instruments. The four telescopes can be used individually, or can be combined in a incoherent mode to provide the light gathering capacity of a 16m equivalent diameter telescope, or combined in a coherent mode to provide the angular resolution of a telescope with a larger than 100m diameter. The latter mode is called the VLT Interferometer (VLTI). The VLTI includes a number of smaller movable Auxiliary Telescopes. These enhance the number of baselines over those provided by the 8m telescopes, and improve the imaging efficiency of the VLTI. By themselves they form an interferometric array which can be used independently.

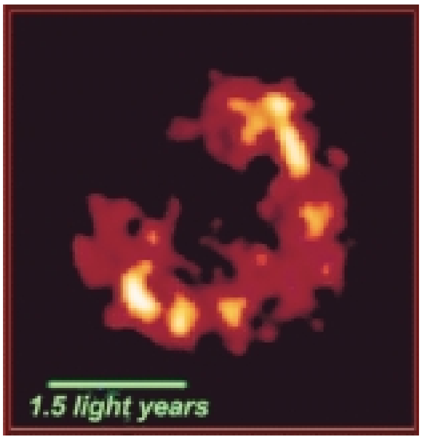
In collaboration with other partners, the Netherlands makes substantial contributions to the following VLT or VLTI instrumentation programs:

VISIR will provide high quality imaging and spectroscopy with resolutions up to 10,000 in the 10-20 micron atmospheric windows. Its capabilities are complementary to SIRTF, and it bridges the gap in time between ISO and HSO. The VISIR project is a university initiative organized through ASTRON in collaboration with the French Center for Atomic Research (CEA), Astrophysics Division at Saclay. Delivery to Paranal is planned for Spring 2002.

MIDI is a prototype fringe detector system that will operate in the 10 micron window at the VLTI. This project is a largely experimental effort to develop the techniques of multi-telescope synthesis imaging at near- and mid infrared wavelengths. MIDI will provide up to 20 milli-arcsecond angular resolution at a spectral resolution of 200-300. MIDI is a collaboration of MPIA (Max Planck Institut für Astronomie at Heidelberg, Germany), NOVA (universities of Amsterdam and Leiden), ASTRON, ESO, and other partners in France and Germany. Delivery to Paranal is also planned for Spring 2002.

OmegaCam is the wide-field camera for the VLT Survey Telescope (VST), a 2.6m telescope being built for ESO's Paranal Observatory, dedicated exclusively to optical imaging. The camera will cover a field of one square degree with very fine resolution (0.2 arcsec pixels). Its focal plane is tiled with a total of 32 CCD's, each having 2048 x 4096 pixels. The instrument is designed and built by a consortium of institutions in three countries, which in turn coordinate the contributions of other institutes: for the Netherlands, NOVA (PI, university of Groningen), and for Germany and Italy, respectively the observatories of München (co-PI) and of Padova (co-PI). ESO designs and builds the dewar containing the CCD detector array. NOVA designs and provides the semi-automatic pipeline software to reduce and analyze the large data volumes (20 Terabyte/year)





(left) MERLIN + VLA radio image of the central part of the nearby galaxy M82 showing some of the supernova remnants present. Inset are images of the youngest remnant observed in 1986 and 1997 by the EVN. The remnant shows clear expansion over the 11 years.
(right) A highly detailed image, observed in November 1988, of the same remnant obtained from a 20-telescope global VLBI array showing for the first time the complex interaction of the ejected material with its surroundings (courtesy JIVE).

The Isaac Newton Group of Telescopes on La Palma, jointly operated by PPARC and NWO. First on the left is the 4.2 meter William Herschel Telescope, second the Dutch Open Telescope (courtesy ING).

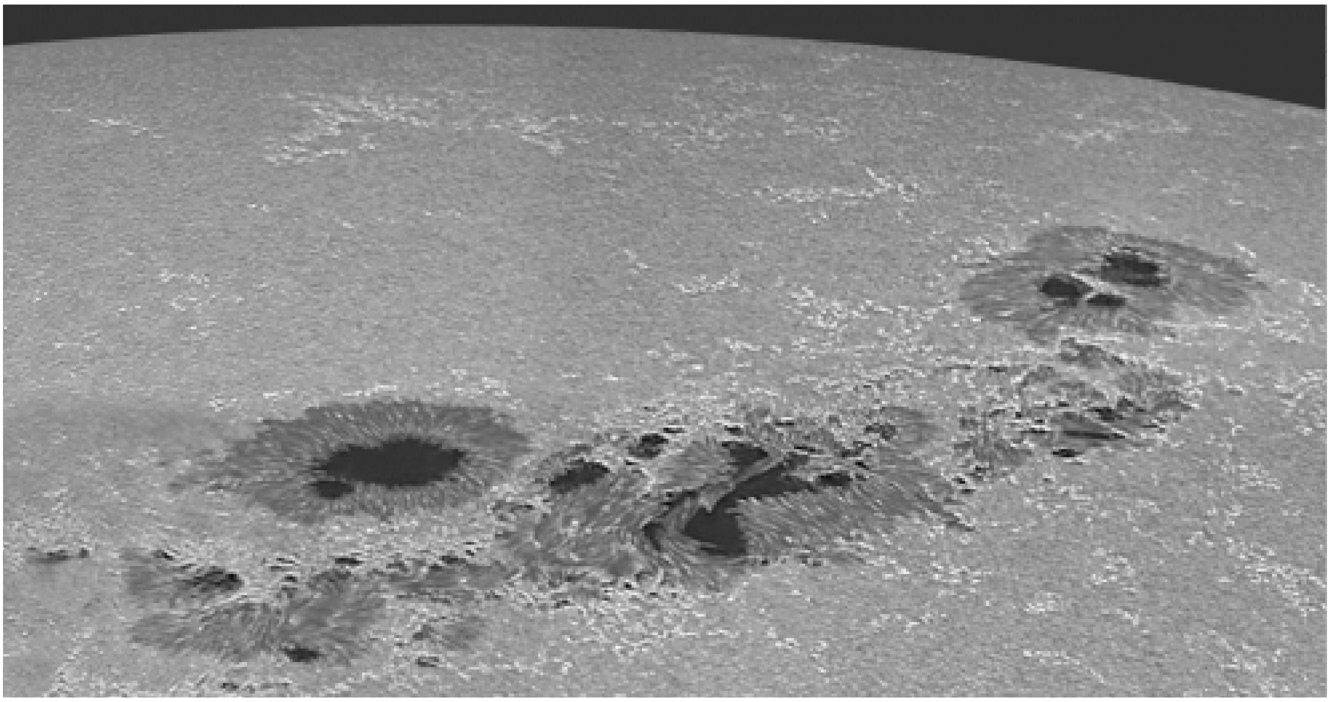
this instrument will produce. Delivery to Paranal is planned in late 2003.

SINFONI is an instrument that combines the advantages of integral field spectroscopy in the near-infrared with adaptive optics. Both integral field spectroscopy and adaptive optics are major growth areas; the combination of these two techniques is even more powerful. In the background-limited near-infrared regime, adaptive optics gives a strong sensitivity increase for small sources. SINFONI will outperform HST by providing higher resolution in the near- infrared, reaching fainter magnitudes in K-band, and delivering fully spectrally multiplexed imagery. This project is a collaboration of the Max-Planck-Institut für Extraterrestrische Physik (Garching, Germany), NOVA (University of Leiden and technical development at ASTRON) and ESO. Delivery to Paranal is planned in 2004.

1.2.2. Westerbork Synthesis Radio Telescope (WSRT)

The WSRT is currently the only major observational facility in astronomy located in the Netherlands. During the 1990's a thorough upgrade of the 30-year old telescope was carried out. New low-temperature multi-frequency front-end systems provide a greatly enhanced frequency coverage and agility. These frontends, an enhanced correlator, a broad-band (6 x 20 MHz) IF system, and a newly designed 'tied-array adding unit' have transformed the WSRT into a state-of-the-art instrument. As a 94-m equivalent single-dish instrument, the WSRT is one of the most sensitive radio telescopes in the world for continuum and spectral line studies. The WSRT also serves as one of the backbones of the European VLBI Network.

The Pulsar Machine (PuMa) has become a workhorse for pulsar studies at WSRT. This state-of-the-art backend, built and designed at the Universities of Utrecht and Amsterdam, and fur-



A giant group of sunspots, observed with the Dutch Open Telescope on 2 April 2001. Later on this day, the group caused the eruption of the biggest solar flare in 25 years. The picture has a resolution of 0″.2 (150 km) and is a mosaic of 10 images at a wavelength of 430.5 nm (courtesy DOT).

ther upgraded with NOVA-funding, is uniquely equipped to use the capabilities of the WSRT systems for pulsar searches and timing studies. It has pioneered interactive remote operations of the facility and observing is regularly carried out from a university.

With proper maintenance of the operational and observing systems, the WSRT can continue its productive scientific lifetime for another 10 years.

1.2.3. European VLBI Network and Joint Institute for VLBI in Europe (JIVE)

The European VLBI Network (EVN) is a consortium of 14 institutes who, between them, control 16 radio telescopes in Finland, France, Germany, Italy, the Netherlands, Spain, Sweden, the UK, Poland, Ukraine and China. Together, these individual centers form a distributed large-scale facility, a continent-wide radio telescope. The combination of simultaneous observations made by this network of radio telescopes generates images of cosmic radio sources with a detail which would otherwise only be achievable by a hypothetical single telescope of (inter)continental dimensions. In the radio wavelength domain the electrical fields of the cosmic radiation can be measured directly, as opposed to other wavelengths where only the energies are measured. This allows for the signals of individual telescopes to be stored on magnetic tapes in order to be interferometrically combined at a later date at a central facility. The importance of this Very Long Baseline Interferometry (VLBI) to astronomy and astrophysics lies in the extremely high angular resolving power achieved which is unequalled by measurements in any other part of the electromagnetic spectrum.

JIVE is the central institute of EVN, and is located in Dwingeloo. Its mission is to support the scientific and technological development of VLBI in Europe. Main elements of the program are: (1) to process EVN observations using the MkIV data processor, which can handle data from 16 radio telescopes simultaneously and is the most advanced of its type in the world, (2) develop the processor's capabilities for continuum, spectral line and pulsar research, (3) support the operations of the EVN and its individual users, including rapid analysis of data quality at the EVN telescopes, and (4) initiate front-line astronomical research using the technical facilities. JIVE also coordinates the EVN's role in space VLBI observations with HALCA.

1.2.4. Isaac Newton Group (ING) on La Palma

The Dutch participation in ING is organized through a bilateral partnership between the United Kingdom and the Netherlands national research councils with a 20% NL share. The ING comprises three optical telescopes, the

4.2m William Herschel Telescope (WHT), the 2.5m Isaac Newton Telescope (INT) and the 1m Jacobus Kapteyn Telescope (JKT), located on the Roque de los Muchachos on La Palma. The ING offers astronomers in the Netherlands guaranteed access to optical telescopes in the northern hemisphere at an outstanding observing site, complementing the ESO telescopes covering the southern skies.

The WHT is one of the two scientifically most productive ground-based optical/IR telescopes in the world. It has a well-balanced set of workhorse instruments which cover a variety of observational possibilities for imaging and spectroscopy at optical and near-infrared wavelengths. It also provides an excellent platform for deployment of fast-track private instruments to tackle specific scientific problems. Dutch astronomers have particular interest in integral-field spectroscopy (presently SAURON and in the future OASIS) and in the Planetary Nebulae Spectrograph for studying the kinematics and stellar populations in galaxies.

The future role of the WHT will be focused on (1) exploitation of adaptive optics, in particular at visible and near-infrared wavelengths, in order to provide imaging and spectroscopy at increased spatial resolution, and (2) multi-object spectroscopy over a wide field. Both areas provide important science capabilities competitive with, and complementary to those at larger telescopes. In this way the WHT optimally exploits the excellent properties of the La Palma observatory site and the quality of the telescope and its infrastructure, whilst offering a long-term development path that provides important instrumentation capability to the astronomical community.

The Roque de los Muchachos is the only quality site for astronomical observations in Europe, and also hosts the DOT (see 1.2.6) and telescopes of Belgium, Italy, and the Nordic Countries, with common services provided by Spain. With the construction of the 10 m Gran Telescopio Canarias (GTC, completion around 2005), this arsenal of national observatories has the potential of becoming an integrated European Northern Observatory. The Dutch astronomical community aims to help establish a European collaboration on La Palma to guarantee access to the next generation groundbased optical telescopes in the northern hemisphere. For the intermediate term, the ING should focus its efforts and resources on the WHT, and the Dutch support for the ING has to be maintained at its present level.

1.2.5. James Clerk Maxwell Telescope (JCMT) on Hawaii

The 15-m diameter James Clerk Maxwell Telescope (JCMT) is the world's largest radio telescope capable of working at submillimeter wavelengths. The large size and high accuracy of its dish, and the quality of the Mauna Kea site, are prime advantages of the JCMT. Heterodyne instruments allow study of molecular line emission which provide physical diagnostics of interstellar and circumstellar gas. Continuum instruments allow study of interstellar dust. Polarimeters are used in conjunction with both heterodyne and continuum instruments to determine magnetic field strengths and alignments.

The JCMT routinely produces outstanding science in a wide range of research areas, and will continue to do so for several more years to come. SCUBA has revolutionized (sub)millimeter astronomy over the last few years, while upcoming array heterodyne line receivers, and the planned interferometric link between the JCMT and the Smithsonian Submillimeter Array (SMA) will be mid-term priority goals to maintain a world-leading position. Further improvements of the surface (to enable the telescope to work better at higher frequencies) and even larger array instruments may enable the JCMT to become a survey instrument to complement the increased sensitivity and resolution of future large millimeter interferometers (e.g. ALMA). However, the Dutch astronomical community will shift their interest towards ALMA, and their involvement in JCMT will diminish when ALMA becomes scientifically productive.

1.2.6. Dutch Open Telescope (DOT)

Solar astrophysics is currently experiencing a renaissance, in which many of the unsolved questions of the past thirty years are being answered. The Netherlands has historically enjoyed a worldwide reputation in the field. Both theoretical and observational research are continuing at a modest level.

Observational solar physics in the Netherlands presently concentrates on the Dutch Open Telescope (DOT) on La Palma, conceived and developed at the University of Utrecht. It has successfully demonstrated the open telescope concept, now being studied for the proposed next-generation national solar facility in the US, and the feasibility of consistent long-sequence speckle restoration of solar scenes over a wide field. The DOT is currently being equipped with a five-camera multi-wavelength imaging system that combines synchronous speckle reconstruction with tomographic diagnostics to provide simultaneous long-duration image sequences of the magnetic field topology in the deep solar photosphere, the middle chromosphere and the high chromosphere. The science that becomes feasible with this high-resolution field mapping addresses the structure and dynamics of magnetic fields throughout the solar atmosphere, a key area of solar physics. The niche is unique in Europe, complementary to Big Bear Solar Observatory (9 hours away), complementary to the adaptive optics efforts at other leading solar telescopes (which will concentrate on high-resolution spectropolarimetry over a single isoplanatic patch), and complementary to the solar telescopes in space which map the coronal field

Table 1: Astronomers in the Netherlands

The number of filled research positions in astronomy and related technical R&D and construction programs funded by the universities, by NWO or through other resources, respectively. Positions at JIVE are excluded because of the multi-national nature of that organization. The NWO funded astronomy positions include 11.9 fte permanent staff and 9.5 fte postdocs and 7 fte PhD students at ASTRON/SRON, and 6.3 fte postdocs and 17.8 PhD positions at the universities funded through the grant program of NWO/GBE (May 2001).

Staff / funding resource	Univ	NWO	Other	Total
Astronomers				
Permanent staff	50.1	12.4	1.0	63.5
Postdocs	10.0	15.8	11.0	36.8
PhD students	45.8	24.8	9.3	79.8
Subtotal astronomers	**105.9**	**53.0**	**21.3**	**180.1**
Technical research staff	**10.7**	**29.4**	**0.8**	**40.9**
Total	**116.6**	**82.4**	**22.1**	**221.0**

Table 2: Annual astronomy budget in the Netherlands

Expenditure in astronomical research in the Netherlands for the year 2000 as shown according funding resources. JIVE is excluded because of the multi-national nature of that organization. The Dutch contributions to JIVE are included in the figures of the GBE and ASTRON.

Annual budget for year 2000		
Universities	**in Mfl**	**in M€**
University departments	13.0	5.9
NOVA program (research+instrumentation)	5.2	2.4
Subtotal universities	**18.2**	**8.3**
NWO general program		
ASTRON basic funding	12.1	5.5
SRON astronomy basic funding	12.5	5.7
Other	2.1	0.9
Subtotal NWO general program	**26.7**	**12.1**
NWO physical sciences	**10.3**	**4.7**
Government		
ESO	12.0	5.5
ESA astrophysical program	37.2	16.9
Subtotal government	**49.2**	**22.4**
External funding	**5.3**	**2.4**
Total NL astronomy	**109.7**	**49.9**

topology in EUV lines. Continuation of the DOT will keep solar physics in the Netherlands at the frontier of solar research, with a new and invigorating emphasis on unparalleled high-resolution observations.

1.3. Human resources

The astronomical community in the Netherlands consists of over 180 researchers, 160 of which work at the university institutes, and another 20 are based at the NWO institutes ASTRON and SRON. The university groups together comprise 50 permanent scientific staff members, about 30 postdocs, and about 80 graduate students. In addition, ASTRON, SRON and the university institutes together have about 40 academic trained researchers working on technical R&D projects, and on construction of instrumentation and related software packages. More details are given in Table 1.

1.4. Financial resources

The Netherlands spends 50 M€ per year on astronomical research, or about 3 € per year per citizen. Details are presented in Table 2. About 98% of the funding comes from the national government, 1% from EU programs, and the remaining part from various resources (private funds, commercial companies, and donations from abroad). The Ministry of Education, Science and Culture provides up to 95% of the resources through three different budget lines. These are 'international collaborations' (22.4 M€ per year), the national funding agency NWO (16.8 M€ per year), and through the funding of the university groups (8.3 M€ per year). In addition, the Ministry of Economic Affairs also contributes to the Netherlands' annual subscription to ESA, and on a case by case basis also to some technology developments programs at ASTRON and SRON. Since the allocations of the Ministry of Economic Affairs are justified on economy stimulating merits only, these resources are not included in the astronomy budget as shown in Table 2.

2. Present Research

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

The study of the high-redshift Universe poses some of the most fascinating and fundamental problems in modern astrophysics. The extremely smooth microwave background reveals that the Big Bang was remarkably uniform. Recent technological developments have made it possible to observe galaxies and quasars out to redshifts beyond 6, corresponding to a time when the Universe was less than 5 % of its present age. This shows that they must have formed in less than a billion years. Instead of drawing conclusions about how galaxies are formed and evolve from a combination of theoretical modeling and observations of their present-day structure in the nearby Universe, it is now possible to observe distant galaxies directly, when they were still young. In this way we can measure, rather than predict, their evolution over most of the age of the Universe.

The formation process appears to have started with the formation of dark matter halos. Inside these halos gas then cooled and star formation took place, followed by the chemical enrichment of the initially pristine gas. When and how did the first structures appear that evolved into galaxies? When and how did galaxies first form stars? How is the mass distributed in galaxies? What causes the different galactic morphologies? When and how did galaxies develop active nuclei? What is the relation between star formation and nuclear activity, and how did it evolve during the history of the Universe? When and how did the first heavy elements, molecules and dust form?

The strong Dutch expertise in studies of galaxies on the one hand, and on stellar evolution on the other, provides an excellent opportunity for collaborative progress in understanding the link between stellar and galactic evolution. The most important facilities for this research area are the VLT, medium-sized optical telescopes equipped with special purpose instrumentation (WHT and VST), the HST, the X-ray observatories Chandra and XMM-Newton, the EVN-JIVE, WSRT, and, in the longer term, ALMA and the NGST. The research currently concentrates on three areas.

2.1.1. High redshift galaxies

Radio observations have turned up objects at high redshifts (e.g. the Westerbork Northern Sky Survey). Efficient techniques in mm and optical wavelengths now exist for identifying the most distant galaxies. Much work still needs to be done to determine the detailed properties of galaxies at redshift around 1, and comparing the properties of these distant galaxies to present-day (nearby) galaxies. The goal of such studies is to map in detail the history of star formation in the universe, and its relation to the assembly of whole galaxies. Key instrumentation includes multi-object spectrographs capable of observing many objects simultaneously, sensitive wide-field cameras enabling efficient searches for rare objects, and sensitive VLBI observations to help distinguish starbursts from active nuclei in these distant objects.

2.1.2. Nearby galaxies

Study of the structure of nearby galaxies provides a vital reference point for the higher-redshift work. Integral-field spectroscopy of the integrated stellar light is used to study the kinematics of stars and gas and the line-strength distributions of the stellar populations in nearby galaxies. Similar studies of the resolved stellar populations are possible for the Milky Way and its nearest satellites and neighbors. The aim is to determine the intrinsic dynamical structure, the history of metal enrichment, the influence of the environment on the star formation history in galaxies, the role of dark matter and a massive central black hole in shaping galaxies, and the nature of activity in nuclei. This research relies heavily on special-purpose instruments such as SAURON, OASIS, the Planetary Nebula Spectrograph on the WHT, and the EVN and WSRT in the radio domain.

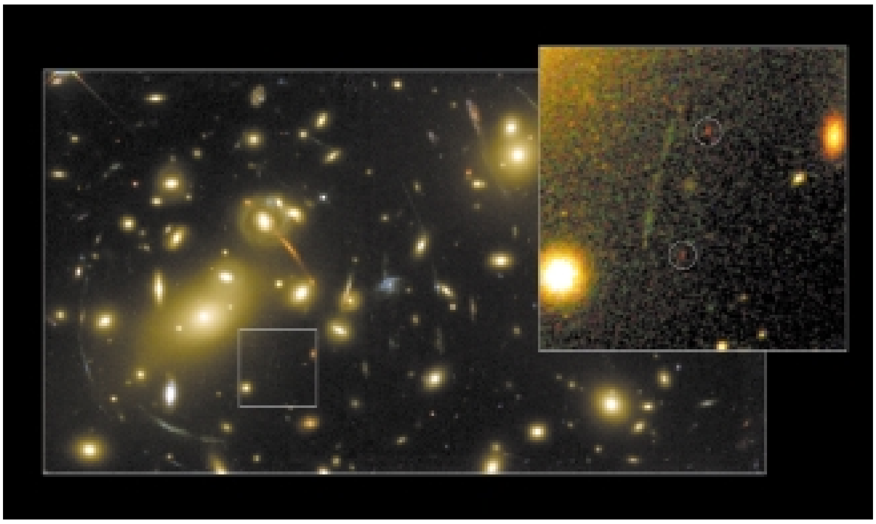
2.1.3. Mass distributions

Galaxies and clusters of galaxies are dominated by extended dark matter, and their mass distributions are therefore very difficult to measure. Several techniques are being used: the traditional measurement of rotation curves of cold neutral hydrogen gas (21 cm line, WSRT), stellar dynamical modeling of spectroscopic data, X-ray measurements of hot gas, microlensing in nearby objects, and weak lensing by galaxy clusters. It is now possible to extend mass determinations for normal galaxies out to substantial redshifts, which also provides information on cosmological parameters.

2.2. Birth and death of stars: the life-cycle of gas and dust

New stars and planets continue to be born deep inside molecular clouds in galaxies. What are the physical processes that lead to these new solar systems, and how do they evolve? What is the role and origin of magnetic fields, and how do they affect the accretion processes? How is the chemical composition of the gas and dust involving the major biogenic elements modified during the collapse from the cold, tenuous interstellar medium to the dense protoplanetary material? During the late stages of their life, stars have a strong wind. The heaviest stars explode as a supernova. Both stellar winds and supernova transport material enriched with nuclei formed by nuclear fusion within the stars into the interstellar medium. How does this material change the chemical evolution of a galaxy and of the newly formed stars? What drives the mass loss, and how does it influence stellar evolution?

Research activities in the Netherlands in this field are aimed at making optimal use of existing observational facilities such as the ISO data base, the VLT and the JCMT, as well as new instrumentation which comes online in the next few years, including VISIR on the VLT, the JCMT/SMA connection, SOFIA, SIRTF and MIDI on VLTI, and, in the longer term ALMA, HERSCHEL and NGST. Present research uses a unique combination of expertise in different disciplines, ranging from observations to astrophysical models, indepth studies of basic physical and chemical processes, radiative transfer and laboratory astrophysics. The present research activities are focused on the three following themes:



Dutch astronomers in an international team used a 'gravitational lens' to find this extremely distant 'baby'-galaxy at more than 13 billion light years.The image (insert) was magnified and split in two by the gravity of the foreground galaxy cluster Abell 2218 (courtesy NASA/HST/Kuijken).

2.2.1. The earliest stages of star formation

Molecular clouds are the primary sites of star formation. Because of (self)gravity, (parts of) clouds can collapse, leading to the formation of protostars in the center. During the initial stages of star formation, the radiation from the protostars is extinguished by hundreds to thousands of magnitudes and the full energy escapes at infrared to mm wavelengths. Existing ISO data, especially the spectra taken with the Dutch/German instrument SWS, combined with new space infrared experiments and ground-based submillimeter data, will be exploited to study the interaction of the radiation and outflow from the young star with its surroundings, and to probe the evolution of the molecular composition of the gas. Comparison with laboratory data will provide identifications of the observed features, as well as insight into the basic chemical processes occurring in the laboratory of interstellar space. High-angular resolution data such as provided by the SMA/JCMT connection will be used to study the formation and growth of disks around low- and high-mass stars. New insight into the most massive young stars in the Galaxy will be obtained through groundbased infrared observations.

2.2.2. Evolution of circumstellar disks and formation of planets

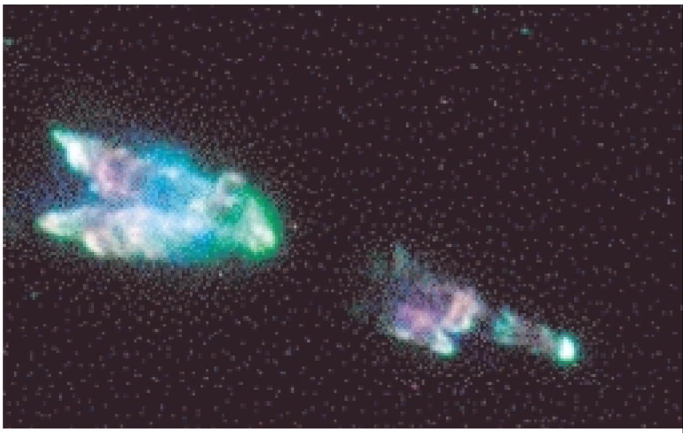
Circumstellar disks, consisting of gas and small dust particles, comparable to the primitive solar nebula have been formed around a large fraction of pre-main sequence stars, but little is known about their evolution. In particular, their development into the much less massive 'debris' dust disks surrounding main-sequence stars is poorly understood. Comprehensive programs using mid-infrared data from VISIR/VLT, SIRTF and/or SOFIA combined with higher angular resolution JCMT/SMA and VLTI data, will be used to study the properties of the dust and the gas-to-dust ratio during the planetary formation period of 1-100 Myr. Comparison has already been made with the physical and chemical properties of primitive bodies in our own solar system such as Kuiper-Belt objects and comets. These studies also serve as a first step into the new discipline of astrobiology, in which the building blocks for life and the possibilities for life elsewhere in the universe are investigated.

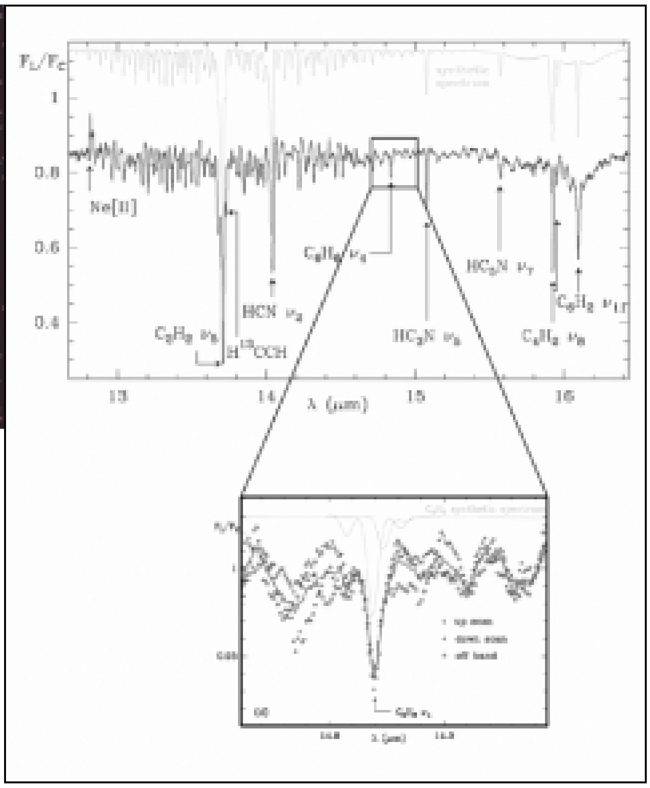
2.2.3. Late stages of stellar evolution

Theoretical models of the physical and chemical structure of stellar winds, as well as the radiative transfer in continuum and lines, will be developed to probe the phase of high mass loss during the death struggle of stars. Future high angular resolution instruments at infrared, millimeter and centimeter wavelengths will be used to reveal the onset of dust formation and the physics of the stellar winds. Systematic studies using the unique ISO database and complementary ground-based observations will provide new insight into the underlying stellar population and their distribution.

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

Neutron stars and black holes – compact objects – are of fundamental physical importance. Their observable properties depend directly on uncertain aspects of space-time and matter and therefore they can be used to learn about these most basic constituents of the physical world. Neutron star matter is the densest known. By measuring the mass, radius or spin of a neutron star one probes unanswered questions concerning the nature of matter. The very strong gravity of a black hole

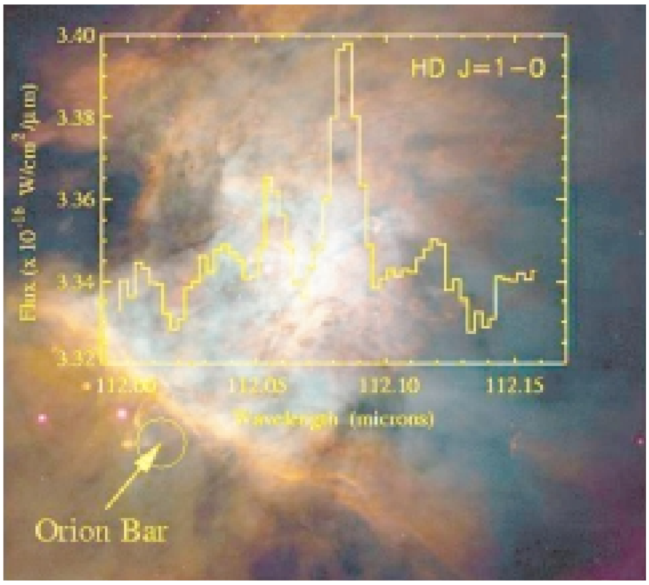




The Short Wavelength Spectrometer on the ISO-satellite, built by SRON, has provided a unique view of the molecular universe.The planetary nebula shows strong jets emanating from the central star (not visible).The 13-16 micron spectrum reveals acetylene (C_2H_2) in the ejected gas; the insert around 14.9 micron provides the first evidence for benzene in space. (courtesy NASA/HST/Tielens).

severely warps nearby space-time, allowing to look for exotic strong-field general-relativistic effects such as unstable orbits, rapid frame dragging and event horizons (black holes). Compact objects exhibit themselves in various ways. The hot relativistic flows in X-ray binary systems diagnose how matter moves in strong-field gravity. Gamma-ray bursts are observable across the Universe, thus providing a unique cosmological probe. Radio pulsars are a relativist's dream: point masses equipped with nature's best clocks, probing any motion or space-time disturbance with exquisite precision. The energetic processes associated with compact objects are the subject of intense theoretical scrutiny – the ultra-energetic cosmic ray particles that occasionally strike our atmosphere must originate there.

The first detection of emission by HD (deuterated molecular hydrogen) outside the solar system provides important data on deuterium in space. Deuterium was only created during the Big Bang and is destroyed in stars, so its abundance is a measure of galactic chemical evolution (courtesy Van Dishoeck)



The research program in the Netherlands is focused on the astrophysics, formation, and evolution of neutron stars, black holes, and their host systems. This research is aimed at extracting fundamental physical information. Recent successes include the discovery (with RXTE) of ultrafast oscillations in neutron stars, probing deeper than ever before into these objects' gravitational well, the first optical and X-ray identifications of gamma-ray bursts (using BeppoSAX and optical observatories), establishing gamma-ray bursts as the most powerful sources of radiation in the Universe, and the 20-year anticipated discovery of the first *accret-*

ing millisecond pulsar. A host of new observational opportunities has just become available to study these objects across the electromagnetic spectrum, and several more will be added over the next years. All areas highlighted below benefit from the giant optical telescopes now becoming readily available. The rapid improvement of numerical capabilities is rapidly opening up many previously intractable theoretical problems to direct investigation. The following summarizes the foci of research in the Netherlands in these areas.

2.3.1. X-ray binaries

Some of the most energetic gas flows in the Universe occur close to a compact object. Strong gravity pulls gas from an accompanying star. By observing the radiation from the gas close to the compact object, i.e. deep down the potential well, fundamental information on the compact objects is obtained. X-ray and gamma ray spectra and, for stellar mass objects, sub-millisecond time-variability are the best observational diagnostics available. Astronomers in the Netherlands have been very successful in exploiting timing and broad-band spectroscopic diagnostics; enormous new opportunities have been opened up to us recently with the launch of the high-throughput high-resolution X-ray spectrographs on Chandra and XMM-Newton, missions dimensioned to last a decade. In 2002, the launch of Integral will provide similar breakthroughs in gamma rays. Often part of the energy associated with the accretion process is converted into near-light-speed collimated outflows (jets). Such flows are seen near some accreting stars in our galaxy, leading to the phenomenon of 'micro-quasars', which may contain information about the physical processes in the much more powerful (and distant) quasars. The new sensitive receivers in the world's biggest radio telescopes (VLA, WSRT) have just opened up this physics for scrutiny in not just the brightest, but the majority of the X-ray binaries.

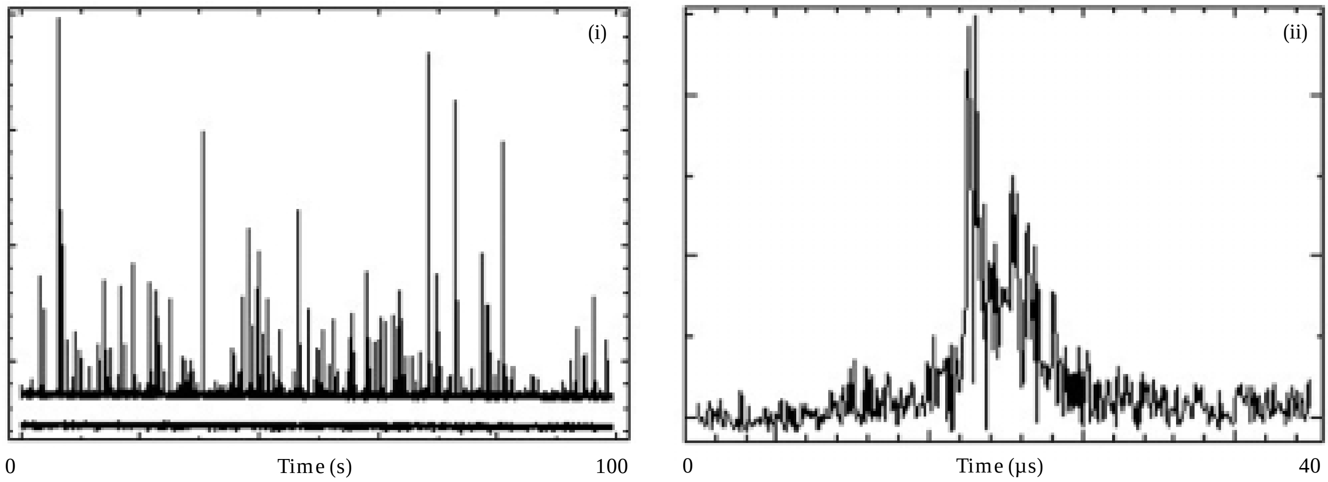
The Crab nebula, the remains of a supernova explosion seen on earth in July 1054 AD (courtesy ESO/VLT).

2.3.2. Gamma ray bursts

The formation of neutron stars and black holes is the outcome of the last stage in the evolution of massive stars. Their birth is believed to be often associated with explosive events such as supernovae, or possibly hypernovae. Hypernova are now believed to be the source of most gamma-ray bursts: the most powerful explosions after the big bang, where the equivalent of one solar mass is converted into energy. Other gamma-ray bursts may be caused by the merger, and hence destruction, of two compact objects. In both scenarios the central engine may be a super massive torus around a forming black hole which produces a hyper-relativistic particle jet. Because they are so very luminous and distant, gamma-ray bursts, in principle observable out to redshifts z of 20, are potentially a unique probe of the high-z universe. With the recent launch of HETE gamma ray burst astronomy has entered a new era, where prompt localization allows immediate follow up observations of radio, optical and high-energy afterglows. Integral (2002), SWIFT (2003) and GLAST (2005) will provide a continuous increase of our observational high-energy capabilities. The Netherlands play a leading role in optical follow-up studies with ESO's Very Large Telescope.

2.3.3. Radio pulsars

Evolutionary links between X-ray binaries and radio pulsars help us understand the evolution of the mag-



The center of the Crab nebula contains a pulsar, which rotates once every 33 milliseconds. It is one of only two known pulsars emitting Giant Pulses, which can be hundreds of thousands of times stronger than normal pulses.
Panel (i): 100 seconds of observation of the Crab pulsar. Large spikes are Giant Pulses (normal pulses are too weak to be seen individually)
Panel (ii): A single Giant Pulse. It last only 30 microseconds, while normal ones last 5 milliseconds (courtesy PuMa/WSRT).

netic field of neutron stars, and thereby the physics of their superconducting interiors. The PuMa pulsar equipment installed at the WSRT allows very detailed observations of the radio pulses generated in pulsar magnetospheres, with a very high time-resolution in a large number of frequency bands. Observations of the detailed pulse profile at different frequencies yield important clues about the physical processes responsible for the generation of the pulsar emission, and its location in the pulsar magnetosphere. The observation of pulsar arrival times allows us to monitor the rotation rate of the pulsar or, for binary pulsars, the change in pulsar orbits due to emission of gravitational radiation, while the propagation of their radio pulses maps out otherwise undetectable components of the non-luminous matter in our Galaxy.

2.3.4. Particles and shocks

A study of the association of pulsars with supernova remnants yields information about the physics of the explosion in which both the remnant and the pulsar were born. Additional information is now becoming available from Chandra and XMM-Newton, which can map the distribution of chemical elements in some nearby supernova remnants. This provides information about how the supernova explosion ejects stellar material into the interstellar gas. Processes powered by the rotational energy of a rapidly spinning pulsar, result in relativistic winds. The large resolving power of Chandra allows us to see the X-ray nebulae resulting from these winds around some nearby pulsars. The production of energetic particles, both leptons and hadrons, seems a common process near compact objects. Jets and supernova remnants produce relativistic electrons which make them powerful radio sources by the synchrotron mechanism. Supernova remnants are believed to be the source of galactic cosmic ray nuclei, while the remnants of gamma-ray bursts may produce the highest energy particles known to man: the ultra-high-energy cosmic rays. A number of the competing production models exist at the highest energies, and observations with near-future instrumentation of gamma-rays (Integral) and neutrinos (ANTARES) can potentially distinguish different production mechanisms.

The barred galaxy NGC 1365 (courtesy VLT/ESO)

Part II. Extrapolation to the future

3. Strategic considerations

Over the past 50 years the pace of astronomical research has been increasing at a remarkable rate, caused by rapid technological developments and by a growing number of astronomers. The public interest in the Universe and all that it contains has increased even faster. The most important of the technical developments are: (i) the widening of the accessible electromagnetic window through the development of telescopes and detectors at radio, infrared, UV, X-ray and gamma-ray wavelengths, (ii) better sites for all observatories, with space as the ultimate platform, (iii) continuing improvements in detector technology, not only in sensitivity, but also in size, reliability, linearity and dynamic range, and (iv) the availability of ever more powerful computers for improved telescope control, data acquisition and reduction, and for developing increasingly sophisticated physical models of what is observed.

All this has provided a view of the Universe that is deeper and more complex. Astronomers often simultaneously study an object at different wavelengths. This problem-oriented multi-spectral approach is essential for understanding the objects and physical processes observed. The discovery that gamma-ray bursts are produced in core collapses of massive stars, presumably leading to black hole formation, that happened early in the history of the Universe is an outstanding example of this multi-spectral approach.

It is impossible to predict which technological and/or computational developments will lead to the most fruitful scientific discoveries. Most likely, as has been the case in the past, the most important breakthrough will be unforeseen. Although unique observational facilities and expertise are a prerequisite for many research programs, follow-up observations at other wavelengths, interpretative and theoretical work, and a stimulating research environment that attracts the best scientists, are crucial.

3.1. International focus, and its national derivative

New observational facilities are organized through international collaborations in order to remain affordable. Within Europe, organizations like ESA and ESO lead the way and take the most important decisions on the future of astronomy. It is good strategy for the Netherlands to be actively involved in the choices made supra-nationally. This can be achieved by active participation in the international science working groups, advisory committees, and councils that prepare or take these decisions. This requires a continuation of the pro-active role from the Dutch astronomical community, as well as support from the national funding agency NWO for long-term strategic development programs (15-20 years) and for financial and organisatorial stability of the research institutes.

ESA's science program foresees the launch of a number of astronomical observatories in the coming decade. University researchers participate in the development of these missions. The X- and Gamma-ray mission Integral will be launched in 2002, and the far-infrared/submm telescope Herschel Space Observatory (HSO, Cornerstone 4, formerly called FIRST) will be launched in 2007 together with the cosmic background radiation mission Planck. Both Integral and HSO have Dutch mission scientists, and the HIFI instrument on HSO has a Dutch PI. The NGST, a 6.5m successor to the HST for the 2-25 micron wavelength region, is being developed jointly with NASA and the Canadian Space Agency and will be launched in 2009. The next ESA Cornerstone mission for astronomy is GAIA, which will be launched before 2012, and will provide distances and motions of over a billion stars in the Milky Way and beyond with accuracies more than a factor 100 improved over Hipparcos. The next generation X-ray telescope XEUS, as well as a mission to study extrasolar planets called IRSI/Darwin are under study for launch around 2015. The same time frame may see the launch of LISA, a gravitational wave experiment developed jointly between ESA and NASA. Dutch scientists also participate in some of ESA's Solar system missions, including Mars Express, Cassini Huygens, and the Rosetta Cornerstone mission.

ESO will add the 4m wide-field telescope VISTA to its arsenal in 2005, and coordinates European participation in the construction of the giant millimeter interferometer ALMA, which will be completed by 2010. ESO has recently initiated the planning for second generation instruments for the VLT and VLTI. While elsewhere in the world, notably in the USA, detailed designs are being developed for 30m class optical telescopes, ESO has decided to develop detailed plans for a ground-based 70-100m class optical telescope (OWL, OverWhelmingly Large Telescope), which would be able to obtain spectroscopic measurements on even the faintest objects detected by NGST. The idea of a 100m class telescope originated in 1997, when it was assessed that true progress in science performance after HST and the 8-10m class Keck and VLT generations would require an order of magnitude increase in aperture size. OWL could operate at full resolution and unequalled collecting power by 2015.

Early on, ESO and ESA provided all the infrastructure required for new and outstanding research with their facilities. In the past two decades, however, both organizations have begun to rely on the development and construction of back-end instrumentation (receivers, detectors, spectrographs) by their member countries. There is a financial aspect to this policy, but it also opens the doors for new concepts and new technology. For example, much of the success of ISO is due to the SWS spectrograph built by SRON. The Dutch astronomical community should be prepared to exploit the advantages of this policy: an early and better awareness of what measurements will soon be made possible and what questions can now be answered. We emphasize this national task (and opportunity!) to prevent the thought that the annual contribution to ESO and ESA is the complete entry ticket for the Dutch scientific community to the international observatories. An active role in the development and construction of new instruments has significant rewards: it allows the builders to do the most successful research. Furthermore, major contributions to a few well-selected instruments strengthen the Dutch role in the international decision making process. Funding for instrument development (including fundamental research on improvements in detectors) at NOVA, ASTRON and SRON (in collaboration with foreign partners) must have high priority because it strengthens the national participation in international organizations. This funding is complementary to the direct contributions to ESO and ESA.

Unlike the situation for other wavelengths, radio astronomy does not enjoy the existence of a large international organization to promote its future. Among the nations active in radio astronomy, the Netherlands has historically played a pioneering and leading role. ASTRON's plan of long term facilities has been predicated on maintaining this leading role. Currently the WSRT is as sensitive in its main modes as any comparable radio telescope in the world. The initiative of last decade to host JIVE and take an active role in organizing the European VLBI Network have established ASTRON as an important facilitator on the European science scene.

The next important step in radio astronomy will be ALMA, and thereafter the Square Kilometer Array. SKA will be an essential complement to ALMA, OWL and NGST. European participation in SKA is foreseen to be financed through the EU beginning with the Seventh Framework Program from 2008 and could be completed by 2012.

A technological step towards SKA that is being planned by ASTRON, with MIT and the US Naval Research Laboratory is LOFAR. This array will open the largely unexplored electromagnetic window on the Universe at wavelengths of order 10 meters. It is planned to start operations in 2006-2008.

3.2. Strategic technical research and development

The time needed to develop a fundamentally new observing technology is typically 15-20 yr. It is crucial that both ASTRON and SRON remain active in two technology areas each, so that at any time each institute has one program in the development phase and the other in the construction phase. In the early R&D phases ASTRON and SRON require strategic collaborations with technical universities, and international partnerships. In the construction phase ASTRON or SRON demand active participation of university astronomers. In-depth investment in human resources and long-term commitments of key-individuals are essential for success. This requires an increase of the structural funding of both institutes. In particular, the optical/IR program at ASTRON needs strengthening to allow participation in the ESO VLT and VLTI second generation instrumentation programs, and - on longer time-scales - in the development of the 100m telescope OWL.

Table 3 summarizes the strategic technical R&D areas, as well as the level of required additional funding for the period 2001-2010.

3.2.1. At ASTRON

ASTRON's long-term program builds on existing expertise and facilities in radio astronomy and develops new instrumentation also in support of university research in optical/IR astronomy. Instrumentation is developed for a wide range of applications and telescopes. Recent major projects concerned apparatus for radio telescopes (WSRT, EVN and JIVE) and for infrared instruments (VISIR for the VLT and MIDI for interferometry at the VLTI, the latter project in collaboration with NOVA). University astronomers participate actively in the development teams.

3.2.1.1. SKA and LOFAR

SKA is a distant, but well identified cornerstone of ASTRON. As part of an international collaboration, ASTRON is focusing on the technical design for SKA at frequencies below 1.5 GHz; this includes the 21cm hydrogen line as it becomes redshifted over the history of the Universe. At radio wavelengths, unlike in other wavebands, primary detection of signals may take place in the aperture plane rather than in the focal plane of the telescope. Complete control of the wave front in the processing electronics of such an array antenna is possible and the telescope can "look" in many directions simultaneously. SKA can thus simultaneously carry out several major research programs and at the same time serve many individual users. In addition, exceedingly clean measurement beams can be constructed and unwanted interfering signals can be suppressed. Once the technology has become mature, SKA will revolutionize radio astronomy. The challenges for SKA R&D are to develop very-wide-band and very-low-noise phased arrays at low cost per square meter (cheaper than wall-to-wall carpet).

The required photonics devices and systems capable of transmitting and rapidly switching many tera-bits of data per second are far beyond what is commercially available today. The projected needs of the ICT industry are very similar, and the development activities for SKA are expected to be of substantial interest for industry. The design of optimized detection circuitry that includes the antenna element as part of the circuit is a formidable computational challenge that requires development of new algorithms and strategies. ASTRON aims to provide a series of demonstrator antennas for system engineering development and for use as testbeds on which the new

Table 3: Strategic technical R&D for astronomical instrumentation in 2001-2010

Planned technical R&D at ASTRON and SRON for future astronomical instrumentation in M€. Figures are the requirements summed over the period 2001-2010, unless stated otherwise.

	Total	New funding	Remarks
ASTRON			
Phased array antenna SKA	10	2.5	a, b
Optical/Infrared instrumentation	4	2.5	a, c
SRON			
Detector development for X-rays	pm	pm	a, d
Optical/infrared space interferometry	4	3.5	a, e, f
Total	**18**	**8.5**	

Remarks

a. Investments on top of regular institute budget.
b. R&D program for 2001-2005 following successful pilot study in 1997-2000. Requirement is 2 M€ per year of which ASTRON + its industrial partners can provide 1.5 M€ per year. NWO-GBE is asked to provide 0.45 M€ per year for at least 2001-2005. The technology demonstrator is incorporated in the LOFAR program.
c. R&D program for 2002-2010 focused on optical interferometry and adaptive optics with applications towards OWL. From 2007 onwards this program might be funded through reduction of the Dutch contributions to the ING and/or JCMT.
d. Major funding through SRON and ESA's technology program. Seed funding (0.45 M€) for the period 2000-2004 is already available through an NWO-GBE grant approved in 2000.
e. Required matching funds for the R&D program to demonstrate imaging opportunities for the IRSI/Darwin mission. Collaboration between SRON, NEVEC and TUD.
f. ESA may fund participation in SMART2, a technology demonstration mission planned as precursor for IRSI/Darwin in 2006-2007.

theoretical insights can be tried out in practice. Individual investigations are being carried out to discover design approaches and computational strategies, which if successful will make new kinds of antenna systems possible. It is essential that fundamental R&D will be continued for at least several more years. Spin-off to the commercial and other sectors seems certain.

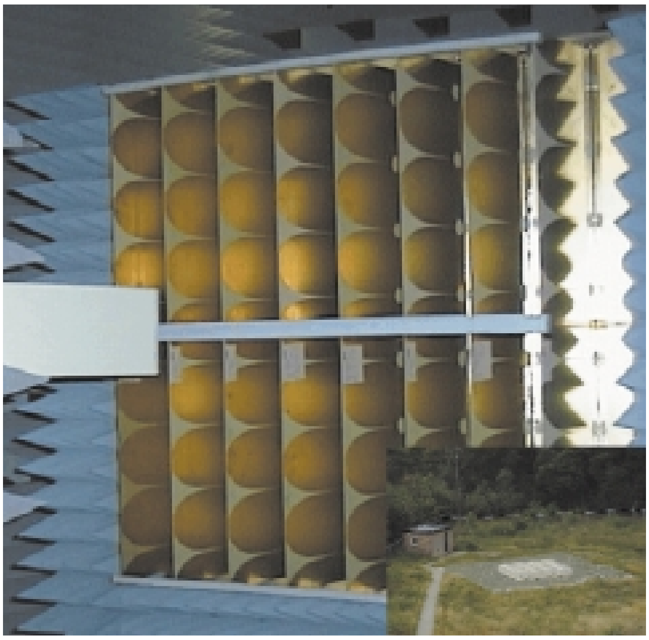
The development program for SKA is currently organized by a world-wide consortium of institutions. ASTRON coordinates the SKA activities and the EU financing in Europe and participates in coordinating global activities. Special attention is being given to industrial spin-off and, through the OECD and International Telecommunications Union, to the selection and protection of the best possible sites in the world.

The LOFAR project combines innovative technologies with strong industrial participation to yield two orders of magnitude improvement in sensitivity and in a similar improvement in angular resolution over any existing or previous telescope in the 10m wavelength range. Apart from its scientific value, which will include innovative studies ranging from cosmology to climate research, LOFAR will be a forerunner or prototype for SKA, although it will operate at lower frequencies and therefore does not require low noise optimization. It will be the first radio telescope that employs aperture plane detection and will thus provide multiple, independently pointed beams, adaptive beam control including interference suppression, and integration into the world wide internet. The project is expected to have strong synergy with the national and international Data-GRID developments. In addition, LOFAR will serve communities outside the usual astronomical institutes and thereby promote inter-disciplinary cross-fertilization.

3.2.1.2. Optical/IR instrumentation

ASTRON also develops innovative auxiliary instrumentation in the optical-IR wavelength range. The focus on optical-IR complements SRON's investment in far-IR/sub-mm technologies. This part of ASTRON's technical development program is currently financed from a diversity of sources, including the competitive grants programs of NWO, the NOVA instrumentation fund, and the ESO instrumentation program. It is particularly vulnerable to unexpected short term fluctuations in funding, and requires substantial structural institutional funding.

For centuries, optical images obtained from the ground have suffered from blurring by "seeing" resulting from atmospheric turbulence. The availability of fast computers has made it possible to correct for seeing by means of a deformable mirror controlled by a wavefront sensor. There is now a very rapid development in these Adaptive Optics (AO) capabilities, not only because of astronomical interests, but also for commercial applications (e.g., eye surgery). All major astronomical observatories are expected to have facility AO systems (accompanied by laser guide stars) in the near future. This will, finally, allow near-diffraction-limited imaging in groundbased astronomy. AO is essential for the next generation of extremely large telescopes, including OWL. Such telescopes with AO will be able to achieve diffraction-limited imaging (without the need for laser guide stars) over all of the accessible sky.



The Thousand Element Array (THEA) tile. This world first wide-band array antenna is the result of an international R&D program sponsored by NWO for the Square Kilometer Array (SKA). Insert shows the test location in Dwingeloo where 16 THEA tiles comprise a small radio telescope of a new generation (courtesy ASTRON).

ESO's design for OWL includes segmented primary and secondary mirrors, integrated active optics and multi-conjugate adaptive optics capabilities. The concept owes much of its design characteristics to features of existing telescopes, namely the Hobby-Eberly for optical design and fabrication, the Keck for optical segmentation, and the VLT for system aspects and active optics control. The only critical area is multi-conjugate adaptive optics, but its principles have recently been confirmed experimentally.

The development of AO in the Netherlands has lagged behind the rest of the astronomical world. Given its importance, it is crucial that this situation is reversed as soon as possible. Two initiatives have been taken recently: (1) NWO-GBE approval for funding for the AO assisted integral field spectrograph OASIS on the WHT; (2) Founding of an expertise center for adaptive optics in Delft by TNO-TPD, in coordination with NOVA. TPD is also developing a test adaptive optics system based on a state-of-the-art pyramid wavefront sensor. This development is extremely welcome, and the resulting expertise, combined with the expertise resulting from the SINFONI program in NOVA (which includes significant research and system development in AO) will likely provide the nucleus of AO expertise in the Netherlands. A joint effort between NOVA, TPD and ASTRON, if properly supported and coordinated, will help to return the Netherlands to the forefront of astronomical instrumentation, will strengthen the expertise on astronomical instrumentation at the university institutes, will allow participation in a major next generation VLT AO instrument, and will be a stepping stone in the development towards OWL.

3.2.2. At SRON

The medium-term program of SRON is basically governed by the choices made more than a decade ago. SRON's technical R&D program is focused on development of new types of detectors for the high-energy radiation (X-rays) and for the low-energy radiation (IR, submillimeter wavelengths). Both astrophysics and earth studies from space will benefit from these developments. These R&D programs are in close collaboration with technical universities.

3.2.2.1. High energy astrophysics (X-rays)

SRON is involved in technical R&D studies for the next generation X-ray detectors for ESA's cornerstone mission XEUS. The present program is strongly oriented towards optimization of single pixel micro-calorimeter performance. Recently a major milestone was reached with respect to the intrinsic physical performance of a spectroscopy cell; a world record energy resolution of 3.9 eV for 5.9 keV X-rays is achieved, quite close to the theoretical limit. A major technical challenge is to build the single pixel into an array device. With recent (2000) funding through the NWO/GBE grants program SRON has started the research and development of a 5x5 pixel prototype imaging array of micro-calorimeters in close collaboration with the MESA+ institute at Twente University and a group in Finland. The collaboration with MESA+ is to develop Si-micro-machining processes, required to produce the imaging sensor array, while the collaboration with the Finnish group is to design and fabricate the cold, SQUID-based, read-out electronics. The level of effort within this collaboration is at present approximately 12 fte and 150 k€/yr. Additional funding in the order of 2 M€ for this R&D program is expected to become available through ESA's research contracts for XEUS.

3.2.2.2. Low energy astrophysics

SRON's goal is to participate in the DARWIN mission at a significant level with an emphasis on astrophysical imaging. In the time-frame 2001-2004, a number of studies will be started related to (i) concepts for imaging large fields, (ii) concepts for co-phasing the whole interferometric array, (iii) end to end modeling of the entire system, (iv) design of a fringe detector for the feasibility mission for Darwin called SMART2. These studies will be carried out in close collaboration with Leiden Observatory, Delft University, TNO/TPD, ESA and ESO. During the years 2004-2006, SRON plans to be involved in building a fringe detector for SMART2. Directly thereafter, significant work will be started on the actual design and implementation of SRON's part of DARWIN. Attractive possibilities include the beam-combiner and a cryogenic instrument.

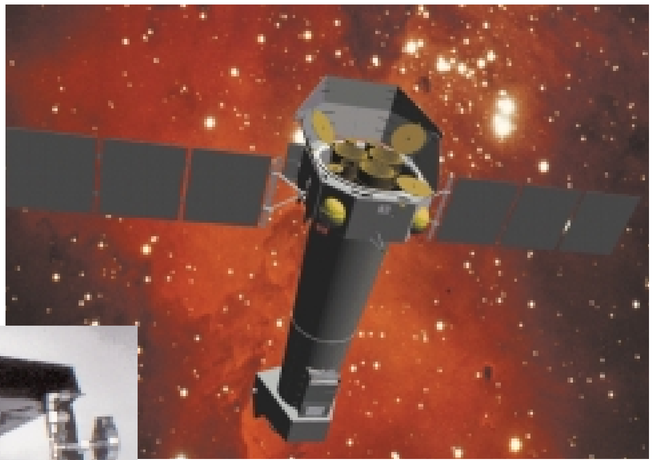
3.3. Coordinated approach in major new investments

One of the strengths of Dutch astronomy is the national coordination of the research, technical R&D, and instrumentation programs between the universities (NOVA) and the NWO institutes ASTRON and SRON. All programs are complementary and each has sufficient critical mass in order to make significant international impact.

The strategy is to terminate funding of an existing observing facility when a new one covering the same wavelength interval comes into operation. Access to groundbased telescopes in the northern and southern hemisphere will remain a high priority because of the need of follow-up work of new discoveries from space observatories.

Major new astronomical observing facilities are international projects with time-scales of order 15-20 years. The investments must be accompanied by relatively modest national investments in computer-infrastructure, database access, and software developments in order to optimize the scientific return of the investments and, at a level of 5% of these investments, financial support for theoretical studies and model simulations.

The Netherlands is amongst the smaller member countries of ESO and ESA. Rather than participating in many projects at the percentage of its gross national product, a major investment in well-selected new initiatives is preferred. Table 4 summarizes the priorities. The major investments listed in the table amount to about 15% of the planned government spending on astronomical research in theNetherlands in the coming decade. In addition ASTRON searches for major additional financial resources (~ 70 M€) outside of NWO to realize LOFAR in the northern part of the Netherlands.



The Reflection Grating Spectrometer, built by SRON, is an integral part of the large European X-ray satellite XMM-Newton. It analyses the X-rays coming from neutron stars, black holes and other violent cosmic phenomena (courtesy SRON).

The present NOVA program (till mid 2005) and its 2nd phase (2005–2010) allows Dutch astronomy to make major contributions to ESO's instrumentation for the VLT and VLTI, as well as to the R&D phase of ALMA. Continuation of the NOVA funding in its 2nd phase is essential to realize an important fraction of the new funding listed in Table 4.

3.3.1. Participation in ALMA through ESO

ALMA will push forward our understanding in at least two of the three research foci of NOVA. It will allow study of the formation and origin of high-redshift galaxies, of obscured active galactic nuclei, of the disks around young stars that can potentially form planets, and of the envelopes of old stars where the interstellar dust is formed. In contrast to the most powerful optical/near-IR telescopes such as the HST or the VLT, ALMA can probe regions that are obscured by up to 100 magnitudes of visual extinction. Its high angular resolution (0.01 arcsec to 1 arcsec) in combination with its high sensitivity will allow applications in many other branches of astronomy as well.

ALMA will be an observatory of the US, Europe and Japan. The required financial contributions from the Netherlands have to be made available through the ESO subscription. The Netherlands will likely contribute to the following work packages for the ALMA construction phase: (1) receiver cartridge of the 600-720 GHz frequency band; (2) the future correlator. It would be natural to terminate the involvement in the JCMT when ALMA starts its scientific operations.

3.3.2. ESO VLT-VLTI instrumentation

Dutch astronomers receive about 6% of the observing time on the ESO telescopes on La Silla, Chili, and the VLT and VLT Interferometer at Paranal, Chili. ASTRON together with university astronomers participated from an early stage in the VLT instrumentation program and has worked with interna-

Table 4: Major investments in astronomy 2001 - 2010

NL share for funding in M€

	Instrument	Total	New funding	Remarks
1	ALMA participation through ESO	20	2	see table 4a
2	ESO VLT-VLTI instrumentation	12	6	see table 4b
3	NGST mid-IR camera/spectrograph	7	7	a
4	LOFAR / SKA preparation	7	7	b, c
5	JIVE real time VLBI	9	3	d
	New initiatives	10	10	see table 4c
	Total	**65**	**35**	

Remarks

a. NL share: funding through NWO-G?

b. Financial contribution from NL astronomy budget; ad hoc investments.

c. Total investment or order 70 M€ with expected major contributions from ICES, ICES-KIS, and international partners.

d. 30% NL share: funding through NWO-M?

Table 4a: specification ALMA participation 2001-2010

NL share in M€

	Total	New funding	Remarks
NL contribution to construction costs	15.0		Through ESO subscription
R&D for 650 GHz mixer	2.0		NOVA phase 1
R&D for Advanced Correlator	1.4		NWO-GBE+ ASTRON
R&D for 2nd generation instrumentation	2.0	2.0	NOVA phase 2
Total	**20.4**	**2.0**	

Table 4b: specification ESO VLT-VLTI instrumentation investments 2001-2010

NL share in M€

	Total	New funding	Remarks
VLTI: MIDI	0.9		NOVA phase 1 + ASTRON
VLTI: NEVEC	1.4		NOVA phase 1
VLT: VISIR	2.7		ASTRON
VLT: OmegaCam for VLT Survey Telescope	1.8		NOVA phase 1
SINFONI	1.1		NOVA phase 1
2nd generation instrumentation	4.5	4.5	NOVA phase 2
Total	**12.4**	**4.5**	

Table 4c: new initiatives instrumentation 2001-2010

NL share in M€

	Total	New funding	Remarks
GAIA	pm	pm	a
Virtual observatory	2.5	2.5	b, c
DOT	pm	pm	d
Next generation pulsar instrumentation	2.0	2.0	e
ANTARES	pm	pm	f
New initiatives	5.5	5.5	g
Total	**10.0**	**10.0**	

Remarks to table 4c

a. Fully funded through ESA. Possible NL participation through contracts with ESA. Link with wide-field imaging (OmegaCam; VISTA) and virtual observatory.

b. ICT infrastructure to explore giant databases produced by facilities like OmegaCam, Vista, GAIA, and LOFAR.

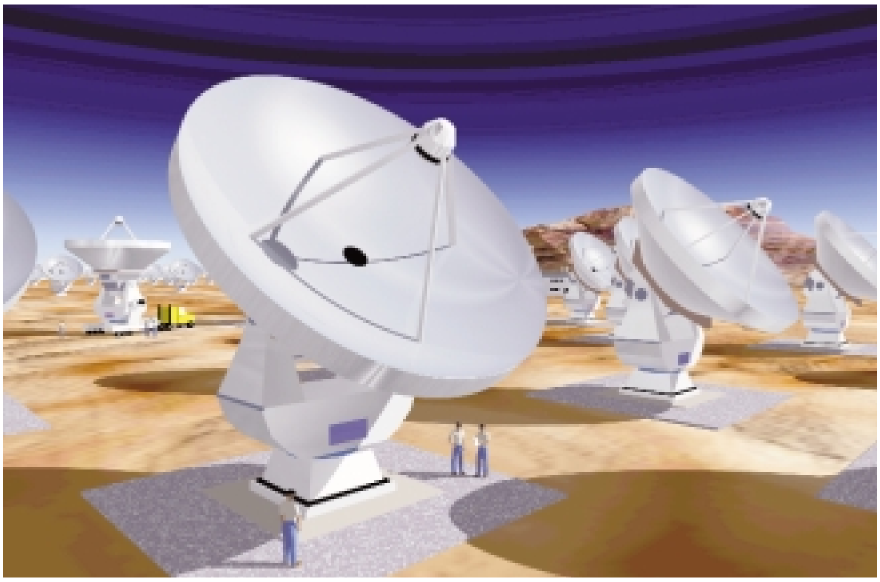
c. NL participation in European program with major funding through EU.

d. Funding through NOVA, Universities, and grants line of NWO-GBE.

e. Funding through NWO-GBE grants line, and/or NOVA phase 2.

f. Funded physics program to demonstrate astrophysical applications.

g. Reservation for 1-2 projects as follow-up of new discoveries/developments in 2006-2010.



Artist impression of ALMA, an array of 64 telescopes for (sub)-millimeter radiation. It will be jointly built by Europe, North America and Japan in the Chilean Atacama desert at 5000 meters altitude.The huge collecting area and interferometric capabilities will allow scientists to probe much deeper into the early universe (courtesy ESO).

tional partners to produce the VISIR imager and spectrometer. When the first phase of the NOVA program was funded, Dutch astronomy became a significant partner in the construction of several first generation VLT and VLTI instrumentations. While ESO's reward of the manpower contributions through the allocation of guaranteed observing time is a well-appreciated driver, the main argument to invest further in the second generation VLT and VLTI instrumentation is to be in the best position to exploit these giant telescopes for scientific breakthroughs.

The NOVA phase 2 instrumentation program will also be centered on ESO. It is expected to include wide-field capabilities, the next step in the development of VLTI, and participation in a second generation VLT instrument that builds on the expertise developed in phase 1.

3.3.3. Participation in the mid-infrared imaging spectrograph of the NGST

NGST is a 6.5m infrared optimized space telescope with at least an order of magnitude improvement in sensitivity compared with the HST. It is designed to detect light from the first stars in the universe, to trace the genesis and evolution of galaxies from their formation to the present, and to determine the nature of luminous galactic nuclei. NGST is expected to revolutionize our view of star- and planet-formation in the galaxy.

As for the HST, ESA will participate in NGST at the 15% level. The negotiations between NASA and ESA have been very favorable to Europe. Among other things, ESA will be responsible for about half of the core instrument payload. The near infrared multi-object spectrograph will be funded by ESA directly. Also, through special contributions from its member states, ESA will take the responsibility for half of the mid-infrared instrument as well.

Dutch astronomers are particularly interested in the mid-infrared spectroscopic capability of NGST which offers the opportunity to study the chemical lifecycle of dust from stellar outflows to regions of star formation through the characteristic fundamental vibrational modes in the mid-infrared. Over the last two decades, SRON has been involved in the IRAS/LRS and the ISO/SWS spectrometers. Presently, SRON is the PI-institute for HIFI - the submillimeter heterodyne instrument for the Herschel Space Observatory. Within ASTRON, infrared instrumentation (VISIR, MIDI) has been developed for groundbased telescopes. The mid-IR spectrograph on NSGT provides a new excellent opportunity for Dutch astronomers to continue and extend a rich tradition in building infrared instrumentation, in particular in spectroscopy. TPD/Delft is also very interested to use its expertise and to participate in a Dutch hardware contributions to NGST. The European contribution to the mid-IR instrument can be split in 5 modules. Each of these is about equal in size and effort. The cost of one of these modules is estimated at 7 M€.

There is considerable time pressure. Originally, the European contribution to the mid-IR instrument was also included in the ESA funding. However, the total costs of the European contribution precluded this and, partly driven by the UK commitment to a mid-infrared instrument, this effort was relegated to the membership countries. Active participation of the Netherlands in the design and construction of this instrument will safeguard the spectroscopic capabilities. In addition it will buy guaranteed observing time proportional to the investments made.

3.3.4. LOFAR and SKA preparation

SKA is planned to be two orders of magnitude more sensitive than existing instruments, and will be able to observe proto-galaxies so distant that they are still at the time before the main epoch of galaxy formation. It will provide new insights in the process of galaxy building and galaxy evolution and will observe the development of large-scale cosmic structure. SKA will uniquely be able to observe the effects of magnetic fields during star formation and in galaxy evolution. It will have enough instantaneous sensitivity to measure rapidly scintillating radio sources, thereby providing an other way of observing galaxies at micro-arcsecond angular resolution. Furthermore, SKA will lead to the discovery of tens of thousands of new pulsars in our Galaxy and in the local group galaxies, and will revolutionize our knowledge of neutron stars and black hole binaries.

Scientifically, LOFAR is designed to be able to detect for the first time the signature of the formation of the very first stars and galaxies immediately after the Big Bang (the so-called epoch of re-ionization). It will be unparalleled for research in a wide spectrum of topics, including solar and planetary physics, studies of starburst and active galaxies, and atmospheric and ionospheric research.

The technologies required for these astronomical instruments have parallel developments in the commercial ICT sector. Unlike the case with most advanced scientific instrumentation, the commercial market is pushing several of the relevant technologies and there can in principle be close and fruitful collaboration with industry, including substantial contributions by industry.

3.3.5. Real time VLBI at JIVE

The techniques of VLBI have advanced dramatically in recent years. Wide field imaging at milli-arcsec resolution is readily possible and new calibration strategies allow deep imaging to almost as deep as connected element interferometers like the WSRT. The future of VLBI lies in higher sensitivity. The EVN is well placed in the short term to achieve this with its present collecting area of the telescopes, and its present recording rate of 1 Gbit/s per station. Taking the wider bandwidth recording available in Europe into account, this means that the sensitivity of the EVN will be 5 times that of the VLBA. The recent detection of three faint compact radio sources in the Hubble Deep Field with the EVN has demonstrated the promise of extremely sensitive VLBI observations. A further factor of five increase in sensitivity is possible with current equipment, making detection of 30 microJansky sources relatively straightforward.

Even higher sensitivity to reach microJansky levels in continuum observations will be essential to keep pace with developments in other regions of the electromagnetic spectrum. This can only be done by widening the bandwidth of the data transported to the correlator using optical fibre links and/or portable hard disks from the telescopes to the correlator. The strategy is to develop both these possibilities in conjunction with partners in the USA at the Haystack Observatory, with the EVN taking the lead in the fibre developments, and Haystack taking the lead in hard disk developments.

3.3.6. GAIA

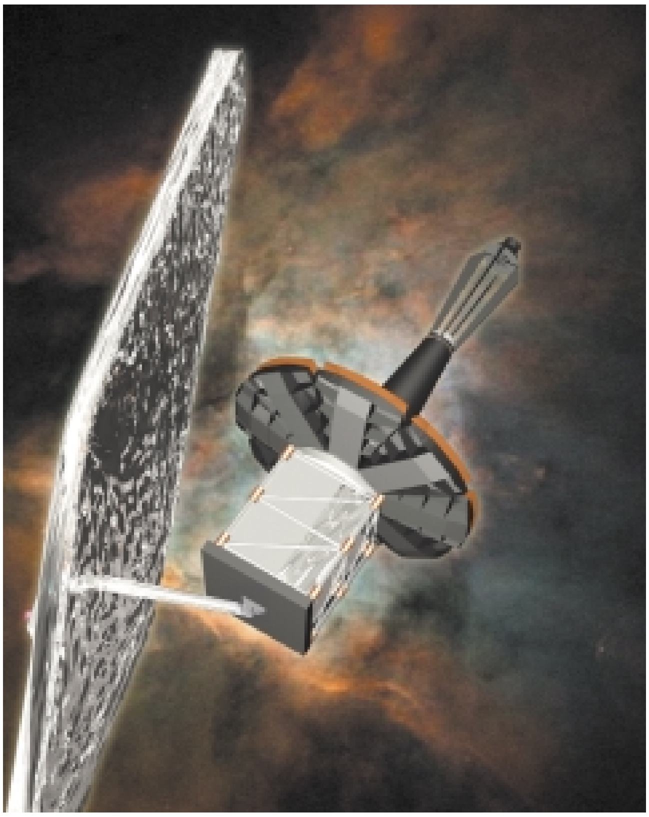
GAIA is ESA's Cornerstone 6 Mission, foreseen to be launched around 2011. By scanning the entire sky about 100 times to magnitude 20, it will determine distances and proper motions for about 1 billion objects in the Milky Way and beyond, with a factor of 100 improvement in accuracy over the Hipparcos mission. It will also measure radial velocities and accurate photometry. As a result, it will provide the three-dimensional motions of the stars in the Galaxy, as well as their age and metallicity distribution. This will allow reconstruction of the entire formation history of the Milky Way, including the role of unseen matter. GAIA will contribute also to the detailed understanding of stellar interiors, will discover tens of thousands of planets around other stars, as well as many minor bodies in the Solar system, and will provide the means for very accurate tests of General Relativity.

Participation in GAIA is attractive, as the ESA budget covers the costs of both satellite and payload. SRON has interest in aspects of focal plane assembly, which builds on expertise developed for XMM-Newton. Involvement in the (massive) data reduction effort would capitalize on the leading role taken by Dutch university groups in the analysis of large-scale imaging surveys such as DENIS, EIS, and in particular the OmegaCam project.

3.3.7. Promises in theory

One can distinguish between applied theoretical research that is closely connected to the interpretation of data, and fundamental research that studies basic physical processes operating in astronomical objects, or the methods used in simulations. Dutch astronomy has a proven track record in the computational astrophysics areas described below.

The increase in computing power (both in CPU and in memory) allows more and more complex systems to be studied such as (magneto) hydrodynamics in more than one dimension and with radiative transfer, allowing for energy and momentum exchange between radiation and fluid, and involving non-linear particle-wave processes; realistic calculations are now possible for flows with velocities that reach the speed of light.
The gravitational interaction of large numbers of stars in clusters is described by N-body dynamics, a field that is revolutionized by very efficient special-purpose computers that make it possible, e.g., to study the evolution of globular star clusters and dense galactic bulges surrounding one or more massive black holes. Effects of



Artist impression of the Next Generation Space Telescope, the successor to the Hubble Space Telescope.To be launched in 2009, it will have an 6.5-meter primary mirror and a large screen to block heat and light from the sun (courtesy Lockeed Martin).

stellar evolution and of stellar mass loss are now included in hybrid codes. Further development of such codes will be a research focus.

Numerical models for the structure of individual galaxies now predict accurately the stellar orbits and may be extended to calculate the effects of age and metallicity of the stellar populations, something which to date has been possible only for our own Galaxy. Models for the interaction between systems now contain enough particles to prevent numerical artefacts caused by the discretisation of the mass distribution. In simulations of the large-scale structure of the early universe, the increased computational power will soon allow a meaningful comparison between the simulation and the observed distribution of luminous matter in galaxies and clusters.

How stars form is a largely unsolved problem. A global scenario exists that agrees with many recent observations. Nevertheless, important details remain obscure such as the loss of angular momentum of proto-stellar clouds, the changes of the molecular composition of the gas and the interaction between gas and dust particles. Similar problems are encountered in starburst galaxies where the star formation rate is exceptionally large and triggered by a rapid succession of supernovae.

The acceleration of cosmic rays can now be studied in detail in computer simulations that describe how particles propagate in the magnetic field in our own Galaxy or between galaxies. These models, often including Monte Carlo simulations, allow a comparison with the distribution observed at Earth.

Numerical simulations of radiative plasmas in pulsar magnetospheres, involving non-linear particle-wave processes, yield important information about the generation of the electromagnetic radiation emitted by these rapidly rotating neutron stars.

The physics required to tackle all these problems is complex. It usually involves the combination of different fields of expertise, and a variety of computational methods. To master these methods requires a long-term investment, especially in manpower. There are many collaborations that often transcend the boundaries of astrophysics, involving scientists from plasma physics, oceanography and applied mathematics. NOVA has established a structure with the required size, diversity, and stability to keep Dutch theoretical astrophysics at the forefront of international research. However, additional investments in manpower and equipment are needed in the coming decade in order to keep up with increased activity in this exciting field abroad.

3.4. Coordinated approach in human resources

Since many of the observing facilities are operated through international organizations, astronomers have access to state-of-the-art telescopes independent of the location of their research institute. Countries which are world-leading in astrophysical research are - in principle - able to offer their research institutes the latest-technology ICT infrastructure. Top-researchers have a lot of freedom to choose their home institute. Availability of a stimulating research environment, sufficient positions for junior permanent staff, postdocs and PhD students, and sufficient administrative support staff are among the most important criteria on which they choose to work in the Netherlands or elsewhere. In the coming decade attracting and keeping world-leading scientists will be crucial for the Netherlands to maintain its forefront position in astronomical research in a global context. Because of its position strong position, Dutch astronomy is at present able to attract sufficient numbers of the most promising young students. In order to offer them an perspective sufficient position for PhD students and postdocs are required. It is therefore recommended - as shown in Table 5 - to make major investments in human resources in order to secure that outstanding researchers will stay in the Netherlands.

Table 5: Required development of research staff

Number of research positions for astronomy in units of full time equivalents. The present NOVA program will strengthen the university research in an environment where the general trend is that the numbers of research positions in physical sciences are declining. It is recommended to at least double the number of research positions for astronomy within the open competition grants program of NWO-GBE.

Funding resource	Present	Aim
Universities		
Permanent staff	50	52
Postdocs, PhD's	56	70
NWO institutes		
Permanent staff	12	12
Postdocs, PhD's	17	20
NWO GBE		
Postdocs, PhD's	24	55
Other		
Permanent staff	1	1
Postdocs, PhD's	20	25
Total	**180**	**235**

4. Concluding remarks

Astronomy in the Netherlands has chosen to focus its efforts in the coming decade on three related research areas which together constitute the overall theme of the NOVA research strategy: The Life-Cycle of Stars and Galaxies. Maintaining world-ranking quality of research in this area requires continued access to state-of-the-art observing facilities on the ground and in space, pro-active participation in decision making processes in ESO and ESA, and long term strategies of the national institutes based on astronomical goals, a strong educational program, and the ability to attract and keep the most brilliant researchers by supporting them with sufficient human resources and access to state-of-the-art observing and computing facilities.

Much of this ambition can be realised within the present funding level for astronomy. About 40 M€ of new resources are required in the period 2001-2010 (of order 8% of the existing budget). The coordinated approach includes

- Continuation of the NOVA program in the period 2005--2010.

- Expansion of the number of temporary research positions supported by the NWO Council for Physical Sciences.

- Focus on technical R&D in four complementary areas, namely phased-array antennes for radio wavelengths and optical/IR instrumentation for the VLT/VLTI at ASTRON, and X-ray detectors and IR interferometry for the next generation ESA space observatories at SRON.

- New investments in a few well-chosen international projects, including ALMA, 2nd generation ESO VLT/VLTI instrumentation, mid-IR spectroscopy on NGST, LOFAR and SKA preparation, and real-time VLBI at JIVE.

Appendix: List of abbreviations

AAT	Anglo Australian Telescope
ALMA	Atacama Large Millimeter Array
ANTARES	Astronomy with a Neutrino Telescope and Abyss environmental RESearch
AO	Adaptive Optics
ASTRON	Stichting Astronomisch Onderzoek in Nederland (Netherlands Foundation for Research in Astronomy)
ATNF	Australia Telescope National Facility
BeppoSAX	Satellite per Astronomia in Raggi X
BIMA	Berkeley-Illinois-Maryland Association: array millimeter telescope
CCD	Charge-Coupled Device
CDN	Canada
CEA	Center for Atomic Research in France
CFHT	Canada France Hawaii Telescope (on Mauna Kea, Hawaii)
Chandra	X-ray Observatory (NASA)
CSO	Caltech Submillimeter Observatory (on Mauna Kea, Hawaii)
CTIO	Cerro Tololo Inter-American Observatory in Chile
GRID	Global Resource Information Database
DIMES	Delft Institute of Microelectronics and Submicron Technology
DOT	Dutch Open Telescope
ESA	European Space Agency
ESO	European Southern Observatory
EU	European Union
EUV	Extreme Ultra Violet
EVN	European VLBI Network
FIRST	Far InfraRed Submm Telescope (ESA Cornerstone 4) now called HSO
GAIA	ESA's Cornerstone 6 mission: Observatory for accurate positional and radial velocity measurements
GBE	GebiedsBestuur Exacte wetenschappen (NWO, Council for Physical Sciences)
GMRT	Giant Meter Radio Telescope (in India)
GTC	Gran Telescopio Canarias
GRO	Compton Gamma Ray Observatory
HALCA	Highly Advanced Laboratory for Communications and Astronomy
HIFI	Heterodyne Instrument for the Far-Infrared
HIPPARCOS	ESA's astrometric satellite
HSO	Herschel Space Observatory
HST	Hubble Space Telescope
ICES-KIS	Interdepartementale Commissie Economische Structuurversterking-Kennis InfraStructuur (OC&W)
ICT	Information and Communication Technology
IF	Intermediate Frequency
ING	Isaac Newton Group (of the Roque de los Muchachos Observatory on La Palma)
INT	Isaac Newton Telescope
Integral	International Gamma-RAy Laboratory
IRAM	Institut de Radio Astronomie Millimetrique
IRSI/Darwin	Infrared Space Interferometer
ISO	Infrared Space Observatory
JCMT	James Clerk Maxwell Telescope (on Mauna Kea, Hawaii)
JIVE	Joint Institute for VLBI in Europe
JKT	Jacobus Kapteyn Telescope
Keck	10 meter Optical and Infrared Telescope on Hawaii
KPNO	Kitt Peak National Observatory
LISA	Laser Interferometer Space Antenna
LOFAR	Low Frequency Array
MIDI	Mid-Infrared Interferometry Instrument for ESO's VLTI
MkIV	Mark IV
MPIA	Max Planck Institut für Astronomie (Heidelberg)
NASA	National Aeronautical and Space Administration
NCA	Nederlands Comité Astronomie (Netherlands Committee for Astronomy)
NEVEC	NOVA-ESO VLTI Expertise Center
NGST	Next Generation Space Telescope
NL	the Netherlands
NOVA	Nederlandse Onderzoekschool Voor de Astronomie (Netherlands Research School for Astronomy)
NRL	Naval Research laboratory
NWO	Nederlandse organisatie voor Wetenschappelijk Onderzoek
OASIS	Integral Field Spectrograph (for WHT)
OECD	OESO - Organisatie voor Economische Samenwerking en Ontwikkeling
OmegaCam	Wide-field camera for the VST
OWL	Over-Whelmingly Large optical telescope
PI	Principle Investigator
PPARC	Particle Physics and Astronomy Research Council (United Kingdom)
PUMA	PUlsar MAchine (for the WSRT)
R&D	Research and Development
RXTE	Rossi X-ray Timing Explorer
SAURON	Spectrographic Areal Unit for Research on Optical Nebulae
SCUBA	Submillimeter Common User Bolometer Array
SINFONI	Single Faint Object Near-infrared Investigation

SIRTF	Space Infrared Telescope Facility
SKA	Square Kilometer Array
SMA	Smithsonian Submillimeter Array
SMART	Small Missions for Advanced Research and Technology
SOFIA	NASA Airborn Observatory
SRON	Stichting Ruimte-Onderzoek Nederland (Space Research Organization in the Netherlands)
SRON-Astro	Astronomy activities at SRON
STW	Stichting Technische Wetenschappen
SWS	Short Wavelength Spectrometer on ISO
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderwijs
TUD	Technische Universiteit Delft
UK	United Kingdom
USA	United States of America
UV	Ultra Violet
VISIR	VLT Imager and Spectrometer for the mid-Infrared
VISTA	Visible and Infrared Survey Telescope
VLA	Very Large Array
VLBA	Very Large Baseline Array (US-VLBI network)
VLBI	Very Large Baseline Interferometry
VLT	Very Large Telescope (ESO)
VLTI	Very Large Telescope Interferometer (ESO)
VST	VLT Survey Telescope
WHT	William Herschel Telescope (part of ING)
WSRT	Westerbork Synthesis Radio Telescope
XEUS	X-ray Evolving Universe Spectroscopy Mission
XMM-Newton	X-ray Multi-mirror spectroscopy Mission