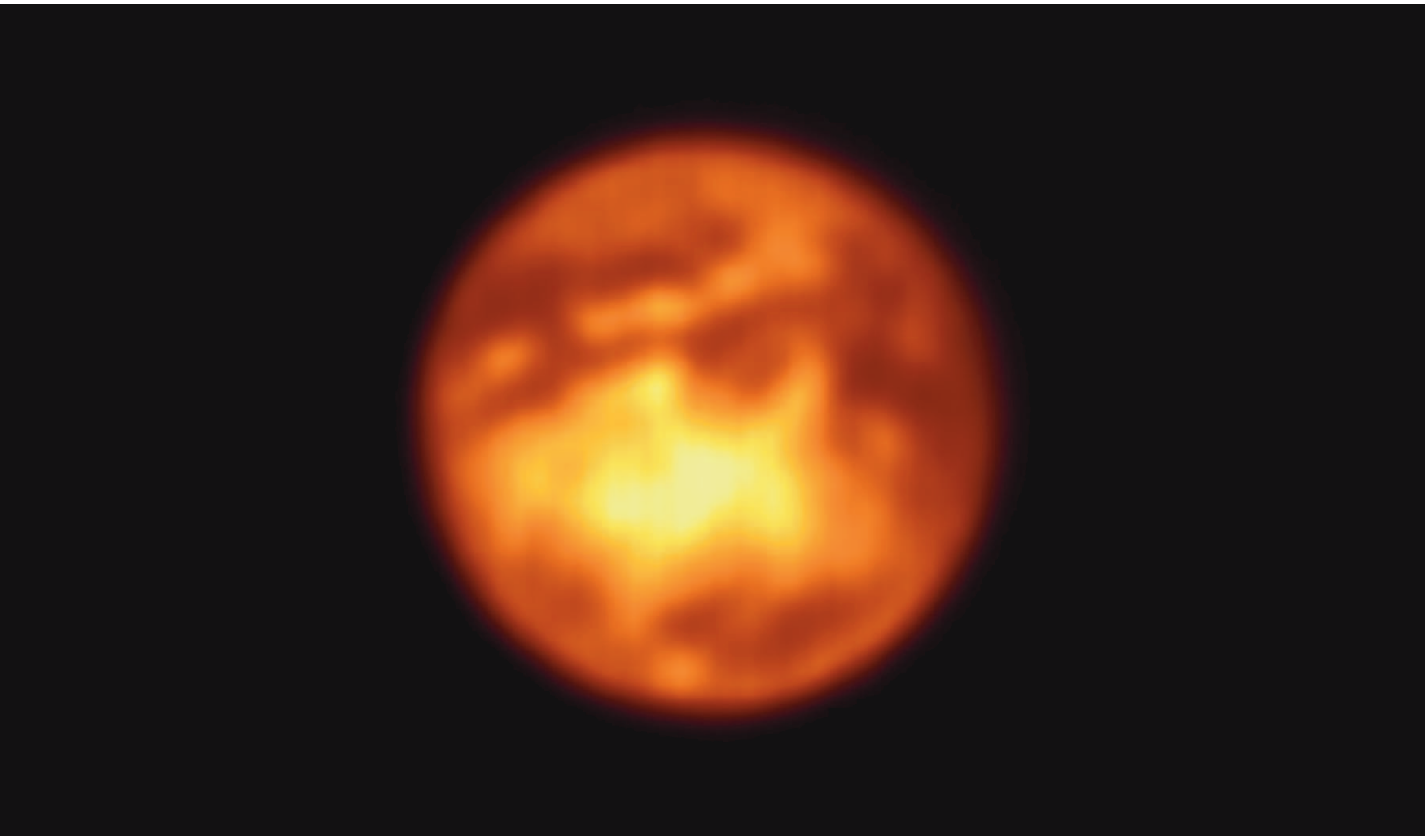
Max-Planck-Institute für Astronomie

Heidelberg-Königstuhl

Annual Report 2003



MAX-PLANCK-GESELLSCHAFT

Cover Picture:

Saturn's moon Titan seen in the near infrared. The picture was taken with ESO's Very Large Telescope and the high resolution camera CONICA which was equipped with the additional optics SDI (see page 91) in conjunction with the adaptive optics NAOS. The diameter of Titan is 0.8 arcsec, the resolution is about 0.02 arcsec which corresponds to about 200 km on the moons surface.

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Max Planck Institute for Astronomy

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Contents

Preface

This Annual Report 2003 will give an overview of the research done at the Heidelberg Max-Planck-Institut für Astronomie. It is intended for our colleagues all over the world as well as for the interested public. We are especially pleased that since this past year the work of our Institute is attended by a newly established board of trustees.

Particularly interesting scientific results are presented as highlights. They demonstrate the high discovery potential involved in the two research fields that are pursued at the Institute: star and planet formation as well as cosmology and galaxy evolution.

This is not least due to new instruments that were built at the Institute or to which major contributions could be made. Here, the adaptive optics system NACO and the interferometric instrument MIDI operated at the telescopes of the European Southern Observatory as well as the new wide field infrared camera OMEGA 2000 for the Calar Alto Observatory should be mentioned in particular. The construction of the Large Binocular Telescope on Mt. Graham in Arizona, in which the Institute is partaking, is making good progress; the same is true for the instrumentation that is developed by us for this telescope. Work on the PACS instrument for the HERSCHEL Space Telescope and on the instruments for the James Webb Space Telescope, the successor to HUBBLE, is equally well proceeding.

Apart from the shorter presentations of current scientific results we report in more detail on main research fields at the Institute. We will continue these extended reports over the next years so that after several Annual Reports an overall picture of the research profile of our Institute will arise.

In our Annual Reports, we also want to illuminate important events that took place at the Institute. At the same time we let visiting scientists and employees of our Max-Planck-Institut get a word in, in order to draw a vivid picture of the working atmosphere at the Institute. Statistical data will give an insight into the structure of the MPIA as well as into its publication activities.

We wish the readers of this Annual Report new insights into the astronomical research carried out at our Institute.

Thomas Henning, *Hans-Walter Rix*

Heidelberg, March 2004

I General

I.1 The Max Planck Institute for Astronomy

The Max Planck Institute for Astronomy (MPIA) (Fig. I.1) was established in 1967 and is dedicated to the exploration of space in the optical and infrared spectral region. Research at MPIA is focused on the formation and evolution of stars and galaxies. Apart from conceiving, conducting, analyzing, and interpreting observational programs, MPIA is dealing with the development of telescopes and observational instruments, mostly within large international collaborations.

With the establishment of the Institute planning and construction of the German-Spanish Astronomical Center (Deutsch-Spanisches Astronomisches Zentrum, DSAZ), generally known as the Calar Alto Observatory (Fig. I.2), was started on Calar Alto Mountain (altitude 2168 m) in the province of Almería in southern Spain. Three telescopes with 1.23, 2.2, and 3.5 m aperture are working there. Until the end of 2003, the observatory was operated as a branch of MPIA with a Spanish partnership. From January 1st, 2004 on, the observatory will be operated on equal terms with the Spanish Consejo Superior de Investigaciones Científicas. In the year under report, the 3.5-m-telescope has been equipped with high-performance instruments for large-scale sky surveys in the optical and infrared spectral region (Chapter IV.1 and IV.2). Furthermore, about 75 percent of the observing time of a 2.2-m-telescope working on La Silla, Chile, has been loaned by MPIA to the European Southern Observatory (ESO).

Fig. I.1: Max Planck Institute for Astronomy on the Königstuhl Mountain in Heidelberg.

Fig. I.2: Calar Alto Observatory.

The instruments developed and built at the Institute are used for ground-based as well as for satellite-borne observations. Today, both kinds of observations are ideally complementing each other. Ground-based telescopes mostly have larger primary mirrors and therefore a larger light-gathering power than space telescopes. By using modern techniques like adaptive optics and interferometry – in the development of which MPIA plays a leading role – , they also achieve higher angular resolution. Space telescopes are compulsory for observations in wavelength regions where the atmosphere absorbs the radiation or generates a perturbing background, as it is the case in wide regions of the infrared spectral regime.

Since the pioneer times of infrared astronomy in the 1970s MPIA was partaking successfully in the development of this branch of astronomy. It was participating significantly in the world's first Infrared Space Observatory (ISO) of the European Space Agency ESA: ISOPHOT, one of four scientific instruments on board of ISO, was built under the coordinating leadership of the Institute. From 1996 to 1998, ISO provided excellent data, particularly in the hitherto inaccessible far-infrared range. The valuable know-how gained this way will be exploited by the Institute's scientists in future projects like the HERSCHEL space telescope and the James Webb Space Telescope (JWST).

Today, the Institute is participating in a series of international collaborations for building new large telescopes and scientific instruments, thereby gaining access to the world's most important observatories. In the southern hemisphere, this is the ESO Very Large Telescope (VLT) in Chile, with its four 8-m-telescopes that can be coupled to form a powerful interferometer. In the northern hemisphere, MPIA is participating in the Large Binocular Telescope (LBT) in Arizona which will be put into full operation in 2005. By then, this extraordinary telescope will be equipped with two mirrors of 8.4 m diameter each, fixed on a common mount, making it the world's largest single telescope. These two collaborations enable MPIA's astronomers to observe the northern and the southern sky with first-class telescopes.

I.2 Scientific Goals

Two main research fields have crystallized at the Institute, on the one hand the formation of stars and planets, on the other hand observational cosmology, particularly the formation and evolution of galaxies. Although these two fields are clearly separated in terms of their research subjects, there are nevertheless common points of contact. Star formation in the early Universe, e.g., is closely related to the formation and evolution of galaxies. Observations with the best instruments available as well as computer simulations carried out by a theory group also working at the Institute are the foundations of scientific progress.

Formation of Stars and Planets

The first stages of star formation take place in the interiors of dense molecular clouds, the dust particles there blocking our view in visible light. Infrared radiation, however, can penetrate the dust, which is why the early stages of star formation are being studied preferentially in this wavelength range. Cold interstellar matter and new stars continuously forming in it also emit most of their radiation in this spectral region. For this reason, the focus of astronomical observations at MPIA has shifted in the recent past more and more from the optical to the infrared spectral range.

Using ISOPHOT as well as sub-millimeter telescopes very cold and dense regions have been detected within large dust clouds – protostellar cores which are on the verge of collapse or already contracting to form stars. In a later stage, the central (proto-) star is already taking shape. It is surrounded by a disk of gas and dust where planets can form that will orbit the newly formed star. But it is also possible that a binary or multiple stellar system will form. What are the conditions for either process to take place? This is one of the questions astronomers at MPIA want to answer, for example by using the NACO (NAOS and CONICA) high-resolution camera and the MIDI interferometer for the mid-infrared range, both at the VLT, as well as the HUBBLE Space Telescope and the SPITZER infrared observatory.

Recently, the investigation of brown dwarfs has also gained significance. These are "failed" stars with masses too low to provide enough pressure within their cores for hydrogen to fuse continuously into helium. They are distinguished from planets with even lower masses by the fact that initially deuterium burning takes place in their interiors. The first brown dwarf had been discovered as late as 1995; meanwhile a little over hundred are known.

Today, there are many questions: How do brown dwarfs form? Which properties do they have and how common are they? Are they too, like stars, initially surrounded by a disk of gas and dust? Scientists at MPIA recently made important contributions to answer these questions. A few years ago they found free floating planetary objects (that are not gravitationally bound to a central star) with a few Jupiter masses. This discovery shed new light on the formation of stars and planets and brought up the issue of re-defining stars, brown dwarfs and planets. In addition, significant information on the "binary nature" of brown dwarfs and the presence of disks around these objects was obtained at the Institute.

Studying massive stars is also of growing interest (Chapter III.1). Here, for one thing, questions about their formation are still open: How do their early stages differ from those of low-mass stars? Are they, too, surrounded by disks where planets can form? Massive young stars are very hot, emit energetic radiation and drive strong particle winds that affect the formation of other stars in their neighborhood. How this happens is another important issue.

These problems can best be studied in nearby star formation regions in our own Milky Way. The observation of star formation regions in other galaxies allows to tackle other problems. As external galaxies can be viewed as a whole, integrated properties of the stellar systems can be derived, e.g. the annual star formation rate as a function of the galaxy properties. So it is possible to determine the rates in different galaxy types or as a function of the surroundings of the respective galaxies. Another question of current interest is how UV emission and particle winds affect the interstellar medium and thereby the morphology of entire galaxies.

Complementing the observations, a small group residing in Jena is working – in close collaboration with colleagues at the Universität Jena – on "laboratory astrophysics", forming a branch of MPIA. It investigates spectroscopic properties of dust particles in the nano- and micrometer size range and molecules in the gaseous phase (Chapter III.2). Findings obtained here under controlled conditions can be used to interpret astronomical observations.

Galaxies and Cosmology

Here, the fundamental questions are: How did the first galaxies form? What was their star formation rate in the early universe? Did galaxies merge, thereby reducing their total number over the billions of years? What effect does dark matter have on these processes? In the recent past, interest has also focused more and more on the role of massive black holes residing at the centers of active galaxies (Chapter II.3). To get a clear picture of what is going on there, astronomers at the Institute have access to the data of the Sloan Digital Sky Survey (SDSS) (Chapter III.4). Today, detailed studies are mainly using the NACO and MIDI instruments at the ESO VLT which allow to investigate the immediate vicinity of the black holes.

The study of the formation of galaxies and their evolution in the early universe makes extreme demands on current observational techniques. Great progress was recently made thanks to deep sky surveys such as the GEMS project (Galaxy Evolution from Morphology and Spectral Energy Distributions, Chapter II.5) carried out under the leadership of MPIA: It resulted in the largest color image taken with the HUBBLE Space Telescope to date; it is used to determine the morphological properties of about ten thousand galaxies whose redshifts are known from the COMBO-17 survey that was conducted at MPIA. First results from the analysis of this unique data set have already been obtained (Chapter II.6): They concern the star formation history of the most massive galaxies and their evolution over the past six billion years.

Fig. I.3: The Very Large Telescope, located in the Chilean Andes. (ESO)

Ground-based Astronomy – Instrumentation

During the last years, MPIA has made great efforts in developing adaptive optics systems. Construction of the ALFA adaptive optics system at the 3.5-m-telescope on Calar Alto has been completed. Currently, this field of research is carried on by developing a multiconjugate adaptive optics system. Experience gained in this work will be incorporated into the development of new instruments for the VLT and LBT. In the adaptive-optics laboratory at MPIA, an experimental set-up of the novel PYRAMIR wavefront sensor has been advanced (see also Chapter IV.3).

Participation of the Institute in the ESO Very Large Telescope on Paranal Mountain (Fig. I.3) is of major importance. In 2001, the CONICA high resolution infrared camera – forming the NACO system together with the NAOS adaptive optics system – was successfully put into operation. At the end of 2002, MIDI saw first light (Chapter II.4). It is the first interferometric instrument at the VLT and is used in the mid-infrared range. In 2003, this instrument allowed for the first time interferometric observations in the mid infrared with a resolution of only a few hundredths of an arc second.

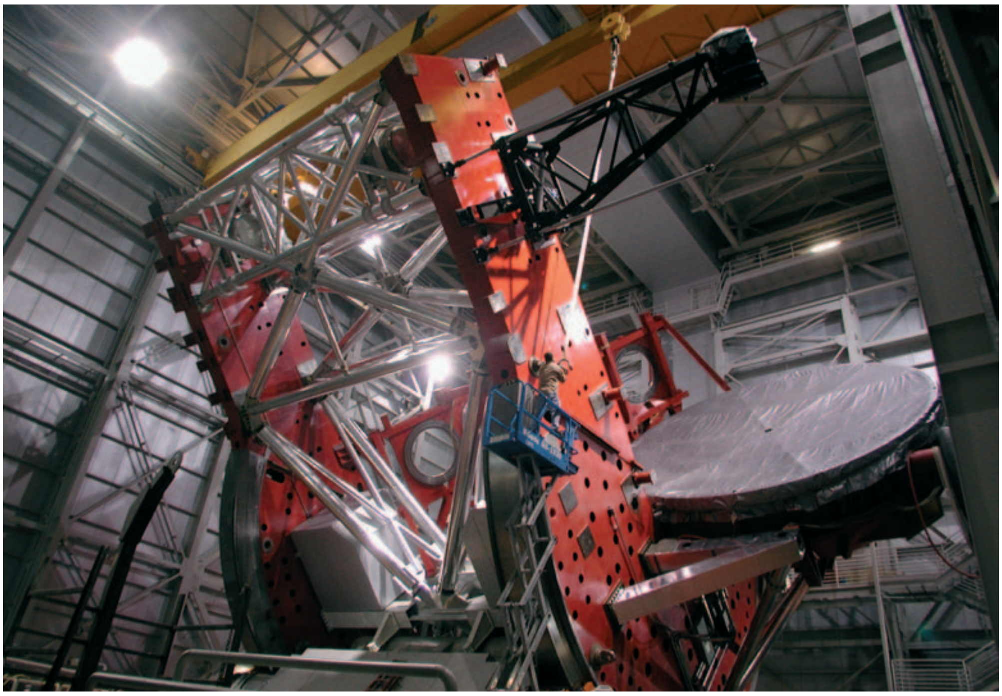
Construction of a common Laser Guide Star Facility (LGSF) that will be used at the NACO and SINFONI instruments at the VLT, which are both equipped with their own adaptive optics system, is entering the crucial phase. The heart of LGSF is PARSEC, a high-performance laser that illuminates the high-altitude sodium layer of the terrestrial mesosphere at 589 nm wavelength, thus providing the adaptive optics systems with a sufficiently bright artificial guide star. Since June 2003, the LIDAR diagnostic instrument built at MPIA is being tested in Garching. Final tests prior to the transfer to Paranal took place in April 2004. The total LGSF consisting of PARSEC, a special fiber optics, and the projection telescope will also be tested in Garching in July 2004. First integration with SINFONI on Paranal is planned for late 2004.

At MPIA, the development of second-generation VLT instruments is already in the works. Under the leadership of MPIA, a consortium of twelve institutes in Germany, Italy, Switzerland, The Netherlands and Portugal is advancing the development of the PLANET FINDER instrument. PLANET FINDER is supposed to be an adaptive optics system for direct detection and spectroscopy of extrasolar PLANETS. The CHEOPS project (Chapter IV.6) is also part of this complex.

Together with the University of Arizona as well as Italian and other German institutes, MPIA is a partner in an international consortium which is building the Large Binocular Telescope (LBT, Fig. I.4). This large telescope consists of two mirrors of 8.4 m diameter each, fixed on a common mount. Together, the two mirrors have a light-gathering power equivalent to a single 11.8 m mirror. This will make the LBT the world's most powerful single telescope. Furthermore, the unique structure of the double mirror will allow interferometric observations. In this mode, its spatial resolution will correspond to that of a single mirror 22.8 m in diameter. First light with only one primary mirror is planned for autumn 2004. One year later, the complete telescope will be put into operation.

Under the leadership of the Landessternwarte Heidelberg, the German partners are building the LUCIFER

Fig. I.4: The Large Binocular Telescope.



near-infrared spectrograph for the LBT (Chapter IV.4). MPIA will supply the total detector package and develop the overall design of the cryogenic system. Integration and tests of the instrument will also be carried out in the laboratories of MPIA. Simultaneously, planning of the LBT interferometer LINC-NIRVANA, which will be equipped with an adaptive optics system, is in full swing. For this instrument, MPIA is developing the optics of the beam combiner (Chapter IV.5), which finally will allow interferometry over a wavelength range between 0.6 and 2.2 μm. For this project, a consortium with colleagues from the Max-Planck-Institut für Radioastronomie in Bonn, the Universität Köln and the Astrophysical Institute in Arcetri near Florence was formed.

Extraterrestrial Infrared Research – Instrumentation

Today, MPIA is still participating significantly in the ISO project of the European Space Agency ESA: ISOPHOT, one of four scientific instruments on board of ISO, was built under the coordinating leadership of the Institute. Meanwhile, numerous papers based on ISO measurements have been published in all fields of astronomy, documenting the efficiency of this space telescope. MPIA runs the ISOPHOT data center where first of all software and calibration procedures for the automated data analysis were developed. The ISO database is planned to be part of a globally accessible »virtual observatory« for all wavelength ranges.

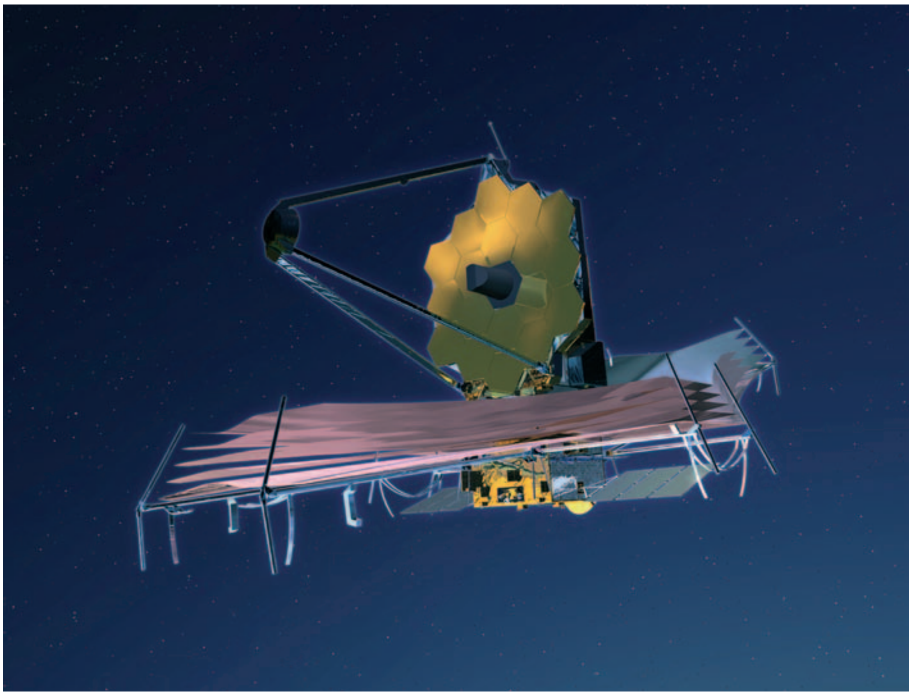
The experience gained with ISOPHOT was decisive for the MPIA's participation in the construction of the PACS infrared camera and spectrometer (Chapter IV.8). This instrument will operate on board the European infrared observatory. The launch of this 3.5 m space telescope is scheduled for 2007.

The Institute is also participating in the successor to the HUBBLE space telescope, the James Webb Space Telescope (JWST) (Fig. I.5). The JWST will be equipped with a folding primary mirror about 6 m across as well as three focal-plane instruments. As part of a European consortium, MPIA develops the cryo-mechanics for the positioning of the optical components in one of the three focal-plane instruments called MIRI (Chapter IV.9). This instrument designed for the mid-infrared range from 5 – 28 μm consists of a high-resolution camera and a spectrometer of medium resolving power. MIRI will be built half by American and half by European institutes.

At the same time, MPIA is partaking in the development of the second focal-plane instrument of the JWST, a near-infrared multi-object spectrograph called NIRSPEC (Chapter IV.9). Here too, the Institute is expected to deliver the cryo-mechanics. Such a contribution will provide the astronomers at MPIA with further excellent opportunities for high-resolution infrared observations. Thanks to the successful development of ISOPHOT and PACS, the Institute is well prepared for both tasks, MIRI and NIRSPEC .

Since 1998, MPIA represents Germany within the DARWIN Science Advisory Group. DARWIN (Fig. I.6) is a space interferometer to be launched by the European Space Agency ESA after 2015. According to current plans it will comprise up to eight telescopes orbiting the sun at the Lagrangian point L2 in 1.5 million kilometers

Fig. I.5: Possible structure of the JWST, with the large primary mirror and the characteristic solar screen.



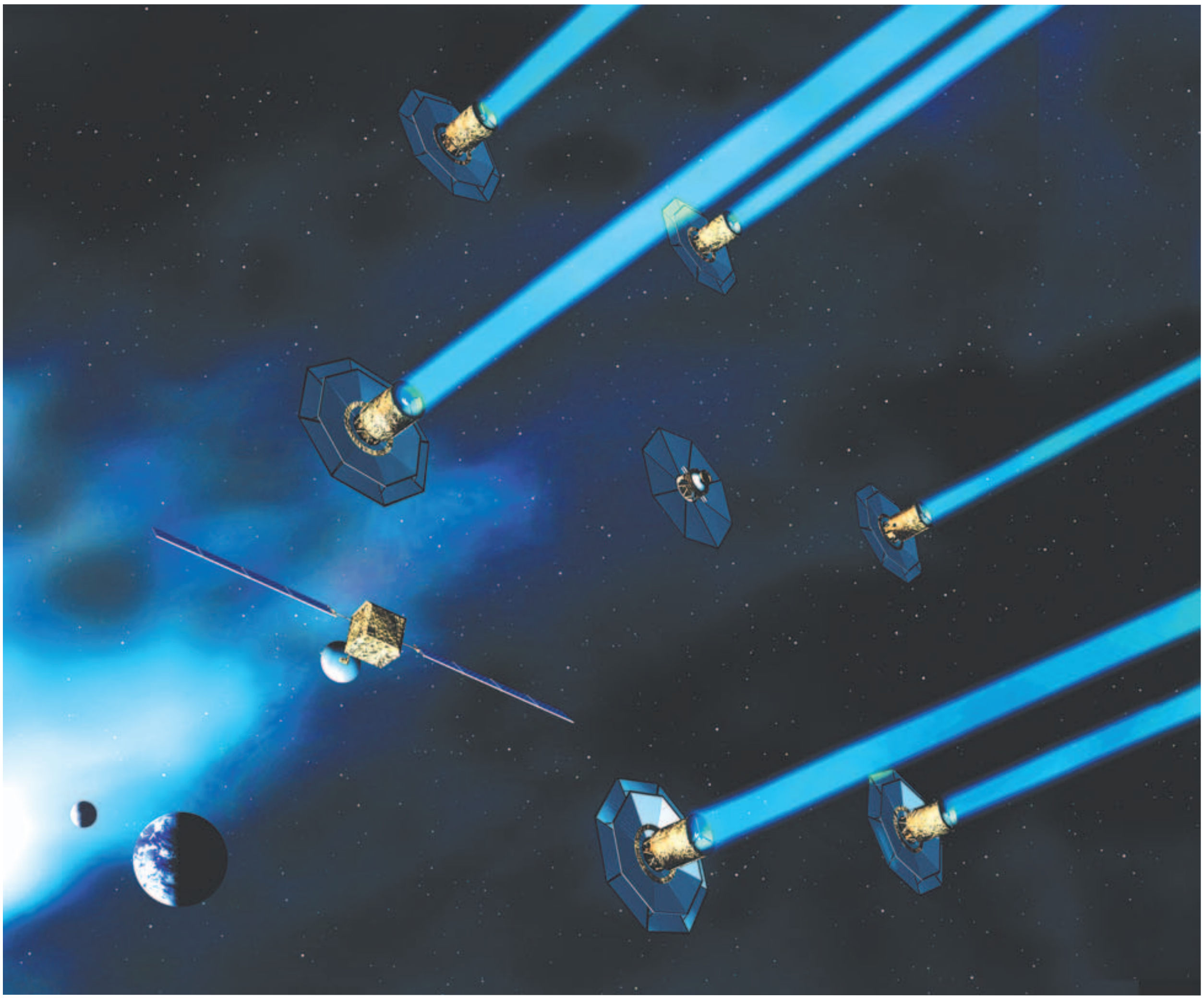


Fig. I.6: Possible concept of the DARWIN space interferometer consisting of eight free-flying individual telescopes.

distance from Earth. This observatory will be used for imaging and spectroscopy of extrasolar Planets in the mid-infrared range. At present, the Institute is participating in preparatory technology studies.

MPIA is also contributing to ESA's GAIA project, a space observatory scheduled for launch between 2010 and 2012. GAIA will be the successor to the HIPPARCOS astrometry satellite, exceeding the latter's sensitivity by several orders of magnitude. GAIA is supposed to measure positions, magnitudes and radial velocities of one billion stars plus numerous galaxies, quasars and asteroids. The telescope will provide photometric data in 15 spectral bands as well as spectra in a selected spectral range. Unlike HIPPARCOS, however, GAIA will not be provided with an input catalogue. An automatic object classification will thus be of major importance for data analysis. This problem is currently dealt with at the Institute. Figure I.7 gives an overview of the major instruments which are already working or are about to be put into operation. Spatial resolution is shown as a function of the size of the field of view.

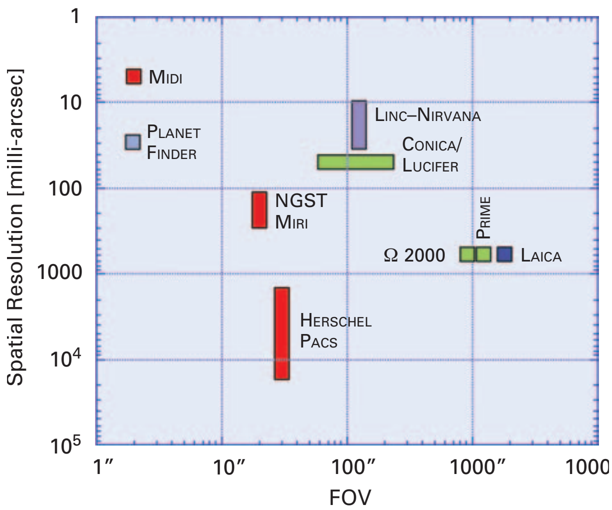


Fig. I.7: The Institute's major instruments. Spatial resolution as a function of the field of view.

I.3 National and International Cooperation

Thanks to its location in Heidelberg, the Institute is able to work within an especially active astronomical environment. Cooperation with the Landessternwarte, the Astronomisches Rechen-Institut, the Institut für Theoretische Astrophysik der Universität or the department Kosmophysik of the MPI für Kernphysik occurs over and over again in manifold ways. Presently, this is especially true for the long-standing DFG-Sonderforschungsbereich No. 439, "Galaxies in the young Universe", in which all Heidelberg institutes named above are participating.

Collaboration with the MPI für extraterrestrische Physik in Garching and the MPI für Radioastronomie in Bonn as well as with institutes at German universities is also quite common. An overview is given in Fig. I.8.

The establishment of the German Center for Interferometry (Frontiers of Interferometry in Germany, or FRINGE for short), located at MPIA, also emphasizes the Institute's leading role in Germany in this trend-setting astronomical technique. The goal is to coordinate efforts made by German institutes in this field. FRINGE will gather tools and software developed by participating institutes. Another specific goal is the preparation of the next generation of interferometric instruments. This includes the expansion of MIDI (Chapter II.4) up to 20 μm wavelength and the design of APRÈS-MIDI – an extension of MIDI to an imaging interferometer consisting of four telescopes. Further tasks are: participation in the definition of new imaging capabilities of the VLT interferometer, and participation in preparing the DARWIN space mission. FRINGE, together with other interferometric centers in Europe, was partaking in the establishment of the European Interferometry Initiative. The long-term perspective is to establish a European interferometric center for the optical and infrared wavelength region. Apart from MPIA, the following institutes are participating in FRINGE: the Astrophysikalisches Institut Potsdam, the Astrophysikalisches Institut der Universität Jena, the Kiepenheuer-Insitut für Sonnenphysik in Freiburg, the MPI für extraterrestrische Physik in Garching, the MPI für Radioastronomie in Bonn, the Universität Hamburg, and the I. Physikalische Institut der Universität zu Köln.

MPIA is participating in a number of EU-networks and worldwide collaborations, partly in a leading position. This includes:

OPTICON: A network of all operators of major telescopes in Europe financed by the European Union. The goal is to optimize use of the scientific-technical infrastructure in order to increase scientific results and reduce costs.

Fig. I.8: Distribution of German partner institutes of MPIA.

Within OPTICON, the Calar Alto Observatory with its 2.2-m- and 3.5-m-telescopes is participating in the COMET program that includes a total of 20 European telescopes. Observing teams from every country of the EU and associated countries that have been allocated observing time at the telescopes by the DSAZ Program Committee get free access as well as scientific and technical support in the realization of their observations. For this service, DSAZ is getting financial compensation from OPTICON.

The APRÈS-MIDI study at MPIA mentioned above is also supported by OPTICON and the European Interferometry Initiative (EII). The same is true for software work on image reconstruction for LINC-NIRVANA (Chapter IV.5).

OPTICON is also supporting a so-called Joint Research Activity (JRA) of MPIA with the Osservatorio Astrofisico di Arceti and the University of Durham. Within JRA a prototype of a multiple-field-of-view wavefront sensor is being built – a special type of multiconjugate adaptive optics system. This project is dealing with problems arising with adaptive-optics image field correction for the extremely large next-generation telescopes (Chapter IV.5).

Fig. I.9: Distribution of the international partner institutes of MPIA.

Together with the universities of Braunschweig, Chemnitz, Dresden, Jena, and Leiden, MPIA is participating in the DFG Research Group "Laboratory Astrophysics". This is a new field of research at MPIA that will be pursued at the newly established branch in Jena (Chapter III.2).

PLANETS: A "research training network" of the EU to study theoretical and empirical aspects of the formation and evolution of protoplanetary disks and planets.

SPITZER Legacy Program: The NASA infrared telescope SPITZER (formerly SIRTF) has started its two and a half year mission on August 25th, 2003. Within a so-called legacy program, collaborations have the opportunity to carry out large-scale observing programs. MPIA is participating in an already approved program to study the earliest stages of star formation.

SISCO (Spectroscopic and Imaging Surveys for Cosmology): This EU network is dedicated to the study of galaxy evolution with the help of sky surveys. Here too, the Institute has made significant contributions with CADIS, COMBO-17, and GEMS (Chapter II.5). Further partners are: University of Durham, Institute for Astronomy in Edinburgh, University of Oxford, University of Groningen, Osservatorio Astronomico Capodimonte in Naples, and ESO in Garching.

GIF (German-Israeli Foundation): Within this collaboration, a program to study gravitational lenses is carried out. Partner of MPIA is the University of Tel Aviv.

The Sloan Digital Sky Survey (SDSS): At the international level, participation in this project is of major importance (see also Chapter III.4). This is the most extensive sky survey to date, imaging about a quarter of the entire sky in five filters. The final catalogue will provide positions, magnitudes, and colors of an estimated one hundred million celestial objects as well as redshifts of about one million galaxies and quasars. The observations are made with a 2.5-m-telescope specially built for this purpose at Apache Point Observatory, New Mexico. The project is conducted by an international consortium of US-American, Japanese, and German institutes. In Germany, MPIA in Heidelberg and the MPI für Astrophysik in Garching are involved. In exchange for material and financial contributions to the SDSS from MPIA, a team of scientists at the Institute gets full access to the data.

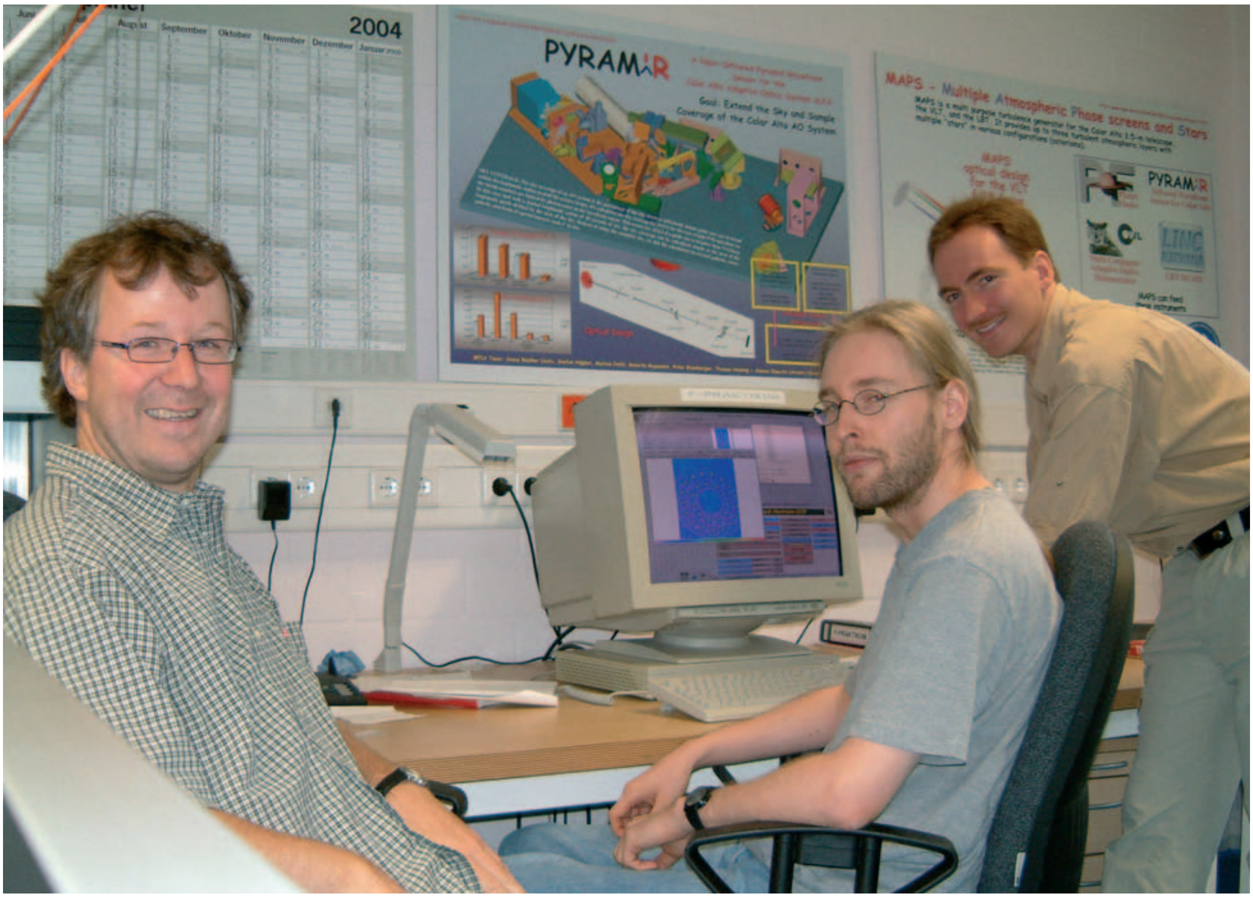


Fig. I.10: Practical course in Physics at MPIA. Left and right: Stefan Hippler and Sebastian Egner (the tutors), in between Felix Hormuth (the student).

I.4 Teaching and Public Outreach

Students from all over the world are coming to the Institute to do their diploma or doctoral thesis. A majority of the scientific recruits complete their studies at the University of Heidelberg. For that reason, a number of scientists at MPIA give lectures there. Within the advanced practical course to all students of the Department of Physics and Astronomy at Heidelberg, MPIA offers an adaptive optics experiment: During four afternoons, the students can set up an analyzer to examine the distortion of light waves and determine optical aberrations such as astigmatism and coma. The experiment is carried out in the laboratory for adaptive optics at MPIA. A second experiment deals with function and operation of CCD cameras.

The Institute's tasks also include informing the general public about results of astronomical research. So members of the Institute give talks at schools, adult education centers and planetaria. They also appear at press conferences or on radio and television programs, in particular on the occasion of astronomical events which attract major public attention. Numerous groups of visitors come to the MPIA on the Königstuhl and the Calar Alto Observatory. A one-week teacher training course which is very popular among teachers of physics and mathematics in Baden-Württemberg is held regularly in autumn at MPIA.

Finally, the monthly astronomical journal Sterne und Weltraum (Stars and Space), co-founded 1962 by Hans Elsässer, founding director of MPIA, is published at MPIA. This journal is intended for the general public but also offers a lively forum both for professional astronomers and for the large community of amateurs in this field.

II Highlights

II.1 Star Formation within the Starburst Clusters Arches and NGC 3603

Numerous star formation regions are known in our Galaxy that differ significantly in age and size. The Arches star cluster near the Galactic Center, discovered only in 1995, holds a special position. Together with two other known clusters, it is classed among the extremely massive starburst clusters. In these clusters, several thousand stars are forming within a small volume within a short period of time. The Arches cluster is excellently suited for studying the formation rate of very massive stars. The CONICA high resolution infrared camera (a component of the NACO system), which was partly developed at the Institute and is now operated at the ESO Very Large Telescope, allowed for the first time to spatially resolve the central part of the cluster containing about 150 hot O stars. Here, NACO yields better data than the HUBBLE Space Telescope. Comparison with the young cluster NGC 3603 located in the Carina spiral arm gave new insight into star formation in massive clusters.

Star forming regions vary considerably in their appearances. There are extended associations with low stellar densities like the Taurus-Auriga complex or compact clusters with numerous stars like in Orion where more than 2000 stars have formed within a small volume. Extremely massive star forming regions are mainly found in interacting galaxies such as the Antennae. There, young star clusters have masses up to one million solar masses.

Basic Problem: the Initial Mass Distribution

Many questions concerning these star forming regions are still open. One of the fundamental quantities characterizing a star forming region is the so-called initial mass function, IMF. It gives the fraction of stars within a given mass interval at the time of formation of a cluster. Is this IMF the same all over the universe, or does it depend on physical quantities such as the chemical composition of the interstellar matter or the young cluster's mass? According to studies going back to the work of E. Salpeter in the 1950s, the IMF can be described universally by a power law with a slope of about -1.3. That means, the number of stars of mass M decreases proportional to $M^{-1.3}$.

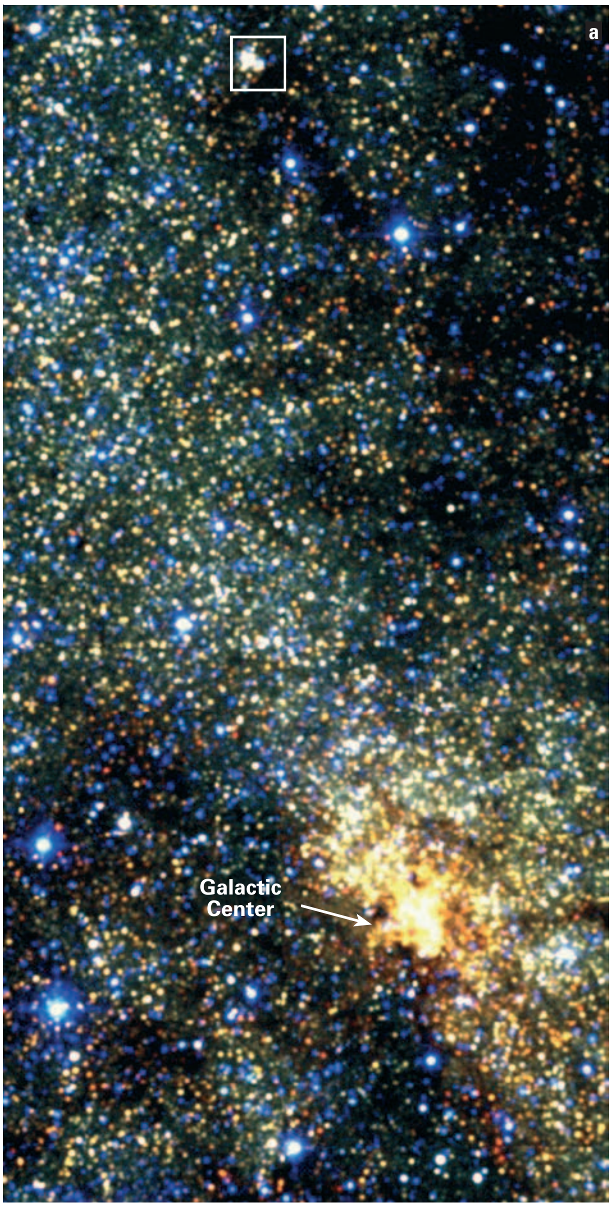
At the same time it is known that the more massive the parent interstellar cloud of the cluster, the more massive stars are forming. Moreover, the most massive stars are thought to form only within the densest regions of the cloud. Such an excess of massive stars can manifest itself in a particularly flat mass function (with a small slope).

Besides these differences in the initial conditions a stellar cluster experiences an early dynamical evolution. Massive stars are suspected to always be located at the center of a cluster – for one thing because the initial density of the cloud is highest there, and for another thing because the massive stars are "sinking" towards the center due to gravity. This would result in a large stellar cluster having a central region with an exceedingly high number of massive stars, surrounded by a more or less developed halo of low-mass stars. These low-mass stars would be removed more easily than massive stars from the cluster by external gravitational influences such as the galactic gravity field.

These processes make it difficult to determine the IMF for a stellar cluster. In addition, there are observational problems: basically, both "ends" of the IMF are often poorly defined. At the lower end, complete detection of the faint objects is rather difficult. At the upper end, a complete census is often prevented by the short lifetime of massive stars: The most massive stars already explode as supernovae after several million years.

Therefore the IMF is best determined for stellar clusters that are very young and as close to us as possible. But with these, another observational problem arises: Their members usually are still hidden within their parental dark cloud. Thus, these clusters generally can be observed only in the infrared spectral region, where the light is less obscured by dust than in the optical.

The IMF is a central quantity of the phenomenon of star formation. It is also used as a tool for obtaining the star formation rate in the early universe. In very distant galaxies, star forming regions are no longer spatially resolved. Instead, the star formation rate is estimated from the spectrum or from the intensities within single wavelength bands, averaged for the entire galaxy. For this purpose, the IMF obtained for the Milky Way or for nearby galaxies is used.



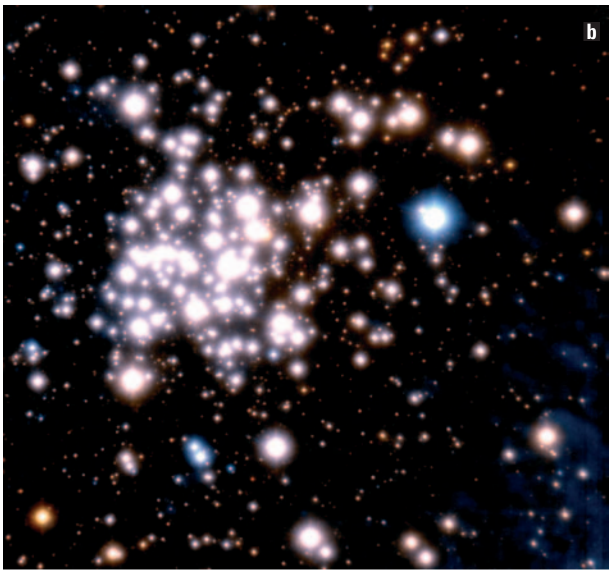


Fig. II.1: a) Near-infrared image of the region around the Galactic Center (image size about 20 arcminutes × 7 arcminutes) with the Arches cluster (image: 2MASS);
b) Arches, obtained with NACO at the VLT. This picture is composed from images at 1.65 µm and 2.2 µm wavelength.

The Arches Cluster at the Galactic Center

Only three clusters are known in the Milky Way, which are classed as starburst clusters based on their stellar densities: the Arches (Fig. II.1) and the Quintuplett clusters, both close to the Galactic Center, and NGC 3603 within the Carina spiral arm (Fig. II.2).

The Arches cluster is spectacular in several respects. It is only about 25 parsecs (about 80 light years) away from the Galactic Center and thus subject to very strong tidal forces. Moreover, this region of the Galaxy appears to be very turbulent. In the radio spectral range, a large gaseous arc has been detected in the vicinity of the cluster, after which the cluster has been named. As the Arches cluster is only two to three million years old, its central part is still populated by about 150 massive O stars and 12 Wolf-Rayet stars (massive stars suffering substantial mass loss). The stellar density is estimated to be 10 000 solar masses per cubic light year in the central region, and with a total mass of more than 10 000 solar masses, Arches is located at the lower end of the globular cluster mass scale.

Its vicinity to the Galactic Center has fatal consequences for the Arches cluster. According to computer simulations it is going to be dynamically disrupted within about 20 million years. The Quintuplet cluster, being almost twice as old with an age of about four millions years, is already showing clear signs of such a dissolution. These starburst clusters are presently the only known places in the Milky Way where a stellar population of common origin can be studied throughout the entire mass range, from the hottest and most massive stars down to brown dwarfs.

However, Arches is a very challenging object to observe. It cannot be seen at optical wavelengths as dense clouds of dust are diminishing the visual light by 24 to 34 mag, corresponding to a reduction of the intensity by 10 to 14 orders of magnitude. This cluster can be studied in detail only in the infrared range. But as its center is extremely crowded, a very high spatial resolution is needed. Thus, Arches is an ideally suited object for the NACO adaptive optics system at the VLT.

NACO is a combination of the CONICA near-infrared camera, which can also perform spectroscopy and polarimetry, and the NAOS adaptive optics system. CONICA was built under the leadership of MPIA together with MPE in Garching) at the Institute's laboratory in Heidelberg, while NACO was contributed by colleagues in France. NACO was commissioned on the NEPUN telescope at the end of 2001. Since then it is yielding images

Fig. II.2: a) The starburst cluster NGC 3603 with the central cluster HD 97950, taken with ISAAC at the ESO VLT at 1.24 μm, 1.65 μm, and 2.17 μm wavelength. The 3.4 arcminutes side length of the image corresponds to about 7 parsecs (20 light years);
b) HD 97950, the densest region in NGC 3603.

that are only limited by the diffraction of the 8-m-aperture of the telescope (see Annual Report 2001, p. 13).

Astronomers at MPIA observed Arches in spring 2002 using CONICA at 1.65 μm (H band) and 2.2 μm (K band); the complicated data were reduced in 2003.

There were not always optimum seeing conditions during the exposures, so NACO did not reach its maximum performance. Nonetheless, a striking result was obtained. Within both filters the spatial resolution was 0.085 arcseconds. Exposure times of 14 minutes in the H band and 7 minutes in the K band yielded detection limits of 22 and 21 mag, respectively.

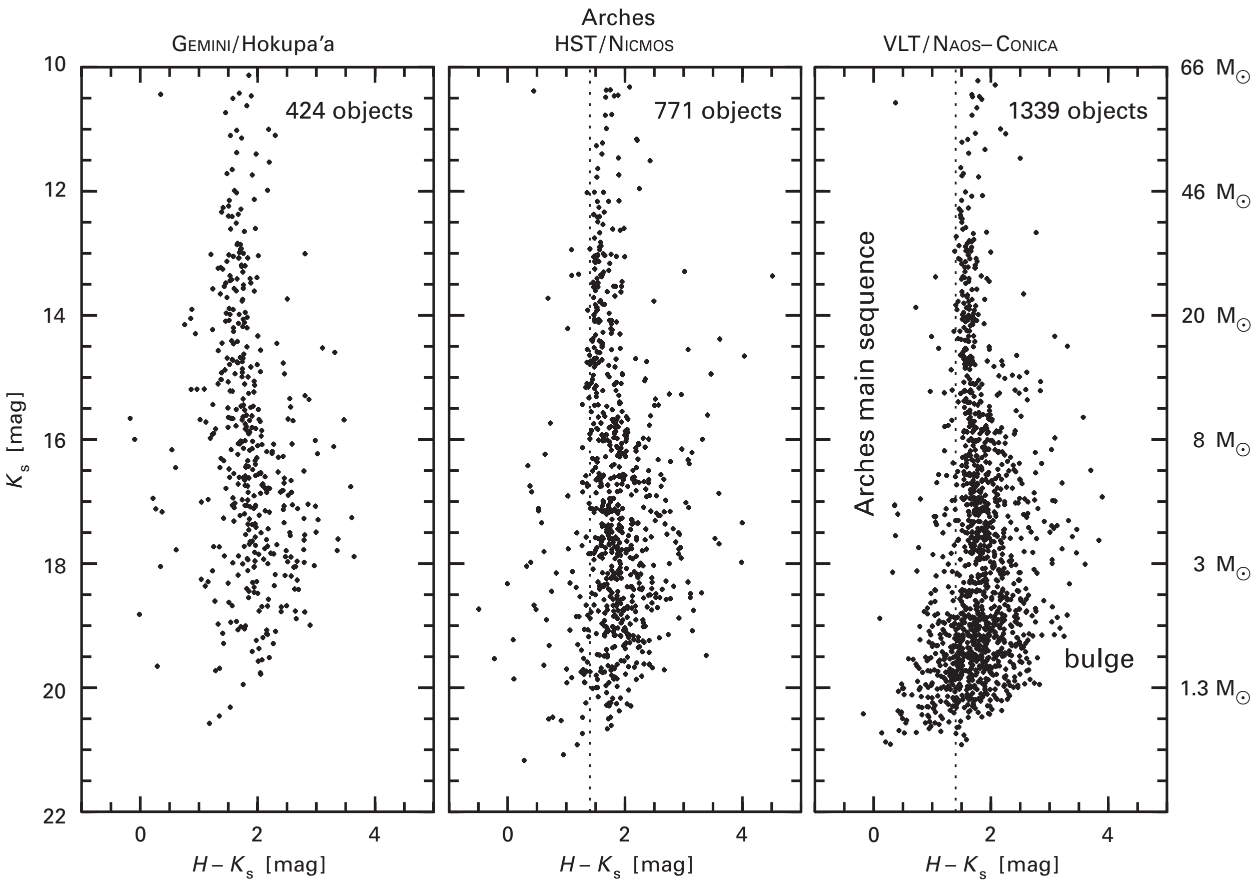
Thus NACO excelled the HUBBLE space telescope, which had observed Arches in the same wavelength range using its NICMOS infrared camera. Thanks to its higher spatial resolution, NACO at the VLT was able to detect stars fainter by one magnitude (factor of 2.5 in intensity), than could be observed with NICMOS. In addition, for the first time the cluster center could be resolved into individual stars. NACO was able to identify 50 percent more stars lying closely together than NICMOS was. A comparison of the color-magnitude diagrams (Fig. II.3) also illustrates the progress achieved with NACO: The main sequence is much better defined than that derived from NICMOS data. Also shown are observational data obtained with the HOKUPA'A adaptive optics camera at the GEMINI telescope on Hawaii. The lower resolution of early adaptive optics systems such as HOKUPA'A leads to a poorly defined main sequence, the errors of which also enter into the mass function derived.

Theoretical evolution models for a cluster with an age of two million years were used to transform observed colors and magnitudes into stellar masses. The cluster distance was assumed to be the same as the distance of the Galactic Center, which is 8 000 pc (26 000 light years). Furthermore, the extinction had to be derived from the colors. In the central part of the Arches cluster, within a spherical volume with a radius of about 0.2 parsecs (0.65 light years), the extinction turned out to be relatively low. Further out to a radius of 0.8 parsecs (2.6 light years) the extinction increases by ten magnitudes. Obviously, the stellar activity of the hot stars already affects their surroundings, their intense winds having swept free a central bubble.

From these data the IMF for the innermost 0.8 parsecs of the Arches cluster could be derived down to two solar masses. With these lower mass stars, however, there is a problem: for one thing they are rather faint, and for another thing they are mainly located in the outer regions, thus increasing the probability of being confused with field stars. Therefore, the astronomers at MPIA confined themselves to determine the IMF for stars ranging from 4 to 65 solar masses.

The 10 to 65 solar mass range could be easily described by a power law with a slope of -0.9, a value slightly smaller than the average for the Galaxy. Within the innermost radius of 5 arcseconds, the slope is even flatter (-0.6), indicating an excess of massive stars (Fig. II.4). Below 10 solar masses, the mass function is showing a rather peculiar behavior, as its slope decreases to almost zero. This means that there is a substantial deficiency of stars in the mass interval of a few solar masses compared to normal regions of the Milky Way, where the mass function is steeply increasing towards lower masses.

Fig. II.3: Arches color-magnitude diagrams: A comparison between the GEMINI/HOKUPA'A adaptive optics camera (left), the HST/NICMOS (middle), and the VLT/NACO (right).



Such a lack of low-mass stars in favor of massive ones had already been suspected in extragalactic regions with intense star formation but had not been observed directly so far.

This result can be interpreted in two ways. Either, the Arches cluster has produced a higher percentage of massive stars than other galactic star clusters, corroborating the theory that very massive stars are forming preferentially in large clusters. Or the massive stars already have wandered towards the center, where they were observed.

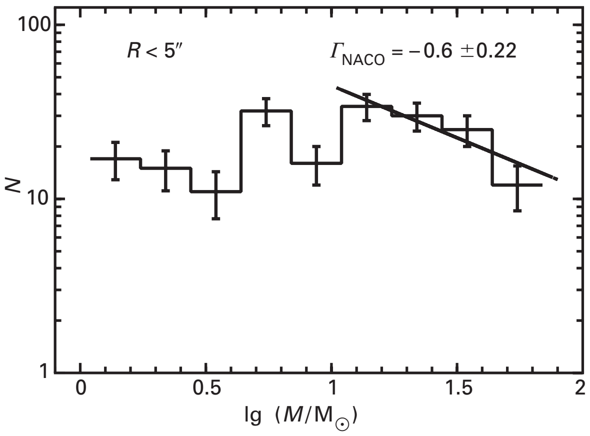


Fig. II.4: Mass function of the central region of the Arches cluster, derived from NACO data.

NGC 3603 in the Carina Spiral Arm

In order to study a possible influence of the nearby Galactic Center on the star formation in Arches, astronomers at MPIA observed NGC 3603, the only known starburst cluster outside the central part of our Galaxy. This star forming region at a distance of 6000 parsecs (19 000 light years) is located in a relatively quiet environment, the Carina spiral arm. The Carina arm merges into the Sagittarius arm, so with a combined length of 40 000 parsecs (125 000 light years) both are forming the longest known spiral arm of our Galaxy, winding two thirds of a complete circle around the Galactic Center.

Other than Arches, NGC 3603 is hardly obscured by dust, with a visual extinction between 4 mag and 5 mag. Therefore the stars are easily observed in visual light, so the cluster was already discovered in 1834 by John Herschel. With a total stellar luminosity of about ten million solar luminosities it excels the Orion cluster by a factor of 100.

The center of NGC 3603 harbors the massive cluster HD 97 950 that contains three known Wolf-Rayet stars and about 36 O-stars. The Wolf-Rayet stars have cleared the dust within 0.6 parsecs (2 light years), so the cluster can be observed easily. Its central density is estimated, as in the Arches cluster, to be 10 000 solar masses per cubic light year, its total mass to be 7000 solar masses.

The comparison between HD 97 950 and Arches was done using images obtained in 1999 with the ISAAC instrument at the VLT under excellent seeing conditions of 0.4 arcseconds (Fig. II.2). This data set allowed the deepest photometry of HD 97 950 to date. The data reveal the stellar cluster to be even younger than Arches, with an age of 0.3 to 1 million years.

The mass function for HD 97 950 was determined using the same method as with Arches. Within 0.8 parsecs (2.5 light years) of the center the interval between 0.4 and 20 solar masses could be described by a power law with a slope of - 0.9, which is almost identical to that of Arches. Due to the high sensitivity of ISAAC, the most massive stars in the cluster center were overexposed, so the upper ends of the mass function cannot be compared. However, preliminary observational results indicate that within the innermost region of 0.2 parsecs radius the mass function appears to become virtually flat, with a slope of - 0.3. Here a similar trend towards an excess of massive stars as in the Galactic Center region appears. But at the lower mass end the mass function remains unchanged, so in this cluster a lack of low-mass stars seems to occur only in the cluster center. This emphasizes the unusual nature of the mass function in Arches, which could be important for the interpretation of star forming regions in the near and distant universe.

So, more massive stars were probably forming in the central region already in the beginning as the density of matter was highest there. And while the cluster evolved, more massive stars were drawn additionally towards the cluster core. This scenario is suggested by the theoretically estimated dynamical time scale of two million years.

For both cases it is currently not clear how field stars in the outskirts of the clusters, where the lower-mass stars are found, are confusing the mass function. Future observations should answer this question. This will require high resolution spectra in the near-infrared range. Stars ejected from the cluster should have higher radial velocities than stars bound to the cluster or than field stars. Future instruments such as CRIRES at the VLT should be able to provide these data. In addition, a detailed analysis of the spectral types should help identifying field stars. This could be done with the instrument SINFONI/SPIFFI, also at the VLT.

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II.2 KH 15D – an Unusual Young Binary Star

During a photometric survey of the young open cluster NGC 2264 a highly variable object was discovered in 1995, that was designated KH 15D. During almost half of its 48-day period it remains at minimum light. Detailed observations show it to be a young object, possibly a relatively close binary system with a bipolar jet, which is obscured by a circum-binary disk of dust. Presently, only one star is peeking out repeatedly from the disk. KH 15D offers a unique opportunity to study structure and evolution of the circumstellar material within a reasonably short time and with high spatial resolution. In the year under report, astronomers from all over the world were putting together their observational data as in a jigsaw puzzle in order to obtain a consistent picture of the object. Astronomers at MPIA contributed significantly to this.

The open cluster NGC 2264 (Fig.II.5) is 760 pc (2500 light years) away and 2 to 4 million years old. This cluster contains the Cone Nebula whose image taken with the HUBBLE Space Telescope in 2002 received a lot of attention from the media. The object KH 15D is north of the Cone Nebula and makes itself conspicuous by its strong variability, showing a period of 48 days: At maximum light its apparent magnitude reaches about 14.5 mag, at minimum light it sinks below 18 mag (Fig. II.6 a, b). The uniqueness of this minimum phase lies in its extreme duration combined with the long period. No other periodically variable star is known having such a combination of period and eclipse phase.

The astronomers participating in the studies soon realized that a faint star or planet could be excluded as the occulting object. Such a body on a Keplerian orbit with an orbital period of 48 days would eclipse the star for half a day at most. Only an extended object such as a dusty disk can account for the eclipse. The behavior of the star during minimum light is unusual, too. During some phases of minimum light, its brightness unexpectedly increased for a short time, sometimes even surpassing the normal level of maximum light. Until recently, this behavior could not be explained at all.

In a color-magnitude diagram, KH 15D is not located on the main sequence. Stellar evolution models indicate an age for the star of 2 to 10 million years, which within the accuracy limits is consistent with the age of the NGC 2264 cluster. According to these models and to spectroscopic observations it is a pre-main-sequence or T Tauri star. It shows relatively weak emission lines which are not untypical for somewhat older T Tauri stars.

Because of the low age of KH 15D astronomers hoped to be able to observe evolutionary stages in circumstellar dust that ultimately will lead to the formation of a planet. During two international observing campaigns running from autumn to spring in 2001/2002 and 2002/2003 the brightness variations of KH 15D were measured photometrically at numerous observatories around the world, among them the Calar Alto observatory of the MPIA in Spain. Other German institutes participating in this project were the Thüringer Landessternwarte Tautenburg and the Universitätssternwarte München. The goal was to record the light curve with a time resolution and photometric accuracy as high as possible.

Detailed analysis of the extensive data showed that the ingress and egress phases of the occultation are not exactly symmetric, lasting 1.5 and 1.9 days, respectively. The period can be determined very precisely to be 48.345 days during which the star is eclipsed for almost 20 days (Fig. II.7). Over the years, the system showed an astonishing behavior: during the eight years since its discovery its brightness at minimum light has decreased linearly (Fig. II.8) and the duration of totality has increased by about one day per year.

Maybe this phenomenon is existing only since one or two decades. Older images taken in 1913 to 1951 do not show any variability of more than one magnitude: So during the first half of the 20th century no such deep eclipses at all or only very short ones had taken place. Examination of images from the archive of the Asiago observatory obtained between 1967 and 1982 helped clearing up the photometric behavior of KH 15D. The star turned out to be already variable with the same period as today (48 days) at that time, although the amplitude was only 0.7 magnitudes. Moreover, during maximum light it had been brighter by 0.9 magnitudes than at present.

More clues to the nature of the occulting material were obtained from photometric observations made in different color ranges. As is shown in Fig. 9 the light is not reddened during totality. This suggests that the dust particles have to be rather large (significantly larger than the wavelength of the light). It is possible that within the disk macroscopic bodies have already formed. During minimum light, the light is slightly bluer by 0.1 mag. This could be caused by small amounts of tiny dust particles scattering the star light.

Although the measurements are less accurate during minimum light than outside of eclipses, real brightness variations of up to 20 percent seem to occur within a period of one hour in this phase. Their cause is unclear, but during this phase light is probably being scattered by small clouds, or it is shining through gaps in the disk. These clouds or gaps cannot be larger than 0.01 AU, provided they are moving on Keplerian orbits around the star. This is about the size of our sun.

Fig II.5: The star cluster NGC 2264 with the Cone Nebula below the center of the image. (Image: Takahashi)

More interesting details of this star were obtained from spectroscopy using the UVES Echelle spectrograph on the ESO Very Large Telescope. The hydrogen Hα emission line, for instance, shows a double profile with a central absorption feature, the wings reaching radial velocities of up to ±300 km/s. This can be explained by the fact that the star is accreting gas from its surroundings. Depending on the phase of the eclipse, the observed profiles of the Hα line are exhibiting quite different structures. From this time variability of the line profiles it is in principle possible to model the structure of the emission line region with unbelievable high spatial resolution (as it could theoretically be reached with an optical 1 km telescope). However, the time density of the data points is still not high enough to reasonably conduct such a reconstruction. There is no other T Tauri star allowing to test models of this kind of young stars directly.

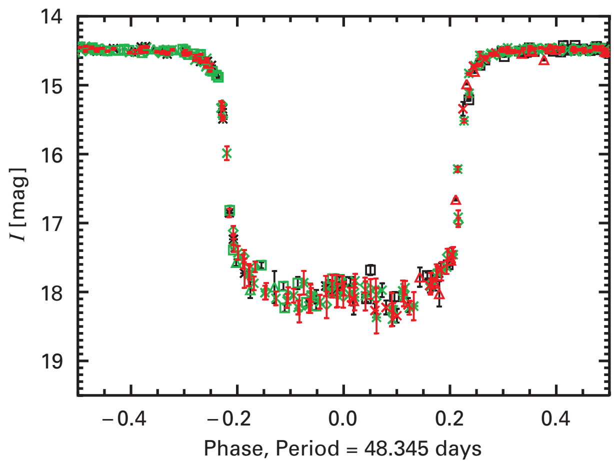
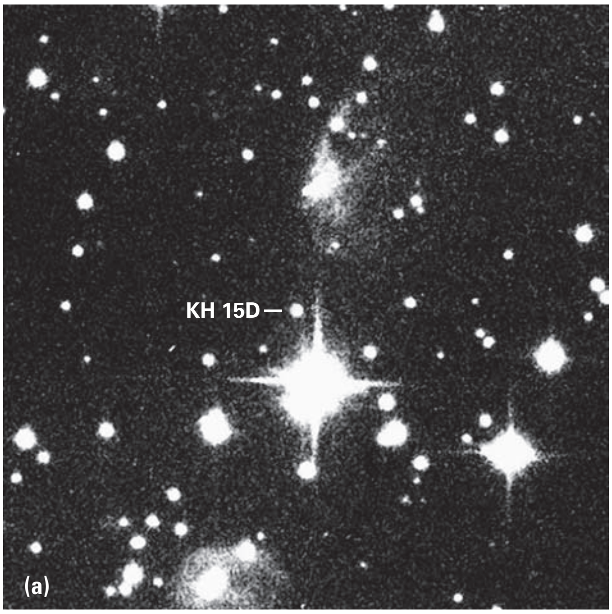


Fig. II.7: Light curve during the 2002/2003 observing campaign. The period is 48.345 days.



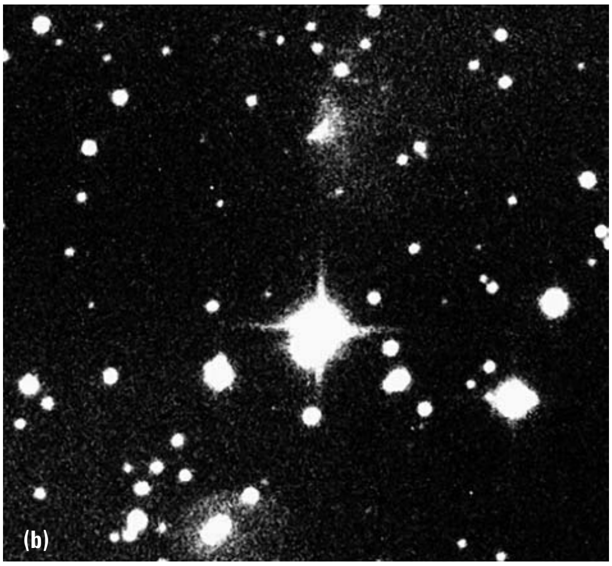


Fig. II.6: Region in NGC 2264 with KH 15D **(a)** at maximum light, and **(b)** at minimum light. (I mage: W. Herbst).

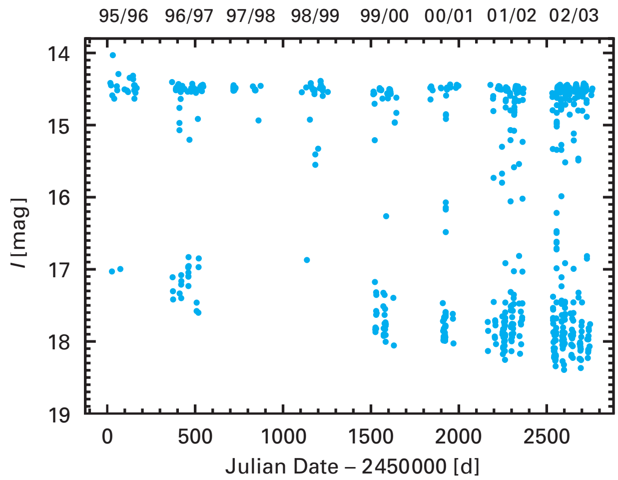


Fig. II.8: The light curves since 1995 show the linear decrease of the level at minimum light.

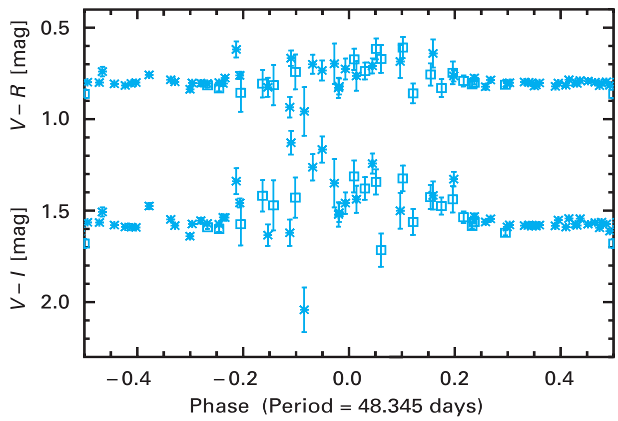


Fig. II.9: Color behavior of KH 15D out of and during the eclipse (around phase 0.0). At minimum light the star looks somewhat bluish.

A forbidden emission line of neutral oxygen [OI] was also detected, that shows a double structure with maxima at about ± 20 km/s. It is of different origin than the hydrogen line, suggesting two well-collimated jets shooting out from the star in opposite direction into space. The more the jet axis is inclined against the line of sight, the smaller are the two radial velocities meas-ured in the spectrum. Assuming a typical flow velocity of 200 km/s for the particles in the jets yields an in-clina-tion of the flow direction against the line of sight of 84 degrees, that is, the bipolar jet is moving almost perpendicular to the line of sight and is seen almost exactly sidelong.

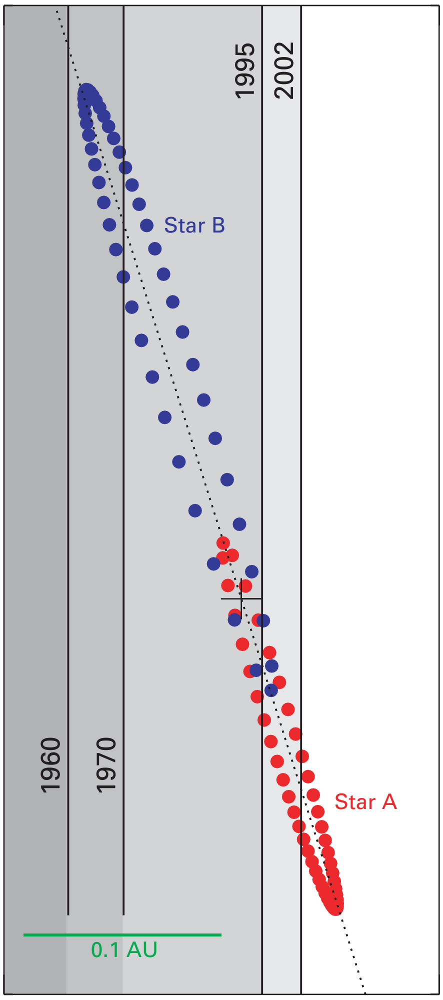


Fig. II.10: The presently best model of KH 15D. The two stars A and B orbit a common center of gravity. The *z*-axis is poin-ting towards the observer, the lines marked with years define the right edge of the dusty disk which is moving from left to right in front of the binary system. (J. Winn, Harvard-Smithsonian Center for Astrophysics).

During the year under report there was intense dis-cussion in order to find a consistent explanation of all observational results. Currently, KH 15D is thought to be a close binary system whose two components are orbiting one another at a distance of 0.25 AU with a pe-riod of 48 days (Fig. II.10). The orbital plane is highly inclined against the line of sight. Both stars A and B are surrounded by a common dusty disk whose equatorial plane is inclined against the orbital plane. Over the years, the inclination of the disk is shifted by preces-sion relatively to the stars´ orbital plane resulting in a changing eclipse geometry. So, in some phases the disk occasionally occults only one star, which explains the 48-day period with a small amplitude that was obser-ved several decades ago. In other phases, both stars are expected to be eclipsed more or less, which will result in the deep minima whose duration is depending on the degree of occultation of both orbits. So, the disk is thought to eclipse the entire orbit of star B and a large part of the orbit of star A since about 1998. This is what causes the long lasting deep eclipse phases ob-served since then. If the currently observed continuous lengthening of the eclipse phase by one to two days per year is continued, the circum-binary disk should occult both stars one to two decades from now.

KH 15D is a fascinating object because here, among other things, changes in the environment of a young star obviously are occurring on short time scales. Astronomers at the Institute therefore are planning further observations, in particular with the HUBBLE Space Telescope or the NACO high-performance infra-red camera. Moreover, planned high-resolution spec-troscopy during the eclipse phase using the UVES spectrograph at the ESO VLT and HIRES at the Keck observatory on Mauna Kea, Hawaii, should offer a unique chance to reconstruct the emission region of the binary star with unprecedented spatial resolution.

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II.3 A New Method for Observing Protoplanetary Disks

Meanwhile it is an undisputed fact that many stars are orbited by planets. This is especially true for solar like stars, as the discovery of numerous extrasolar planets has demonstrated over the last years. The notion that these planets are forming in dust disks around young stars is equally well established. However, many details of planet formation are still unclear, because protoplanetary disks cannot be observed in spatial detail. Astronomers at MPIA have employed a new technique to study the structure of the circumstellar disks. For this purpose they used the NACO infrared camera, which was partly developed at MPIA, in its polarimetric mode on the ESO Very Large Telescope. The first observation of a disk around the young star TW Hydrae was very promising. The disk could be mapped at such a close distance to the star as it had never been possible before.

Stars are forming through the gravitational collapse of interstellar clouds. When such a cloud exceeds a certain mass limit it starts to contract under the influence of its own gravity. While the cloud initially rotates slowly, the rotation accelerates as the collapse advances. The increasing centrifugal forces stretch the cloud perpendicular to rotational axis, flattening it into a disk. A star forms in the center, planets form in the disk.

Planet Formation and Structures in Protoplanetary Disks

According to the current notion, planet formation proceeds in several stages. Initially, dust and gas are mixed and the solid particles continue to grow while they are colliding and sticking together. The particles, getting heavier and heavier this way, are sinking gravitationally towards the mid plane of the disk where they form a rather thin dust disk. As the density of the dust increases by this process, the particles collide more often and grow to form planetesimals several kilometers across. These bodies can then grow by collisions caused by gravitational interactions to form planets, since their gravitation is sufficient to attract and accrete more dust and gas from their surroundings.

At a distance of about 5 AU, it takes a few hundred thousand to one million years to form a Jupiter sized planet. Computer simulations show that during this process interesting interactions with the disk occur. The gravitational field of the planet causes a disturbance within the circumstellar disk, which results in the development of spiral density waves reminiscent of the arms of spiral galaxies. There is also an exchange of angular momentum between disk and planet. Particles inside the orbit of the planet are moving faster around the star than the planet itself and therefore get slowed down by its gravity. In other words, the particles loose angular momentum and wander inwards. Particles beyond the orbit of the planet, however, are moving slower and thus are gaining angular momentum from the planet, which causes them to wander further out. This way, an annular gap around the orbit of the planet develops within a few thousand years. At the same time, particles of the inner disk are loosing angular momentum and fall into the central star.

This way, structures such as density waves and gaps develop within the disks. Direct observations of these phenomena would be a great step forward towards a real understanding of planet formation, which currently is still based essentially on models. But this step cannot be done yet, because the central star is outshining the disk, and because very high spatial resolution is needed to observe structures within the innermost regions of the disk.

Polarimetric Differential Imaging with NACO

Several research teams have tried in vain to probe structures at scales similar to our inner Solar System within circumstellar disks using the HUBBLE Space Telescope. Astronomers at MPIA now have employed a very promising technique: polarimetric differential imaging, PDI. It allows to image polarized scattered light from the dust disk and enhances the contrast between the disk and the star.

PDI is working on the following basic idea: The light coming directly from the star is unpolarized. Stellar light scattered by the disk, however, shows linear polarization, the degree and direction of which varies with the position angle on the disk. The trick is to simultaneously take two orthogonally polarized images of the same object and then to subtract them from one another in a computer in order to remove the unpolarized component of the star's light.

At present, PDI combined with extremely high spatial resolution can be done only with very few instruments worldwide. The best opportunities are offered by the NACO infrared camera on the Very Large Telescope. For measurements of polarization degree and angle, NACO is provided with four grid polarizers and two Wollaston prisms.

Fig. II.11: MPIA team during the commissioning of the high-performance camera NACO at the Very Large Telescope.

The Protoplanetary Disk around TW Hydrae

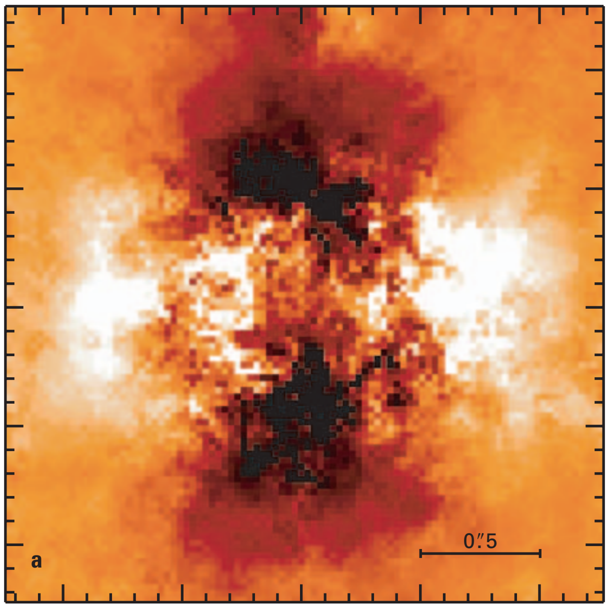
In the year under report, astronomers at the Institute demonstrated the potential of this new method on the pre-main-sequence star TW Hydrae, 56 parsecs (180 light years) away. In 1998, a variable, spatially unresolved polarization in the visual wavelength regime was observed in this eight million years old T Tauri star providing strong evidence for a circumstellar dust disk. Subsequently, attempts were made to directly observe the disk. In 2002, astronomers succeeded in imaging the disk with NICMOS on board the HUBBLE Space Telescope. The image showed scattered light from the disk in a region between 20 and 230 AU around the star. The innermost 0.3 arcseconds (corresponding to almost 20 AU), however, were hidden behind the coronographic mask blocking the star's direct light. Thermal infrared spectra revealed silicates in the dust of the disk. Moreover, the spectral energy distribution suggested the presence of a giant planet. Thus, this interesting object was an ideal candidate for testing the new PDI technique.

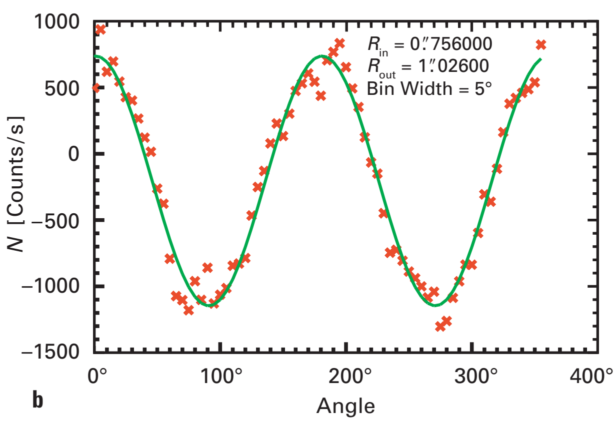
The observations were carried out in April 2002 at a wavelength of 2.2 μm (K band). In order to measure the polarization, one of the two Wollaston prisms was used. A beam of light passing through the prism is split into two orthogonally polarized beams. To eliminate the unpolarized component of the light, these beams are subtracted from one another.

The detector resolution was 0.027 arcseconds per pixel; the diffraction limited angular resolution of the telescope at this wavelength is 0.07 arcseconds, corresponding to 4 AU at the location of TW Hydrae. Two series of observations were obtained: The first comprises long exposures with a total exposure time of 30 minutes. These show the outer faint regions of the disk but are overexposed in the central part. The second set of short exposures (with a total of 24 seconds of integration time) reveals the inner region.

The result of the long exposure series is shown in Fig II.12a. Apart from the innermost overexposed region within a radius of 0.06 arcseconds, a spatially varying polarization pattern is recognized as it is expected for a circumstellar disk. In such a case, the direction of the polarization vector varies with the position angle, yielding a kind of "butterfly pattern". Fig. II.12b illustrates the variation of the polarization angle. Here, the intensity within an annular region between 0.75 and 1 arcsecond from the star was plotted against the position angle. The butterfly pattern was detected between 0.5 and 1.4 arcsecond from the star, corresponding to distances between 30 and 80 AU around TW Hydrae. In the short exposure images, a less obvious, but nevertheless significant butterfly pattern appeared in a region between 0.1 and 0.4 arcseconds (5 to 20 AU) from the star.

Fig. II.12: a) Fraction of polarized light in the close vicinity of TW Hydrae. It is generated through scattering of the star's light by the protoplanetary disk; **b)** variation of the polarization angle as a function of position angle.





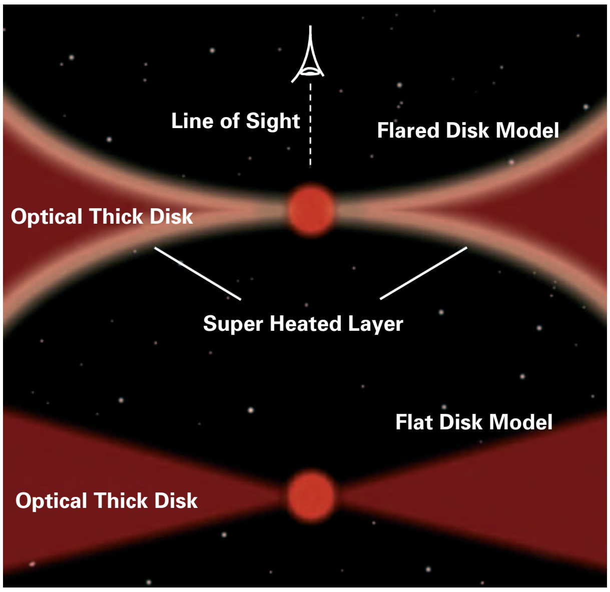


Fig. II.13: Diagram of possible protoplanetary disks around young stars. Above, the model of the flaring disk, below, that of the optically thick, flat disk.

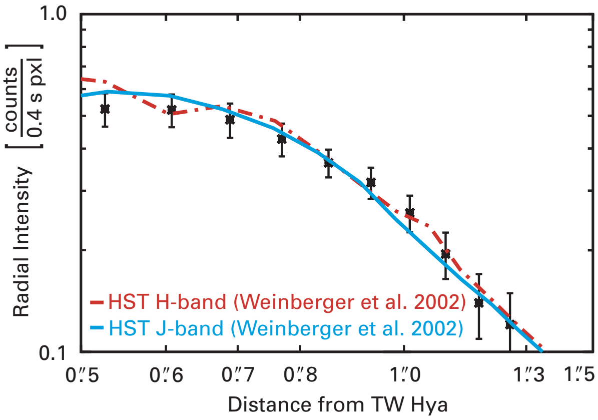


Fig. II.14: Radial surface brightness distribution of the disk around TW Hydrae, obtained with the HUBBLE Space Telescope (solid and dashed curves). The radial polarized intensity distribution measured with PDI is shown for comparison (asterisks).

These observations allowed to image a protoplanetary disk closer to the star than any previous observations had done. The data prove that the inner edge of the disk is not more than 5 AU away from TW Hydrae. This is in contradiction to a model published in 2000 that is based on the analysis of the radial surface brightness profile of the disk in the near-infrared range. According to this model the disk should begin only at a distance of 18 AU from the star. Another model proposing a gap in the disk at a distance of about 4 AU, caused by the gravitational effect of a large planet, could not be tested with these data.

A second result concerned the radial profile of the degree of polarization. The data show that it is independent of the distance to the star; thus the measured polarized intensity characterizes the surface brightness of the disk. In a detailed analysis of the measurements the intensity was found to decrease with the third power of the radius. This result is in good agreement with previous observations (Fig. II.13). Such a behavior is expected for a flat, optically thick dust disk (Fig. II.14). However, it is not consistent with the model of a so-called flaring disk, which according to some astronomers should apply to T Tauri stars. In that case an optically thin layer covers the surface of the disk, which is heated by the star's radiation and should glow in the thermal infrared regime.

Within the annular region between 0.5 and 0.7 arcseconds, the profile of the surface brightness is remarkably flat, as it was already implied by previous observations. Here, the intensity is decreasing proportionally to radius. This change cannot be explained conclusively. A possible reason might be a local density disturbance within the disk material as described above, caused by a large planet. Another possibility would be that the dust particles in the relevant region have a different size distribution and thus different reflecting properties. To answer this question, further observations with high spatial resolution are needed. In principle, it was demonstrated for the first time that the technique of polarimetric differential imaging is a very effective tool for studying protoplanetary disks in the close vicinity of their stars.

(D. Apai, W. Brandner, Th. Henning, R. Lenzen, I. Pascucci. Participating institutes: Steward Observatory, Tucson, Arizona, Observatoire de Grenoble, ONERA, Chatillon).

II.4 MIDI – a Breakthrough in Astronomical Observation

After the first successful tests of the mid-infrared interferometric instrument MIDI at the ESO Very Large Telescope at the end of 2002, the phase of Science Demonstration followed in the year under report. MIDI fully met the high expectations and thus opened up a new field of astronomical observations: for the first time a resolution of one hundredth of an arcsecond can be achieved in the mid-infrared spectral range. Observations of circumstellar disks around young stars as well as of the dust ring in the center of an active galaxy demonstrate the enormous power of the instrument. MIDI was built by a consortium of German, Dutch, and French teams under the leadership of MPIA.

For decades, optical interferometry had been a playground for technical puzzlers and unwaveringly optimistic astronomers. This technique combines the light coming from two or more telescopes so that it appears to come from one single mirror. If the largest distance between these telescopes is, say, one hundred meters, the interferometer can achieve the same resolution as a single 100-m-telescope. Thus, an excellent image definition of a few thousandth of an arcsecond in the near infrared and one hundredth of an arcsecond at 10 μm wavelength is achieved. This is more than ten times better than is theoretically possible with a single 8-m-telescope of the VLT and exceeds the natural, seeing-limited resolution by a factor of 100. These numbers demonstrate the enormous astronomical potential of interferometry. Moreover, the interferometric facilities at the VLT are currently being extended by a set-up of smaller auxiliary telescopes (Fig. II.15), which were partly financed by the Max Planck Society.

After the first successful test of MIDI at the end of 2002, ESO put the instrument officially into operation, so that it is now available to all astronomers. Thus, a very ambitious goal was achieved as planned. MIDI is the first instrument at large telescopes covering interferometrically the mid-infrared range at wavelengths around 10 μm.

Fig. II.15: The VLT on Cerro Paranal. Three of the four 8-m-telescope are seen in the background; in front is the first of the additional 1.8-m-telescopes which will be part of the interferometer array. (Image: ESO)

Fig. II.16: A short discussion break for Christoph Leinert, Thomas Henning and Rainer Köhler (sitting from left to right), while the telescope operators Lorena Faundez and Hector Alarcon are locating the object.

But it was still a strenuous way to go from the first observation of a bright star on 15 December 2002 to the routine operation at present. Errors in the instrument and in the complex infrastructure of the VLT 8-m-telescopes had to be found and eliminated; one had to determine exposure times, optimize the sequence of the measurement steps and ensure the smooth interplay between the instrument control and the interferometrically coupled telescopes. Great expense was needed for data storage and online data reduction as it is practiced at ESO. Here, mainly the software specialists of the instrument team and of ESO had been in demand. After occasionally hectic work during day and night in February, May, and December, the goal was reached shortly before the end of 2002 (Fig. II.16).

The routine operation of MIDI is a breakthrough in astronomical observation technique. Now any astronomer – and not only a few specialists – can profit from the splendid image definition of this method. However, this should not obscure the fact that infrared interferometry is a highly intricate and complex technique.

First, for both telescopes used by MIDI the infrared image has to be identified on the detector. This is not always easily done because some of the objects studied are not visible at all on the monitors, which are only sensitive to optical light, and do not always fall right onto the infrared detector while the object is acquired. The next step is to provide the conditions for making the light beams coming from the interferometrically coupled telescopes appear to come from one large single telescope. For this purpose, the images delivered by the individual telescopes have to be shifted exactly to a certain position on the detector in such a way that they can merge into one undistinguishable image. In addition, the paths traveled by the light from the telescopes to the detector have to have the same length within a few hundredths of a millimeter. This is accomplished using delay lines constructed of movable mirrors set up in a tunnel below the telescopes.

Now comes the crucial test: Does the interference necessary for achieving the high image definition occur? If so, the interference pattern consisting of a series of dark and light stripes is discernible, caused by destructive and constructive superposition of the light waves. A short test is enough, then the measurement of the interference pattern can be started. Online analysis of the data during the measurements shows when the light paths of both telescopes start to differ due to atmospheric turbulences. In this case, these light path differences are corrected by a command to the delay line and the measurement is continued until a sufficient amount of data has been obtained.

The astronomically relevant information is contained in the contrast of the interference pattern, that is, in the intensity contrast between the maxima and minima of the pattern. This quantity is called visibility. Its value varies between 1 and 0. An unresolved point source has a visibility of 1; for resolved objects, it is smaller than 1, decreasing with increasing size of the objects.

In the near-infrared regime, the thermal emission of the telescopes and of the night sky hampers the observations considerably. It can exceed the brightness of a celestial object by a factor of 1000. Thus, special additional measurements are needed in order to disentangle the visibility of the objects from this disturbing background emission. However, there are still unavoidable shortcom-ings of the numerous optical elements in the light path and the effects of atmospheric turbulences which blur the interference pattern. These perturbations can be corrected by observing a reference source that is known to appear pointlike even at the high interferometric resolution.

This procedure indeed involves considerable efforts and can last up to one hour – only to obtain a single information about the size of the object studied. However, MIDI is provided with an additional function that greatly increases the information content: a prism that spectrally diffracts the light. Thus the size information is obtained simultaneously in 30 wavelength bands around a central wavelength of 10 μm. As it is demonstrated by the examples below, this constitutes the particular value of these interferometric observations.

Circumstellar Disks around Young Stars

In recent years, circumstellar disks have become a focal point of interest since they are believed to be the sites of planet formation. The majority of young stars of low or moderate masses up to about two solar masses (T Tauri stars) are surrounded by circumstellar gas and dust disks. They have been studied intensely for more than a decade and are a main field of research at MPIA (cf. Chapter II.3 on the disk of TW Hydrae).

More massive stars, however, have not attracted much attention in this respect although there is no reason why many of these stars should not have disks, too. Actually, intense emission in the infrared or millimeter wavelength range was found in some young stars of spectral type A and B (so-called Herbig Ae and Be stars). This is attributed to circumstellar dust that appears to be arranged in a disk.

From the intensity of the radiation at different wavelengths the theoreticians have developed models for such disks. Most of them assume that the millimeter emission stems from cold grains that have accumulated in the mid-plane of the disk. The layers above and below this plane – the "skin" of the disk – are heated by the central star, causing the particles there to emit in the mid-infrared regime. The heating is particularly effective if the disk gets thicker with increasing distance from the star (a so-called flaring disk).

Detailed computer simulations suggest the following scenario: The central hot Ae or Be star heats its immediate surroundings to such an extent, that no dust particles can exist there, since they would evaporate. Adjacent to this gap is the dust disk. Its inner rim is heated with particular intensity reaching temperatures of 1200 K to 1500 K. It therefore puffs up to form a doughnut-like torus that can cast a shadow on the region behind it out to a distance of a few AU from the star. Depending on the size of the torus and the geometry of the disk, the shadow affects the temperature profile and thus the mid-infrared emission.

However, it had been impossible so far to confirm these assumptions on the geometry of the disks by direct observations. MIDI, though, is ideally suited for this task, as it achieves the necessary spatial resolution of a few AU in objects that are typically 100 pc to 300 pc (320 to 1000 light years) away.

In June 2003, astronomers of the team and from other institutes observed seven Herbig Ae/Be stars with ages of three to seven million years using the VLT interferometer. Based on previous near- and mid-infrared spectra these stars were suspected to be surrounded by circumstellar disks. Some of them exhibit strong emission in the 10 μm spectral range, that has to stem from silicate particles of amorphous or crystalline structure. In some of them, the characteristic emission of Polycyclic Aromatic Hydrocarbons (PAH) was found, that are more common in the vicinity of hotter stars.

The interferometric observations using MIDI were carried out in the spectroscopic mode described above with low spectral resolution. For this purpose, the astronomers combined the light of the two 8-m-telescopes Antu ("Sun") and Melipal ("Southern Cross") which are 102 m apart. At 10 μm wavelength, this arrangement yielded a maximum resolution of 0.01 to 0.02 arcseconds.

Since the objects studied are at distances between 100 and 250 pc, intrinsic structures down to about 2 AU could be resolved. The spectroscopic mode described above allowed about 30 measurements of the size at different wavelengths. Moreover, the stars were imaged directly at 8.7 μm using a single telescope. The interferometric measuring technique described above also includes the recording of spectra in the 10 μm wavelength region.

These spectra are shown in Fig. II.17 in comparison to older data. The good agreement of these measurements, which have not been the primary goal of the MIDI observations but were taken as auxiliary data, is a first proof of the flawless performance of the instrument. All spectra show the silicate emission feature mentioned above as it is expected from disks whose surface is heated by stellar light.

The actual result, however, was the successful interferometric observation of all objects, meaning that the resolving power was sufficient to spatially discriminate the infrared emission of these objects. This is demonstrated by the measured visibilities in the spectral range between 7.5 μm and 13.5 μm (Fig. II.18). Typical for all objects is the fact that the run of the visibility does not show any obvious structure where silicate emission is expected. This reflects an almost even distribution of the emission of the small and big silicate grains in the disk. The general drop of the measured visibilities with increasing wavelength is due to the fact that the emis-

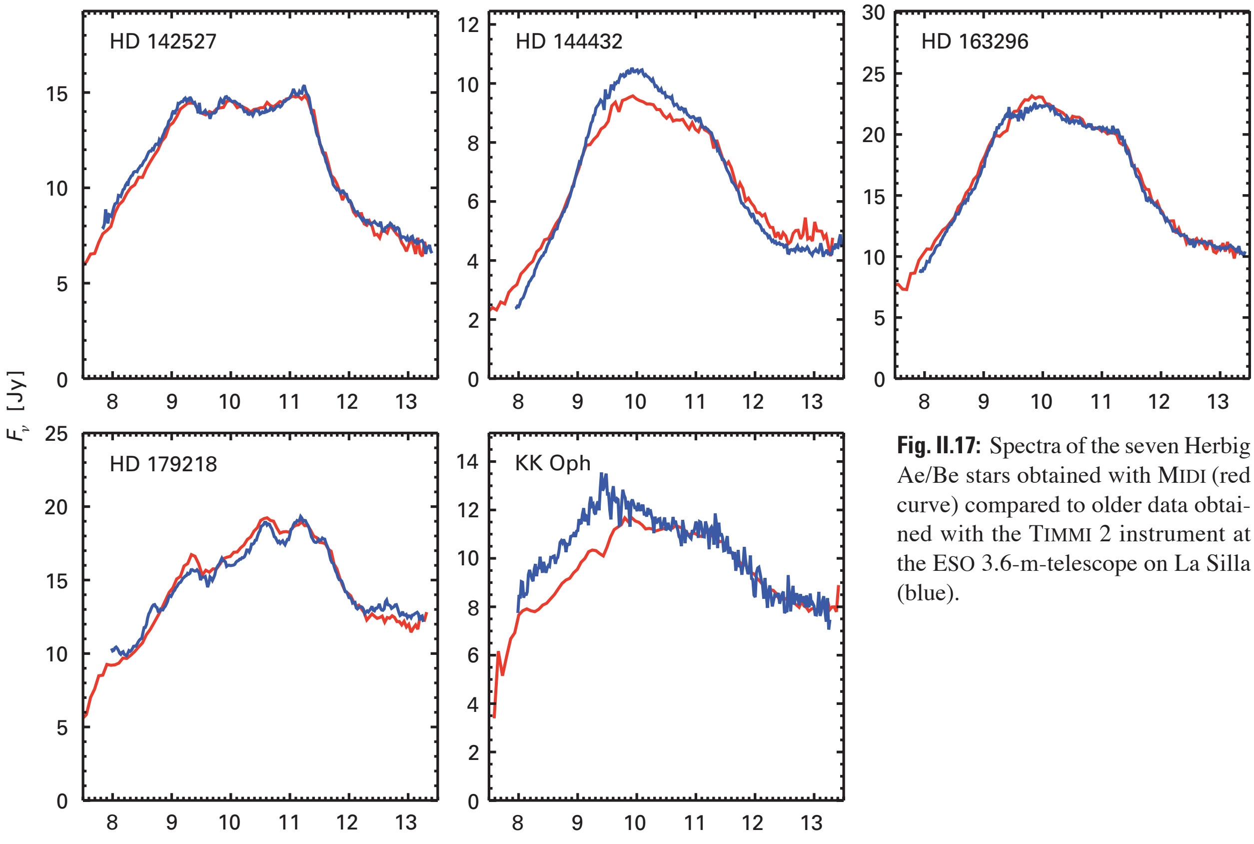


Fig. II.17: Spectra of the seven Herbig Ae/Be stars obtained with MIDI (red curve) compared to older data obtained with the TIMMI 2 instrument at the ESO 3.6-m-telescope on La Silla (blue).

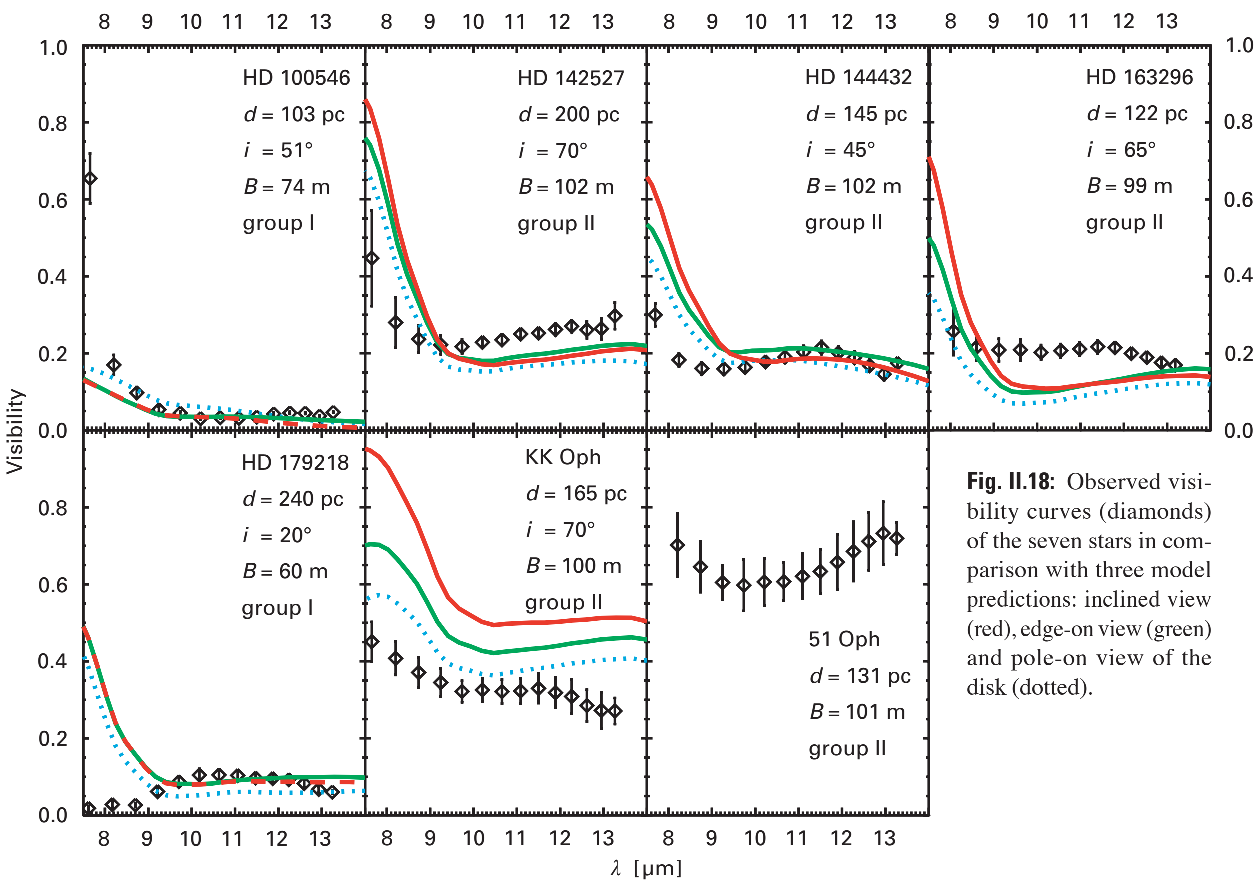


Fig. II.18: Observed visibility curves (diamonds) of the seven stars in comparison with three model predictions: inclined view (red), edge-on view (green) and pole-on view of the disk (dotted).

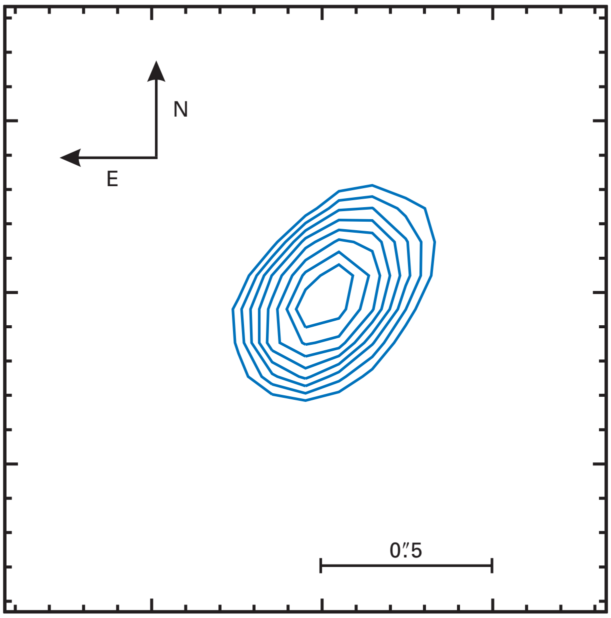


Fig. II.19: Single dish image of HD 100546 obtained with MIDI. The contour lines show that the disk is spatially resolved in every direction.

sion of cooler particles increases at larger wavelengths, resulting in the detection of more extended regions lying further out.

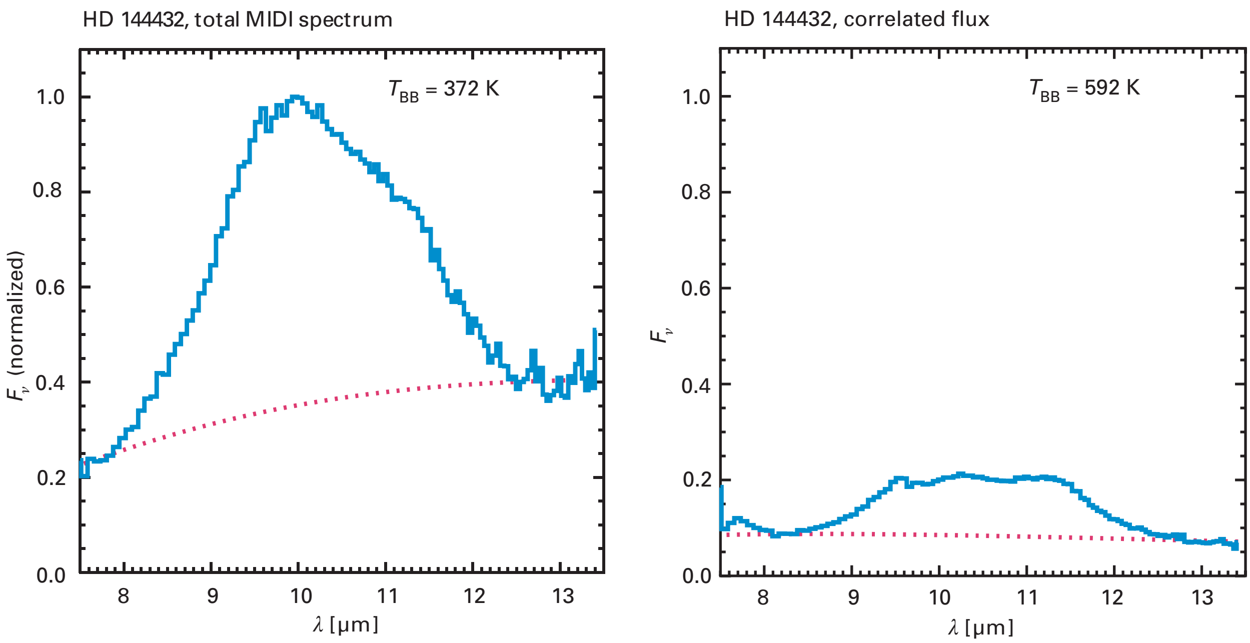
For comparison, the predictions of the model described above were also plotted in this figure, taking into account the inclination of the disk against the line of view as an additional unknown parameter. Three cases (inclined view, edge-on view, and pole-on view) are shown in Fig. II.18.

Qualitatively, the models correspond with the observations of the visibility as a function of wavelength (Fig. II.18): between 8 μm and 9 μm there is a notable drop, followed by roughly constant values out to 13 μm. Quantitatively, however, discrepancies of several tens of percent occur. Usually these discrepancies can be attributed to varying disk sizes. So for HD 163296, for instance, a deviation of up to 80 percent between model and observation could be removed by a 15 percent larger disk. Obviously only the spatial information, which is presently only obtainable by interferometry, can yield more information on the actual structure of the disks.

The disk radii derived from the measured visibility values range between 1 AU and 10 AU. These values relate only to dust emission in the mid-infrared spectral regime. An interesting trend was showing in these inferred quantities: the redder a given star (i.e. the stronger it emits around 25 μm wavelength compared to the region around 10 μm), the larger its disk, i.e. the more extended the mid-infrared emission. This effect is a first direct confirmation of the assumed disk geometry with a thick inner edge and a flared outer region. Indeed, the relation above is an inevitable consequence of this model.

Two objects are worth to be looked at more closely. HD 100546 was the only one that could be spatially resolved by direct imaging (Fig. II.19). The tilted disk is extended along both axes by 0.28 arcseconds and 0.18 arcseconds, respectively, at a distance of 103 pc (310 light years) corresponding to 29 and 19 AU. It is also the reddest of the observed objects. The analysis of the spectra obtained from the interferometric measurement shows the warm dust to have similar properties out to

Fig. II.20: Spectra of HD 144432, taken with MIDI– above the spectrum of the entire object, below that of the „interferometrically magnified" inner part of the disk.



at least 40 AU from the star. This implies that even in this early stage the disk material surrounding the star is well mixed in regions extending far out – an important clue for planet formation theories.

Also of special interest is the object HD 144432 (Fig. II.20). Here, two spectra demonstrate the potential of interferometry. The left part of Fig. II.20 shows the spectrum of the entire object. The characteristic silicate emission feature at 10 μm is clearly recognized. The spectral distribution found here is due to the emission of small amorphous particles as they are also detected in the interstellar medium. The right part of Fig. II.20 shows the corresponding spectrum of the "interferometrically magnified" inner 2 AU of the disk. Here, the much flatter intensity distribution indicates the domination of larger, partly crystalline particles. Maybe we are watching here the first stage of the growing of dust particles that eventually may lead to the formation of planetesimals and finally planets.

The Heart of the Active Galaxy NGC 1068

Active galaxies are distinguished from normal galaxies such as our Milky Way System by an unusually large energy production within their nuclei. Astronomers believe to have found the source of this energy output: It is widely accepted now that the center of each active galaxy harbors a massive black hole surrounded by a hot accretion disk. Infalling matter, first onto the disk and then into the black hole, releases the emitted energy.

The accretion disk is surrounded by a dense torus of gas and dust. The entire structure measures only a few tens of light years – corresponding to an angular diameter of less than 0.05 arcseconds at the distance of the nearest active galaxies. This is the size under which a coin would appear at a distance of 40 km – even the new large telescopes of the 10-m-class are not able to resolve features that small. Models of this structure are therefore based on indirect evidence and accordingly vague. The doughnut-shaped dust distribution could be very dense and compact or very extended and dilute.

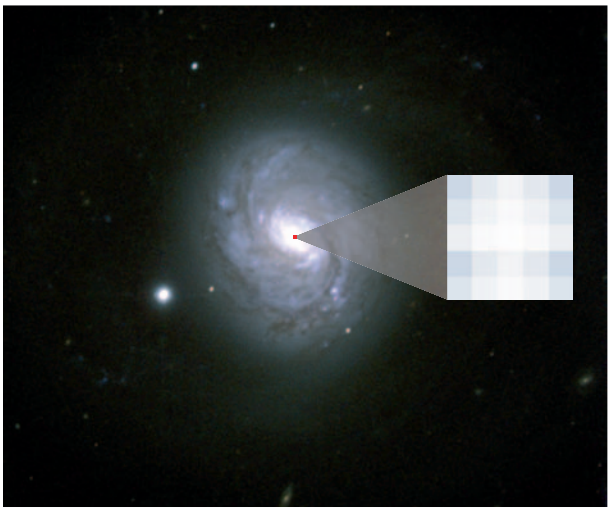


Fig. II.21: The Seyfert galaxy NGC 1068 (M 77) imaged in the optical range.

In order to settle this question it is necessary to spatially resolve such tori. This was first achieved in June 2003 for the active galaxy NGC 1068, listed in the historic Messier catalogue as M 77 (Fig. II.21). At the same time, this was the first interferometric observation of an extragalactic object in the mid-infrared region that is dominated by the thermal emission of dust.

At a distance of 17 Mpc (55 million light years), NGC 1068 is one of the nearest and therefore best studied active galaxies. Galaxies of this type are characterized by rapid brightness variations in their compact core regions. Such galactic nuclei strongly emit in the ultraviolet and infrared spectral region and in addition they are strong X-ray sources. The X-ray emission must come from the immediate surroundings of the black hole in the center of NGC 1068; the mass of the black hole is estimated to be about one hundred million solar masses.

In the case of NGC 1068, the torus is so thick that it obscures the view to the inner accretion disk. The dust within the torus is heated by the hot disk to temperatures between 100 K and 1500 K (the latter being the sublimation temperature of dust) and thus strongly emits in the infrared wavelength range around 10 μm. Moreover, a jet is forming in the center that can be traced by radio observations very closely to the black hole.

First interferometric observations with MIDI were carried out in June during an ESO program that was intended to publicly demonstrate the scientific potential of the instrument. Further observations followed in November. Here too, as with the Herbig Ae/Be stars, the spectroscopic mode was used, and a direct image was obtained with a single telescope at 8.7 μm. (Fig. II.22, middle). The interferometer was operated at baselines of 42 and 78 meters, yielding a resolution of 0.026 and 0.013 arcseconds, respectively. The observation at the longer baseline was orientated along the symmetry axis of the object marked by the radio jet.

As the measurements were aligned with the symmetry axis of the object, the spectra obtained with MIDI could be analyzed using a model as simple as possible (Fig. II.23). Only two dust components were needed to model the data: The first is a hot compact distribution with a temperature of 1000 K. Its length along the sight line is constrained to 0.8 pc (3 light years); its width is not resolved but is assumed to be between 0.3 and 1 pc (1 to 3 light years). The second is a warm component with a temperature of 320 K. Its size along both baselines is 2.5 pc × 4 pc (8 light years × 13 light years).

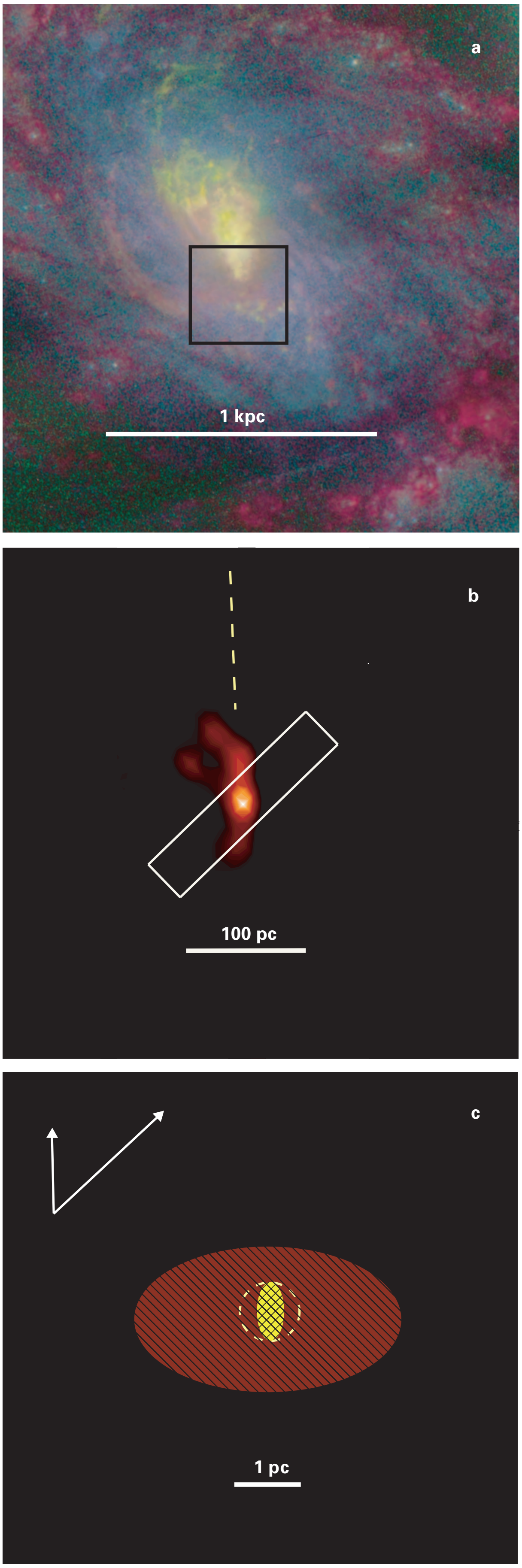


Fig. II.22: NGC 1068 on various scales. (Top) The central region imaged with the HUBBLE Space Telescope; (middle) single-telescope image taken by MIDI at 8.7 μm; (bottom) sketch of the innermost part, derived from interferometric observations with MIDI.

From the spectra an important conclusion about the spatial configuration of the two dust components can be drawn. The silicate absorption feature appears less pronounced in the total spectrum dominated by warm dust (Fig. II.23, top) than in the interferometrically magnified spectrum that shows mostly emission from hot dust in a smaller central region. Thus, the hot component seems to be embedded within the warm one. So naturally radiation from the hot component in the inner region of the surrounding warm dust will suffer additional absorption.

Based on these observational data the astronomers favor the following model: The accretion disk surrounding

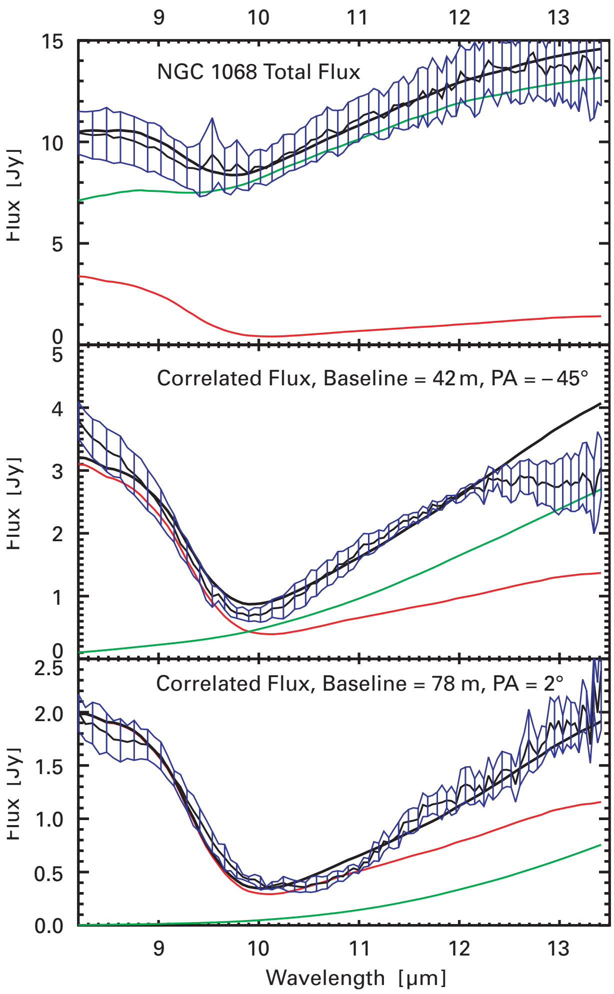


Fig. II.23: Spectra of NGC 1068, obtained with MIDI. The cross-hatching indicates the measurements with their uncertainty, the solid line shows values for a model. The red and green lines show the contributions of the hot and warm components, respectively. Top: Single-telescope spectrum with the characteristic silicate absorption feature at 10 μm. Middle: Interferometrically "magnified" spectrum at 0.026 arcseconds resolution; bottom: the same at 0.013 arcseconds.

Table 1: Some basic parameters of the MIDI instrument

Baselines available with 8-m-telescopes:	47 - 130 m
Baselines available with 1.8-m-telescopes:	8 - 200 m
Resolution at 10 µm:	0.″25 - 0.″01
Wavelength coverage:	8 -13 µm
Field of view (diameter) with 8-m-telescopes:	2″
Field of view (diameter) with 1.8-m-telescopes:	10″
Current sensitivity (8-m-telescope):	4 mag (stellar)
Current sensitivity (1.8-m-telescope):	0.5 mag (stellar)

the central black hole is in turn surrounded by a doughnut-shaped torus of at least 2 pc (6.5 light years) radius. This torus has to be very thick, with a vertical height to radius ratio of at least 0.6. The wall of the small inner hole of this torus is being heated by the central energy source, forming a "funnel". The surrounding warm dust can be traced out to 4 pc (13 light years) from the center.

This dust configuration is subjected to the strong gravity of the central black hole and therefore should transform itself into a flat disk in the symmetry plane of the galaxy within a few hundred thousand years. Since one assumes the torus to exist much longer, a continuous injection of kinetic energy into the configuration is required, stabilizing it against gravity. How this could be done is still unclear. So, already the first interferometric observations of the nucleus of an active galaxy have answered old questions concerning the geometric configuration and dynamics, but also have raised new ones.

From MIDI to APRÈS-MIDI

While the first data have been analyzed and results have been submitted to the scientific journals, planning continues. In December 2003, the constitutional meeting on the extension of the measuring range of MIDI towards larger wavelengths took place in Heidelberg. In cooperation with Dutch institutes, the instrument will be expanded till late 2005 to also allow interferometry in the region between 17 µm and 26 µm.

Finally, planning for the project APRÉS-MIDI was started. It had been proposed by French colleagues of the MIDI team in Nice, the name being a pun in their language (APRÈS-MIDI meaning "after MIDI" as well as "afternoon"). Within this project, an additional optical setup will allow to link up to four telescopes instead of the two ones in the original version of the instrument. Thus MIDI would become an instrument that could yield real images. At present, a common study is underway to investigate the technical feasibility and scientific possibilities of the proposed concept.

The advancement of the VLT interferometer will also positively affect future observations with the instrument. The "fringe tracker" that will soon be put into operation should eliminate the quivering and wandering of the fringes caused by atmospheric turbulences. This way, it will be possible with faint sources to "blindly" integrate numerous measurements within the instrument without the risk to smear the fringes as they move. This should increase the instrument's sensitivity by a factor of twenty and open up numerous new possibilities. The introduction of the 1.8-m-auxiliary-telescopes, which are intended exclusively for interferometric operation, will allow considerably more detailed studies of brighter objects than would be possible with the otherwise occupied 8-m-telescopes.

(Ch. Leinert, U. Graser, A. Böhm, O. Chesneau, B. Grimm, Th. Henning, T. M. Herbst, S. Hippler, R. Köhler, W. Laun, R. Lenzen, S. Ligori, R. J. Mathar, K. Meisenheimer, W. Morr, R. Mundt, U. Neumann, E. Pitz, I. Porro, F. Przygodda, Th. Ratzka, R.-R. Rohloff, N. Salm, P. Schuller, C. Storz, K. Wagner, K. Zimmermann.
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ASTRON, Dwingeloo;
Kapteyn Institut, Groningen;
Frankreich: Observatoire de Meudon;
Laboratoire d'Astrophysique,Observatoire Grenoble;
Observatoire de la Côte d'Azur, Nizza;
USA: National Radio Astronomy Observatory, Charlottesville;
Deutschland: Kiepenheuer-Institut für Sonnenforschung, Freiburg;
Thüringer Landessternwarte Tautenburg;
Max-Planck-Institut für Radioastronomie, Bonn;
Max-Planck-Institut für Astrophysik, Garching;
ESO, Garching, als Partner des Instrumentenkonsortiums)

II.5 GEMS Sheds Light on Galaxy Evolution

Galaxy formation and evolution has always been a major issue of cosmology. But only since recent years it is possible to determine the redshifts of numerous galaxies out to large distances, and thus to early epochs, and to investigate their spectral and structural properties. Recently, astronomers at the Institute have contributed significantly to this research work with the COMBO-17 survey; in the year under report, they succeeded in achieving another breakthrough. Within project GEMS (Galaxy Evolution from Morphology and Spectral Energy Distribution) an international team under the leadership of MPIA produced the largest color image taken with the HUBBLE Space Telescope to date. It will help to determine the morphology of 10 000 galaxies whose redshifts are known from the COMBO-17 survey. Using these data, astronomers want to find out how large galaxies similar to our Milky Way system have evolved over the last seven billion years, that is over the second "half of life" of the universe.

In its early stages, the universe had been much smaller than today. Therefore the spatial density of galaxies had been higher and interactions between them occurred much more often. Close encounters and even mergers of galaxies took place continuously. In both cases strong gravitational forces acted on the interstellar gas within the galaxies, compressing it and whirling it around. This resulted in bursts of star formation, and in some cases increased amounts of dust and gas were directed into the galactic centers where it disappeared within a massive black hole, emitting high-energy radiation.

In the currently favored so-called hierarchical model of galactic evolution, these early interactions are the major cause for the formation of present-day large elliptical galaxies [2]. According to this model they grew to their present size by the merging of smaller galactic building blocks in the early universe. Most galaxies – including our own Milky Way system – therefore have had a very eventful evolution history. Now it is the time to decipher these "cosmic biographies".

Because of the finite travel time of light, with increasing distances of the galaxies one looks further and further back into the past of the universe. The distance of a galaxy can be derived from the redshift in its spectrum. In addition, the spectrum contains information on the stellar population and the total energy emitted by the stars. In the COMBO -17 project, this spectral energy distribution was not determined from spectra but from numerous direct images obtained through different color filters [1]. For this purpose, the astronomers used a wide-field camera developed under the leadership of MPIA and built together with ESO. Since several years, it is working at the 2.2-m-MPG/ESO-telescope on La Silla. From these images a special software determines the spectral types of stars and identifies galaxies of class E (elliptical) to Sc (spirals with high star formation rates) as well as star burst galaxies with unusually high star formation rates. Moreover, the redshifts (and thus the distances) of the galaxies can be determined down to a red magnitude of 24 mag with an accuracy of a few percent.

The COMBO-17 data go deeper by two magnitudes compared to earlier sky surveys with reliable redshift data in the corresponding distance range; consequently, about ten times more galaxies can be identified within a given volume (and thus within a given epoch). So this unique data set is perfectly suited to study the evolution of galaxies on a solid statistical basis.

These data, however, only yield information about integrated properties of the galaxies (age, distance, color and luminosity). A more complete picture is obtained when their inner structure is known, too: What is their size? Are their stars distributed in a disk or in a spherical volume? Are there extended star forming regions? Do the galaxies display an asymmetric brightness distribution due to interactions with other galaxies? Do they contain an intense central energy source? Statistically relevant answers to these questions can only be obtained when high-resolution direct images of a sufficiently large sample of distant galaxies are available. For large areas on the sky, currently such images can only be taken with the HUBBLE Space Telescope within a reasonable observation time.

Fig. II.24: GEMS, the largest color image taken with the HUBBLE Space Telescope to date, displays about 40 000 galaxies. Here, a section of 1 arcminute 14 arcseconds × 1 arcminute 46 arcseconds is shown, corresponding to 0.2 to 0.3 percent of the entire GEMS field.

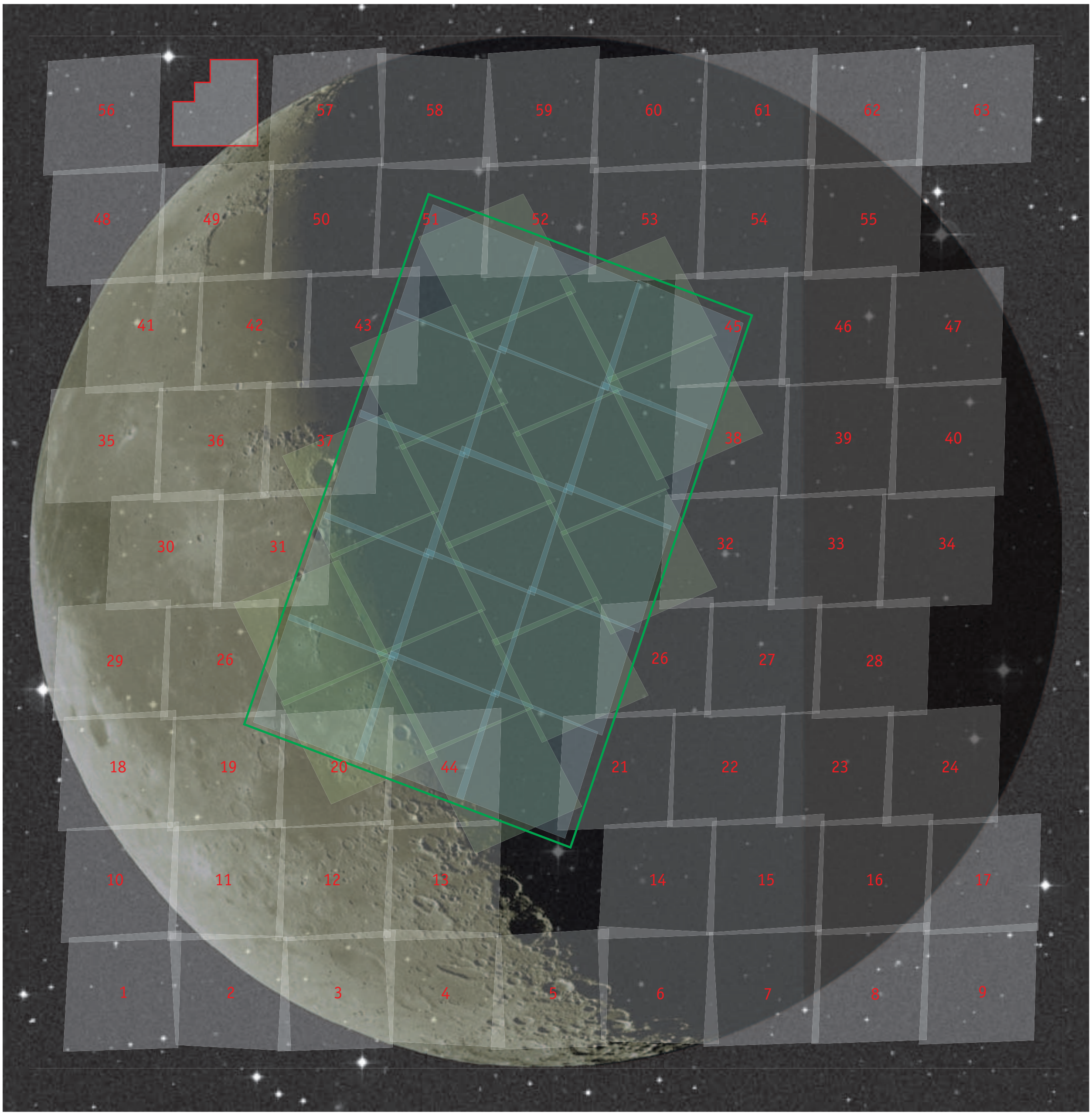
GEMS – Strategy and Analysis

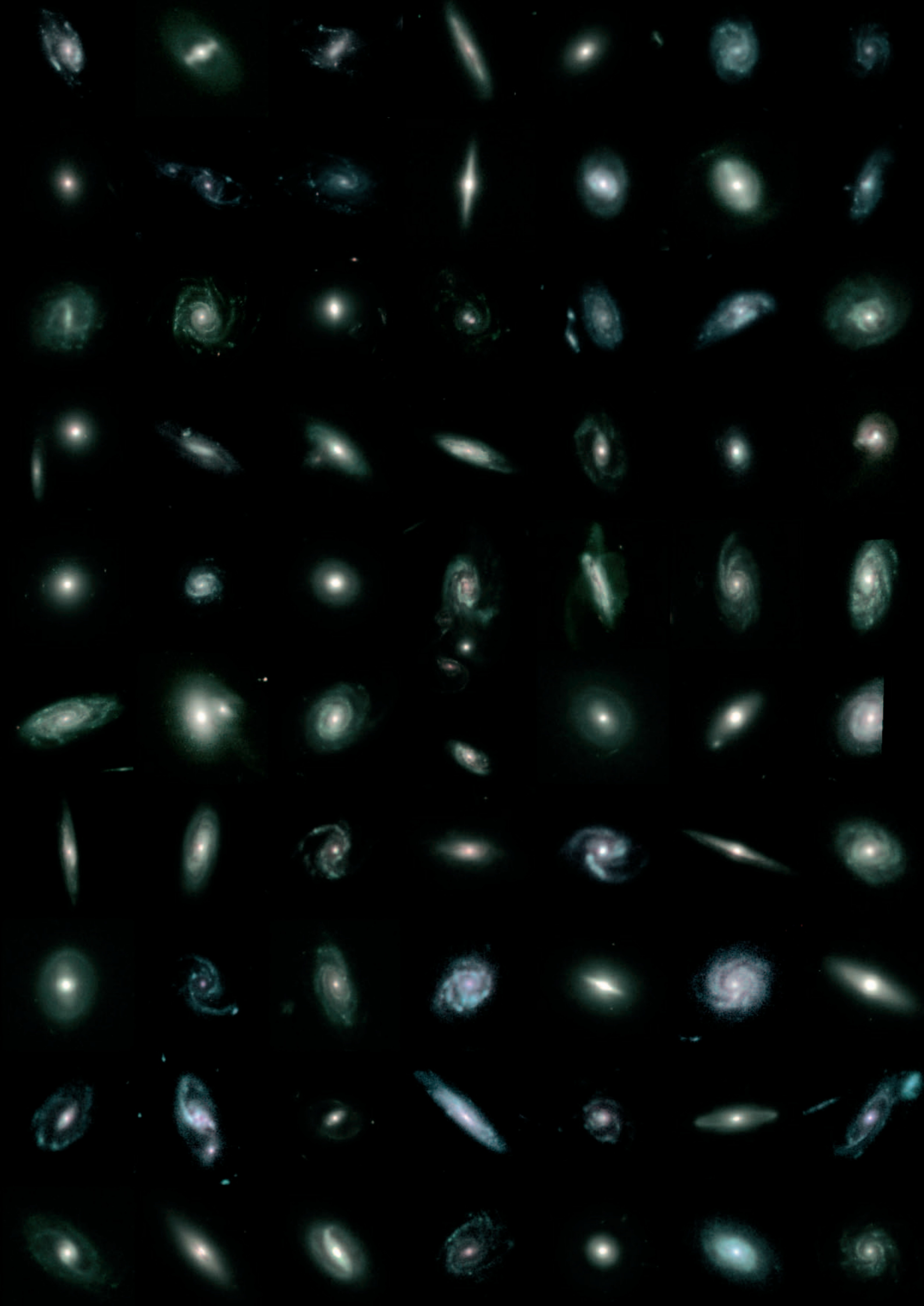
The field of the GEMS image lies in the southern constellation Fornax; its size is 30 × 30 arcminutes, corresponding to about the area of the Moon. The image (Fig. II.25) is a composite of 78 single exposures taken with the Advanced Camera for Surveys (ACS), each of which was obtained in two wavelength ranges around 606 nm (yellow) and 850 nm (red). The total exposure time of the image mosaic in both filters was 150 hours, keeping the HUBBLE Space Telescope busy for two entire weeks.

The field (Fig. II.25) had been chosen according to several criteria. Firstly, it had to be large enough to yield information averaged on the inhomogeneities of the universe (galaxy clusters). At the same time, it was positioned according to previous sky surveys. Firstly, as mentioned above, GEMS covers the COMBO -17 field (underlying sky image in Fig. II.25). Moreover, the field covered by the GOODS Survey (Great Observatories Origins Deep Survey) is marked by purple lines. This

Fig. II.25: Array of the numbered single exposures in the GEMS field. The data of the unnumbered fields come from the Great Observatories Origins Deep Survey, GOODS. All exposures together cover an area in the southern sky the size of the full moon.

Fig. II.26: Eighty bright galaxies in the GEMS field. The variety of shapes, sizes and structures – ellipticals, spirals, some of them with a distinct barred structure – and spectacular pairs and groups of interacting galaxies are clearly visible.





survey was also carried out with the ACS camera on board of the HUBBLE Space Telescope. It encompasses a smaller field than GEMS does, but it is deeper. The area marked in green will soon be observed in the infrared by the SPITZER Space Telescope (formerly SIRTF). Finally, the GEMS field lies within the CHANDRA Deep Field South that had been obtained in the X-ray regime by the CHANDRA Space Telescope within 278 hours of exposure time. The field marked by black lines (top left) shows the HUBBLE Deep Field for size comparison.

So this area offers unique possibilities to determine galactic properties in the spectral regions from X-rays to the infrared and to study galactic evolution over billions of years. The GEMS picture displays more than 40 000 galaxies with an excellent image sharpness (Fig. II.26 and II.27). The resolution in the two colors is 0.055 and 0.077 arc seconds, respectively. The image of an individual galaxy with redshift $z = 0.75$ shows details of 500 and 700 pc (1600 and 2300 light years), respectively. Thus, large star forming regions and other characteristic structures with sizes of a few kpc are clearly visible.

Fig. II.27: This section of the GEMS field shows two impressive pairs of interacting galaxies. At far greater distance a third pair can be recognized.

The high-resolution images of the galaxies in the GEMS field gain their unique significance only in combination with the spectral data of the COMBO-17 survey. In a first step it was possible to identify a total of 10 000 GEMS galaxies with objects in the COMBO-17 catalogue, thus ascertaining their redshifts (and thus their distances).

The redshift is of great importance also because it shifts the spectral properties (colors) towards larger wavelengths. Knowing the redshift allows to transform all color data into the rest frame of the respective galaxy. Only then the galaxies can be compared to one another. Finally, one wants to compare the galaxies of the early universe with the present-day ones. The characteristics of the galaxies in the present-day universe were taken from data of the Sloan Digital Sky Survey (SDSS) – another survey the MPIA is participating in [3].

This way, the prerequisites were created to analyze the GEMS image as regards galactic evolution. The evolution of individual objects cannot be observed directly as it takes millions of years, but the evolution of the galaxy population can be derived from the data since the properties of numerous galaxies at different redshifts and thus at different epochs can be compared statistically. In order to describe the galaxy population, the frequency of galaxies is determined as a function of certain fundamental quantities such as luminosity, color, size or morphology.

The GEMS/COMBO-17 sample of 10 000 galaxies is the first one that is large enough to provide data relating to the last half of the universe's age. A first result concerning the evolution of massive galaxies is presented in the following chapter.

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II.6 Origin and Evolution of Massive Galaxies

With the COMBO-17 and GEMS surveys, scientists at the MPIA have a unique astronomical data set at their disposal that can be used to reconstruct the evolution of galaxies over the past nine billion years. The large number of galaxies contained in it and the wide area of sky covered allow studies of unprecedented statistical significance. In the year under report, it was possible to confirm an important aspect of the hierarchical scenario of galaxy formation. According to it, the most massive galaxies, mainly the elliptical ones, were growing to their present-day size only during the past seven billion years. This happened primarily by mergers of smaller galaxies.

According to the hierarchical model galaxies of these types should have continuously grown over the past eight billion years (redshift $z < 1$). This prediction was already tested in 2002 by astronomers at MPIA. The central result then was: In the early universe, irregular and star burst galaxies with intense star formation contributed 80 percent of the luminosity density in the blue spectral region. In the course of time, however, the relative fractions have significantly shifted: At present, these galaxy types contribute only 20 percent of the luminosity density while elliptical and early spiral galaxies dominate.

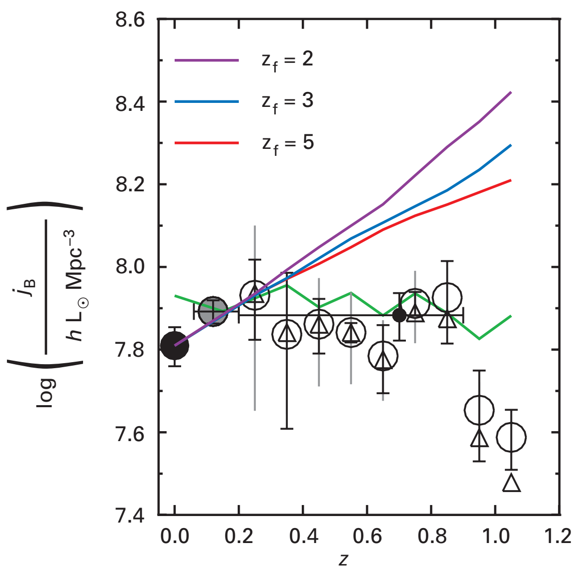


Fig. II.28: Evolution of the luminosity density of red galaxies in the blue spectral region. At large z (early epochs), the data deviate considerably from those models that claim that the galaxies have formed at high redshifts ($z_0 = 2, 3, 5$) and then slowly aged without further interactions. However, the data do confirm a semi-analytic model of hierarchical galaxy formation.

Although this result supports the hierarchical scenario it could in principle also be explained by the aging of the stellar populations in the galaxies and by reddening through dust. Therefore, the astronomers tried a different approach to tackle the problem of galactic evolution. They utilized the observational fact that galaxies can be roughly classified into two groups: red galaxies that include the early types (E, S_0 and S_a galaxies) without massive star formation, and blue galaxies that primarily include star-burst and spiral galaxies of types S_b and S_c. There is an additional interesting relation: galaxies appear increasingly redder with increasing luminosity. This is explained by the fact that the mass of the galaxies and their fraction of heavy elements are increasing with age.

In their most recent study the astronomers focused on the evolution of early-type red galaxies as a function of redshift (and thus of time). They found that the colors of the galaxies evolve with time. The data are consistent with passive aging of an ancient stellar population. But such an aging should also result in a decrease of luminosity for the individual galaxies and therefore for the entire population.

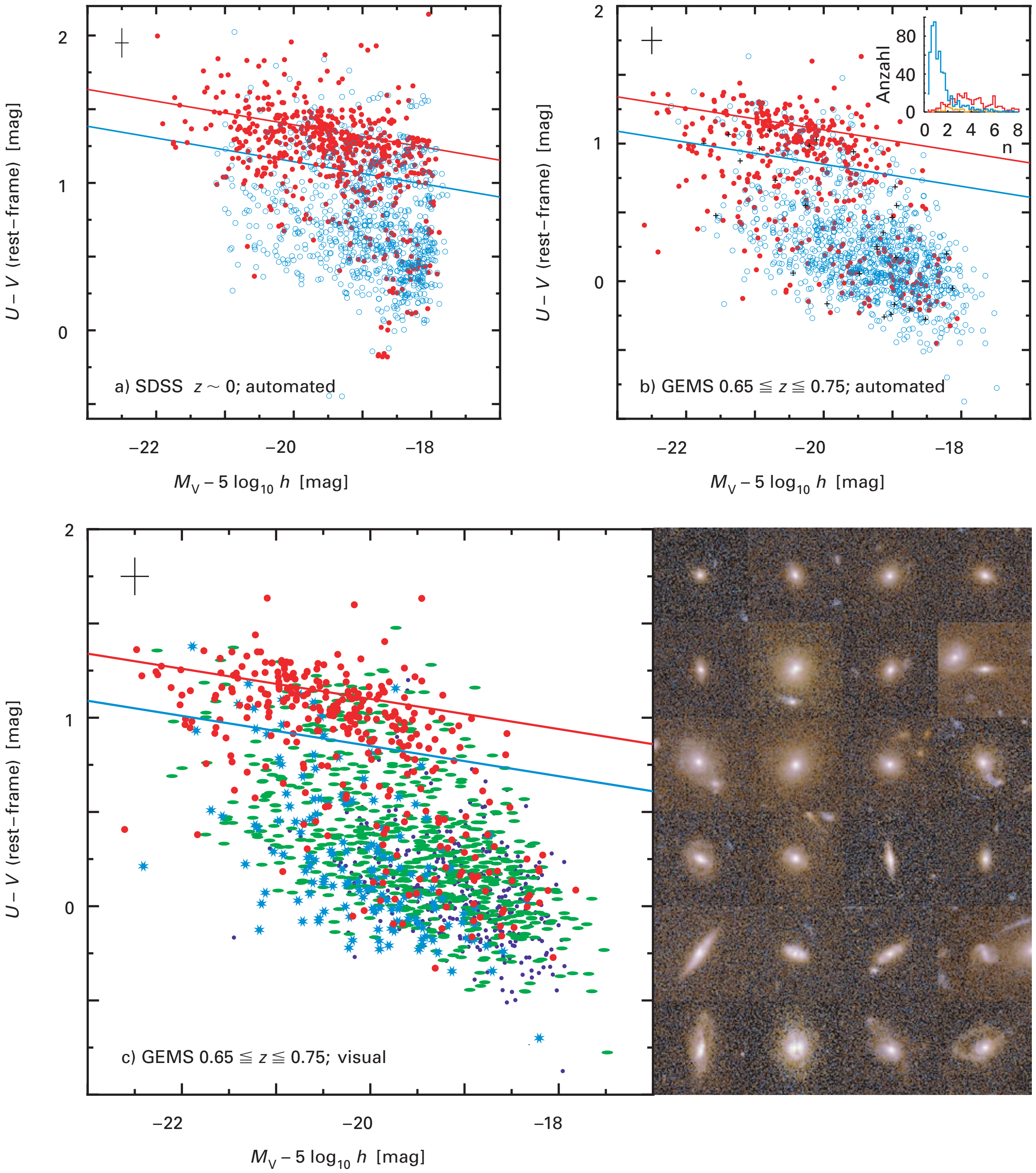
Contrary to this expectation the astronomers found the blue luminosity to be almost constant within a unit volume over the past eight billion years ($z < 1$) (Fig. 5). This finding is in disagreement with models claiming that the large galaxies in the early universe formed monolithically ("at one go") and then simply aged over billions of years (dashed curves in Fig. 5). Good agreement with the observations is obtained, however, if one assumes that the number of stars and their total mass in the luminous red galaxies have doubled within the observed time interval. This assumption is consistent with the predictions of hierarchical models claiming that the luminous galaxies have formed over time through mergers of smaller galaxies.

Analysis of the three COMBO-17 fields has shown, though, that inhomogeneities due to the large-scale structure of the universe are limiting the validity of the results. Therefore, it will be necessary for future studies to cover substantially larger areas to high redshifts.

So, these results show for the first time that the stars in the galaxies are aging passively but that the population of massive galaxies is evolving through hierarchical merging. Some questions still remain open, in particular that one concerning the nature of the red galaxies. Relatively nearby galaxies can be recognized as systems that contain mostly old and therefore red stars, as described above. More distant galaxies, on the other hand, where no details can be distinguished, might also be reddened by large amounts of dust.

Using the COMBO-17 data, about 1500 galaxies with redshifts between 0.65 < z < 0.75 have been identified in the GEMS image and their morphologies determined. This way, a statistically significant sample could be used to examine whether the morphology of early-type galaxies has changed over time until today. In particular, the role of dust in the reddening of the galaxies had to beexplored. The morphological classification was carried out both by eye on the monitor and automatically using a special software. The results were very similar as can be seen in Fig. 6. Blue dots denote late morphological galaxy types, red dots early ones. The red line shows a fit to the red galaxies, and the blue line discriminates blue galaxies from red ones. The sample of selected galaxies (bottom right) displays visually classified E and S0 galaxies (upper three lines), Sa to Sm galaxies (middle two lines), and interacting irregular galaxies (bottom line).

Fig. II.29: The U-V color of galaxies of different types in the present-day universe (a) and at redshifts around z = 0.7 (b: automated classification; c: visual classification). Blue asterisks: irregular and interacting systems; green: spiral galaxies. The colors are in the rest-frame of the galaxies.



Visually, 85 percent of the red galaxies were classified as early E, S0, and Sa galaxies while the software got 78 percent. Within their uncertainties, these values are identical to those for the present-day universe as they were derived from the Sloan Digital Sky Survey. Here, the value is 82 percent. The remaining red galaxies around $z = 0.7$ are highly inclined spirals (8 percent) and interacting irregular systems (5 percent; see also Fig. 6c). Thus, 13 percent of the red galaxies at most can be reddened by dust, although the fraction is probably much smaller.

The essential result is: Star formation in the most massive galaxies was completed already six billion years ago ($z = 0.7$). Hierarchical models predict galactic evolution in regions of high galaxy density to start early and to lead to massive galaxies. Current models, however, cannot explain why the evolution was completed so early.

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III Scientific Work

III.1 Massive Stars – Formation and Early Stages

The enormous influence exerted by massive stars on their environment even affects the evolution of entire galaxies. It manifests itself most strongly during their formation in molecular clouds and their deaths as supernovae. In this section we summarize the current research at MPIA about the formation of these fascinating objects. We examine how this knowledge has been achieved and how it can be extended with the help of the latest observational methods.

Massive stars dominate the optical appearance of a galaxy. In the far infrared spectral region, the most luminous galactic point sources can be identified with OB stars deeply embedded within the gas and dust clouds at their birth sites. How dramatic the effects of the formation of massive stars can be is best seen in starburst galaxies, whose structure is entirely determined by the almost explosive formation of OB stars

Compared to solar type stars, massive stars dominate the stellar input of energy and momentum into the interstellar medium. For instance, several lightyears from a main sequence star of spectral type O3 (luminosity ≈ 10^6 $L_\odot$), the UV radiation emitted by that star exceeds that of the interstellar radiation field in the solar neighbourhood by a factor of 1000. Stellar winds of O stars can reach mechanical energy rates within one percent of the stellar luminosity. Finally, at the end of their lives, massive stars deposit 10^{44} Ws of energy in the form of radiation into the interstellar medium during a supernova explosion. The kinetic energy of the expelled gas masses can exceed this value by a factor of 10, while the amount of energy carried away by neutrinos per second is even a hundred times larger, equalling the normal energy output of all stars in the whole Universe at that moment. During a formation »burst« of massive stars the interstellar medium of a galaxy can be heated by the stars' strong UV radiation, which eventually may even stop large scale star formation.

During their formation, massive stars can become rather »unpleasant« for their neighbours. On the one hand, their radiation ionizes and evaporates the gas and dust disks around nearby low-mass stars as well as smaller dark clouds. On the other hand, their birth can lead to the compression of molecular clouds and thus trigger a new round of star formation.

When considering the chemical evolution of a galaxy, it is massive stars again which dominate this evolution by enriching the gas with heavy elements whose abundances are crucial to the heating and cooling processes within the interstellar medium.

Having discussed the importance of massive stars for their environments and entire galaxies, the question now is: From which mass upwards is a star called massive? The lower mass limit can be set quite well to be 8 – 10 solar masses (i.e. main sequence stars earlier than spectral type B3). Only stars at least that massive are capable of producing enough UV photons to ionize the surrounding gases, to create supersonic winds and finally to explode as supernovae. Moreover, it is known that because the accretion phase is longer than the contraction period, newly forming massive stars are still deeply embedded in their parental molecular cloud. Therefore, no optically visible massive pre-main sequence stars are observed. This is in strong contrast to the low mass pre-main sequence stars – the so-called T Tauri stars – and to those in the medium mass range – the Herbig-Ae/Be stars.

The primary interest of the MPIA's Planet and Star Formation group is how these massive stars form: The formation of massive stars represents one of the major astrophysical problems, which is still unsolved despite the crucial role these stars play in the evolution of galaxies. The single key question is how these stars manage to accumulate that much matter during their birth process. Even while they are still undergoing accretion, they already exhibit very high luminosities. Indeed, modelling the accretion process of such objects showed that the radiation pressure on the infalling dust particles and the prevailing coupling between dust grains and gas molecules can stop or even reverse the mass infall. This occurs above a critical luminosity-to-mass ratio of about 700 $L_\odot/M_\odot$ – which is easily satisfied by very young massive stars. The formation of massive stars by spherically symmetric mass infall therefore seems improbable, unless the optical characteristics of the dust grains within the dense cores of the molecular clouds differ fundamentally from those in the interstellar medium and in low-mass star forming regions.

However, if the material is accumulated from a circumstellar disk – as it has been assumed for quite some time now –, this dilemma disappears. The reason is that due to the presence of a disk, a highly anisotropic radiation field is formed, with different energy flows parallel and perpendicular to the disk's axis. First evidence for such accretion disks was thought to be found in the bipo-

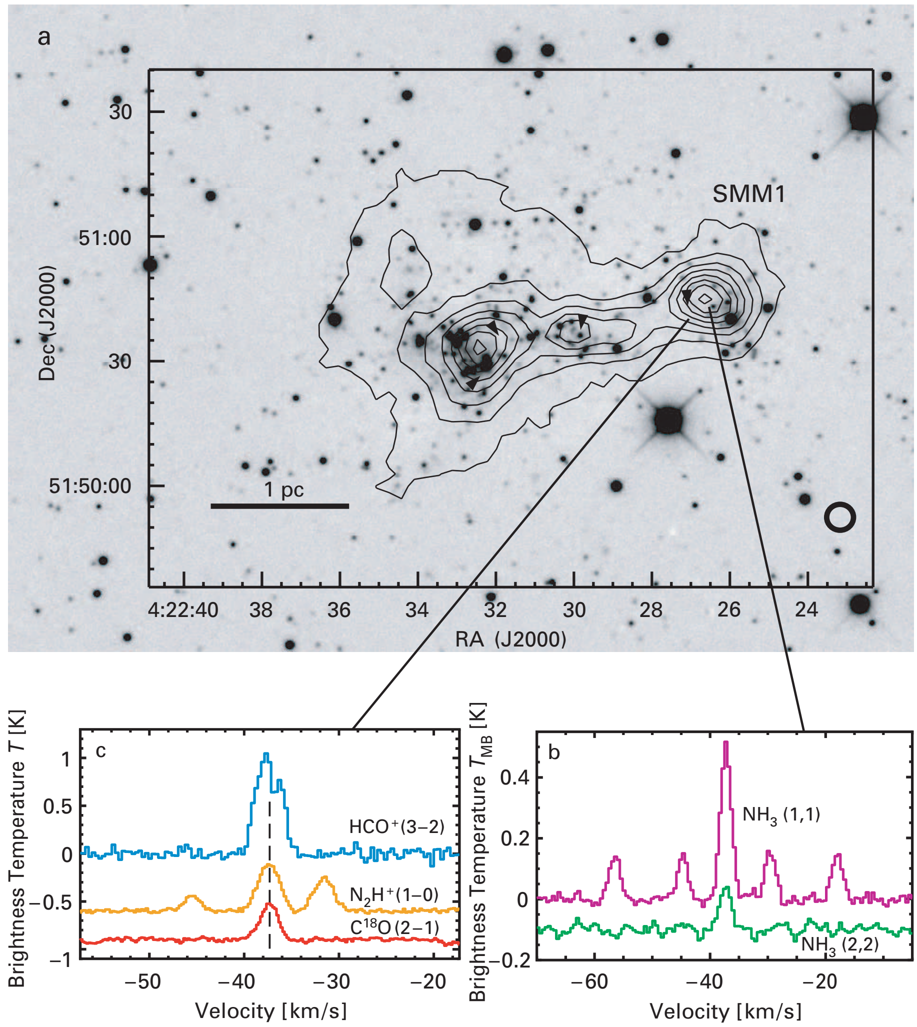


Fig. III.1: Map at 450 micron wavelength of the newly discovered massive star forming region ISOSS J 04225+5150, where three compact dust condensations can be seen. (SCUBA bolometer, JCMT)

lar morphologies of the ionized regions around some well known massive young stars, e.g. S 106. About 10 years ago, however, it was found that these regions usually are quite complex and that dusty filaments – not necessarily associated with an accretion disk – in the neighbourhood of the young massive stars often dominate the appearance of the immediate surroundings of the star. However, the most recent discoveries of very energetic and massive molecular flows probably connected to the accretion process, again support the notion of accretion disks around massive stars.

An alternative theory to explain the formation of massive stars is based on the merging of low mass stars. The »coalescence« scenario implies that tidal friction in close binary systems and dense clusters melt a number of low-mass stars into one high-mass star. The primary problem of this scenario is the prediction of a top-heavy »initial mass distribution function« (IMF), which is not observed in »normal« clusters, but may be present in starburst clusters (see Section II.1). The concept of coalescence may still play a role in massive star formation in very dense clusters, but indications such as the omnipresent outflows are in favour of a conventional accretion scenario for more typical galactic environments.

The Early Stages of Evolution

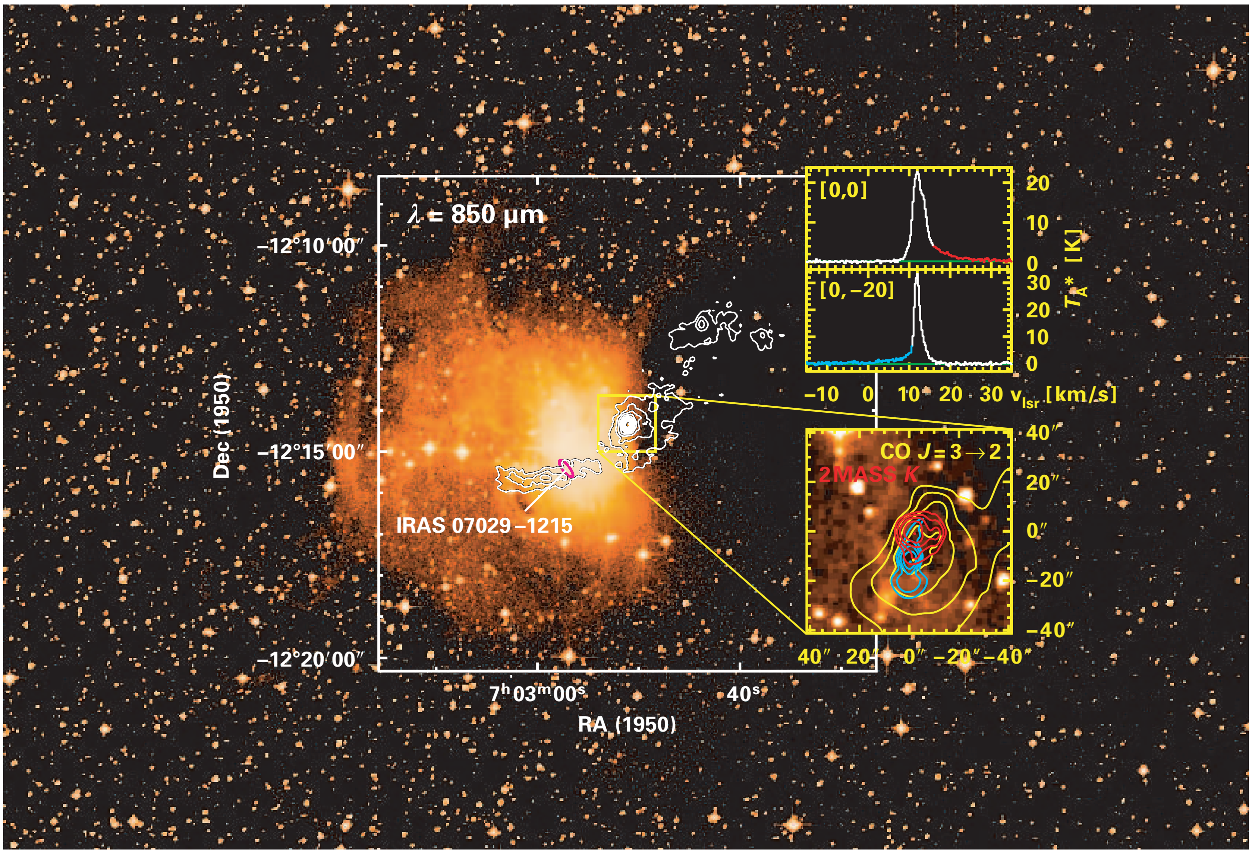
Cold Cores

The very earliest stage of star formation is the collapse of a molecular cloud to a protostellar object. These objects are rather cold and usually not detected at near- or mid-infrared wavelengths.

The best tool to find such cold and massive molecular cloud cores is an unbiased, large survey at far-infrared and sub-millimeter wavelengths. With more than 15 % sky coverage, the ISOPHOT 170 µm Serendipity Survey (ISOSS) is currently the largest survey performed beyond the IRAS 100 µm band at high spatial resolution. In this survey, more than 50 objects with masses of $10^2 - 10^4$ $M_\odot$ and bolometric luminosities of $10^3 - 3 \times 10^4$ $L_\odot$ have been identified so far. Although most objects are located at distances between 2 and 6 kpc, follow-up high-resolution submillimeter continuum maps at 450 µm, 850 µm and 1200 µm (obtained with bolometer cameras at the James-Clerk-Maxwell Telescope on Mauna Kea and IRAM 30 m telescope on Pico Veleta) could actually resolve the dust emission in the target regions (See Fig. III.1). Ammonia observations (VLA and Effelsberg 100 m telescope, Fig. III.2) of the targets confirmed that both dense gas and dust have the expected low temperature of ~ 12 K. The line profiles also indicate that the protostellar collapse already began in some of the objects (see the inverse P Cygni profile of the HCO+ spectral line in Fig. III.1c). Deep JHK images obtained with the new wide-field camera OMEGA 2000 at the Calar Alto 3.5 m telescope show associated low-mass clusters in a number of sources which indicate that active star formation has already begun in the vicinity of the cold cores, while the non-detection of any counterpart on our deep K-band images at the position of the core centers proves that the object is not yet in a more evolved phase.

Another survey for massive star formation (MSF) candidates was performed in the vicinity of bright IRAS sources using SCUBA and IRAM bolometers. These millimetre observations yielded the detection of a particularly interesting object (Fig. III.2): Near IRAS 07029-1215, an object with a luminosity of 1700 $L_\odot$ and located at a distance of 1 kpc, a deeply embedded object was discovered. This object appears to be in a particularly early evolutionary stage, since it has no detectable counterpart in the near or mid infrared. Yet, it is already driving a high-velocity bipolar CO outflow with a total mass of $M_{outflow} = 5.4$ $M_\odot$. Mass estimates and subsequent empirical relations as well as considerations of the spectral energy distribution (SED) point to the object being an early B star surrounded by an envelope of 30 – 40 $M_\odot$.

Fig. III.2: The far Infrared source IRAS 07029-1215 and the cold core detected at the edge of the molecular cloud. The lower right panel shows in blue and red contours the two wings of the outflow emanating from a source without any IR counterpart.



Hot Cores

The next stage in the evolution of a massive star towards the main sequence is the so called hot core stage. Here, massive stars are located within dense molecular cloud cores and - because of the high extinction – are neither visible in the optical nor in the near-infrared, but in the mid-infrared spectral region. These cores, however, are heated by the embedded or neighbouring massive stars to temperatures between 100 and 200 Kelvin, forming »hot cores« about 0.1 pc (0.3 light years) across, which have a density of molecular hydrogen of 10^7 particles per cm^3. Typically, in this stage the objects are not yet surrounded by greater amounts of ionized hydrogen. The formation of HII regions is possibly suppressed by the high rate of mass infall. This also means, that the youngest massive stars are only observable in the thermal infrared (IR) whereas due to the lack of plasma in their surroundings they do not emit radio continuum radiation. As shown in Fig. III.3, when observing the ultracompact HII region G10.47+0.03 with the TIMMI 2 instrument in the mid-infrared (MIR), an MIR-source was discovered close to the position of three ultra-compact HII regions, for which no NIR-counterpart exists. While the initial idea was that this might be a young hot core object, a more detailed analysis showed that it belongs to a different class of hot cores: It is not heated internally but rather by three adjacent ultracompact HII regions.

Ultra-compact HII Regions

During the next evolutionary phase of massive stars – now in or very close to the zero-age main sequence – »ultra-compact HII-regions« (UCHIIs) are forming around the young stars. In these ionized regions of about 0.1 pc diameter with electron densities of about 10^5 pro cm^3, electrons decelerating in the plasma emit strongly at radio wavelengths (free-free emission). Thus, these objects can be found by radio continuum surveys. These very compact objects have lifetimes of about one million years (see below). Eventually the regions of ionized hydrogen expand, forming »compact HII-regions« of 0.5 pc diameter and electron densities up to 1000 electrons per cm^3. These then evolve into »diffuse HII-regions« which are well known to us in the form of the Orion Nebula.

The UCHII regions are often themselves embedded in complex regions, such as IRAS 09002-4732, shown in Fig. III.4. The image, taken along with ISAAC observations at the VLT between 1 μm and 5 μm wavelength, shows a stunning view into the region dominated by a bipolar nebulosity and more than a thousand stars, reddened by the dust. The examination of the images led to the discovery of some highly elongated dark filaments, identified as obscuring strings of interstellar dust. These filaments, the length of which can reach up to 40 times their diameter, criss-cross in front of the nebulosity. The images open several exciting questions: Which forces confine these filaments? Are they remainders of the molecular clouds after violent episodes of star formation or, on the contrary, are they formed by newborn stars sweeping up the residual ambient dust? We identify several high-density knots inside the filaments: These objects might be short-lived unstable density fluctuations. However, they may possibly also be gravitationally collapsing globules and thus the precursors of a next generation of stars. The analysis of the near-infrared colours of the stars seen towards the infrared peak (see Fig. III.4) indicate that many of them have infrared excess emission. Such an excess usually rises from hot circumstellar dust around the young stars. As the circumstellar material is relatively short-lived, it is evident that these young stars are part of the star-forming complex.

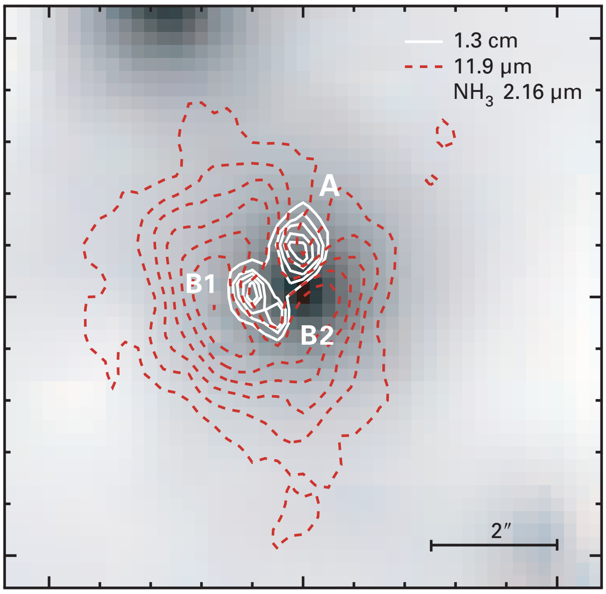


Fig. III.3: TIMMI 2 image at 11.9 μm (shown as dashed red contour) superimposed on the ISAAC image (grey scale) at 2.16 μm. The white contours indicate the three components A, B1 and B2 detected at 1.3 cm of the ultracompact HII region G10.47+0.03.

The long lifetime span of the ultra-compact HII-regions inferred from their great number – about 1500 such objects are known in the Milky Way – presents a real puzzle, as one would expect them to loose their ultra-compact form by expansion within approximately 10^4 years. To solve this problem, several scenarios have been proposed: a »fixture« of the regions by increased outer pressure, a stabilisation due to their motion with respect to the surrounding interstellar medium (developing a bow shock), the supply of ionized material by photo evaporation of circumstellar (or neighbouring) disks or globules, and, finally, a one-sided expansion at the edge of the molecular cloud (»champagne-flow«).

One major problem in distinguishing between these scenarios is the difficulty to actually identify the stellar population of ultra-compact HII regions. Only for about 8 years, adaptive optics (AO) systems have been available, which are able to provide sufficient spatial resolution at the dust-penetrating infrared wavelengths (~2 μm) to directly detect and identify at least part of the massive stellar population. In earlier times, and for regions still not accessible to AO systems (due to lack of guide stars), indirect methods were and are being used. These usually imply some budgeting of either the total mid- and far-infrared luminosity seen by IRAS or MSX, or Lyman continuum photons compared to the integrated free-free emission seen at cm wavelengths by radio interferometers. These indirect methods are burdened with strong problems: Usually they imply an assumption on the geometry of the region. Specifically, it is quietly assumed that the massive star(s) sit approximately in the centre of what is seen as the ultra-compact HII region. From the consequence that in such a case all emitted photons are converted to free-free emission and FIR radiation, the number of emitted photons and the spectral type of the emitting star are derived. However, if the radiation-supplying star is not in the centre, or if the ionized region shows an inhomogenious appearance (both of which are usually the case), the derived photon number will be too small. In reality, more photons are needed to heat and/or ionize the far-away and the peak-emission regions than estimated from the integrated fluxes alone. A catalogue paper published by our group which directly identifies the massive stellar population inside or in the vicinity of 9 ultra-compact HII regions from NIR colours shows that the indirect methods indeed usually underestimate the total luminosity output of the embedded stellar population (See Table 1). The catalogue is a result of an AO survey campaign carried out between 2000 and 2002 using the ALFA (Calar Alto, Spain) and ADONIS (La Silla, Chile) systems on their respective 3.5 and 3.6 m telescopes.

Object	Sp Type (NIR)	Sp Type (Lyman Cont.)	Sp Type (IRAS)
G309.92+0.48	> O6V / OI	B0.5V/B0V	O6.5V
G351.16+0.70	O6V	< B0.5V	< B0.5V
G5.89-0.39	O5V	O9.5V	O7V
G11.11-0.40	O6V	< B0.5V	B0V
G18.15-0.28	O6V	< B0.5V	O7V
G61.48+0.09B1	O9I/A0I	O9V	O8V
G61.48+0.09B2	B0V	< B0.5V	O8V
G70.28+1.60	O9I/A0I	O6.5V	> O3V
G77.96-0.01	O8V	< B0.5V	O9.5V

> = means „earlier than“, < = means „later than“

Table 1: The spectral types of embedded massive stars, as inferred from different observations.

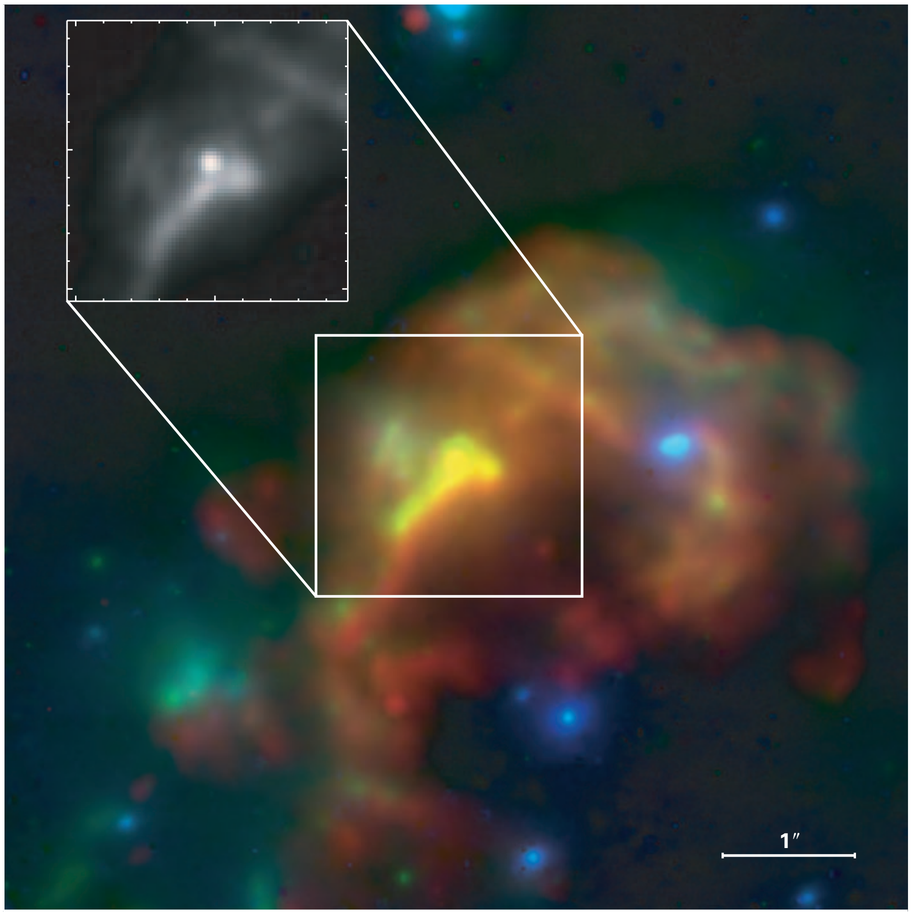
Fig. III.4: True colour image of G 268; J-band (1.2 μm) emission is coded as blue, H-band (1.6 μm) emission as green and K-band (2.2 μm) emission as red. The red circle marks the position of the ultracompact HII region G268.42-0.85.

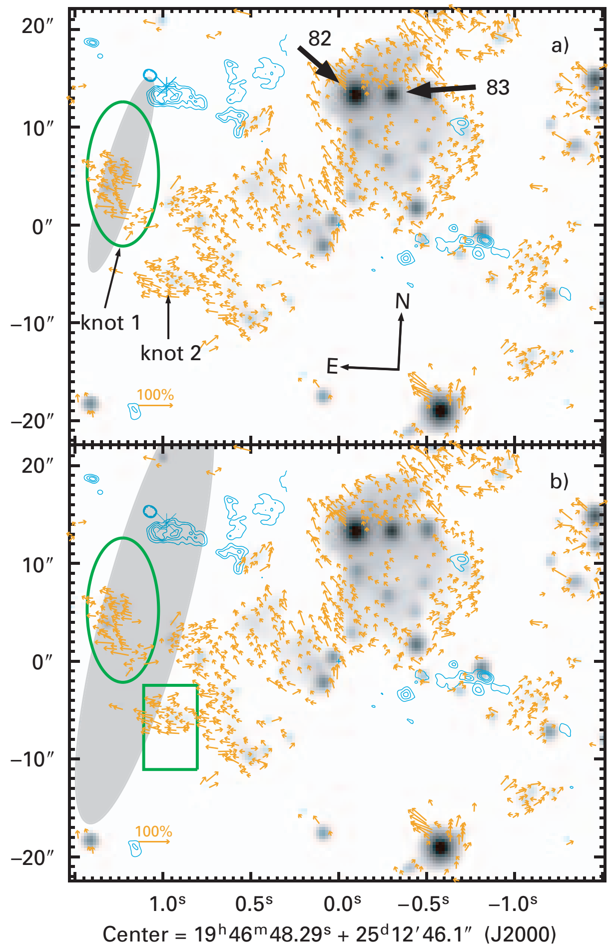
One possible explanation is that the most massive stars are usually not embedded in the centres of the ionized regions, but close to them. Consequently, a large fraction of the ionizing and heating (and in fact all) radiation »escapes« and can contribute to the formation of extended halos. Such halos are usually detected with the more compact configurations of the radio interferometers which are more sensitive to large-scale spatial distributions of emission than the high-resolution configurations used for detecting ultracompact HII regions. The fraction of luminosity actually used for ionization and heating of the IRAS and VLA objects then mimics a lower-luminosity star than actually seen in the Near Infrared (NIR). The external »illumination« has also been proven for at least one of the elongated structures close to the ultra-compact HII region G 268.42-0.85 (see Fig. III.4).

An alternative explanation is that with our NIR AO observations we are still missing the actual central stars of the ultra-compact HII regions. More deeply embedded stars may exist that become detectable only at even longer wavelengths or through different observational methods, such as polarimetry. These stars would then be responsible for most of the IRAS luminosity and the Lyman continuum budget, while the very massive ones we are seeing in the near-IR provide a huge luminosity which would be mostly escaping and contributing only a minor part to the overall appearance of the ultra-compact HII region.

Two examples show that this may indeed be the case: the spectacular discovery of the central star of the ultra-compact HII region G5.89-0.39 using NAOS/CONICA (NACO) at the VLT UT4 during an early commissioning run, and the detection of a hidden star in S 88 B2, which was first inferred from the polarization pattern of a reflection nebula about 5” away from the actual ultra-compact HII region. The star ionizing G5.89-0.39 was discovered in the L’-band at 3.5 μm. The star is embedded in ~70 mag of visual extinction and its K-L colour index is about 6 mag (See Fig. III.5). The presence of a star in S 88 B2 was later confirmed by a follow-up L-band observation with NACO within one sigma of the predicted position (See Fig. III.6). The same polarimetric observations indicate that more than one single star is contributing to the illumination of the western B1 part of the UCHII S 88 B, contradicting previous findings that one single object was dominating the ionization and illumination of S 88 B1. A re-calculation of the ionization and luminosity budgets taking into account

Fig. III.5: True-colour image of G5.89-0.39. L’ emission is shown in red, Ks emission in green and H-band emission in blue. The ionizing star candidate is at coordinate (0”,0”). The inset shows the L’ emission in square root scaling. Here, the central star is clearly visible.





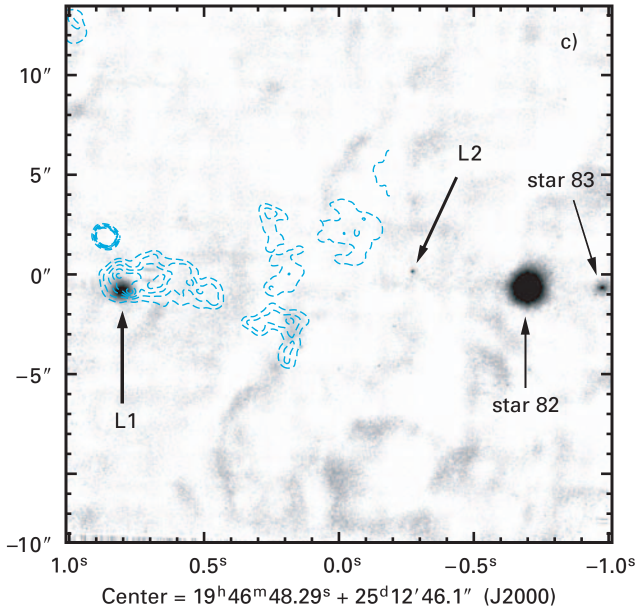


Fig. III.6 : a) and **b)**: Polarimetric pattern of scattered light in the S 88 B area. The dash-dotted ellipse marks the 1σ error of the position of a suspected illuminator calculated from the polarization pattern inside the yellow-framed areas. The contours denote 6 cm emission measured with the VLA. (c): L-band image taken with NACO. The illuminator close to the eastern ultra-compact HII region is clearly detected in this band (L1).

the detailed geometry of the region shows that also the photon budgets indicate the presence of more than one contributing massive star.

The discoveries described above illustrate that detailed modelling of ultra-compact HII regions with radiative transfer tools require the complete knowledge of the 3D geometry of the ionized regions, and also of the positions and spectral types of the ionizing stars. Only then, robust conclusions on the interaction of the radiation field with the molecular clouds, the »lifetime problem«, and actually the evolution of the young massive stars are possible.

Another interesting finding obtained from our AO data is that the stellar population in UCHII regions may not be as co-eval as one usually assumes. In three of the regions appearing in the catalogue, most profoundly in G61.48, spectral, luminosity, and colour analyses indicate that the most likely candidate for being the primary ionizing star is indeed a supergiant.

Outflows and Disks

Besides identifying the ionizing sources of ultra-compact HII regions it is of course important to directly observe disks surrounding and outflows emanating from massive young stars. A particularly interesting result was obtained in 2003 with the mid-infrared interferometric instrument MIDI on the VLTI. M8E-IR, a young B3 star, had one spectrally resolved visibility point measured during the first guaranteed observing time of MIDI. The visibility was measured along the major axis of an inc-

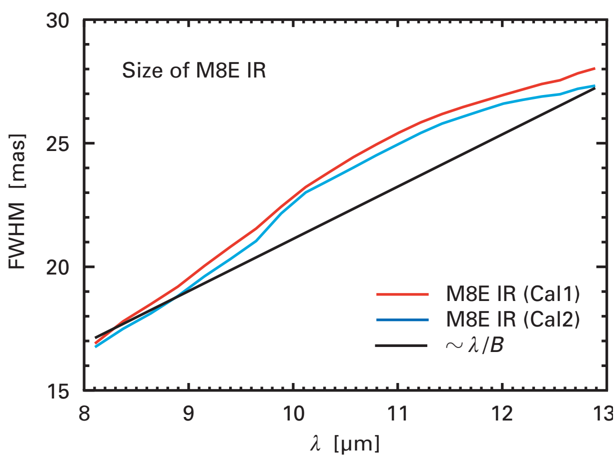


Fig. III.7 : Extension of M8E-IR, measured with MIDI at the VLTI. The measured size is increasing with wavelength. The visibility was measured along the axis predicted to be the elongated disk by Simon et al. 1985.

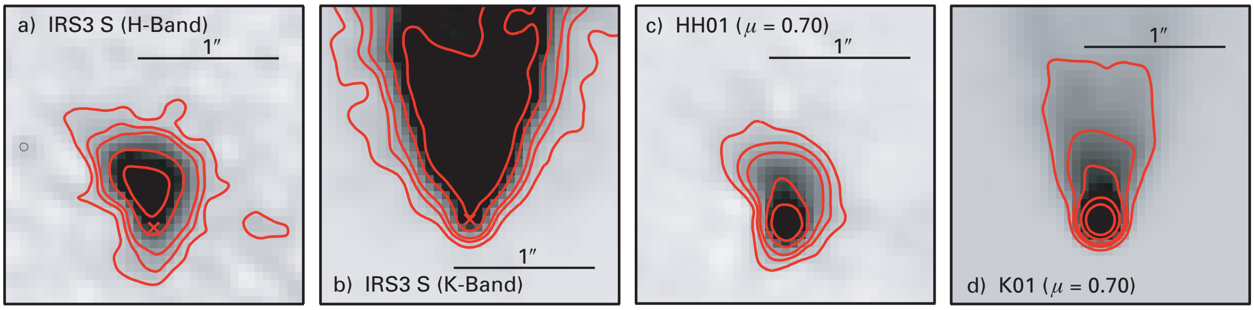


Fig. III.8 : Above (**a** and **b**) the observed sub-arcsecond near-IR nebula for Mon R2 IRS3 S; below for comparison (c and d) our scattering simulations. The orientation is such that the presumed cavity axis is along the vertical axis. The cross in the H-band images indicate the location of the embedded star.

lined disk that has been predicted to surround the star for almost 20 years. The fringe contrast of 0.2 which was measured at this orientation indicates an extension of about 21 mas (~30 AU at 1.5 kpc) at the observing wavelength of 10 µm (see Fig. III.7), a factor of two less than predicted from lunar occultation observations at 3.8 µm in 1985.

Star formation through disk accretion is usually associated also with the phenomenon of an outflow. Outflows can take the form of highly collimated jets that may help solve the angular momentum problem. This picture has mostly been developed for low-mass star formation. There are good reasons for supposing that this may not apply to the formation of the more massive OB stars. Although bipolar molecular flows are just as common, there are very few cases where highly collimated jets are seen. On the contrary, high resolution radio imaging has revealed a few cases where ionized winds are equatorial in nature, i.e. perpendicular to the bipolar molecular outflow.

A better knowledge of the circumstellar density distribution morphology can be inferred from the near-IR observations of the sub-arcsecond reflection nebula produced by light from the young star that is scattered off the dust in the cavity walls. However, no study up to now has covered a large sample of sources. Observations of the sub-arcsecond morphology over a large sample allows to address the questions of how frequent reflection nebulae and close companions are amongst massive young stars. In Fig. III.8, we show a comparison between NIR speckle data of Mon R2 IRS3 S obtained during a survey using MAGIC at the Calar Alto 3.5 m telescope and IRCAM 3 at UKIRT, and a Monte Carlo radiative transfer model of the light scattered back from cavity walls created by outflows. This indicates that the appearance of Mon R2 IRS3 S in the near infrared indeed is consistent with a cavity of 20° opening angle seen under an inclination of 45°. The model, however, can not reproduce the extension of the nebula in the two bands simultaneously. Special dust compositions in the surroudings of massive young stars or a truncated density distribution in Mon R2 IRS3 S may explain this discrepancy.

Conclusions

In 2003, great progress has been achieved at MPIA in the quest of understanding massive star formation. Successful observations of very young massive stars in the stage of a cold core and hot cores complement detailed observations of slightly later stages, in particular ultra-compact HII regions. Here, the identification of the ionizing and illuminating sources and the detailed study of the interaction between them and nearby molecular cloud structures has opened the way for much better modelling of these important and abundant objects. Finally, for the first time, the mid-infrared interferometer MIDI was applied to observe the immediate surrounding of a massive young star, M8E-IR, on scales of a few tens of AU. Indications of a disk have immediately been identified. Outflow cavities, the second important indicator besides disks for an accretion-driven formation mechanism for massive stars, have been observed on slightly larger scales using speckle interferometry.

It is clear that the riddle of massive star formation is not yet solved. However, our observational methods are getting closer to the very early stages of formation and the very immediate surroundings of young massive stars. Especially the mid-infrared interferometer MIDI has the potential to determine how frequently the young massive stars are accompanied by disks and/or outflow cavities. New 3D radiative transfer models will help interpreting the highly abstract data measured by interferometers, aided by input from 8 m telescope diffraction limited observations between 1 µm and 5 µm wavelength. With these methods, we can hope to determine the mechanisms and time scales of the early evolutionary stages of massive stars within the next few years.

(Carlos Alvarez, Daniel Apai, Markus Feldt, Thomas Henning, Oliver Krause, Ilaria Pascucci, Elena Puga; collaborating Institutes: Max Planck Institute for Radio Astronomy, Astrophysical Institute and Observatory of the Jena University)

III.2 Laboratory Astrophysics – a New Research Field of MPIA

Within a cooperation between the MPI for Astronomy and the Friedrich-Schiller-Universität in Jena, a new astrophysical laboratory was opened in Jena on February 12th, 2003. It is located at the Institute of Solid State Physics and is managed by Prof. Dr. Friedrich Huisken.

The objective of this joint laboratory astrophysics group is to investigate astrophysical issues by means of laboratory experiments and to support the interpretation of astronomical observations. This is done by using instrumentation that can simulate relevant astrophysical conditions as exactly as possible. Current work concentrates on the spectroscopic characterization of neutral and ionized polycyclic aromatic hydrocarbons in the gas phase and in ultra-cold helium droplets as well as on the study of optical properties of silicon nanoparticles, both isolated and embedded in solid matrices. While the first project is supposed to contribute to the identification of the diffuse interstellar bands the study of silicon nanoparticles should help to explain the „extended red emission“.

Introduction

Astrophysically relevant processes are based on a broad spectrum of elementary physical and chemical processes the knowledge of which is compulsory in order to draw scientific conclusions from astronomical observations. Of particular importance are the elementary processes attributed to physical chemistry: the behavior of atoms, molecules, clusters, nanoparticles and dust particles during collisions with each other and in radiation fields. Knowledge of these processes largely determines the interplay between observations and the mathematical-physical modeling of the structures and macroscopic processes. Just now, when a wealth of observational data is already available or expected for the near future, this knowledge is of increasing significance.

Because of the broad spectrum of processes involved, an interdisciplinary cooperation of astronomers, astrophysicists, physicists, chemists and perhaps even biologists offers the most promising approach. These considerations are relevant for research fields such as star formation, stellar atmospheres, the interstellar and circumstellar medium, aspects of solar physics or the study of comets. Recent results in astrophysics also open up perspectives for the evolution of terrestrial life.

The considerations mentioned above apply in particular to the research field dealing with the interstellar medium (ISM). Therefore, it seems appropriate for an laboratory astrophysics institution to devote its research essentially to the physics and chemistry of this medium.

An important goal of the activities of a laboratory astrophysics group should be to gain experience and to provide information that can be used to interpret the wealth of observational data increasingly obtained by ground-based and satellite-borne observatories. This way, the chemical composition and physical properties of the interstellar medium can be studied with the help of laboratory experiments. This is the only way to understand the elementary processes affecting the dynamical evolution of this complex system. In a further step, the knowledge obtained will also define new tasks for future missions.

In order to analyze and interpret the wealth of data in an optimum way, the physics and chemistry of various materials have to be studied under the conditions prevailing in interstellar space. In doing so, experimenters should focus on the investigation of collisions and reactions in the gas phase (regarding atoms, molecules, radicals, electrons, ions, and photons), on the characterization of large molecules (structure, dynamics, formation and dissociation mechanisms), and on the study of nanoparticles, dust particles, and surfaces (physics and chemistry). By investigating their optical properties under astrophysically relevant conditions, we hope to contribute to the elucidation of the diffuse interstellar bands (DIBs), the unidentified infrared bands (UIRs), and the extended red emission (ERE). Theoreticians will have to concentrate their efforts on fundamental theory (ab-initio calculations, collision dynamics, and theory of light scattering) and on modeling (chemical networks, radiation transfer, and simulations of spectra). Beyond astrophysics, the successful investigation of the processes described above will lead to a new understanding of the properties and interactions of matter under extreme conditions.

In what follows we will describe in more detail the various fields of research where laboratory experiments should be useful. New experimental methods and developments will be considered that should not be ignored by successful studies. However, we must first mention that it will be impossible for a small laboratory astrophysics team to deal with all those fields.

Collisions in the Gas Phase

Exact cross sections for energy transfer processes and reliable rate constants for chemical reactions are crucial for a significant modeling. Apart from a few exceptions, only insufficient data are available for the relevant temperature range below 80 K. As the rate constants are extremely temperature-dependent, especially adapted experiments are compulsory. At these low temperatures, only exothermal reactions with low or missing threshold in the entrance channel can be of any importance. These include in particular ion-molecule and radical reactions. In addition to the rate constant the kinetic energy of the initial products as well as the distribution of the internal energy is of great significance. Also related to these processes is photodissociation, also called half-collision, that is especially important in the radiation field of the ISM. The reverse process – radiative association – is also important at the prevailing low densities.

In order to carry out the intended measurements at low temperatures, molecular-beam experiments, matrix-isolation experiments combined with laser irradiation, and cooled ion traps are used. In recent years, dissociation and reaction experiments in cold and ultra-cold nanoreactors provided by rare gas clusters of argon (35 K) and particularly of helium (0.4 K) have turned out to be especially promising. Many systems that were investigated experimentally can also be studied theoretically; smaller systems can already be calculated with exact methods.

Large Molecules

The diffuse interstellar bands (DIBs) are currently the oldest unsolved puzzle of astronomical spectroscopy. Based on observational data it is known today that gas-phase molecules rather than dust particles are the carriers of the DIBs; but a definite identification is still missing. Carbon or hydrocarbon chains, polycyclic aromatic hydrocarbons (PAHs), and fulleranes are currently the candidates discussed most . Recent laboratory experiments at the NASA Ames Research Center indicate the PAHs to be particularly attractive candidates not only as the carriers of the DIBs but also of the unidentified infrared bands (UIRs). Despite significant progress, the spectroscopic properties, in particular of larger PAHs, under the extreme conditions of the ISM (isolated, cold, and in various charge states) are still mostly unknown.

There is evidence that PAHs are more common in the ISM than all other known interstellar molecules and that they contain 5 – 10 percent of the interstellar carbon. Models show that PAHs are playing a leading role in interstellar chemistry and are determining the charge state of interstellar clouds. This shows that, in addition to spectroscopy, many other properties and interactions with the surroundings (photoionization, electron recombination, photodissociation, chemical reactions, cluster formation and so on) have to be studied.

Mass-spectrometric studies on board of the STARDUST space probe have shown that interstellar dust particles also contain polymeric heterocyclic aromatics, which unlike the planar PAHs are forming three-dimensional structures (J. Kissel, MPI für extraterrestrische Physik). Detection of precursor molecules of all classes of substances (nitrogenous bases, sugars, phosphates, amino acids, and lipids), that are important for the biochemistry of living beings, in cosmic particles has lead to the speculation that terrestrial life could have originated from cosmic particles that came into contact with water on the surface of earth.

The characterization of astrophysically significant molecules, including supposedly simple molecules like water, methanol, ammonia, formic acid, et cetera, under the conditions of the ISM requires most modern laboratory analysis techniques. These include the matrix isolation spectroscopy combined with laser excitation in all wavelengths regions. However, there is more need for studies in the gas phase, which in many cases is difficult to access, though. Here, the laser vaporization technique as well as the embedding of large molecules in non-interacting nanoscopic helium droplets mentioned above can be used. Furthermore, experiments with mass-selected molecular ions in molecular beams and traps should be of prime importance. In order to understand the evolution of molecular clouds, it is compulsory to obtain information about the reactive and dynamic properties (formation and dissociation), the correlation between aliphatic and aromatic interstellar species as well as about the charge state of the molecules (neutrals, cations and anions).

Dust Particles and Surfaces

Today it is generally accepted that dust particles play an important role in the interstellar chemistry of dense clouds. This does not only apply to the production of molecular hydrogen but also to the catalytic synthesis of a number of larger hydrocarbons. The dust particles are often coated with ice, and in very dense regions the total supply of molecules may be deposited in a frozen state on the surfaces of dust grains. So obviously studying the interactions between interstellar molecules and the surfaces of dust grains is essential for an understanding of interstellar chemistry.

Laboratory experiments should also deal with the production of analog materials for cosmic dust particles. Silicates, carbon particles in various modifications, carbides, silicon nanoparticles and the ice particles mentioned above are of major importance. Spectra obtained with the Infrared Space Observatory (ISO) indicate a variety of both crystalline and amorphous silicate particles in circumstellar and interstellar environments. Carbon particles are presumed to account for the interstellar extinction at 217.5 nm and hydrogen-rich carbon particles to be the carriers of some UIR bands. But this remains still unproven, especially since the PAHs mentioned above are discussed as an alternative. A luminescence phenomenon, the so-called extended red emission (ERE), that is observed in numerous dust clouds is also attributed to nanoscopic dust particles. A promising explanation is based on the assumption that crystalline silicon nanoparticles with various size distributions account for this phenomenon.

When analog materials are produced in the laboratory the nanoparticles should be created under conditions as similar as possible to that prevailing in interstellar space. This is done mainly by methods based on particle growth in the gas phase, e.g. the method of chemical vapor deposition (CVD). Cooling could be achieved subsequently by transfer into a cryogenic matrix. Especially attractive experiments are conceivable for individual, electrically charged particles that can be stored in a Paul trap for a long time.

In discussing the optical properties of nanoparticles, the occurrence of quantum-mechanical effects should be taken into account that are caused by the localization of the electronic wave function. This may lead to properties that differ drastically from that of the solid body. Such a size effect was observed, e.g., for silicon nanoparticles used to explain the extended red emission (ERE). In order to study photoluminescence of nanoparticles it is desirable to use the most recent methods like single molecule spectroscopy, confocal microscopy, scanning microscopy, and ion-storage techniques.

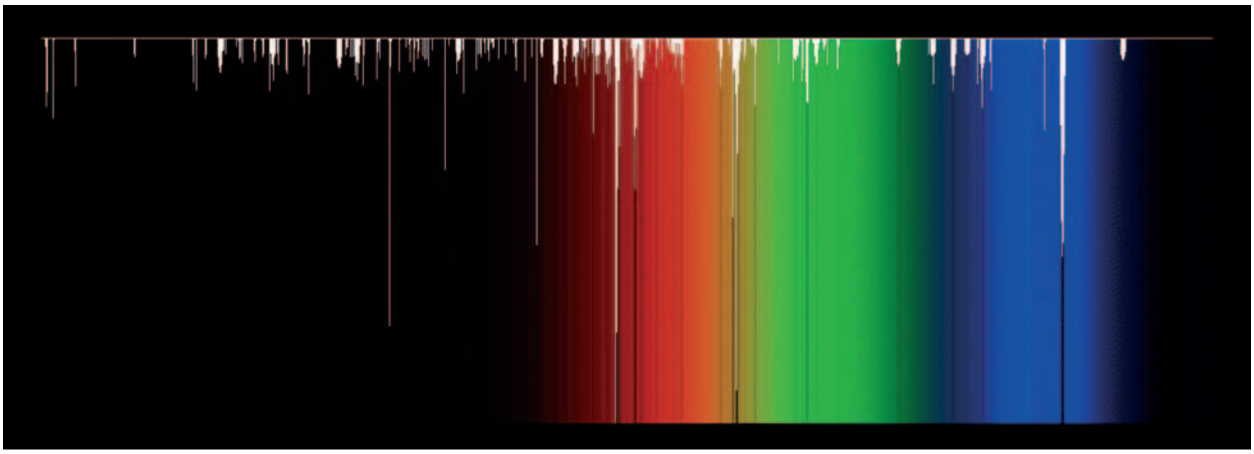
As emphasized above, the joint laboratory astrophysics group in Jena is only able to pick out and deal with some specific aspects of the „research catalog" described. However, complementary activities will be developed by cooperation partners in the Research Group „Laboratory Astrophysics" that is supported by the Deutsche Forschungsgemeinschaft. Thus, teams located at the TU Chemnitz are dealing with elementary astrophysically significant ion-molecule reactions, with the storage and uni-molecular dissociation of molecular ions or with spectroscopy of single silicon nanoparticles. The Research Group also includes three theoretical teams. One of them is also located at the TU Chemnitz and is dealing with the theory of the optical properties of silicon nanoparticles. Another theory group, at the TU Dresden, is conducting molecular dynamics simulations of the formation and reactivity of molecules and clusters. Finally, one of the projects of the Research Group is located at MPIA. It is dealing with the modeling of the chemical evolution of protoplanetary accretion disks, which is expected to lead to a better understanding of the initial conditions within the solar nebula and the formation of extrasolar systems.

The work of the joint laboratory astrophysics group of MPIA and the FSU Jena concentrates on three focal points: (1) absorption spectroscopy of neutral and ionized PAHs in supersonic jets, (2) spectroscopy of molecules in ultra-cold helium droplets, and (3) characterization of the luminescence properties of crystalline silicon nanoparticles. In what follows a more detailed description of the projects is presented.

Absorption Spectroscopy of Neutral and Ionized PAHs in a Jet

The diffuse interstellar bands (DIBs) are currently the oldest unsolved puzzle of astronomical spectroscopy. Being discovered already in 1920 in connection with work on the Henry Draper Catalog and their interstellar origin being established in 1936 by Merril, their definite identification is still missing. Surveys using sensitive CCD detectors showed that there are more than 300 of these absorption bands, their number increasing from year to year. The DIBs are located beyond 440 nm and extend into the near infrared; the highest band density is found between 540 and 690 nm. Fig. III.9 shows a spectrum published by Jenniskens and Désert, displaying the near-infrared and visible spectral region from about 1000 nm (left) to 400 nm (right). Within the colored spectral region black lines are visible that are produced – similar to the Fraunhofer spectral lines in the solar spectrum – by (in this case still unidentified) species along the line of sight absorbing light of the corresponding wavelengths. The plot is superimposed with the absorption

Fig. III.9: Spectrum of the diffuse interstellar bands. (P. Jenniskens and F.-X. Désert)



spectrum (white) that of course coincides with the black lines but in addition shows the strength of the absorptions. A zoom-in clearly shows the individual bands to considerably vary in strength and width, their full widths at half maximum ranging from 0.06 to 4 nm.

Most of the lines are too broad to be identified with atomic lines. Instead, molecules seem to be a better choice. However, taking into account the variety of the bands and the fact that their strengths are not correlated, rather indicating the presence of „families“ of bands, one soon realizes that they cannot be produced by a single molecule. Furthermore, the carriers of the DIBs appear to be gas phase molecules rather than dust particles. This is supported by the facts that the individual DIBs are located at a constant wavelength, that they do not show profile variations, and that they are unpolarized. In addition, at extremely high spectral resolution, the DIBs at 661.4 and 597.7 nm show fine structures similar to the rotational structure in electronic molecular spectra.

Some wrong tracks had been followed during the attempts to identify the DIBs. On the other hand, an effective way to synthesize fullerenes was found as a „by-product“ by Krätschmer at the neighboring MPI für Kernphysik in Heidelberg in 1990. Gas phase molecules that are possible carriers of DIBs should have the following properties:

1. Their synthesis should be possible under the prevailing conditions;
2. consistency with the cosmic abundances of the elements;
3. sufficient photo-stability to survive under the radiative conditions within the diffuse interstellar medium;
4. spectroscopic correspondence of their bands in position, shape and strength with the DIBs;
5. consistency of the spectral properties with observed astronomical variations caused by modified physical conditions (e.g., DIBs getting fainter in dense regions shielded from the radiation field).

Possible candidates meeting these criteria are saturated and unsaturated carbon chains C_nH_m ($n \ll m$), polyaromatic hydrocarbons (PAHs) as well as fulleranes. The laboratory astrophysics group in Jena is focusing on PAHs, currently the most discussed carriers of the diffuse interstellar bands. In their neutral state small PAHs absorb in the UV spectral range. Therefore, they are out of question as possible candidates. With an increasing number of aromatic rings, however, their absorption is shifting more and more towards the visible spectral range. Positively charged small PAH ions (PAH cations) on the other hand have absorption bands in the visible range even if they are small. Moreover, because of the external radiation conditions prevailing in space, a large fraction of the PAHs is expected to be in their cationic state anyway. Summarizing, it can be said that our attention should be directed to both larger neutral and smaller cationic PAHs.

For a significant comparison between laboratory data and astronomical observations the PAHs have to be prepared under astrophysically relevant conditions, i.e. at low temperatures and low densities. These are realized in a vacuum chamber into which an argon beam doped with PAH molecules is expanded. The PAH molecules are cooled to temperatures around 10 K by collisions with the argon atoms. Moreover, the expansion into the vacuum results in a drastic reduction of density so that already after a few mm the PAH molecules do no longer interact with one another or with the argon atoms. In order to minimize the use of vacuum pumps and to facilitate the production of ionized PAHs the expansion is carried out in a pulsed mode and matched to the repetition rate of the laser used.

Fig. III.10 shows a schematic cross section of the pulsed jet source used in Jena. An electromagnetically driven plunger opens the nozzle on an electric pulse allowing the argon gas to expand into the vacuum. The

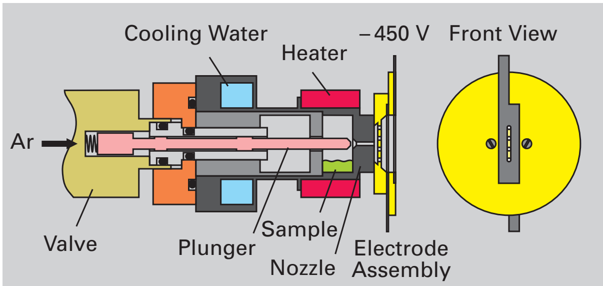


Fig. III.10: Schematic view of the pulsed supersonic jet source. The PAH molecules are contained in the sample in a crystalline form. The electrode assembly is only installed when PAH cations are to be studied.

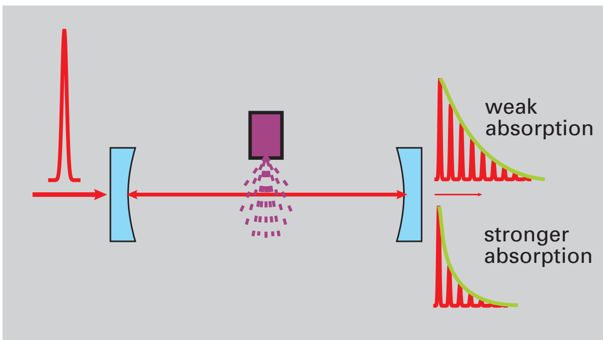


Fig. III.11: Principle of the cavity ring-down spectroscopy (CRDS).

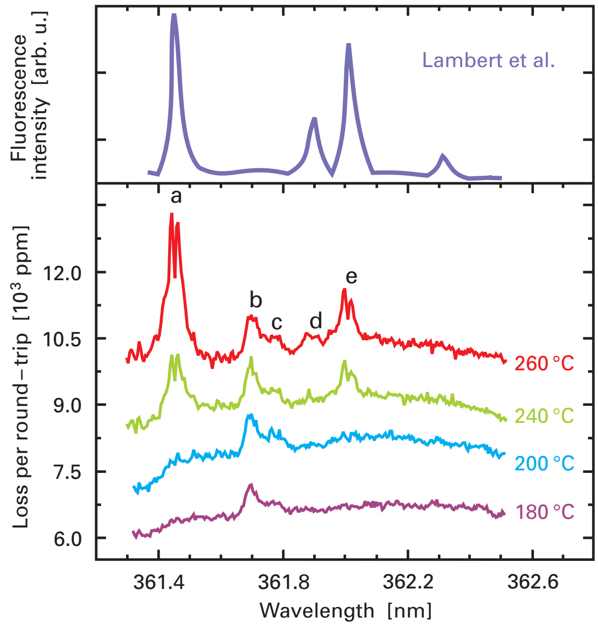


Fig. III.12: CRD spectra of the neutral anthracene molecule taken in the expansion of a supersonic jet on the red side of the 0 ← 0 band for different nozzle temperatures. For comparison with the absorption measurements, the upper frame shows a LIF spectrum obtained by Lambert et al.

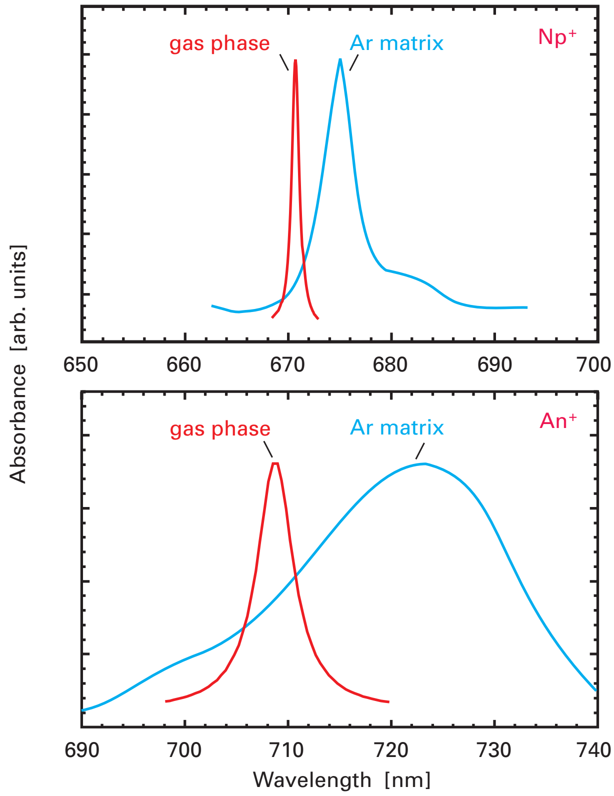


Abb. III.13: Gas phase absorption spectra of naphthalene (Np^+) and anthracene (An^+) cations (red curves) taken with CRDS in comparison to Ar-matrix data (blue curves).

PAH molecules (sample) are vaporized by a heating system and thereby added to the argon carrier gas. This way (without the electrode assembly depicted on the right hand side) a supersonic jet is produced that is rapidly cooled and diluted downstream of the nozzle exit. The electrodes are used to produce PAH cations by applying a voltage of about – 450 V to the outer electrode. This way a plasma is created in which a considerable fraction of the PAH molecules is ionized by collisions with metastable argon.

The absorption behavior of neutral or ionized PAH molecules is studied using a laser beam which interacts with the molecules a few mm downstream from the nozzle exit (or the electrode assembly). Here a direct absorption method is used, the so-called cavity ring-down spectroscopy (CRDS). This extremely sensitive method works in the following way: the pulsed laser beam interacting with the molecular beam is reflected many times within a resonant cavity of very high quality. Every time the laser pulse hits the back mirror a small fraction is transmitted, amplified by a photomultiplier and finally recorded by an oscillograph or transient recorder. The resulting waveform, whose envelop curve is decreasing exponentially, is shown in the schematic representation of Fig. III.11. If the laser beam is absorbed on its way through the cavity by a gas the curve is decaying more rapidly than without absorption. So the absorption cross section can be derived directly from the decay time using a simple formula. By tuning the laser across a certain spectral region, the absorption spectrum of the molecular beam is eventually obtained.

One of the first PAHs that we studied was the neutral anthracene molecule (An; $C_{14}H_{10}$). This molecule comprises three aromatic rings arranged in a row. The electronic absorption spectrum shows a strong band at 361.176 nm corresponding to the $S_1(0) \leftarrow S_0(0)$ transition. It displays a temperature-dependent splitting from which the rotational temperature of the anthracene molecule can be derived. Of special interest, however, is the spectral region shifted further to the red that is shown in the lower half of Fig. III.12. The bands that are showing the same splitting as the main band (bands a, d, and e) are attributed to transitions from vibrationally excited states. Their presence proves that the vibrations are not yet frozen in the expansion. The two remaining bands (b and c) are assigned to two different isomers of the An•Ar van-der-Waals molecule that is also formed in the expansion but is of no astrophysical relevance. The temperature dependence shown in Fig. III.12 has helped us with the assignment. The intensity of the hot bands (a, d, and e) increases with temperature while that of the van-der-Waals complexes is almost constant. The curve shown in the upper frame of Fig. III.12 has been measured by Lambert et al. in a neon expansion using the method of laser-induced fluorescence (LIF). Of course, the An•Ar complexes are missing here. Furthermore, the hot bands do not show any splitting which may be due to the lower resolution or the different expansion conditions. But all in all, there is good agreement. A priori this is not selfevident since our method directly determines the absorption of the anthracene molecule while the LIF method is sensitive only to transitions that subsequently emit light of longer wavelengths. Summarizing the results, it can be said that, although the neutral anthracene molecule cannot help to explain the DIBs because its absorption bands are in the UV spectral range, it is an excellent test molecule that can be used for testing the spectrometer and for obtaining information about the temperature in the molecular beam.

In order to determine the absorption spectra of positively charged PAH ions, the electrode assembly described in Fig. III.10 was used. As our first cation we chose the smaller relative of anthracene, naphthalene, consisting only of two aromatic rings, since it had already been studied by other authors. The spectrum we obtained was in excellent agreement with earlier results. This encouraged us to carry on with the anthracene cation (An^+) that had not been studied before, its absorption bands therefore being unknown. With a sufficiently high source temperature we actually succeeded in obtaining reproducible spectra. The results will be discussed in the following with the help of Fig. III.13.

In Fig. III.13, the absorption bands of Np^+ and An^+ measured by us with the CRDS method in a supersonic jet (red curves) are shown and, for comparison, spectra obtained before in argon matrices (blue curves). Matrix spectroscopy is an elegant technique to freeze astrophysically relevant molecules at low temperatures and to study their spectra, but the results obtained are of low significance regarding the identification of DIBs since the molecular absorption bands are both shifted and broadened considerably by the interaction with the matrix. This fact is clearly visible in Fig. III.13. For An^+ we read a shift of 13.6 nm, and the matrix spectrum is broader by a factor of five.

Although the An^+ absorption measured by us is much narrower than that observed in the argon matrix, it is still too broad to correspond to any band from the published DIB spectra. There is a DIB at 708.7 nm being very close to the An^+ band (708.76 nm), but the latter is too broad by a factor of 20. Nevertheless, one should not be rash in discarding the anthracene cation as a possible DIB candidate. With the naphthalene cation (cf. Fig. III.13, upper spectrum), the situation was quite similar at first. Only after a detailed search, Krelowski et al. found interstellar absorption bands that were very close to the spectra taken in the laboratory and that showed similar widths. So we would recommend to astronomers to also search the spectral region around 710 nm in the surroundings of those stars in which some coincidences with the Np^+ spectra were found..

A certain problem with the experiments carried out in the expansion of a supersonic jet is the fact that, although translation and rotation of the molecules are cooled down to astrophysically relevant temperatures, the vibration is characterized by significantly higher temperatures. It is still unknown, though, to what extent the increased vibrational temperature affects the shapes of the absorption bands (in particular their widths), but it would be advantageous to be able to freeze the vib-

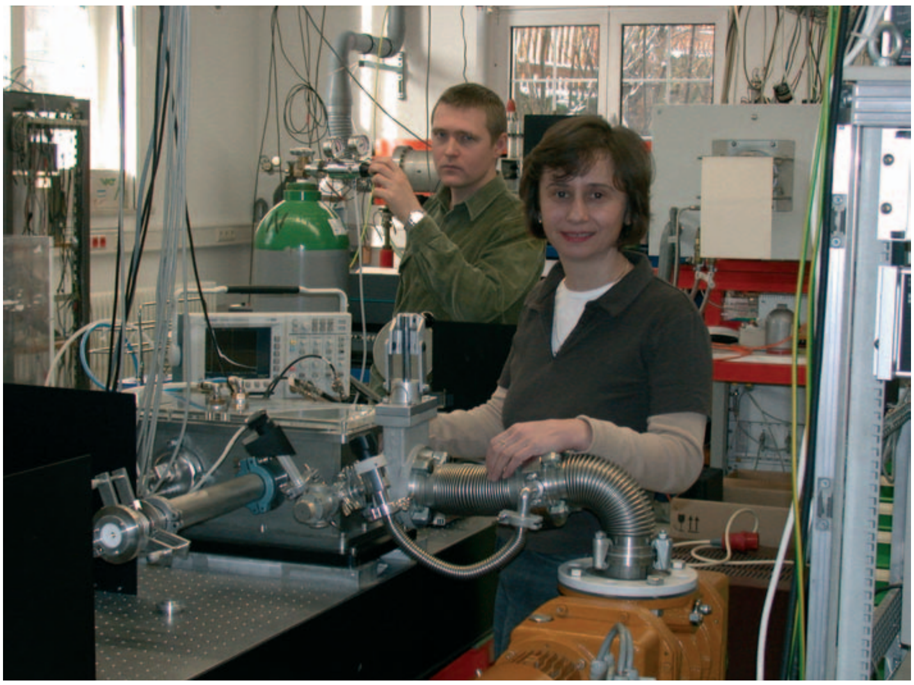


Fig. III.14: The CRD spectrometer with co-workers Dr. Angela Staicu (in front) and Oleksandr Sukhorukov. One can recognize the rectangular vacuum chamber that houses the pulsed supersonic jet source and the resonator arm pointing forward. The laser beam is coupled through the highly reflective mirror behind the white Teflon pinhole.

rations too. A suitable technique capable of this will be presented in the following chapter. Fig. III.14 shows a photo of the cavity ring down spectrometer operated in Jena and the colleagues participating in this project, A. Staicu and O. Sukhorukov.

(E. Diegel, Th. Henning, F. Huisken, G. Rouillé, A. Staicu, O. Sukhorukov)

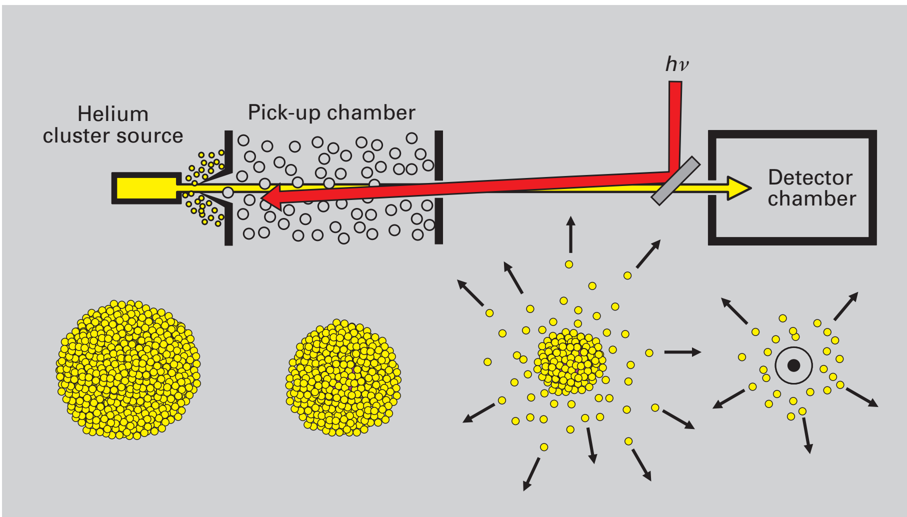
Spectroscopy of Molecules in Ultra-cold Helium Droplets

Matrix spectroscopy was mentioned in the previous chapter. With this technique, molecules to be studied are frozen into rare gas matrices (mainly argon and neon). Typical working temperatures range between 8 and 25 K. A particular advantage of this method is the fact that molecules and matrix are in equilibrium. In contrast, jet experiments have the disadvantage that the temperature characterizing the vibration is generally significantly higher than that of the other degrees of freedom (translation and rotation). Another advantage of matrix spectroscopy is the possibility to work also with materials of low vapor pressure since the molecules can be „collected“ for a longer time. Unfortunately, these advantages are partly compensated by a serious disadvantage. The van-der-Waals interaction of the molecules with the surrounding rare gas atoms causes a considerable shift of the molecule‘s absorption lines that can easily amount to several hundred wave numbers. Moreover, the spectral lines are significantly broadened by the interaction. As a result of both effects, as already discussed along with Fig. III.13, a comparison between matrix data and astrophysical observations is not at all meaningful.

In order to minimize the interaction between molecule and matrix, the rare gases used in conventional matrix spectroscopy, argon and neon, should be replaced by helium. Unfortunately, this cannot be done in a standard way since under normal or low pressure conditions helium does not exhibit a solid phase. An elegant method to still use helium as matrix material is to embed the molecules to be studied in nanoscopic liquid helium droplets that are traversing a vacuum apparatus in form of a molecular beam. This method, pioneered by Scoles and Toennies and their teams, was already used to spectroscopically characterize a number of molecules.

The principle of spectroscopy in helium droplets is explained with the help of Fig. III.15. In a multi-stage vacuum apparatus, helium gas is expanded at high pressure (p = 20 – 40 bar) through a cooled nozzle (T = 10 – 20 K) with a diameter of 5 mm. Under these conditions, strong cooling takes place so that the gas condenses and forms nanoscopic droplets consisting of hundreds or even thousands of helium atoms. These droplets – also called clusters – propagate in the form of a „molecular beam“ towards the detector. The helium droplets cool down on their own as helium atoms evaporate until the characteristic temperature of 0.4 K for helium clusters is reached. In a differential chamber, the so-called pick-up chamber, the molecules to be studied (M) are transferred into the gas phase by heating their respective powders. When they get in contact with the helium droplets they stick to their surface and subsequently migrate into their interior because this is energetically more favorable. The energy released in this process is given off by evaporating a certain number of helium atoms so that the original temperature of 0.4 K is very rapidly restored. In the further course of the experiment, the helium cluster beam interacts with a laser beam. If the laser is tuned to a molecular resonance the photons are absorbed by the

Fig . III.15: Principle of spectroscopy in helium droplets. In the pick-up chamber, PAH molecules (depicted as purple spheres) are incorporated into the helium droplets and excited by a laser, which leads to the evaporation of He atoms.



molecule and, as a result, some hundred helium atoms are evaporated anew. Eventually, the helium droplets and the incorporated molecules are detected in the detector chamber using a mass spectrometer.

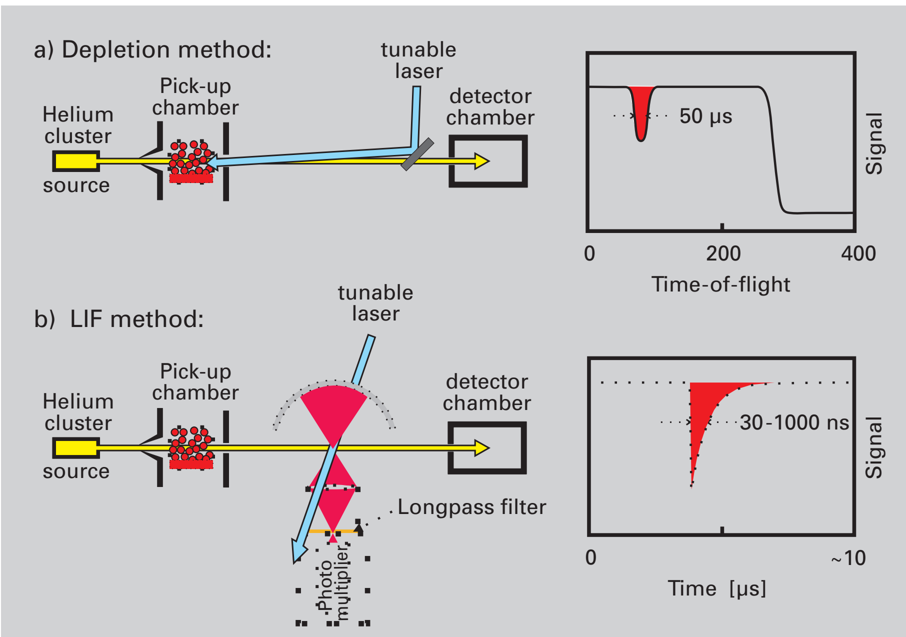
Usually, there are two possibilities to perform the spectroscopy (sketched in Fig. III.16). With the depletion method, the absorption is detected by a depletion of the signal measured on the mass of the ionized molecule (M^+). The depletion is caused by the facts that when absorption took place the molecular beam is widened so that fewer molecules pass through the detector aperture and that the ionization probability has decreased because of the reduced diameter of the helium cluster. The second spectroscopic method (LIF method) utilizes the fact that part of the energy transferred to the molecules by the laser photons is re-emitted in the form of (longer-wave) photons. However, this method – called laser-induced fluorescence (LIF) – can only be used in combination with electronic excitation. It should be mentioned that, in principle, both methods (depletion and LIF) can be used simultaneously but are somehow complementary. Thus, it is possible that in specific systems only one or the other technique may be employed appropriately.

The following will summarize the advantages of the spectroscopy in helium droplets. Helium droplets provide an ultra-cold nanoscopic and suprafluid matrix with a constant temperature of 0.4 K. As a matrix, helium interacts only weakly with the chromophore molecules so that the induced matrix shift is minimal. As opposed to conventional matrix spectroscopy, the experiments are carried out in a molecular beam. So it is possible to use a mass spectrometer, thus achieving additional selectivity. By extending the interaction zone, the pick-up time can be prolonged which allows to study even molecules whose solid phase is characterized by low vapor pressure. Gas pressures of the order of 10-6 mbar will be sufficient. Finally, the possibility to use both depletion spectroscopy and LIF considerably extends the range of applicability of the helium droplet method. So molecules that are characterized by a short radiation life time can be studied very sensitively using the LIF technique. On the other hand, molecules that do not fluoresce at all, e.g. large PAHs, can be detected with a mass spectrometer using the depletion method.

It should not be concealed, however, that helium-droplet spectroscopy has some disadvantages that shall also be listed here: As in conventional matrix spectroscopy, absorption bands are shifted due to effects caused by the helium matrix. But since the interaction of the molecules with helium is much weaker than that with neon or even argon the shift is much less pronounced. And as in conventional matrix spectroscopy, the absorption bands also show a broadening, although it is considerably smaller. Finally, with higher laser power a new phenomenon occurs in helium-droplet spectroscopy, which is characterized by the so-called phonon wing. The phonon wing consists of an absorption profile extending over 30 cm^{-1} that is shifted by about 5 cm^{-1} from the actual molecular transition towards higher energies. It occurs because internal modes of the supraliquid helium droplet (rotons and maxons) can be excited together with the excitation of the molecule. In spectra that are not too complicated, the phonon wing can be taken into account. Usually, it does not occur at all when continuous lasers are used.

The first PAH molecules we studied in detail were the anthracene and tetracene molecules. Their structure consists of three and four benzene rings, respectively,

Abb. III.16: The two spectroscopic techniques used by us to study PAH molecules in helium droplets: depletion (a) and LIF (b).



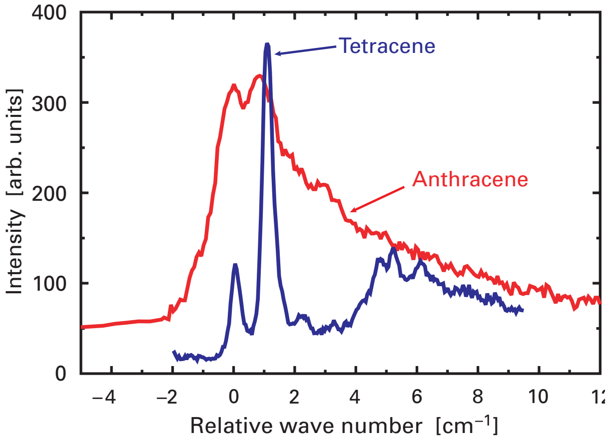


Fig. III.17: LIF-spectra of the PAH molecules anthracene and tetracene in helium droplets.

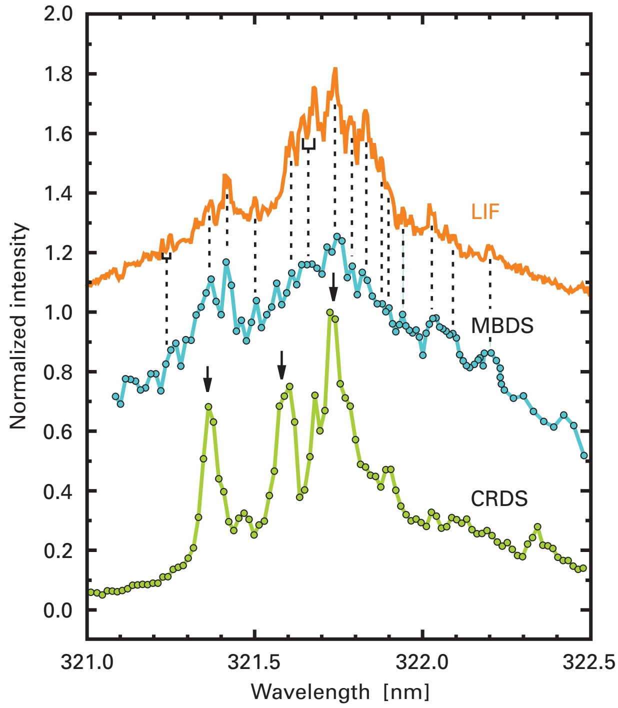


Fig. III.18: Three absorption spectra of the pyrene molecule, measured in He droplets with the LIF as well as the depletion method (MBDS) and in the gas phase (CRDS). The CRDS spectrum was shifted by 0.8 nm towards longer wavelengths.

arranged in a row. Fig. III.17 shows a comparison of the two absorption spectra measured with LIF, that can be assigned to the respective $S_1 \leftarrow S_0$ transitions. The band origins of these transitions are at 27627.4 cm^{-1} (362.0 nm) for anthracene and 22295.8 cm^{-1} (448.5 nm) for tetracene. The band origin of tetracene displays a splitting of 1.1 cm^{-1} the cause of which is not yet understood but which surely arises from an interaction with the helium cluster. Further to the right, from 4 cm^{-1} on, the phonon wing described above starts to appear in the spectrum. The anthracene spectrum displays similar structures (splitting of the maximum and a slowly decaying wing at higher energies) but is considerably broadened. In particular, the gap between the band origin and the phonon wing is missing here. As the spectra of anthracene and tetracene do not correspond with any of the known DIBs they shall not be further discussed.

The UV spectra of the pyrene molecule measured by us are shown in Fig. III.18. The upper two spectra were measured in helium droplets using the LIF and depletion method, respectively. As can be seen with the help of the vertical dashed lines both spectra agree very well as far as the total width and even structural details are concerned. The spectrum below was obtained using the CRDS method in the gas phase described in the previous chapter. For better comparison, the latter spectrum was (red-)shifted by 0.8 nm towards longer wavelengths. The seemingly untypical, rather complicated structure of the spectra is due to the fact that the measured $S_2 \leftarrow S_0$ transition is mixing with the first excited electronic state (S_1). Apart from the shift, the comparison of the helium and the gas-phase spectra shows that the three bands denoted by arrows are less pronounced in the helium spectra. This is due to the fact that, in the helium spectra, for each band observed in the gas phase there is a phonon wing shifted by 0.05 nm to the left that partly fills up the minima between the bands. Simulations convoluting the CRDS spectrum with a typical phonon wing are qualitatively in rather good agreement with the spectra measured in helium droplets. In summary, it can be said that the absorption spectra of pyrene in helium droplets are redshifted by 0.9 nm, but the overall character of the gas phase spectrum is preserved and the broadening of the features is understood. Considering the fact that the redshift of the pyrene absorption is 4.9 nm in the neon matrix and even 9.7 nm in the argon matrix, the matrix effect of the helium droplet seems to be very small.

Fig. III.19 shows the molecular-beam apparatus used by Serge Krasnokutski for the helium-droplet experiments. The hose seen in the foreground conveys the liquid helium used for cooling the nozzle from which the helium droplets are expanded.

(F. Huisken, S. Krasnokutski, Th. Henning)

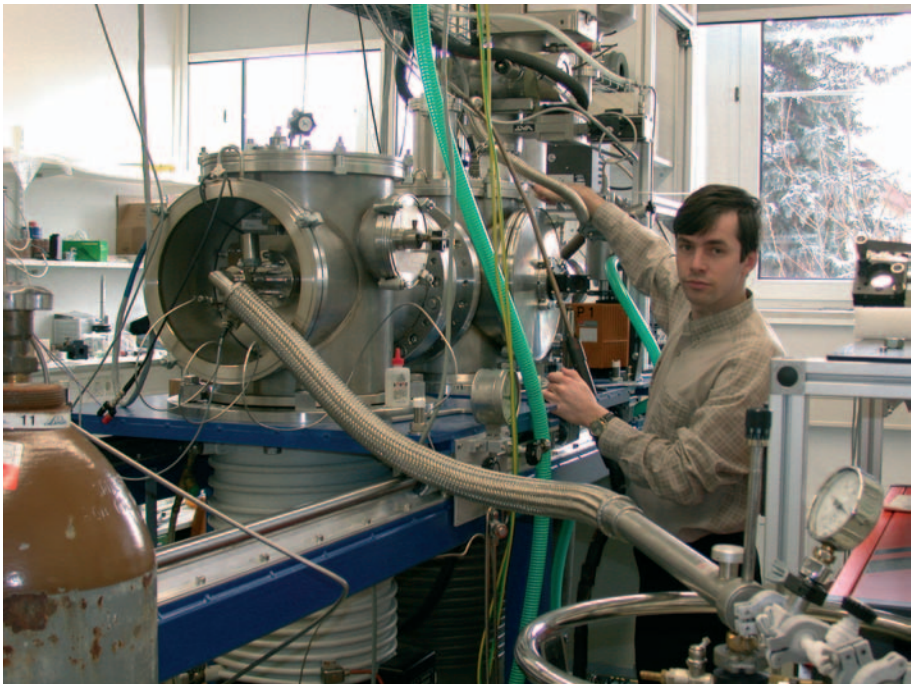


Fig. III.19: Molecular-beam apparatus used to produce and spectroscopically characterize the helium droplets with embedded PAH molecules. Serge Krasnokutski tightens the last screw before evacuating the chambers. The hose seen in the foreground conveys the liquid helium used for cooling the nozzle.

Photoluminescence Properties of Silicon Nanocrystals

For some years, our research group is studying silicon nanoparticles produced by laser pyrolysis with a CO_2 laser. A particular property of these particles, rendering them astrophysically interesting, consists of the fact that they show an intense red luminescence when they are exposed to ultraviolet light. While solid silicon, being an indirect semiconductor, does not show any photoluminescence, this phenomenon only occurs when the size of the silicon crystal is reduced to nanoscopic dimensions. In a silicon particle of, say, 2 nm diameter the electronic wave function is locally so well defined that – as a result of Heisenberg's uncertainty principle – the corresponding momentum distribution is considerably broadened. This renders the material quasi a direct semiconductor in which photoluminescence (PL) is now enabled. The radiative recombination of the electron-hole pairs is additionally favored by the fact that the influence of defects is less effective in silicon nanocrystals.

Widening of the band gap (the energy gap between conduction band and valence band) is another quantum-mechanical effect occurring due to the reduced dimension. The band gap and thus the energy of the emitted photons increases with decreasing particle diameter. So the PL wavelength is expected to shift from infrared over red to orange with decreasing size of the silicon nanoparticles while the efficiency of the PL increases in this direction. The cause of these new properties, which are unknown for bulk silicon and only occur as a result of the reduced dimensions, is also called quantum confinement.

The effect described above was first discovered by Canham in 1990 in porous silicon. The surface of a silicon wafer was etched through chemical treatment with hydrofluoric acid so that nanostructures of crystalline silicon were formed. When illuminated with UV light the samples displayed an intense luminescence in the red spectral range. Because of the important role of silicon in the electronics industry and the newly opened prospect of producing light-emitting electronic components on silicon basis, a real research boom set in. The studies were first focused on porous silicon, but in the following years they increasingly concentrated on silicon nanoparticles that are much better characterized and produced in the form of powder or thin films on substrates.

Apart from the importance of silicon nanoparticles for various technological applications it was soon recognized that dust particles consisting of silicon might also be of interest for astrophysicists. For it turned out that the so-called „extended red emission“ (ERE) – a red luminescence first observed in the Red Rectangle, then in some other celestial objects and finally even in the diffuse interstellar medium – bore a striking similarity to the photoluminescence of silicon nanocrystals. So it was rapidly assumed that silicon nanoparticles might be the carriers of the ERE. In order to investigate this issue a decided research project was carried out in collaboration with the French team of Cécile Reynaud at CEA Saclay.

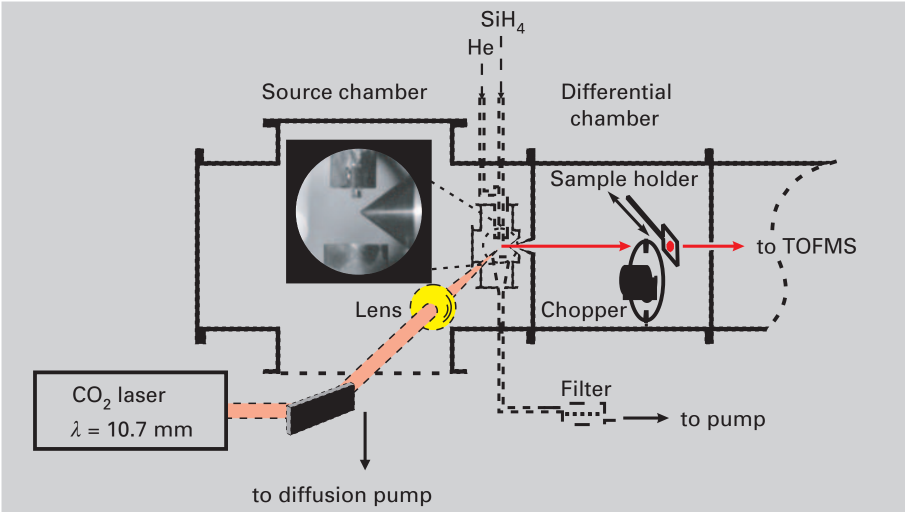


Fig. III.20: Schematic representation of the molecular beam apparatus for production, selection and size determination of silicon nanoparticles.

In order to obtain significant results, we thought it especially important to produce silicon nanocrystals with extreme purity and a strongly confined but optional size distribution and to determine their absorption and emission behavior qualitatively as well as quantitatively.

The silicon nanocrystals are produced in a flow reactor through pyrolysis of silane molecules (SiH_4) with a pulsed CO_2 laser and subsequent condensation of the silicon atoms to clusters and nanoparticles. In the otherwise schematic representation of Fig. III.20 the reaction region is shown as a photo. A conical nozzle extending from the right into the reaction volume extracts a fraction of the Si nanoparticles, transferring them to a „molecular beam“ propagating to the right (denoted by a red arrow). Depending on whether or not a sample holder was placed into the beam, the Si nanoparticles are deposited onto a substrate or their masses and sizes, respectively, are determined in a downstream time-of-flight mass spectrometer (TOFMS). Fig. III.21 shows a photo of the Si-nanoparticle apparatus together with our colleague Alban Colder. In the foreground to the left, the 2 m long time-of-flight tube of the mass spectrometer is to be seen. The CO_2 laser (not visible) is installed on the red frame on the right.

Since the velocity of the nanoparticles correlates with their size the chopper installed before the sample holder allows a size selection of the Si nanoparticles. Thus it is possible to distribution the Si nanoparticles onto the substrate so that their size increases continuously from left to right. Structure analysis with a high-resolution transmission electron microscope showed that the Si nanoparticles produced by laser pyrolysis have a monocrystalline core displaying the same crystal structure as bulk silicon and that this core is surrounded by an amorphous SiO_2 layer formed through oxidation in the air. It should be emphasized that the oxide shell plays an important role as it passivates unsaturated chemical bonds at the surface of the silicon nanocrystal. Without this passivation the Si nanoparticles do not show any luminescence.

Fig. III.21: The molecular beam apparatus depicted schematically in Fig. III.20 together with Dr. Alban Colder.

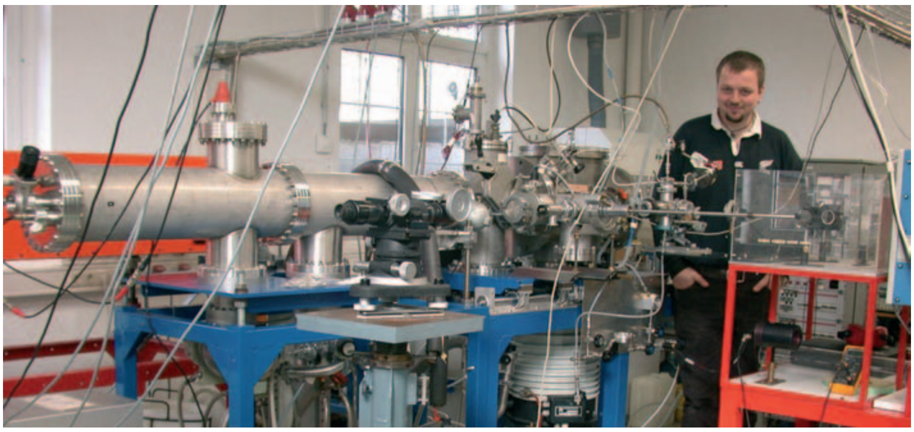


Fig. III.22 shows a photo of a layer of silicon nanoparticles produced with this technique exhibiting strong visible photoluminescence when exposed to UV light. The lower part of Fig. III.22 shows a photomontage displaying the 1×1 cm^2 quartz substrate and the black spot indicating the area where Si nanoparticles were deposited. A fragment of the quartz substrate has been exposed to UV light and photographed with a digital camera. The color of the luminescent Si nanoparticles is clearly seen to vary from orange to dark red. Furthermore, the photoluminescence of the Si nanoparticles was analyzed along a horizontal line using a sensitive spectrometer. This way, the PL curves shown in the upper part of the figure were obtained. These curves illustrate that the Si nanoparticles in the right section of the deposited layer emit light in the near-infrared range. Altogether the maxima of the PL curves cover a spectral region ranging from about 600 to 850 nm.

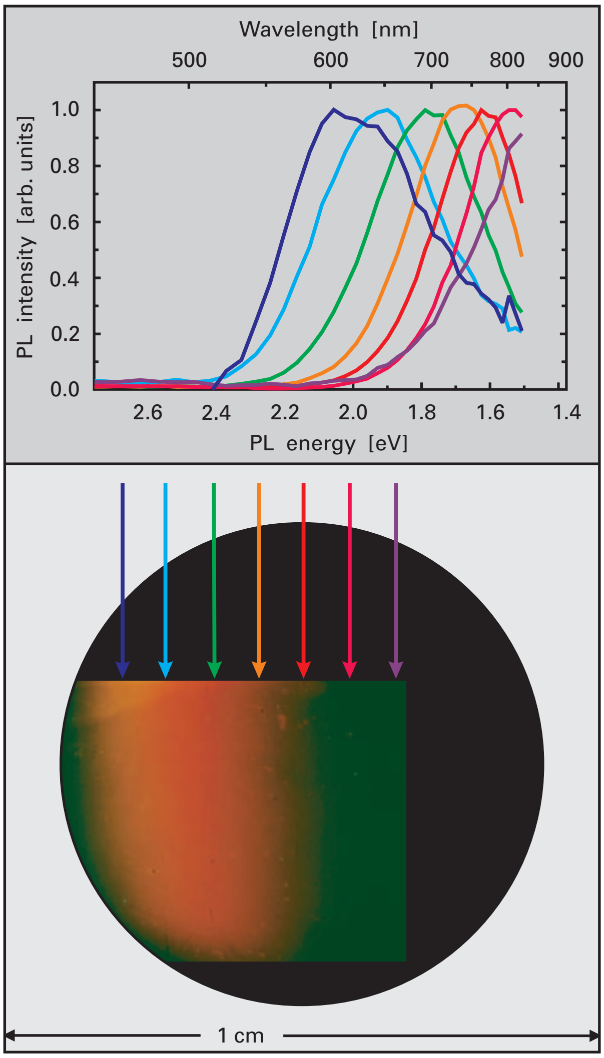


Fig. III.22: Photoluminescence curves of Si nanoparticles of various sizes deposited on a substrate after size selection in the molecular beam. The photo below shows the luminescent layer of the Si nanoparticles after excitation with a UV light source.

The varying colors of the luminescent Si nanoparticles can be explained on the basis of quantum confinement. The size of the Si nanoparticles is increasing continuously from the left to the right and, as mentioned earlier, this increase of the diameter is accompanied by a decrease of the band gap and thereby a shift of the photoluminescence towards longer wavelengths. Theoretical studies show the band ΔE_{gap} (relative to the band gap of bulk silicon) to increase according to an inverse power law $\Delta E_{gap} \sim d^{-1.39}$ where d denotes the particle‘s diameter. Fig. III.23 shows that our Si nanoparticles follow nicely this functional dependence. This confirms that the luminescence of the Si nanoparticles produced by laser pyrolysis is due only to quantum confinement and no other effects are involved. Moreover, the correlation between particle diameter and PL energy shown in Fig. III.23 illustrates that a varying size distribution of silicon nanoparticles (different maximum or varying width of the distribution) also causes a varying PL spectrum. Vice versa, for any PL curve, the size distribution of the Si nanoparticles causing this PL can be determined.

Fig. III.24 shows the Red Rectangle where the extended red emission was first observed. The ERE appears as a 120 – 190 nm wide emission band in the red spectral region between 600 and 850 nm. Having been observed in various regions of the interstellar medium, it is now generally thought to originate from the photoluminescence of an interstellar dust component. Interstellar dust is composed of small particles with diameters ranging from 1 to 100 nm that mainly consist of the elements carbon, oxygen and silicon. The constraint that the quantum efficiency of the ERE carrier has to be larger than 10% has considerably limited the number of possible candidates, reviving the interest in the ERE. Actually, carbon particles favored before – e.g. hydrogenated amorphous carbon, polycyclic aromatic hydrocarbons (PAHs) discussed earlier in connection with the DIBs, fullerenes, and other organic compounds – can now probably be excluded because of their extremely low photoluminescence efficiency in the red spectral range. Instead, crystalline silicon nanoparticles appear to meet the prerequisites much better, as it will be shown in the following.

Firstly, we will compare the astronomical observations with laboratory spectra taken by us for various samples of silicon nanoparticles. For Fig. III.25 four ERE observations from three different regions were selected (blue curves). To cover a range as large as possible, the selection was made so that, in the order (a) to (d), the maxima shift continuously from red to infrared (from 650 to 800 nm). These curves are compared to four PL bands of silicon nanoparticles selected from our laboratory data base with the purpose to achieve an agreement as good as possible (red curves). It should be noted that the red curves do not represent model calculations fitted to the astronomical observations, but experimental data. The mean size of the Si nanoparticles for which the spectra were taken varies from 2.8 (a) to 4.5 nm (d), the

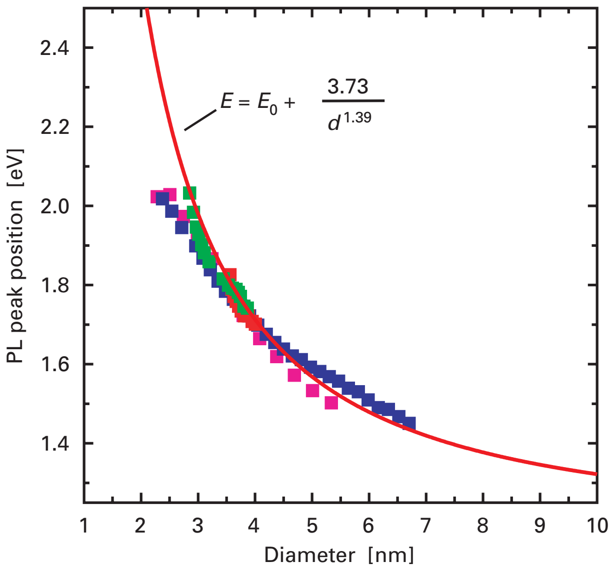


Fig. II.23: Theoretical correlation between the position of the PL maximum and the size of the silicon nanoparticles (red curve) compared to experimental data obtained from various samples.

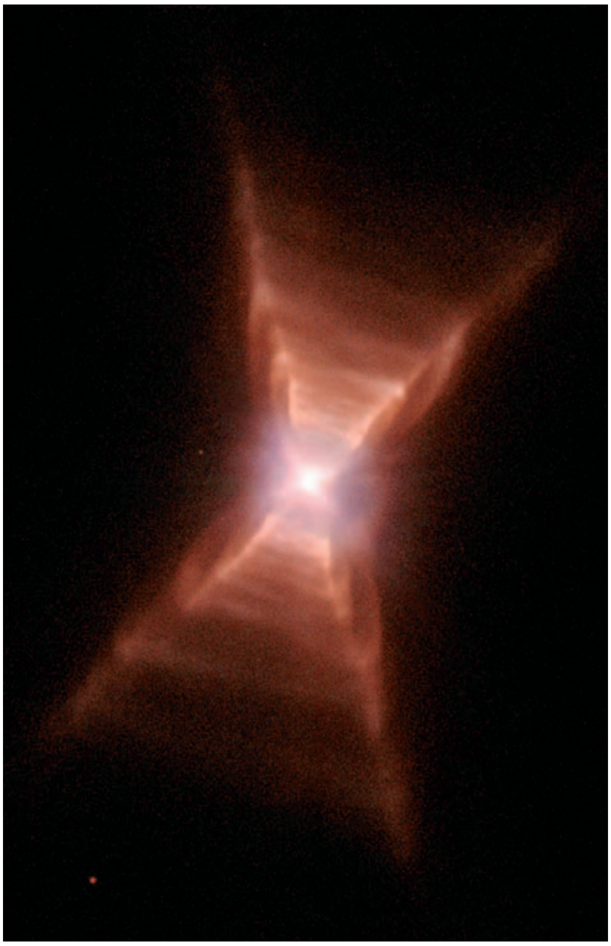


Fig. III.24: The Red Rectangle (HD 44179), a protoplanetary nebula 1000 light years away from earth. (HST)

full widths of half maximum of the size distributions varying between 1.0 and 1.5 nm. Although there is already a rather good agreement between observational and laboratory data it should be mentioned that an even better comparison is achieved when the correlation between the size of Si nanoparticles and PL position is used to fit simulated PL bands to the observed ERE spectra. This yields the parameters of the Si nanoparticle distribution that would produce exactly the same PL curve.

Before concluding the discussion of the spectral variance of the Si nanoparticle spectra it should be mentioned that the shortest wavelength observed for a PL maximum in the laboratory is 600 nm, coinciding with the shortest-wave ERE maximum. In the long-wave region the theoretical limit for Si nanoparticles is at 1060 nm. But the corresponding quantum efficiencies are extremely low; therefore it is not surprising that these wavelengths cannot be observed in interstellar dust clouds. As mentioned earlier, the upper limit here is at about 850 nm.

Now what about the quantum efficiencies of the photoluminescence of Si nanoparticles? (After all, carbonaceous dust particles have been excluded as carriers of the ERE because of the extremely low probability for them to transform UV light into PL photons.) In order to answer this question, quantitative PL measurements have been carried out using calibrated optics and instruments. By measuring the UV absorption and the intensities of the emitted PL photons, quantum efficiencies of up to 30 percent were measured in high-quality Si nanoparticle films. This value, however, represents a lower limit since larger Si nanoparticles, which are also encountered in the sample, force down the measured value. When the contribution of the larger particles is taken into account quantum efficiencies of about 90 % are achieved. These extremely high PL efficiencies are another argument in favor of Si particles as carriers of the ERE. Finally it should be mentioned that the high quantum efficiencies only apply to Si particles of 3.5 nm diameter. With increasing particle diameter the PL probability decreases drastically, which explains why the theoretically achievable large wavelengths are not observed in reality.

Knowing the quantum efficiency allows one to calculate the fraction of Si nanoparticles in the total dust of the diffuse interstellar medium needed if Si nanoparticles were to account for the ERE. If for simplification the quantum efficiency of the Si nanoparticles is assumed to be 100 %, meaning that each UV photon absorbed is transformed into a PL photon, the fraction of Si nanoparticles needed in the total dust is calculated to be only 1 % by mass. In many other objects the conditions are far less restrictive so that the concentrations of Si nanoparticles needed there may be smaller by several orders of magnitude.

Despite the many attractive properties recommending Si nanoparticles as the carriers of the ERE there

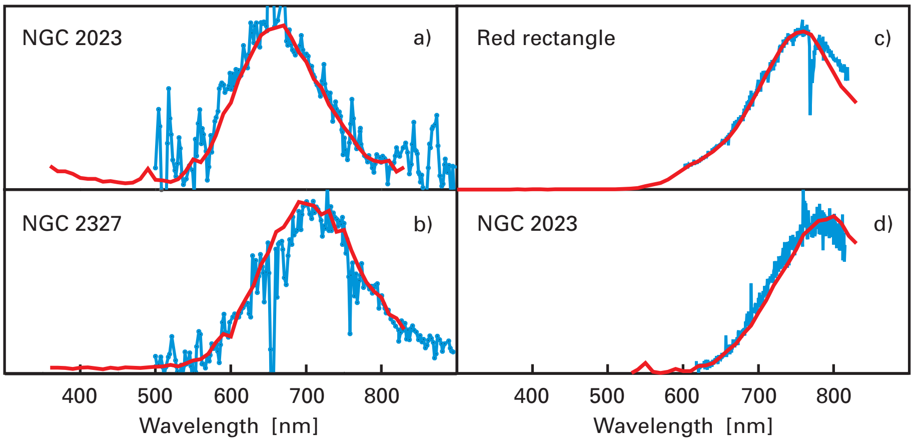


Fig. III.25: Comparison of some ERE spectra (blue curves) with spectra taken in the laboratory from silicon nanoparticles of various sizes.

are also some critical remarks. So, e.g., Li and Draine have shown in simulations that oxygen-passivated Si nanoparticles with a diameter of 3.5 nm should reach a temperature of about 70 K in NGC 2023 and at this temperature should emit at a wavelength of 20 µm because of excited SiO vibrations, which, however, has not been observed. An argument against this is the fact that the simulations are based on oxide layer thicknesses as they are assumed for the high-oxygen atmosphere of the earth. Low-oxygen environments would lead to Si nanoparticles with much thinner oxide layers, which would result in a considerably fainter emission at 20 µm. Another solution of the problem would be if the Si nanoparticles were agglomerated to clusters or embedded within larger dust particles. Both would result in lower temperatures and thus a fainter emission. Studies of agglomerates and Si nanoparticles embedded within solid state matrices are presently conducted by the joint laboratory astrophysics group in Jena.

A particularly attractive feature of silicon nanoparticles as a carrier of the extended red emission is the fact that a single species suffices to explain the entire variance of the astrophysical observations. The only parameters determining the position and width of the ERE band are the mean diameter of the Si nanoparticles and the width of their size distribution. Since the characteristic luminescence properties of the Si nanoparticles are determined by the quantum confinement, a quantum-mechanical effect would be invoked for the first time to explain an astrophysical phenomenon.

(A. Colder, J. Gong, O. Guillois,

III.3 The Enigmatic Centers of Galaxies

Detailed studies of the center of our own Galaxy, which now is known to harbour a massive Black Hole, and extensive observations of Quasars, the most extreme cases of nuclear activity, have raised the question, whether the centers of all galaxies exhibit unique physical properties. The HUBBLE Space Telescope, as well as CONICA and MIDI, the new instruments at the VLT with extremely high angular resolution, offer the means to address this question observationally.

Why are Galaxy Centers interesting?

The laws of physics do not necessarily imply that the centers of galaxies – either defined as the geometric center or as the lowest point in the gravitational potential of a galaxy – must exhibit unique local physical conditions, much different from any other place within the surrounding galaxy. In other words, galaxy centers need not be »special« beyond their geometric interpretation. Yet, the last half century has increasingly revealed that, at least in most galaxies, the centers are indeed special, not only with respect to the often high stellar densities. Historically, the first clear clue was that galaxy centers exhibited a wide variety of »activities«, often very energetic processes that manifest themselves across the whole electromagnetic spectrum from Gamma-rays to radio waves, and that cannot be powered by »normal« stellar populations, which are the dominant source of radiation in today's universe in all places but galaxy centers. Already 40 years ago, black holes that are accreting material have been identified as the most likely underlying driver of active nuclei, on the basis of the high efficiency of energy production, on the basis of the tight upper limits on the volume available for energy production, and on the basis of directly observed relativistic effects. The most extreme cases of such nuclear activity, called luminous quasars (QSOs) or radio galaxies, the nuclear luminosity can outshine the surrounding galaxy by orders of magnitude. However, the complexity of the issue has also become clear, as young star and star-formation in the central parsecs play a role in most active galaxies at the same time.

Although such QSOs are much more rare than normal galaxies at all epochs, it has become clear that active nuclei are not exotic beasts, but relatively short-lived phases, likely to occur at some point in the lives of all massive galaxies. In part, this insight was driven by the emerging evidence that inactive galaxies also harbor super-massive black holes (10^6 – 10^9 $M_\odot$) The most beautiful and persuasive evidence for such central black holes has come from our own Milky Way. The last five years have also brought to the fore that all galaxies, at least as long as they have significant stellar bulges, harbor black holes, whose masses can be predicted from the structural properties of the surrounding galaxies to better than a factor of 2. As black holes grow through mass accretion, it implies that most massive galaxies must have had similar histories of central accretion (or, nuclear activity).

It has been a long-standing issue, to which extent the broad, almost bewildering, breadth of observational manifestations of nuclear activity reflect a variety of underlying physical circumstances, rather than other factors, such as the orientation of the "central engine" with respect to our particular viewing angle as observers. In particular, some active nuclei only manifest themselves at wavelengths at which the radiation can penetrate dust easily, such as the infra-red, the radio and the hard X-ray bands. A dust and gas torus, surrounding a central accretion has often, and successfully, invoked to created a "unified model" that may appear very differently to observers, when viewed from different vantage points.

As always in active research fields, new discoveries, clues and insights lead to more new questions than answers. In 2003, research on galaxy nuclei at the MPIA has actively pursued a number of these.

- Are galaxy nuclei always special in their physical properties?
- What physical properties of the surrounding galaxies can predict the mass of the central black hole?
- Can one demonstrate directly that there is a central dust torus that contributes to the variety of observational properties?
- What circumstances in the surrounding host galaxies determine whether the nucleus is active or not?

Are All Galaxy Centers Special?

In galaxies that have concentrated stellar bulges, it is clear that gravity's vector points forcefully at the center. Whenever the angular-momentum barrier is overcome, material will quickly accumulate in the galaxy's nucleus and perhaps from this perspective unique physical properties may not come unexpected. However, there are at least two types of galaxies, where such a qualitative argument may not hold: small barred galaxies, such as the Magellanic Cloud, and ultra-late-type galaxies, that seem to have no stellar bulge to speak of, but only a disk. In these types of galaxies the question arises anew, whether the centers have unusual local properties. MPIA researchers, Jakob Walcher and Hans-Walter Rix, have explored this question for "bulge-less" galaxies (see Fig. III.26), in collaboration with colleagues in the US. The first step, headed by Torsten Boeker at STScI, was to image the centers of such galaxies with HST. The enhanced contrast, afforded by HST's superior resolution, revealed that 70 % of such galaxies had a compact, but resolved, very luminous star cluster at the center (Fig. III.26). In most cases the center harboured indeed the brightest, or one of the brightest, clusters to be found in the galaxy.

Nine of these nuclei were targeted for high-resolution spectroscopy with UVES, the Echelle spectrograph at the VLT. From these spectra one can derive both the stellar velocity dispersion and information about the age, or the age distribution, of the stars in the nuclear cluster. The analysis of these spectra, emerging from the PhD work of Carl Jakob Walcher at the MPIA, has revealed that these clusters have unique properties not only within the galaxy, but indeed are presumably unparalleled in any other environment.

First, the spectra showed that their blue light is dominated by a young population (typically 0.5 Gyrs), much younger than the age of the universe. Either the majority of these galaxies "waited" with their nucleus formation until the present epoch, or, more likely, the nuclei undergo repeated epochs of star-formation, the last merely dominating the light. This latter picture is supported by the velocity dispersion measurements, typically 25 km/s. In conjunction with the HST light profile, they allow a mass estimate, revealing that the clusters have masses of $10^7\,M_\odot$. These masses are often in excess of the masses derived from a single-age population fit, rejecting the hypothesis of a simple population. In summary, the nuclear clusters have the size of globular clusters, but often ten times their mass (see Fig.III.27) and have clearly multi-age populations.

The measurements imply that these nuclei are a distinct class of stellar systems, separated from normal bulges by mass and size (see Fig III.27), and from globular clusters by mass and star-formation history. Given their tiny sizes (≈3 pc) they are the stellar systems with the highest mean density known to date. In a surprising way, also very late-type galaxies have revealed that their centers have unique physical properties. Looking at Fig. III.26, it is not obvious from the surrounding stellar mass distribution, what it is that that makes this environment so special. One plausible avenue is to speculate that the cuspy dark matter halo plays an important role. Obviously, one should pursue in the future why one third of these late type galaxies have NO cluster in the middle. Is this just statistical fluke, or is there something more fundamentally different about their potential well? Making two-dimensional maps of the velocity field to trace the overall (dark) matter distribution in the inner part of these galaxies should yield the answer.

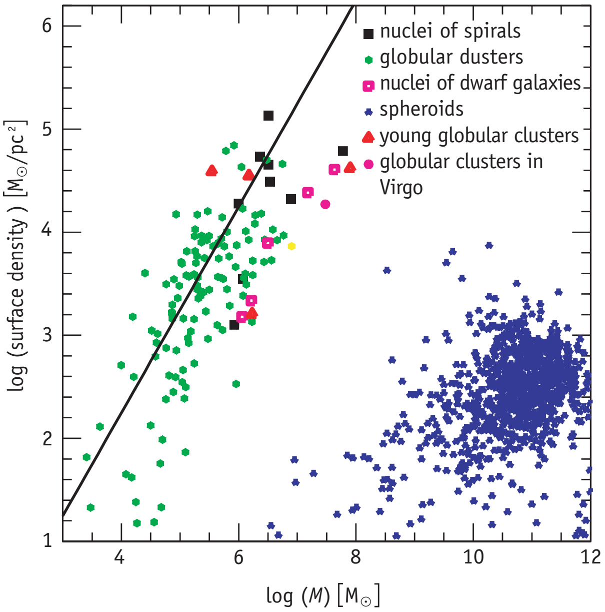
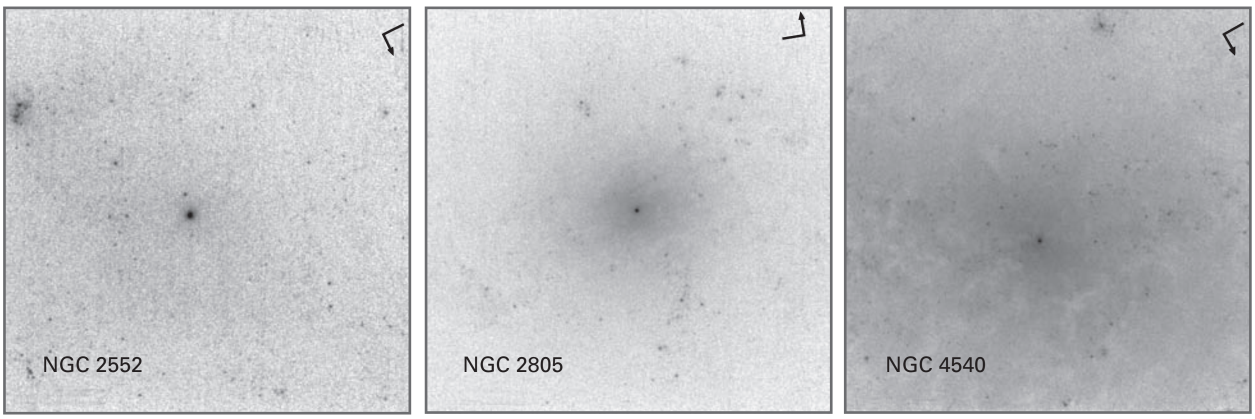


Fig. III.27: The fundamental plane of galaxy bulges and spheroids (cloud on the right), globular clusters (small symbols at the left), and the nuclear clusters in late-type galaxies, first studied here.

Fig. III.26: HST Images of several »bulge-less« galaxies, revealing a bright, but tiny (≈ 3 pc) stellar nucleus, or nuclear star cluster in the center, in the center of an otherwise very diffuse galaxy.



What Galaxy Parameters Can Predict the Mass of the Central Black Hole?

The last few years have seen two related breakthroughs in assessing the present-day population of super-massive black holes at galaxy centers: first, detailed dynamical modeling, one object at a time, has shown that wherever kinematic data of sufficient spatial resolution were available, the presence of a massive dark object can be demonstrated. There are now 30 to 50 galaxies, mostly ellipticals or massive bulges, where it is now absolutely clear that models with only the observed stellar mass fall short of matching the kinematics at the center. Only for a small subset of these can it be shown directly that the density of the dark object at the center is so high that a black hole is the only astrophysically viable alternative. In the center of the Milky Way there are for the first time observations that may probe the event horizon of the black hole. However, in all the other cases it seems eminently plausible to presume that the unidentified central mass is a black hole. From these lines of evidence, general consensus has emerged that super-massive black hole are nearly ubiquitous in the centers of big galaxies.

The second step of progress, resulting from the same data, was the realization that some overall properties of the bulge (not the disk!) correlate well with the black hole mass. The most widely used correlation is between the velocity dispersion within the bulge, σ, and M_{BH}: remarkably, the rms velocity of stars at typically 1 kpc can predict to ≈ 30 % accuracy the mass of the black hole, whose size, represented by the Schwarzschild radius, is 10^{12} times smaller. There is now a flurry of activity to devise theoretical explanations why the stellar velocity dispersion, a combination of the stellar mass, the bulges size and the isotropy of the stellar, correlates particularly well with M_{BH}. None of these models have proved persuasive, yet. The focus on the velocity dispersion within the bulge arose from earlier work by Magorrian, that seemed to show only a much poorer correlation between M_{BH} and the bulge mass and luminosity.

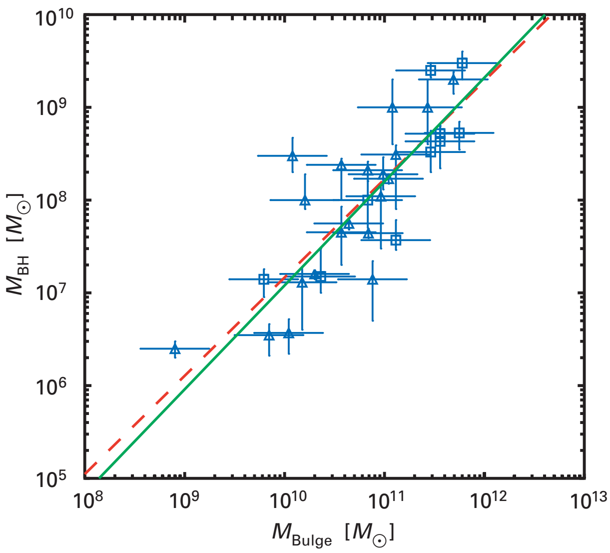


Fig. III.28: Revised relation between the stellar bulge mass M_{Bulge} and M_{BH} (from Häring and Rix, 2004). With good data and modeling, the correlation is excellent, as good as M_{BH} - σ.

Nadine Haering and Hans-Walter Rix at the MPIA decided to re-examine the relation between M_{BH} and the stellar mass of the bulge. This study was prompted by the insight that newer HST-based values for M_{BH} in Magorrian's sample were found to be five times smaller than his original ground-based data and restrictive modeling had implied. Haering re-modelled existing data for a sample of bulges with well-determined black hole masses, in order to estimate consistently the spheroid masses. From this she could evaluate the M_{Bulge} – M_{BH}relation for a sample where both parameters had been well measured. Fascinatingly, with good measurements, the M_{Bulge} – M_{BH} becomes just as tight as the s– M_{BH} relation: $M_{BH} = 0.0015\ M_{Bulge}$ with a scatter of ≈ 35 %. This result provides a much more intuitive interpretation of the co-evolution of bulges and black holes. It also sets the ground for very exciting tests at high redshift. If indeed $M_{BH} = 0.0015\ M_{Bulge}$ holds at all redshifts, the host galaxies of $z \approx 6$ QSOs, known to harbour black holes of $3 \times 10^9\ M_\odot$ should have enormously bright, and hence detectable host galaxies.

The Central Parsec of Active Galaxies

Complementary to the population statistics of active and inactive galaxies and their black holes are detailed case studies of nearby nuclei. Such studies should elucidate how the accretion of material onto a black hole works in practice. Is there indeed a thin accretion disk, does the accretion occur steadily or episodic, is the broad-line region surrounded by a dust-torus, and does the dust and gas structure on parsec-scales indicate that material is inflowing now?

Much progress has been made on these question over the last decades interpreting spectral information, time-variability and multi-wavelength energy distributions. Resolving the central parsec at optical or near-IR wavelengths to check the model geometries directly has proven difficult. Two instrument developments at the MPIA over the last years, have opened new windows of opportunities to understand nuclei: CONICA, the near-infrared camera that can deliver diffraction-limited images at the VLT in conjunction with the NAOS adaptive optics system; and MIDI, the mid-infrared interferometer that can combine light from different unit telescopes at the VLT, with "baselines" in excess 100m. CONICA can deliver a factor of eight improvement compared to the best ground-based imaging and a factor of over three compa-

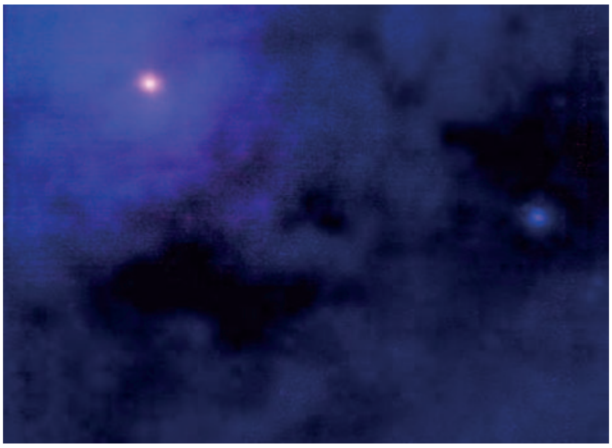


Fig. III.29: Diffraction-limited image Cen A's nucleus obtained with CONICA at the VLT.

red to HST. MIDI is providing a giant leap in resolution (1-2 orders of magnitude) albeit at the price of providing only interferometric information rather than bona-fide images to date.

With CONICA, MPIA researchers have initiated a collaborative program to study nearby active nuclei, such as the Circinus galaxy and Centaurus A. Fig. III.29 shows the nucleus of Cen A in the H-band (and K-band). The diffraction limit was achieved by correcting the atmospheric distortions using the light from the nucleus itself. As the nucleus is completely obscured at all wavelength $< 1\ \mu$m, also HUBBLE cannot provide images of comparable angular resolution at shorter wavelength. The nucleus is unresolved and shows no spectral features, attesting to its origin as accretion disk emission. Also, there is no evidence for a second nucleus. As Cen A is a recent merger, such a second nucleus might have been expected, as many models predict that two respective central black holes of the progenitors get "hung-up" at very small radii (0.3"). The results imply that the merger of central black holes after the merger of two galaxies is quite rapid.

Even in its initial configuration, the MIDI interferometer has provided spectacular results on the nearby active nucleus NGC 1068. At 5 – 10 μm emission in an AGN, presumably comes from hot dust, surrounding the accretion disk and being heated by it. With MIDI it has been possible for the first time to resolve this dust torus, determine its size directly and show that different emission regions have different geometries. In particular, it has been possible for the first time to show that the hottest part of the dust torus is at its inside. The overall result is shown in Fig. II.22, p. 34 (from Jaffe, Meisenheimer et al., published in Nature). In practice, MIDI can only measure fringe contrasts along one particular direction on the sky. The smaller the emitting region at a given wavelength, the higher the fringe contrast. Using a dispersive element, MIDI measures the fringe contrast as a function of wavelength.

Exploiting the rotation of any object on the sky, different baselines, i.e. cuts across the object, can be explored.

Once MIDI has improved tracking and guiding, its sensitivity will increase dramatically, opening up many more objects to such studies.

When are Black Holes Accreting Actively?

The fact that at all epochs luminous AGNs are much rarer than luminous galaxies, taken together with the fact that all massive galaxies have a black hole of predictable mass at their center, implies that all galaxies are AGNs at some point, and it implies that these AGN phases last only a short fraction of their overall age. This naturally leads to a crucial question in understanding the AGN phenomenon and the growth of black hole: what "triggers" luminous and rapid accretion onto the black hole. It has long been known that mergers or strong tidal interactions are correlated with enhanced nuclear activity. Yet, not all mergers seems to produce AGN activity, nor do all AGNs show any signs of tidal interactions. Stellar bars, for example, provide an internal mechanism that might funnel gas into the center. Neither of these mechanisms leads naturally to the $M_{\mathrm{Bulge}} - M_{\mathrm{BH}}$ relation, discussed above. Local studies, where it is straightforward to study both the AGN and the surrounding galaxies are limited in their interpretation, because we know that much of the black hole growth occurred at earlier epochs and that much of the black hole growth occurs during the very bright QSO phase of AGNs. But: QSO's are all but extinct at the present epoch. For relatively luminous AGNs at the present epoch, it has recently been shown that statistically, enhanced nuclear activity goes along with enhanced star-formation throughout the whole galaxy.

The GEMS team, with researchers from Potsdam, Heidelberg and the US, has combined the COMBO-17 survey, providing the deepest optically selected AGN sample with the imaging power of HST, to study the properties of host galaxies. The COMBO-17 selected AGNs, many of them bona fide luminous QSO range in redshift from 0.3 to beyond 3. As a first analysis step, GEMS explored the hosts of luminous AGNs in the redshift range to z =1.2, as a comprehensive picture of the overall galaxy population is available from the same data set in this redshift range.

For the first time, GEMS enabled the complete detection of all host galaxies for a sample of AGNs to z = 1.2 (see Fig. III.30). It was possible not only to derive luminosities, but also rest-frame colors (indicative of the fraction of young stars in the stellar population), and the radial profiles. The functional form of the radial light profile is a good quantitative discriminator between early-type, spheroidal galaxies and late-type galaxy disks. Fig. III.31 places the properties of the host galaxies with

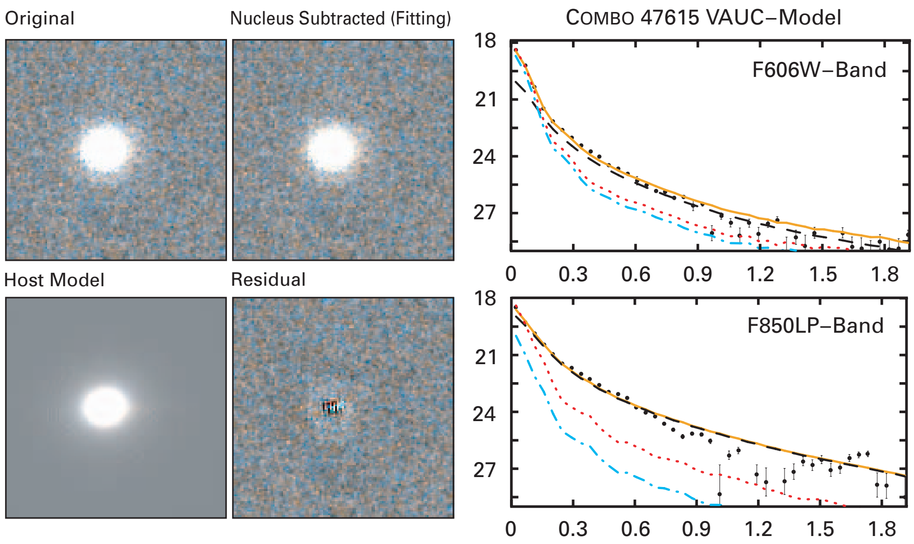


Fig. III.30: Example of a AGN host galaxy detection in GEMS. The panel of four images shows various stages of the image analysis, where a nucleus + host galaxy model is fit to the data: top left shows the original image, the top right the image after subtraction of the best fitting point source representing the AGN, where this point source had been fit simultaneously with the host galaxy model (bottom left); the bottom right shows the overall residuals of the nucleus + host galaxy fit.

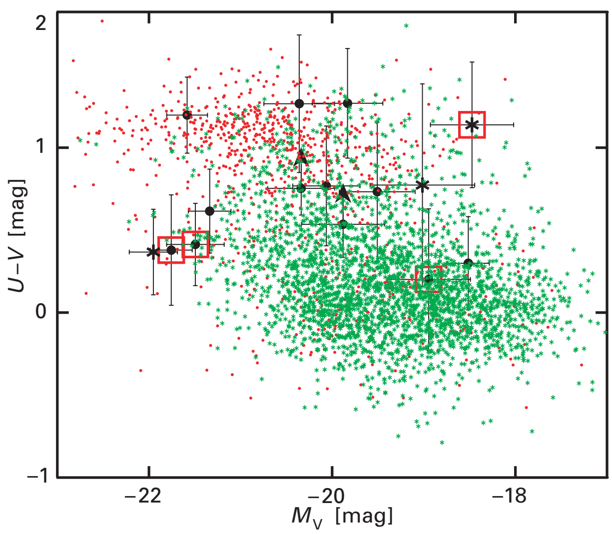


Fig. III.31: GEMS-AGN-host galaxies ($z < 1.2$), compared to the »general« galaxy population at the same epoch. The plot shows the distribution of galaxies in the (rest-frame) color – luminosity plane, where red dots indicate galaxies with early type light profiles, and green dots galaxies whose radial profiles resemble exponential disks. Almost all AGN hosts have the morphology of compact spheroids (full circles), only three are disks (asterisks). Four of them are clearly interacting (red box), confirming that mergers are conducive to nuclear activity, but not necessary. Note the very large fraction of blue spheroids among the AGN hosts, compared to the quiescent phases.

active nuclei in the context of those with in-active centers. First, the vast majority of AGN hosts are spheroids: luminous AGNs occur in galaxies that have already massive black holes. Only one quarter of all host show manifest signs of merging or interactions, implying that such interactions are conducive but not necessary to produce a luminous AGN. In the general, inactive galaxy population, most spheroidal galaxies at the more recent epochs are red, i.e. contain few if any newly formed stars. The AGN hosts differ most from the general population in that they are much more young stars. This result is a direct clue that in spheroids star formation, leading to blue colors, and black hole growth, through the luminous accretion of material, go together.

What is Next?

These examples have shown that both detailed studies of individual objects, as well as an understanding of the population properties are starting to come together to a coherent picture. A number of follow-on steps are obvious. With NAOS/CONICA and MIDI we now have powerful tools at hand to study local AGNs. Upcoming instrument developments, such as the laser guide-star facility PARSEC to support CONICA, will greatly expand the realm of accessible objects. Similarly, interferometry in the infra-red has only scratched the surface of possibilities. With GEMS and other studies, we are also now poised to place AGN hosts in the context of the general population of high-redshift ($1.5 < z < 5$) galaxies, to probe the epoch when by far the most substantive black hole growth occurred. With QSOs at $z > 6$ now known to contain black holes of $>10^9$ $M_\odot$, the next years will also allow explore whether black holes or their host galaxies grew more rapidly in the early phases of the universe.

(J. Walcher, N. Häring, A. Prieto, K. Meisenheimer and the GEMS-Team)

III.4 The Sloan Digital Sky Survey

Besides increasingly high angular resolution of the newly developed instruments, it is the ability to perform increasingly deep and extended surveys of the nightsky, which presently drives the fast progress in extragalactic research and observational cosmology. Here we describe the largest current survey in Astronomy.

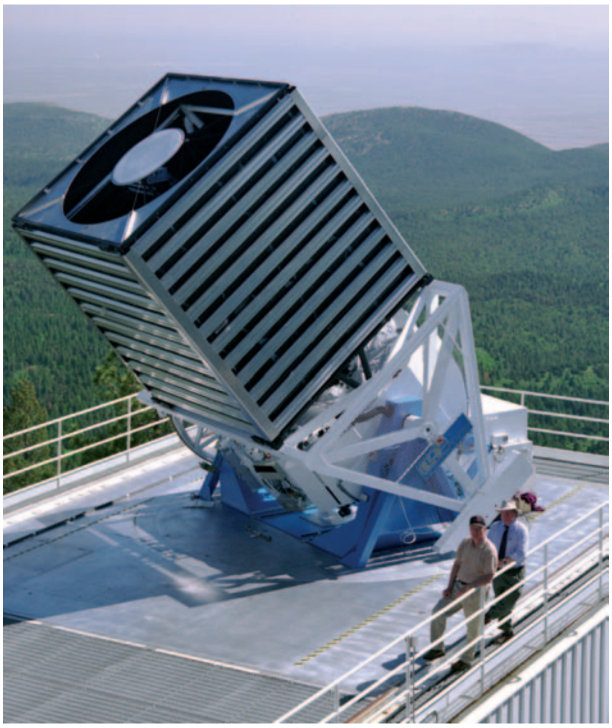


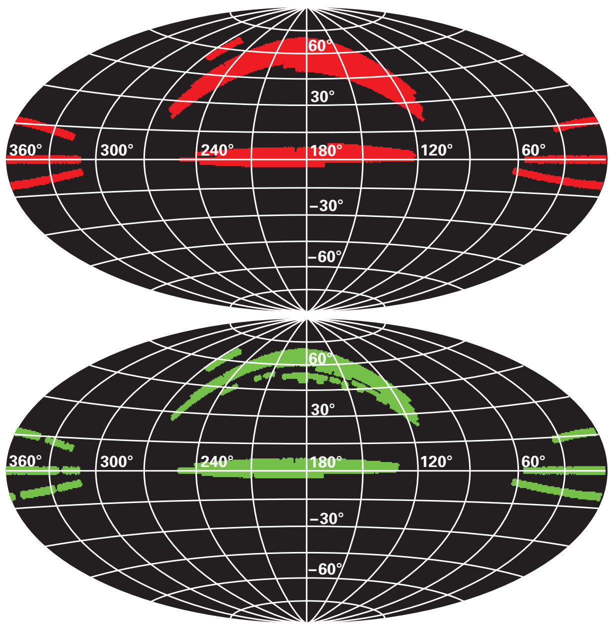
Fig. III.32: The 2.5-meter telescope of the Sloan Digital Sky Survey, located in the Sacramento Mountains of southern New Mexico in the United States. The box-like structure protects the telescope from being shaken by the wind.

The MPIA is a partner institution in the Sloan Digital Sky Survey (SDSS), which will ultimately image approximately 1/4 of the entire sky to unprecedented depths, obtaining images of more than 10 galaxies using a special purpose-built telescope and imaging camera. The SDSS survey telescope (Fig. III.32) also has a specially designed fibre-fed spectrograph; with th is, the project will eventually take spectra for nearly a million astronomical objects, most of them distant galaxies or quasars. In 2003, the SDSS collaboration achieved a major milestone toward the survey goals, Data Release 2, covering approximately 1/3 of the final survey area (Fig. III.33), which was subsequently released to the general public. The year 2003 also saw astronomers at the MPIA – in collaboration with members of the SDSS team from around the world – using the SDSS to explore the nature of galaxies from the Milky Way and Andromeda right out to the most distant known quasars. We will not discuss here recent exciting results by MPIA researchers on the discovery of significant numbers of chemically unevolved galaxies in the local Universe, and on an exploration of the properties of the most distant known quasars. For this review, we focus on the discovery and analysis of faint, ghostly streams of stars torn off of dwarf galaxies by the Milky Way and Andromeda, and on a census of the present-day stellar and baryonic mass in the Universe.

Cannibalism in our Galaxy and in the Andromeda Galaxy

Because the SDSS images such large areas of the sky, it has proven to be a remarkably efficient tool in the search for diffuse streams of stars torn off of galaxies and star clusters by the powerful galactic tides of the Milky Way and the Andromeda Galaxy. These ghostly streams, among the most diffuse and faint structures ever detected, are ideal probes of the distribution of dark and luminous matter in galaxies. A single well-studied stream can give important insight into the extent and quantity of dark matter in a galaxy; multiple streams (or

Fig. III.33: Sky coverage of SDSS Data Release 2, shown in equatorial coordinates. The top panel indicates the extent of the imaging data included in the release (red) and the bottom panel the extent of the spectroscopic data (green).



multiple wrappings of a single stream, to a lesser extent) can allow estimation of the shape of a galaxy's dark matter halo – non-spherical dark matter haloes are a generic prediction of most dark matter theories, and detailed studies of multiple tidal streams are one of the few ways that this important prediction can be tested. The ongoing disruption of the Galactic globular cluster Palomar 5 was reported previously (cf. Annual Report 2002, p. 22); here we focus on the recent discovery and study of the debris from disrupted dwarf galaxies around the Milky Way and the Andromeda Galaxy.

A Giant Stellar Ring around the Milky Way

Using SDSS data, astronomers from several SDSS member institutions, among them MPIA, found evidence for a giant ring of stars around the Milky Way roughly in the plane of the Galaxy. The ring was initially detected as an overdensity of stars in the constellation Monoceros, which subsequent SDSS spectroscopic observations confirmed as a stellar stream distinct from the previously-discovered Sagittarius stream (see below). Fig. III.34 shows a histogram of radial velocities for over 200 stars in one particular line of sight that intersects the Monoceros stream. The stars have an average heliocentric radial velocity of 54 km/s with a remarkably small one-dimensional velocity dispersion of 18 km/s, after subtraction in quadrature of typical instrumental errors of 20 km/s. Also plotted are several models representing expected contributions and projected radial velocities of stars from the Milky Way's thin disk (red) and thick disk (green), both negligible for objects of this color at this distance from the Galactic center, and for the stellar spheroidal halo (blue). The density excess and narrow dispersion are striking for these stars, which are roughly 20 kpc from the Galactic center. The stream of »extra« stars has a distinct velocity from the thin disk, thick disk and stellar halo of the Milky Way, and comparatively narrow velocity dispersion, indicating that it is a stream of stars rather than a density enhancement of a known Galactic structure.

Unfortunately, there are not enough data to specify a unique orbit at this stage. The colors and spectra of the stars in the stream suggest that they have metallicities of [Fe/H] = –1.6 ± 0.3, i.e., elemental abundances approximately 1/40 those in the Sun. By fitting models to the positions and velocities of stream stars, the research team came to the preliminary conclusion that the stream is likely a ring around the Milky Way, lying close to the plane of the Galactic disk. At a distance of 18 – 20 kpc (60 000 – 65 000 light years) from the Galactic center, the ring could contain between 2×10^7 $M_\odot$ and 5×10^8 $M_\odot$ in stars, and, if there is associated dark matter, the total mass of the ring (and hence the mass of the progenitor) could be a factor of 10 larger. From the range in chemical composition and stellar mass, the progenitor of

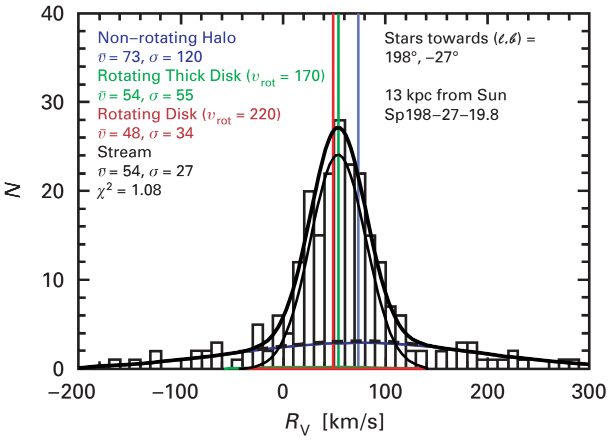


Fig. III.34: Histogram of radial velocities for over 200 stars in one particular line of sight that intersects the Monoceros stream. Also plotted: expected contributions from the Milky Way's thin disk (red), thick disk (green), and spheroidal halo (blue). Black dotted line: sum of thin disk, thick disk, and halo components; thin solid line: Gaussian fit to the »extra« stars.

the ring is plausibly a dwarf satellite galaxy of the Milky Way, torn apart by the tidal forces of its larger neighbour just as the Sagittarius dwarf is being shredded in the present day. Because this stream and the Sagittarius stream pass through very different parts of the Galaxy's dark matter halo, ongoing spectroscopic and imaging studies of this ring's stellar content will help to constrain not only the extent but also the shape of the Milky Way's dark matter halo.

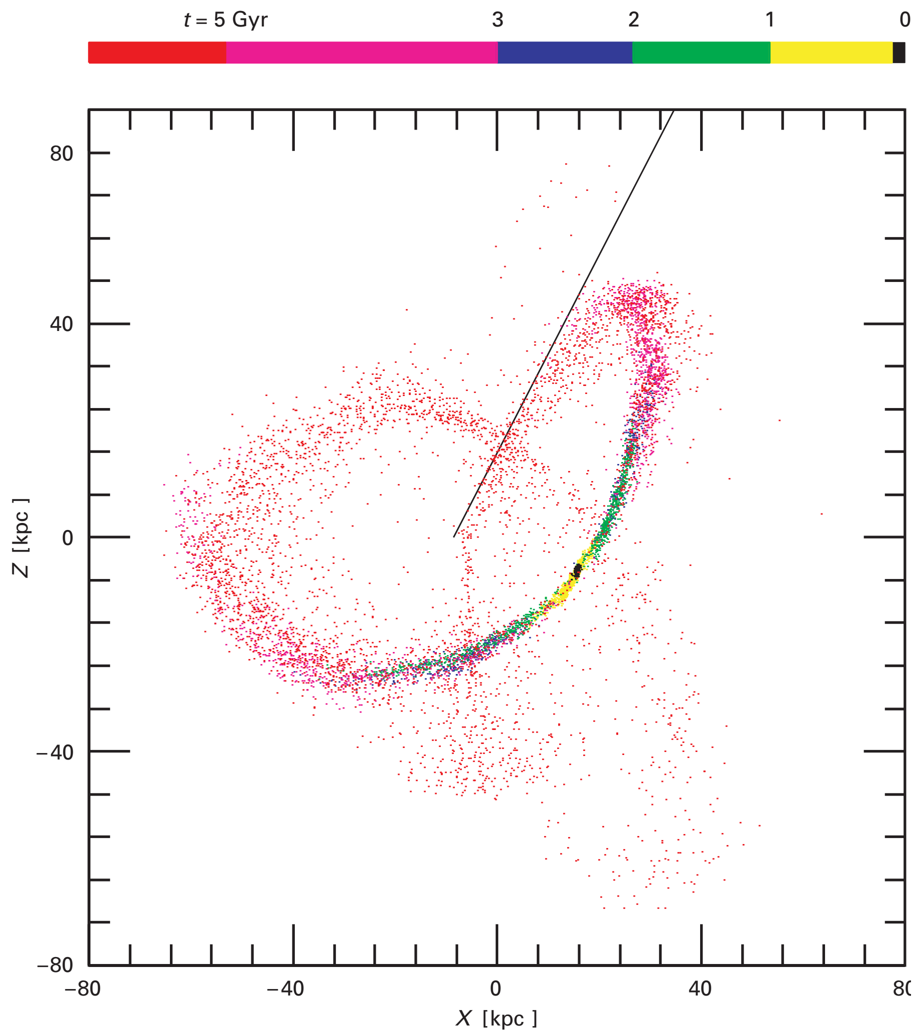
Extending the Sagittarius Stream: Probing the Shape of the Milky Way's Dark Matter Halo

Discovered a decade ago, the Sagittarius dwarf galaxy is in the process of being torn apart by the tidal forces of the Milky Way. Stellar overdensities detected in SDSS and other survey data have been identified as parts of a stellar stream stripped from Sagittarius, roughly tracing its path as it has orbited our Galaxy.

In the past year, astronomers working at MPIA and other SDSS member institutions have significantly advanced our understanding of the Sagittarius stream. On one front, a new overdensity of stars with the colors of A stars was discovered in distant parts of the Milky Way's stellar halo using the SDSS. A number of RR Lyrae candidates are associated with this feature, supporting the interpretation of this overdensity of stars as luminous blue horizontal branch stars at distances of roughly 90 kpc (nearly 300 000 light years) from the center of the Milky Way. The new tidal debris is within 10 kpc of the same plane as other confirmed tidal debris from the disruption of the Sagittarius dwarf galaxy, and could be associated with a trailing tidal arm. Furthermore, the globular cluster NGC 2419 is located within the detected tidal debris and may also have once been associated with the Sagittarius dwarf galaxy. Tidal debris associated with the trailing tidal arm of the Sagittarius dwarf was discovered along other lines of sight also using other imaging surveys, at distances of approximately 50 – 60 kpc from the center of the Galaxy. These detections strengthen the observational evidence that the stellar stream discovered by the Sloan Digitized Sky Survey is tidally stripped material from the Sagittarius dwarf and support the idea that the tidal stream completely enwraps the Milky Way in an almost polar orbit.

Fig. III.35: Two-dimensional X, Z- projection of the Sagittarius (Sgr) stream model with respect to the Galactic center. The Sun's coordinates are $(X,Y,Z)_{\odot} = (-8.5, 0.0, 0.0)$ kpc, and Sgr center is placed at $(X,Y,Z)_{Sgr} = (16,2, -5.9)$ kpc. The black particles are still bound to the Sgr galaxy, the yellow particles became unbound during the last gigayear, the green particles between 1.0 and 2.0 Gyr ago, the blue particles between 2.0 and 3.0 Gyr ago, the purple particles between 3.0 and 5.0 Gyr ago, and the red particles more than 5.0 Gyr ago.

In a related research project, MPIA astronomers in collaboration with astronomers from Spain have run numerical simulations of the historical orbit of the Sagittarius dwarf with respect to the Milky Way. Fig. III.35 shows a two-dimensional X, Z- projection of the Sagittarius (Sgr) stream model with respect to the Galactic center. This model reproduces the present position and velocity of the Sagittarius main body and presents a long tidal stream formed by tidal interaction with the Milky Way potential. The model is in excellent agreement with the above new observations, confirming the notion that they are detections of a trailing tidal arm, as well as with existing constraints from over a decade of intense observational effort. Because debris from more than one orbit of the Sagittarius dwarf has been observed, the shape of the Galaxy's dark matter halo can be explored, although with much less accuracy than if two or more independent streams are used. Preliminary results suggest that the Milky Way halo is not quite round, with an oblateness of the matter distribution of roughly 0.7 (the short axis is 0.7 times the long axis), in excellent agreement with simulations of dark matter halo formation.



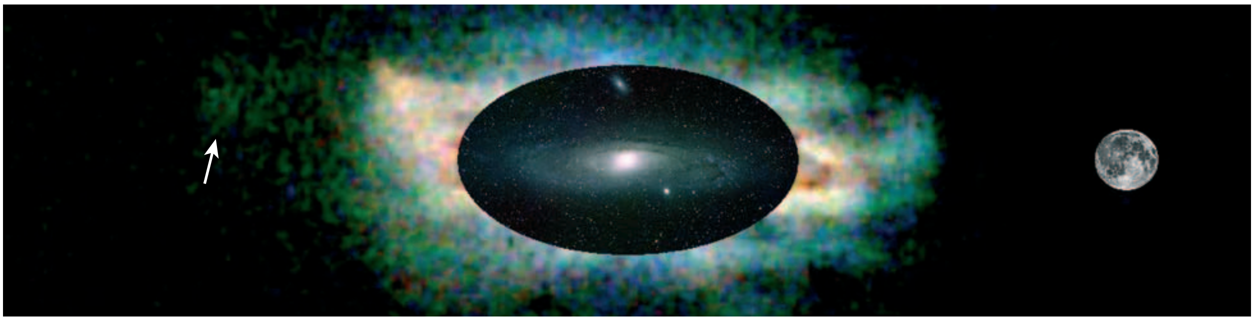


Fig. III.36: The location of Andromeda NE (arrow), the complicated stellar structures in the halo of M 31 (inset image to scale) and the moon as a size reference. (SDSS; M 31 inset: B. Schoening, V. Harvey/REU/NOAO/AURA/NSF; full moon: from Lick Obs.)

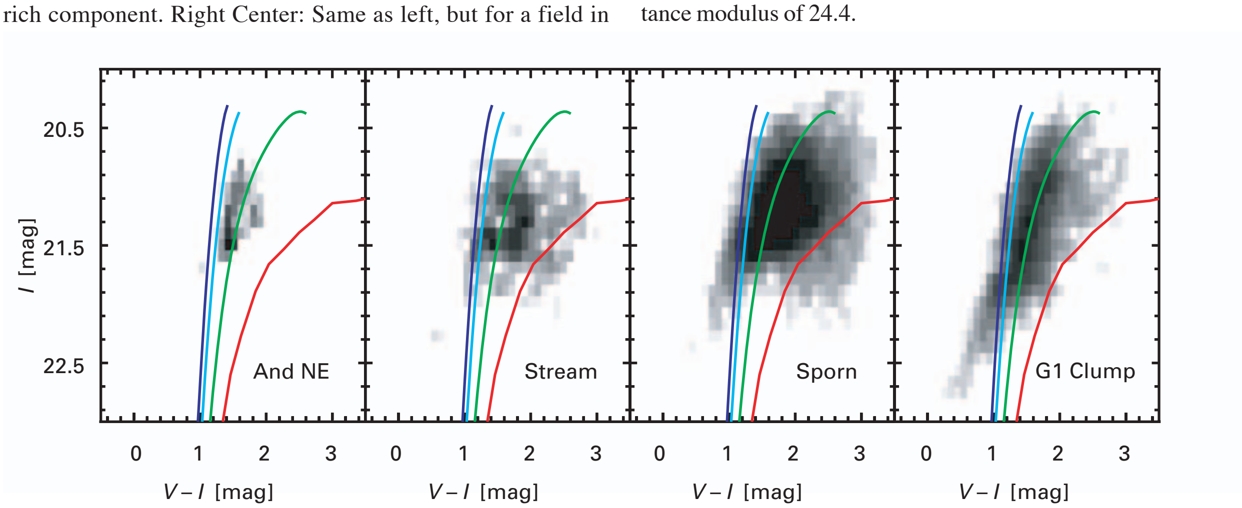
A New Stellar Structure in the Halo of the Andromeda Galaxy

In October of 2002, the SDSS telescope was used for a special scan of the Andromeda Galaxy (M 31). This scan, extending some 18° along the major (long) axis of M 31, has yielded a wealth of detail about the structure and stellar populations in the halo of M 31, but has also revealed a new, previously unknown overdensity of stars ≈ 3° to the north-east of M 31, which astronomers at MPIA dubbed Andromeda NE. Ist location is indicated by the arrow in the composite illustration shown in Fig. III.36, which also illustrates the complicated stellar structures in the halo of the Andromeda Galaxy and a scaled photo of the moon as a size reference. The colors in the image reflect the relative colors of stars that are predominantly red giants at the distance of the Andromeda Galaxy. Bluer and whiter colors generally indicate lower metallicity (elemental abundances) and yellow and red stars indicate increasing elemental abundances.

This new stellar structure, detected as an excess of luminous red giant stars at approximately the same distance as M 31, is incredibly diffuse, with a g-band central surface brightness of ≈ 29 mag/arcsec^2. However, Andromeda NE is so large, spanning almost a square degree, that its integrated luminosity (≈ –11.6 mag) is comparable to several known Local Group dwarf galaxies. The color of the red giant branch in Andromeda NE is unlike that of some known halo structures, like the northern spur or the giant stream to the southwest, but it does resemble that of the so-called G1 clump, on the opposite site of M 31's disk (Fig. III.37).

The nature of Andromeda NE thus remains unclear; it could be a satellite galaxy undergoing tidal disruption or even stellar debris from the outer part of M 31's disk,

Fig. III.37: Red Giant Branch Colors of Stellar Structures in the Halo of M 31 from SDSS data: Left: Hess diagram (stellar color-magnitude density plot) of Andromeda NE, minus an appropriately scaled control field Hess diagram, divided by the square root of the sum of the two Hess diagrams. Note the comparatively narrow red giant branch (RGB) at moderate metallicity (elemental abundance). Left Center: Same as left, but for a field in the Giant Stream (cf. Ibata et al. 2001). Note the extension of the RGB toward the red, indicating the presence of a metal-rich component. Right Center: Same as left, but for a field in the Northern Spur, showing an even more pronounced metal-rich stellar population. Right: Same as left, but for a field in the so-called G1 Clump, revealing an RGB comparable to that of Andromeda NE when the superior signal-to-noise of the G1 Clump field is taken into account. Data are binned by 0.1 in I and V – I, and smoothed with a Gaussian filter. Fiducial sequences are overplotted for Galactic globular clusters with metallicities of (left to right) [Fe/H] = –2.2 (M 15), –1.6 (M 2), – 0.7 (47 Tuc), and –0.3 (NGC 6553), shifted to the adopted M 31 distance modulus of 24.4.



scattered by some as-yet unknown past cataclysm. From morphological and structural considerations it is more likely a stream of stars from an already-disrupted dwarf galaxy; follow-up observations are being planned to help distinguish between these scenarios. If this structure proves to be a tidal stream, detailed study of the velocities and distances of stars in this stream and another already-discovered stellar stream around Andromeda will allow robust estimation of the shape of Andromeda's dark matter halo.

The distribution of stellar mass and cooled baryons in the local Universe

Owing to its accurate and complete photometric and spectroscopic coverage of large numbers of galaxies, the SDSS is ideal for understanding the distribution of matter in galaxies in the present-day Universe. Researchers at the MPIA and the University of Massachussetts have combined SDSS with the Two Micron All-Sky Survey, a near-infrared survey of the sky, to estimate the distribution of stellar and cold gas mass in galaxies in the local Universe, and the overall 'efficiency' of galaxy formation.

Understanding where the baryons are is an important problem in astrophysics. The fraction of mass in the Universe that is in baryons (the building blocks of »normal« matter, such as electrons, protons, and neutrons) is relatively well known; the abundance of light elements and the shape of fluctuations in the cosmic microwave background radiation suggest that around 15 % of the total matter density of the Universe is in the form of baryons. Initially all baryons in the Universe are very smoothly distributed, but as time passes they are drawn into concentrations of dark matter. The gas cools and condenses, forming dense clouds of gas which in turn form stars. The most massive of these stars have intense stellar winds, and die in powerful supernova explosions, oftentimes ejecting large quantities of this cooled gas back into intergalactic space (this process is called feedback). Therefore, building a detailed understanding of where the stars and cool gas are in the local Universe can shed important light on the poorly-understood baryonic processes of gas cooling, star formation and feedback.

An important prerequisite for constructing a census of stellar mass is a deep understanding of the optical and near-infrared luminosities of galaxies. The optical light from galaxies is strongly affected by young, massive, bright blue stars and clouds of obscuring dust; in contrast, the near-infrared is much less affected by young stars and dust, offering a much more robust estimate of stellar mass. Furthermore, a highly complete and unbiased sample of galaxies is required to be able to understand how many of a given type of galaxy there are per unit volume. The SDSS and the near-infrared Two Micron All Sky Survey (2MASS) are ideal tools, offering spectroscopy and optical/near-infrared photometry for large and relatively unbiased samples of galaxies.

In order to estimate stellar masses for any given galaxy, however, one must assume that the distribution of newly-formed stellar mass (the stellar initial mass function, or IMF) is a universal constant; that is, for example, for every 10 stars formed like the Sun, there is only one star with three times the mass of the Sun. Under this assumption of a universal IMF, the mass contained in the stars of galaxies was estimated by fitting the optical and near-IR luminosities of the galaxies with a wide range of detailed stellar population models. This gave stellar masses accurate to typically 30 % in a random and systematic sense. Using these accurate stellar masses, a census of the location of the stellar mass in the local Universe was constructed. Between 3 % and 8 % of the expected mass density in baryons is accounted for in this detailed census of stellar mass – clearly, the formation of stars in galaxies is a highly inefficient process! Furthermore, as illustrated in Fig. III.38, it is clear that most of the stellar mass is in galaxies with masses of $\approx 3 \times 10^{10}$ $M_\odot$ around the mass of the Milky Way galaxy.

In the local Universe, there are two broad classes of galaxies. On the one hand, one sees large numbers of disk-dominated galaxies, like our own Milky Way, as illustrated in Fig. III.39: these galaxies typically are called late-type galaxies. On the other hand, there is a lower number of galaxies dominated by a spheroidal stellar component, such as the galaxy in Fig. III.40: these galaxies are called early-type galaxies. Their difference in shape betrays a diversity in formation history: a

Fig. III.38: The distribution of stellar mass in all galaxies (green line), disk-dominated late-type galaxies (blue line, see e.g., Fig. III.39) and spheroid-dominated early-type galaxies (red line, see e.g., Fig. III.40).

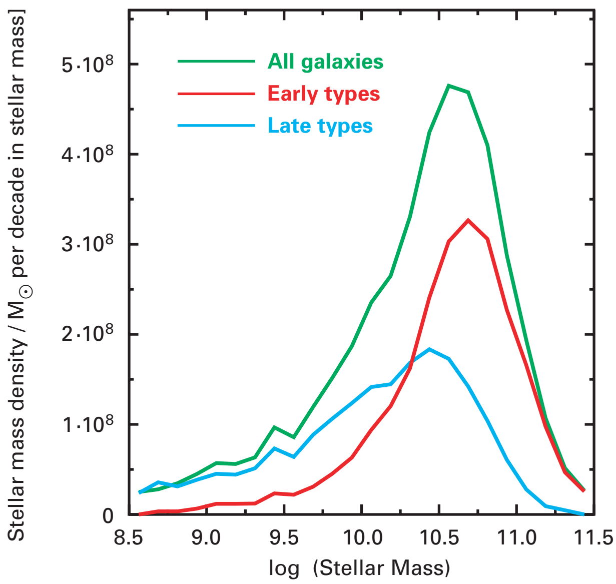


Fig. III.39: NGC 4536: an example of a disk-dominated late-type galaxy, taken from the SDSS. (R. Lupton/SDSS)

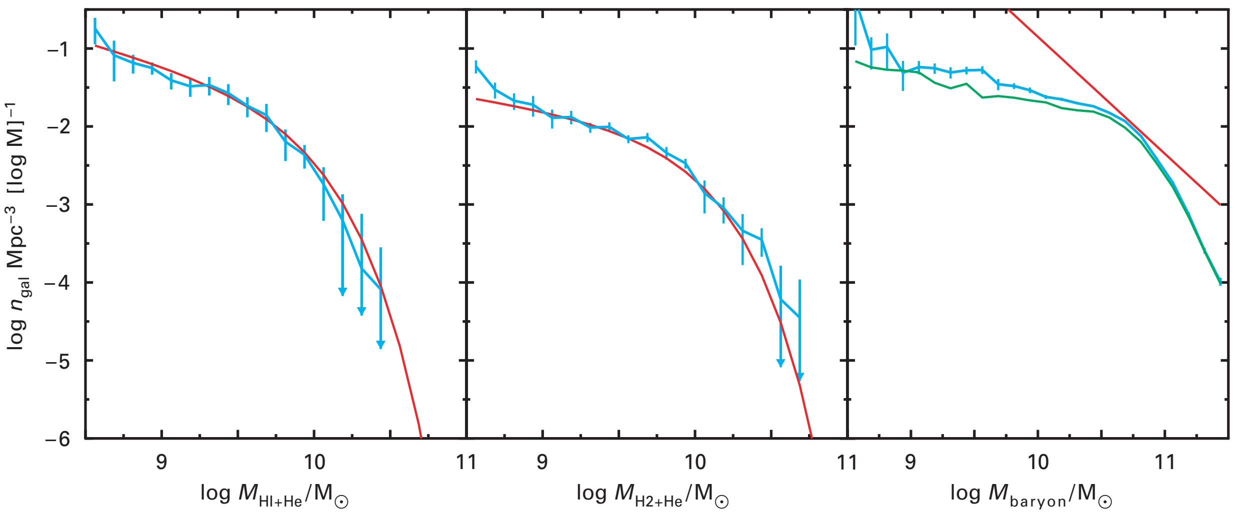
Fig . III.40: NGC 5846: an example of a spheroid-dominated early-type galaxy, taken from the SDSS. (R. Lupton/SDSS)

spheroidal stellar distribution means that the galaxy was assembled in a rapidly changing potential well, indicating that the galaxy probably underwent a violent major merger with another galaxy at some stage in its past. On the other hand, a thin disk-like distribution of stars cannot survive such a violent encounter. Therefore, the relative amount of stellar mass in late-type and early-type galaxies will reflect the fraction of stars in the Universe that did not undergo a major galaxy interaction, vs. the fraction of stars that have undergone a major interaction. As illustrated in Fig. III.38, between 50 % and 75 % of the stellar mass in the Universe is in spheroid-dominated early-type galaxies – most of the stellar mass in the Universe has been affected by major galaxy mergers in the past!

Furthermore, it is possible to use these data to estimate the amount of cold gas in each of these galaxies. One can use smaller but well-characterised samples of galaxies with robust stellar masses, galaxy sizes and gas masses to act as a training set for the SDSS/2MASS sample of galaxies. Using these training sets, it became clear that there is a relatively tight correlation between the fraction of mass in cold gas and the stellar surface density. This relatively tight correlation can be used to estimate the cold gas mass for each SDSS/2MASS galaxy, with typical galaxy-to-galaxy accuracy of a factor of 2 or 3, but with rather better statistical accuracy for large samples of galaxies.

The result is remarkable; using this technique, it is possible to reconstruct the mass function of atomic and molecular hydrogen in the local Universe, as illustrated in Fig. III.41. This figure shows the distribution of gas and stellar mass in the local Universe. Using a statistical technique, it is possible to use the SDSS to estimate the distribution of atomic and molecular hydrogen in the local Universe, as shown by the blue line in the left and central panels. The observations are shown in red – it is clear that this statistical method reproduces the amount and distribution of ‚cold' atomic and molecular gas in the local Universe. Using these gas mass estimates to augment the stellar mass (green line in the right panel) gives the distribution of baryonic mass that has cooled and condensed into cold gas and stars in the center of dark matter haloes (the blue line in the right panel). Comparison with the expected distribution of total baryonic mass (with arbitrary normalization), including hot gas which is yet to cool and participate in galaxy formation (red line in the right panel) shows that the fraction of gas that cooled and condensed is a strong function of halo mass, peaking in efficiency for haloes with roughly the mass of the Milky Way's dark matter halo.

Despite the simplicity of the approximations going into this gas mass estimate, the overall amount and distribution of molecular and atomic hydrogen in the local Universe is robustly reproduced. Using this, the distribution of the stellar plus cold gas mass can then be estimated. Taking into account all the uncertainties, between 4 % and 12 % of the total expected baryonic mass is in either stars or cold gas (i.e., gas eligible to form stars sometime in the future). This implies that a very small, almost negligible fraction of baryons in the Universe manages to make it into galaxies. Furthermore, comparing the shape of the galaxy cold gas + stellar mass function (blue line in the right panel of Fig. III.41) with the expected shape of the dark matter halo mass function (which should be the same shape as the total



baryonic mass function, including hot gas which has not cooled into the central parts of galaxies where it can be observed; red line) shows that the fraction of baryons that make it into the inner part of galaxies at the present day is a strong function of galaxy halo mass. Whereas many of the baryons in Milky Way-sized galaxies can cool and condense into galaxies, at both low and high halo masses, the fraction of gas managing to cool and condense into observable stars and cold gas is drastically reduced. By itself, this offers powerful insight into the physics of gas cooling and feedback, allowing theoreticians to test and tune their models of galaxy formation and evolution.

Fig. III.41: The distribution of gas and stellar mass in the local Universe. Left and central panel: blue line – distribution of atomic and molecular hydrogen; red – observations. Right panel: green line – stellar mass distribution; blue line: baryonic mass in gas and stars; red line: total baryonic mass (including hot gas)

(Eva Grebel, Hans-Walter Rix, Eric Bell, Stefan Kautsch, Alexei Kniazev, Andreas Koch, David Martínez-Delgado, Jakob Walcher, Daniel Zucker)

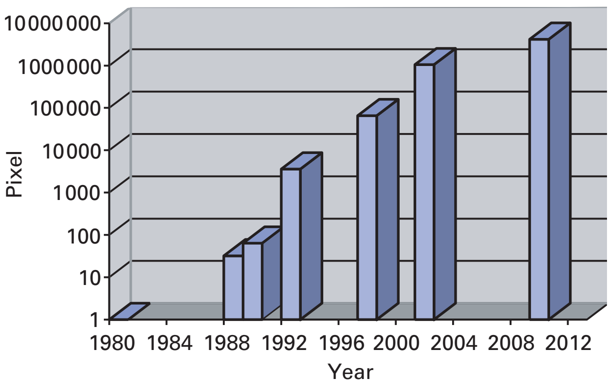
IV Instrumental Developments

Development of new instruments is an essential part of the work at the Institute. It goes hand in hand with the evolution of new scientific questions and encompasses projects of quite different size.

While the contemporary instrumentation for the Calar Alto telescopes can in most cases be accomplished with the resources of the MPIA alone, in collaboration with smaller and larger industrial companies, this is not the case for instrumentation projects for the large telescopes at ESO and for the LBT, as well as for the space-borne experiments. These require collaborations of numerous institutes working together in worldwide consortia. Collaboration with industry in the development of latest technologies is an essential and sociologically relevant aspect of this.

IV.1 OMEGA 2000 – a Camera for the Infrared Regime

Observations in the near infrared spectral range have a long tradition at the institute. The astronomers at Calar Alto always had state-of-the-art infrared equipment at their disposal: from the first image tubes, sensitive up to wavelengths of 1μm, the bolometers and photometers with one "pixel" as a detector, to the MAGIC cameras and to OMEGA-prime and OMEGA-Cass, the current work horses at the 3.5-m telescope (Fig. IV.1). Based on previous experience it was decided in March 1999 to build a wide-field camera for the prime focus of the 3.5-m telescope, centered around the just announced HAWAII-2 detector.



This new detector, whose smaller variant was already in use in OMEGA-prime, would have 2048 × 2048 pixels. This for the first time opened up the opportunity to survey large areas on the sky in the infrared range for faint objects within realistic observing times. These in turn could then be studied in detail with 10-m-class telescopes. In the four years between this decision and first light in January 2003 the former Coudé front ring had to be converted in its mechanical structure to house the new instrument, a large dewar had to be built, optics was designed and fabricated and a new read-out electronic system was developed.

The Detector

The detector for OMEGA 2000 is manufactured by Rockwell in Camarillo (California). With its 2048 × 2048 pixels it is currently the largest focal plane array available for the infrared range. It is a semi-conductor device, whose light-sensitive layer consists of HgCdTe. Each pixel measures 18 μm on a side, making the whole detector as large as 14 cm^2. On average it detects more than 70 percent of the incident photons. The high quantum efficiency together with the very low read-out noise, equivalent to 15 photons, are ideally suited for the detection of weak infrared sources. Its sensitivity ranges from 850 nm, i.e. the short wavelength end of the infrared spectrum still accessible to optical CCDs, up to 2.5 μm, where the thermal emission of the surroundings (telescope, dome, atmosphere) has increased considerably and severely hampers the detection of faint astronomical objects. The operating temperature of the detector is at –196 °C. At higher temperatures the thermal noise becomes dominant, prohibiting sensitive measurements. Thus the instrument has to be cooled with liquid nitrogen.

Fig. IV.1: Development of infrared detectors at the 3.5-m telescope on Calar Alto since 1980. The increase of the number of image elements as a function of time is shown.

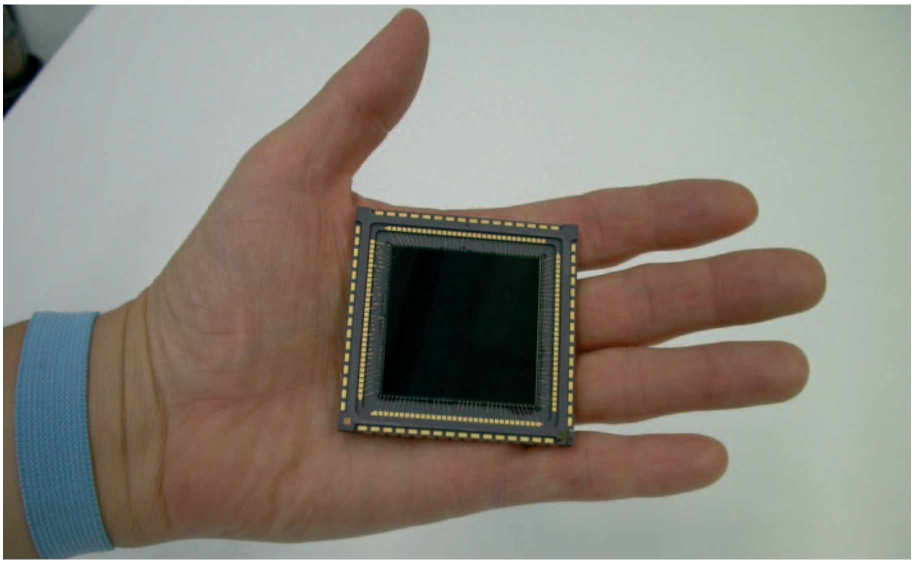


Fig. IV.2: The detector for the infrared camera OMEGA 2000

The Optics

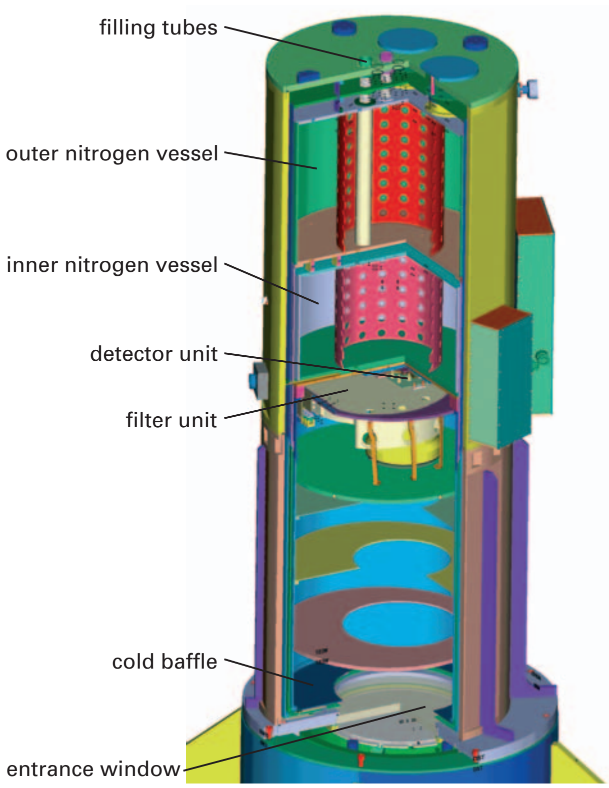
As the camera is operated in the prime focus of the hyperbolic main mirror a corrector lens is necessary. The optics should be achromatic over the whole range of sensitivity of the detector, i.e. the image quality should not depend on the wavelength of the incident radiation. Furthermore the large collecting area has to be taken into account with the image scale (arcseconds / pixel) being a compromise between resolution and the solid angle captured in one exposure. As OMEGA 2000 would be primarily a survey instrument a relatively large pixel scale of 0.45 arcseconds/pixel was chosen. According to the calculations by the engineers at MPIA this could be accomplished by a combination of four lenses made of CaF_2, fused silica, BaF_2 and ZnSe. In the optical calculation even the bending of the dewar's entrance window had to be taken into account, which bends by 106 μm when the dewar is evacuated (see below). The calculations show that this optics will deliver images practically free of distortions. To accomplish this, however, the tolerances for mounting the optics are extremely tight. The lenses have to be centered on the optical axis to better than 50 μm and must not be tilted by more than 30 arcseconds.

The Dewar

The dewar is a large thermos for detector, optics, filters and a cold entrance pupil, all being cooled with liquid nitrogen down to about –190°C to suppress thermal noise and thermal radiation background (Fig. IV.3). The dewar for OMEGA 2000 was the largest built by "Infrared Labs" till then. With a diameter of 60 cm and a height of 168 cm its two nitrogen tanks hold 47 and 72 liters, respectively. Mounted on the front ring, the tanks can only be filled half, as the telescope must be able to move to all directions without spilling the liquid nitrogen. With this supply of liquid nitrogen the dewar keeps its operating temperature for about 35 hours, i.e. well over a long winter night of observing.

The long distance between the detector and the cold entrance window facilitates an effective shielding of the warm background from the detector, leading to the

Fig. IV.3: The dewar and its interior components.



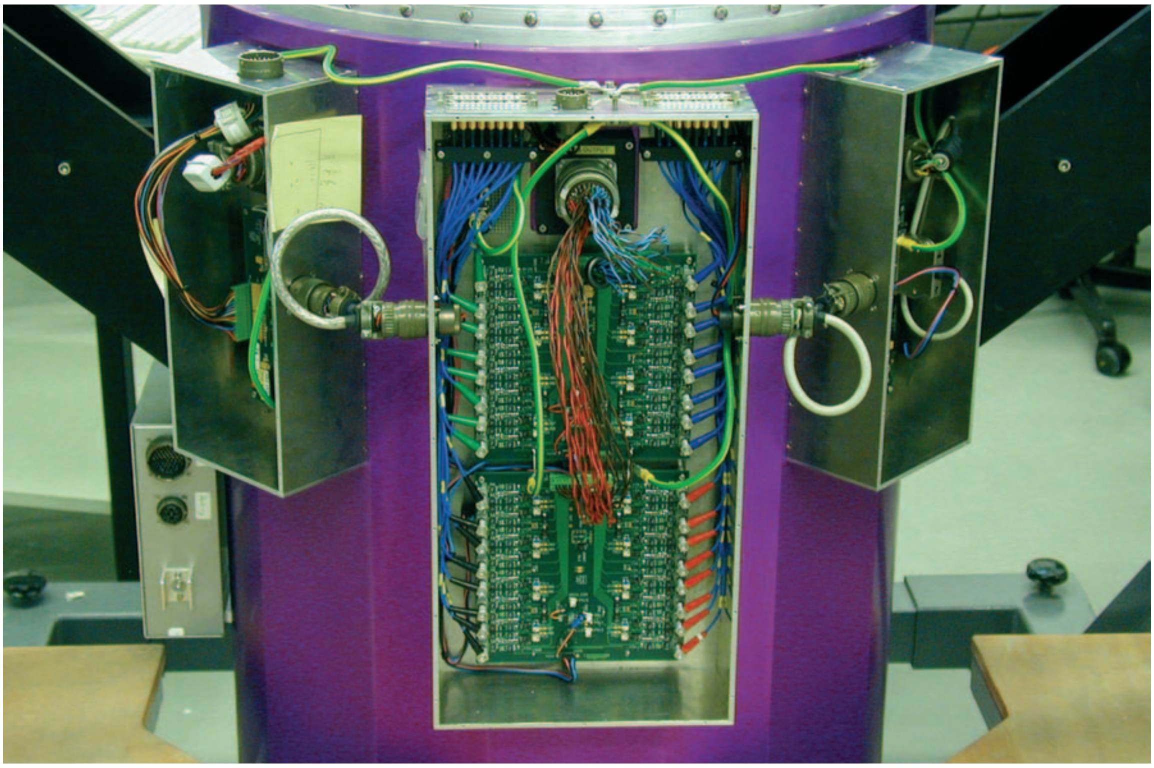


Fig. IV.4: Control and read-out electronics of the infrared camera.

long overall construction of the instrument. Given the geometric opening angle of the incident radiation this requires a diameter of the entrance window as large as 35 cm. Once the dewar is evacuated the entrance windows bends inwards under the atmospheric pressure by $^{1}/_{10}$ mm even though it has a thickness of 22 mm. It thus acts as a lens, whose properties have to be taken into account when calculating the optics to achieve the high image quality desired.

Cryo-techniques

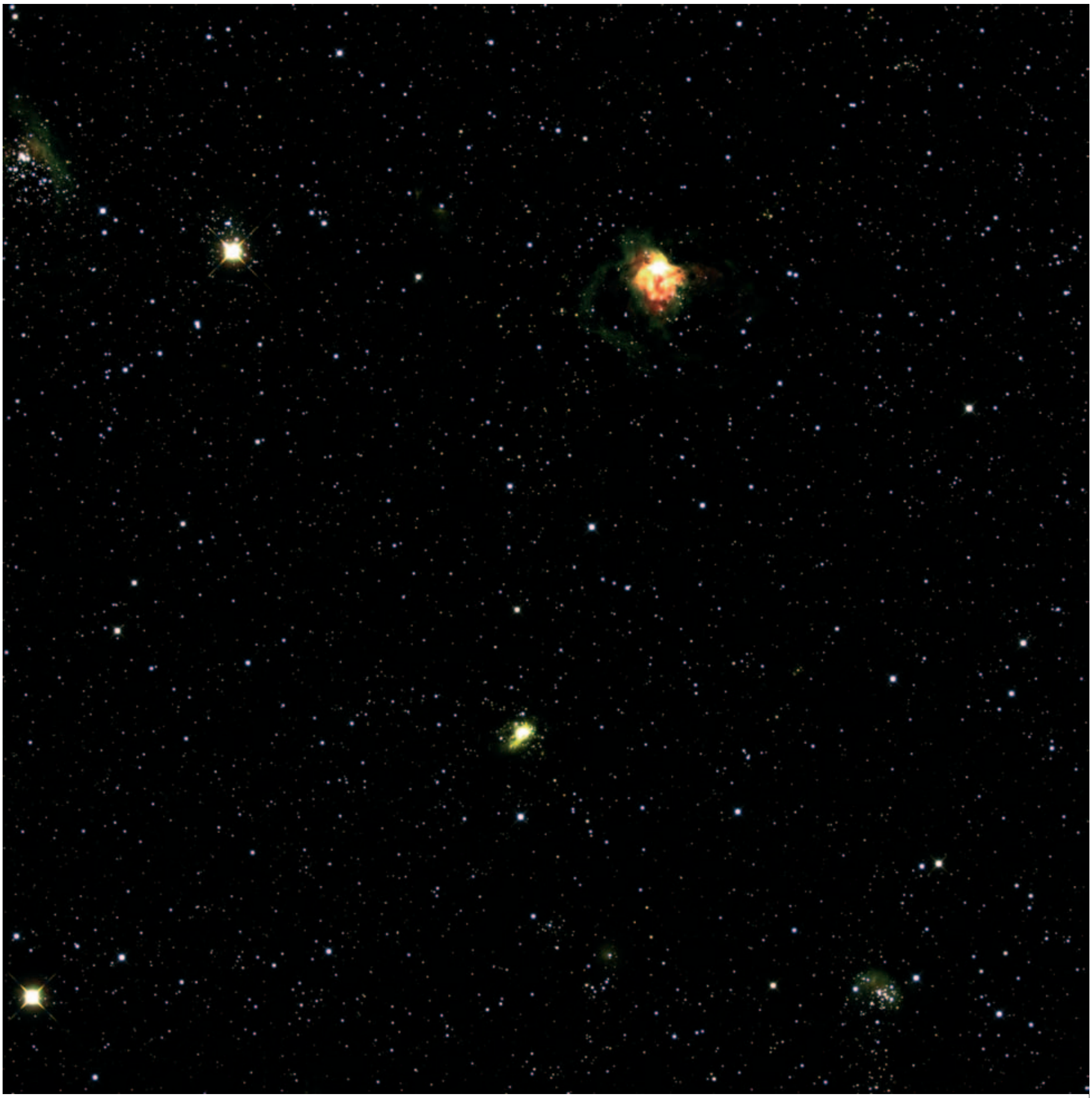
Detector, optics and filter wheels are cooled down from room temperature to about –190°C for operating the instrument. This is especially demanding for design and manufacturing of the individual parts of OMEGA 2000. The four lenses, e.g., are all made of different materials, rendering their thermal behavior in turn being different from the mounting made of aluminum. Without taking specific measures the lenses would not survive a cool-down cycle without breaking. Therefore design engineers at MPIA used a trick to mount the lenses. They rest on 45° bevels and are hold in place by means of a ring pressed onto them by springs. Although the lenses shrink with different rates during cool-down, they can move on the bevels without mechanical stress. The accuracy demanded for centering the lenses (see above) is guaranteed by an exact manufacturing of the bevels' surfaces and the strength of the springs. Nevertheless it was exciting to watch the first image being taken and verify that the anticipated good imaging quality was actually being obtained.

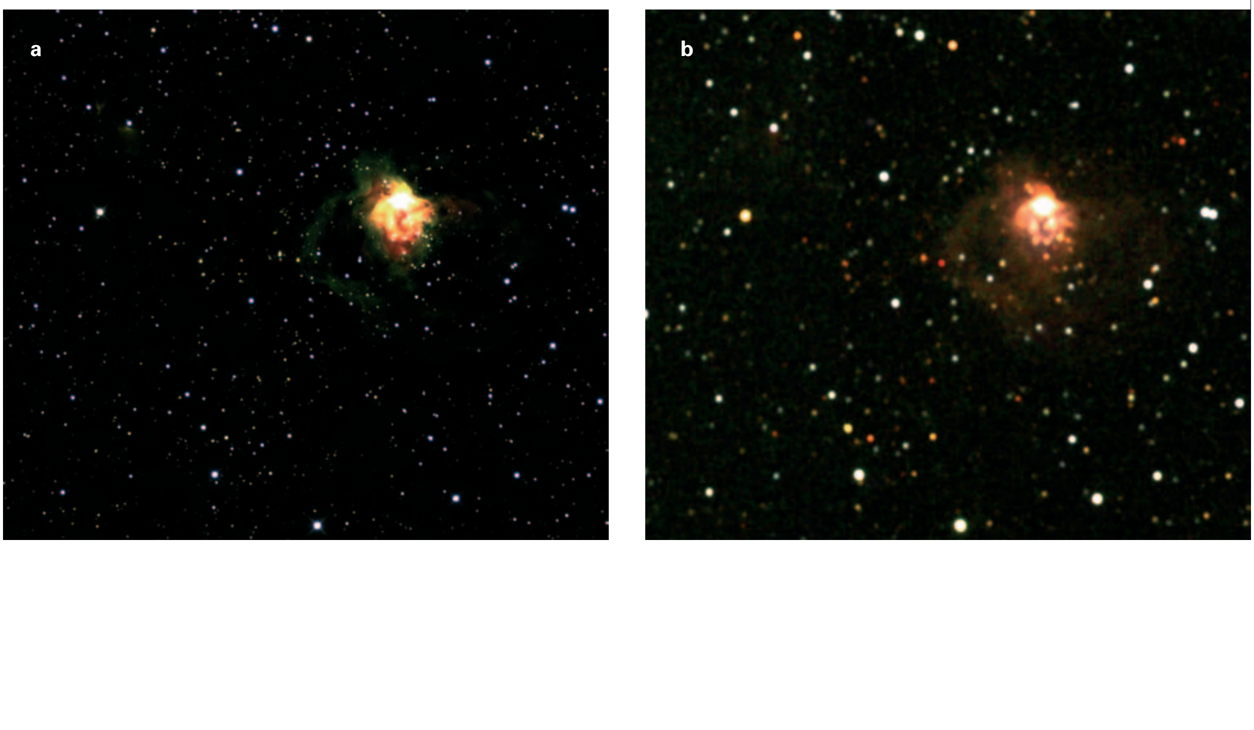
Another trick had to be utilized in the construction of the filter wheels. Although they are driven by commercially available cryo-motors it would take them extremely long to reach the operating temperature: The ball bearings are very good insulators due to the small thermal contact surfaces on which the wheels rest. A metallic finger clicking in place once the desired wheel position is reached largely reduces the time to reach thermal equilibrium due to its large contact area.

Electronics

All of the electronics needed to read out the detector and control the instrument have been designed and built at MPIA. Especially high are the demands on the read-out electronics in terms of speed and quality (low noise level). Due to the high thermal background an infrared detector has to be read out fast enough to avoid saturation

Fig. IV.5: The HII-region IC1470 and its surroundings. *Above:* The full field of 15.4 arcminutes on a side in the original pixel scale. **a)** A blow-up of the HII-region. **b)** The same field as seen in the 2MASS survey.



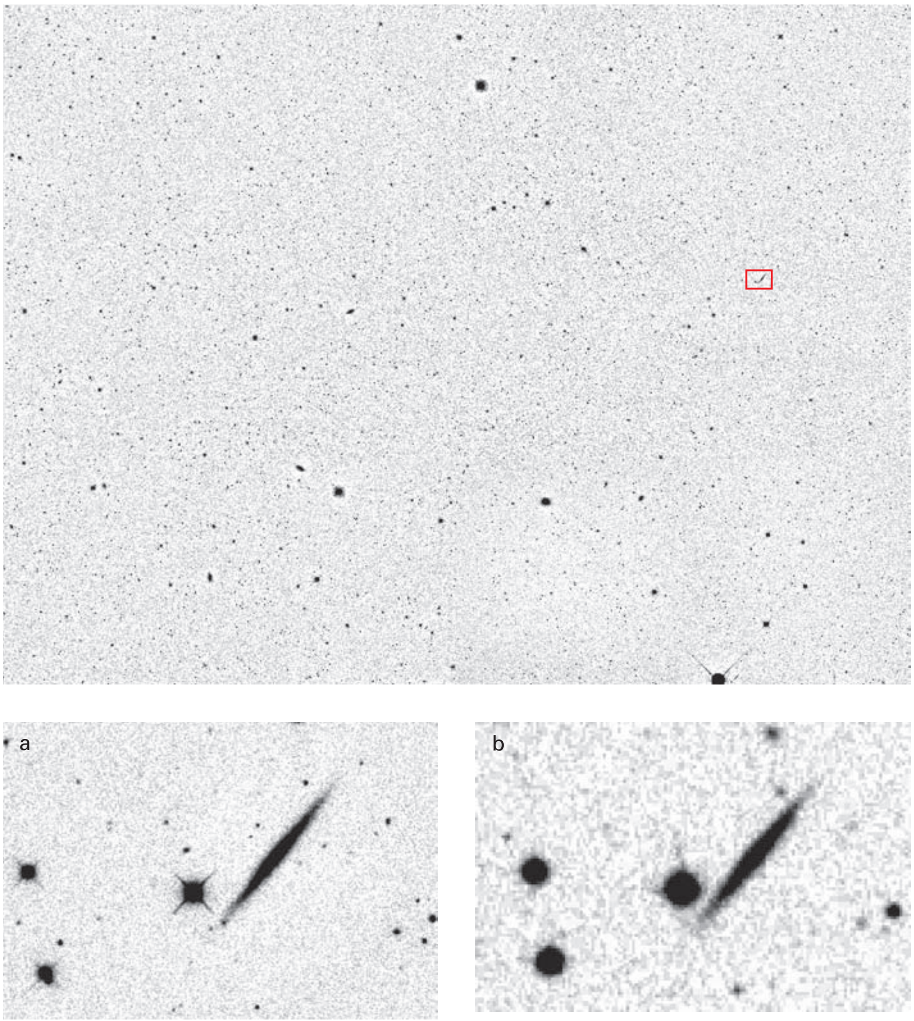

a
b

of the detector. In praxis this means transferring all 4 million data values in less than a second to the computer. By reading in parallel over 32 channels a minimum read-out time for OMEGA 2000 of 0.8 seconds is achieved! Any read-out process inevitably adds noise to the signal. Thus all electronic components have to be tuned to the detector and among each other carefully to reduce this noise. In our system the read-out noise introduced by the electronics is well below the noise inherent to the detector. This makes all observations background limited – also those in narrow band filters, where the sky background is low. Thus the instrument operates in an optimal range.

Fig. IV.6: Mosaic of 1°.0 × 0°.75 (= 4 × 3 pointings) from images taken with OMEGA 2000. of the HIROCS survey field at 22 h. Exposure time was 1 500 sec for each pointing. Lower left: Blow-up of the area in the red rectangle of the main image. Lower right: Same area as seen by the Digital Sky Survey II.

Observing with OMEGA 2000

The camera (filter, exposure time etc.) is configured interactively with a graphical user interface. With this GUI also the raw images can be displayed and the observations be optimized. However, interactive work is always subject to time delays. In order to use the telescope time most effectively and to reduce errors in operating the camera, both telescope and instrument can be run with programs prepared in advance, so-called macros or procedures. The macros may also be used from within an astronomical image processing system which allows an automated preliminary reduction of the data online at the telescope. This is especially important in the infrared range. As described above, typical integration times are a few seconds only in order not to saturate the detector by the background signal. The total integration times on the order of many minutes or even hours needed to detect faint objects can thus be achieved only by adding up hundreds or even thousands of individual images. Furthermore, the constantly changing sky background requires special treatment. Taken together, all this leads to the fact that the astronomical information is in general not readily discernable in the raw data. With the instru-



ment collecting data automatically in pre-programmed mode, a first data analysis may be performed in parallel and independently, including the correctly centered summation of all images of a given object. Within a few minutes after the end of an observing sequence the astronomer thus has the opportunity to judge the data quantitatively. This is also in the interest of further optimizing the use of valuable telescope time as due to this analysis subsequent observations may be fine-tuned further.

First results

With its large field of view OMEGA 2000 is especially suited for survey projects. As soon as the new camera became available several projects were started at the Institute aiming at the identification of certain types of objects – both galactic and extragalactic.

Members of the planet and star formation group (Birkmann et al.) surveyed star forming regions in the Milky Way. The large frame in Fig. IV.5 shows the region around IC 1470 in H, K_S and Br-γ corresponding to the colors blue, green and red of the false color representation with the full field of 15.4 arcminutes and the original pixel scale of 0.45 arcseconds/pixel. The image is dominated by IC 1470, the extended HII-region to the north. To provide an impression of the resolution and depth of the image a blow-up depicts an area of 5.6 arcminutes centered on IC 1470. To the north a bipolar nebula is seen, color representation is as in the original figure, but the pixel scale has been stretched to 0.225 arcseconds/pixel. For comparison the third image shows the same region from the 2 MASS all-sky survey. Here the colors blue, green and red represent the filters J, H and Ks. The pixel scale of the 2 MASS data is 1 arcsecond/pixel.

In the extragalactic group at the institute, OMEGA 2000 is mainly used for two projects combined under the name MANOS (MPI für Astronomie Near Infrared and Optical Surveys): Within OMEGA-17+4, the existing survey with the Wide Field Imager in 17 filters (see previous annual reports) will be extended by four additional filters to the near infrared range using OMEGA 2000. This will enable a census of the galaxy population out to redshifts of about 2 (the original data set could be used only to redshifts of about 1.2).

Studies of clusters of galaxies, the largest gravitationally bound systems in the universe, are currently restricted to a redshift range below about unity, due to the search methods available. Since distant and thus also young clusters contain significant numbers of red elliptical galaxies, progress can be achieved – like with COMBO-17+4 – by extending the wavelength coverage of a survey to infrared wavelengths searching for concentrations of these red galaxies. For the HIROCS project (Heidelberg InfraRed/Optical Cluster Survey) COMBO 2000 is used to establish this way a sample of distant clusters of galaxies with redshifts of up to 1.5. The optical data needed to supplement the survey are collected with LAICA. In an observing run in September data could be obtained for two survey fields totaling more than tw o square degrees. Exposure time per OMEGA pointing was 3000 sec. Figure IV.6 shows a mosaic of $1\overset{\circ}{.}0 \times 0\overset{\circ}{.}75$ using data reduced with the pipeline directly at the telescope. The data used for this figure encompass only half the observing time for each field, i.e. 1500 sec. The red rectangle is the area zoomed into in the blow-up at lower left. At lower right, the same area is shown from the photographic Digital Sky Survey II (red plates).

(H.-J. Röser, P. Bizenberger, M. Alter, C. Bailer-Jones, H. Baumeister, A. Böhm, F. Briegel, B. Grimm, Z. Kovács, W. Laun, U. Mall, R.-R. Rohloff, C. Storz, K. Zimmermann, S. Zoltán)

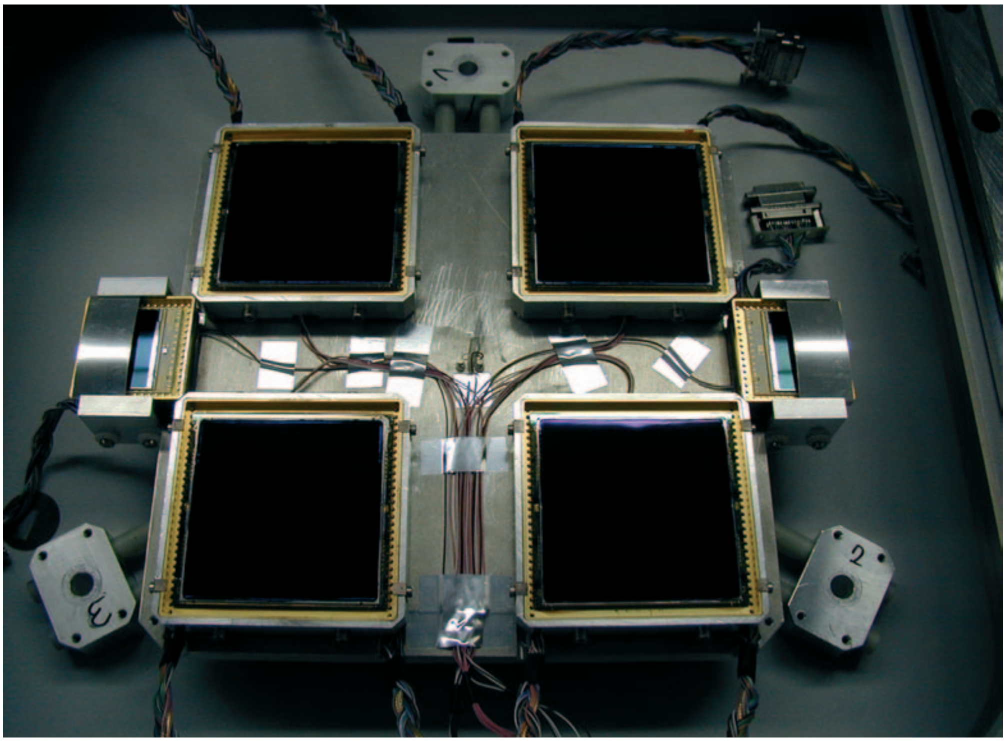


Fig. IV.7: The LAICA detector consisting of four CCDs. Also to be seen are two smaller CCDs used for tracking.

IV.2 The Wide Field Camera LAICA

The wide field camera LAICA, presented already in the Annual Report 2002 was finally completed in the year under report. The camera had been developed with the goal to fully utilize the large field of view of one degree diameter available at the prime focus of the 3.5-m telescope. Astronomical applications of a wide field camera are manifold, ranging from the search for distant galaxy clusters, distant galaxies and quasars to the search for brown dwarfs in the solar neighborhood.

LAICA is working in the optical spectral region, i.e., from 350 to 1000 nm wavelength. Four CCDs with 4096 × 4096 pixels each are used as detectors, providing a total of 67 million pixels. At a pixel size of 15 μm an image scale of 0.225 arcseconds per pixels is obtained so that even under good seeing conditions (the median value at Calar Alto is 0.85 arcseconds) all exposures are very well sampled. For technical reasons, the CCDs cannot be joined without gaps; therefore an arrangement was chosen where the separation between the CCDs almost equals a side length of a single CCD (see Fig. IV.7). A set of four images then covers a contiguous field of one square degree.

Electronically, the CCDs are subdivided into quadrants that are read out by an electronic system especially developed for this purpose at MPIA. Because of this parallel read-out a short read-out time of about one minute for all four CCDs is achieved. Each exposure with LAICA yields 142 Mbyte of data. Two filter sets are available: Johnson UBVRI and SDSS u'b'g'r'i'z'. These filters are housed in a magazine with 20 storage places.

Final completion of LAICA was delayed mainly because three out of the four CCDs were defect and had to be replaced. Since August 2003, however, four functional CCDs are available. It also turned out that the primary mirror of the telescope was slightly tilted and had to be re-adjusted since all exposures taken with LAICA displayed a strong field-independent coma. Exposures taken at a seeing of 0.8 arcseconds show the image quality now achieved to be very good. In order to ensure a good image quality a cooling system was installed that removes heat dissipated by the camera electronics, thus preventing a deterioration of the seeing by bubbling warm air; this cooling system can also be used in combination with other instruments. During first observations carried out by staff members of the Calar Alto observatory at the end of the year LAICA was working without any problems.

(J.W. Fried, H. Baumeister, W. Benesch, F. Briegel, U. Graser, B. Grimm, K.H. Marien, R.-R. Rohloff, H. Unser, K. Zimmermann)

Fig. IV.9: PYRAMIR is being tested by Karl Wagner in the adaptive-optics laboratory.

IV.3 The Wavefront Sensor PYRAMIR

PYRAMIR is a novel wavefront sensor for the near-infrared spectral range. It will be used with the ALFA adaptive optics system at the 3.5-m telescope on Calar Alto where it will complement the classic Shack-Hartmann wavefront sensor (SHS) that works in the optical range. Similar to the SHS, PYRAMIR will provide a signal which is a measure of the local wavefront tilt. With the help of this signal the shape of a deformable mirror will be controlled so that the local wavefront tilt is corrected for.

The working principle of the PWS is shown schematically in Fig. IV.8. A distorted light ray will not hit exactly the top of the pyramid and therefore fall preferentially into one of four pupils (for simplification, the schematic only shows two of them). The difference of the int ensities in the images P_+ and P_- thus yields the sign (the direction) of the local tilt of the wavefront. If the pyramid is oscillating circularly the distorted light ray will fall into each of the pupils during an integration time corresponding to several oscillation periods. The local wavefront til ts are then obtained from the differences of the intensities.

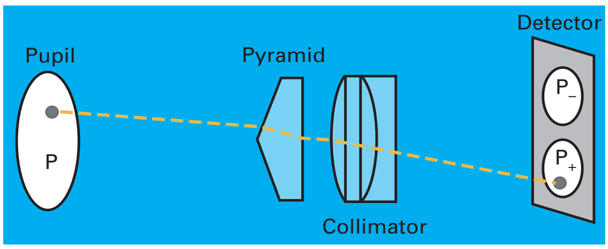


Fig. IV.8: Working principle of the pyramid wavefront sensor. A local tilt of the wavefront in a given point P of the telescope pupil leads to a shift of the focus of the light wave emerging from P. If a pyramidal beam splitter is placed at the focus the light ray in our example will fall only to one side. Comparison of the pupil images shows that the intensity is once increased (P_+) and at other another time decreased (P_-). The difference of the intensities is a measure of the local wavefront tilt in the telescope pupil.

Although the PWS, like the SHS, measures the local tilt of the infalling wavefront it exhibits a significantly better noise behavior in the control loop than the SHS since the PWS records a straightening of the wavefront across the entire telescope mirror.

The design phase of PYRAMIR was completed by the end of 2003. All components – dewar, detector, readout electronics, real-time computer, control electronics of the deformable mirror, optical components, motors, metrology, software – are ordered or have already been delivered.

In the year under report various glass pyramids have been tested in the adaptive-optics laboratory. The specifications set for Pyramir have not yet been achieved. At the end of the year, more glass pyramids were tested.

According to the current schedule commissioning on Calar Alto is planned for late 2004.

P. Bizenberger, Joana Costa, B. Grimm, M. Feldt (PI, Science), Th. Henning, S. Hippler (PM, Software), R.-R. Rohloff, R. Ragazzoni, K. Wagner; S. Esposito, Osservatorio di Arcetri)

IV.4 LUCIFER: A Multi-purpose Infrared Camera for the LBT

LUCIFER is a near-infrared camera with grating spectroscopy for the Large Binocular Telescope (LBT). The instrument will be used for many purposes, mainly for extragalactic observing programs. It is developed by a consortium of five institutes.

The project management for LUCIFER (LBT NIR-Spectroscopic Utility with Camera and Integral-Field Unit for Extragalactic Research) lies with the Landessternwarte in Heidelberg; MPIA is developing the read-out electronics, the MPI für Extraterrestrische Physik in Garching is responsible for the development of the MOS unit, the Universität Bochum provides the software while the Fachhochschule Mannheim is responsible for the design of the cryo-mechanical components. LUCIFER is built in two identical units planned to be put into operation at the LBT at an interval of about one year.

LUCIFER is designed for both seeing-limited and diffraction-limited applications. The following observing modes will be available:

- Seeing-direct imaging with a field of view of 4 × 4 arcminutes
- Seeing-and diffraction-limited long-slit spectrotroscopy
- Seeing-limited multi-object spectroscopy with a slit mask
- Diffraction-limrect direct imaging with a field of view of 0.″5 × 0.″5 arcseconds
- Integral field spectroscopy and imaging with suppression of the atmospheric OH lines (planned for the extension phase).

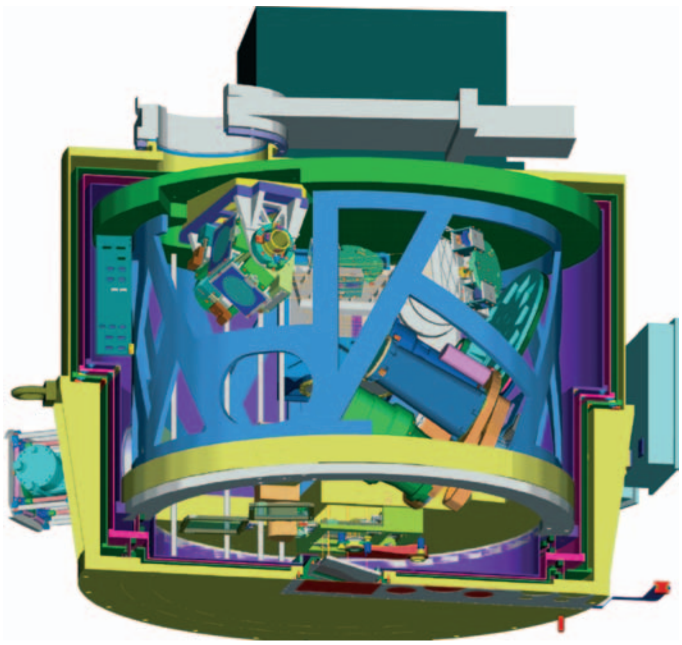
For seeing-limited direct imaging two image scales are available (0.12 arcseconds/pixel and 0.25 arcseconds/pixel); an additional high-resolution camera (15 mas/pixel) matches the diffraction-limited resolution. For the multi-object spectroscopy the replacement of focal masks will be assisted by a cryogenic roboter. Replacement of the mask magazine will be possible without warming up the entire cryostat: the magazine will be moved through an air-lock into an auxiliary cryostat.

A first version of the read-out electronics has been completed. The detector of LUCIFER-1 is presently been tested in a laboratory cryostat at MPIA, the read-out electronics is being optimized. The detector for LUCIFER-2 has been ordered.

The cryo-mechanical design is completed to a large extent, the cryostat is being manufactured. Essential single components are ordered or have already been delivered. Integration and tests of the first instrument LUCIFER-1 should be completed by the end of 2004, commissioning is scheduled for spring 2005. The second instrument LUCIFER-2 will be put into operation at the LBT about a year later.

(R. Lenzen, H. Baumeister, P. Bizenberger, B. Grimm, T. Herbst, W. Laun, R.-R. Rohloff)

Fig. IV.10: LUCIFER in a three-dimensional representation: The cryostat measures about 1 m × 1 m.



IV.5 LINC-NIRVANA – The Beam Combiner for the LBT

The Large Binocular Telescope (LBT) has two primary mirrors supported by the same mounting. This unique structure allows very interesting interferometric applications, provided the light beams collected by the two mirrors are combined properly. This central task will be performed by the instrument described below.

LINC-NIRVANA is a near-infrared image-plane beam combiner with Multi-Conjugated Adaptive Optics (MCAO). (LINC stands for the LBT Interferometric Near-infrared Camera, NIRVANA for Near-IR/Visible Adaptive iNterferometer for Astronomy). It will combine the the light collected by the two 8.4 m primary mirrors of the Large Binocular Telescope (LBT) in so-called »Fizeau« mode. This configuration preserves phase information, and allows true imagery over a wide field of view. Using state-of-the-art detector arrays, coupled with the MCAO system, LINC-NIRVANA will deliver the sensitivity of a 12 m telescope and the spatial resolution of a 23 m telescope, over a field of view up to two arcminutes square.

The optics of the two LBT telescopes that are mounted on the same mounting structure, is a Gregorian design. The secondary mirrors are fully adaptive with 672 voice-coil actuators each and will allow effective correction of the ground layer turbulence to an altitude of about 100 m above the telescope.

The instrument is located at the Gregorian foci platform of the telescope (Fig. IV.11). The light coming from the two tertiary mirrors of the LBT is collimated into a folded light path to the piston mirror that is loca-

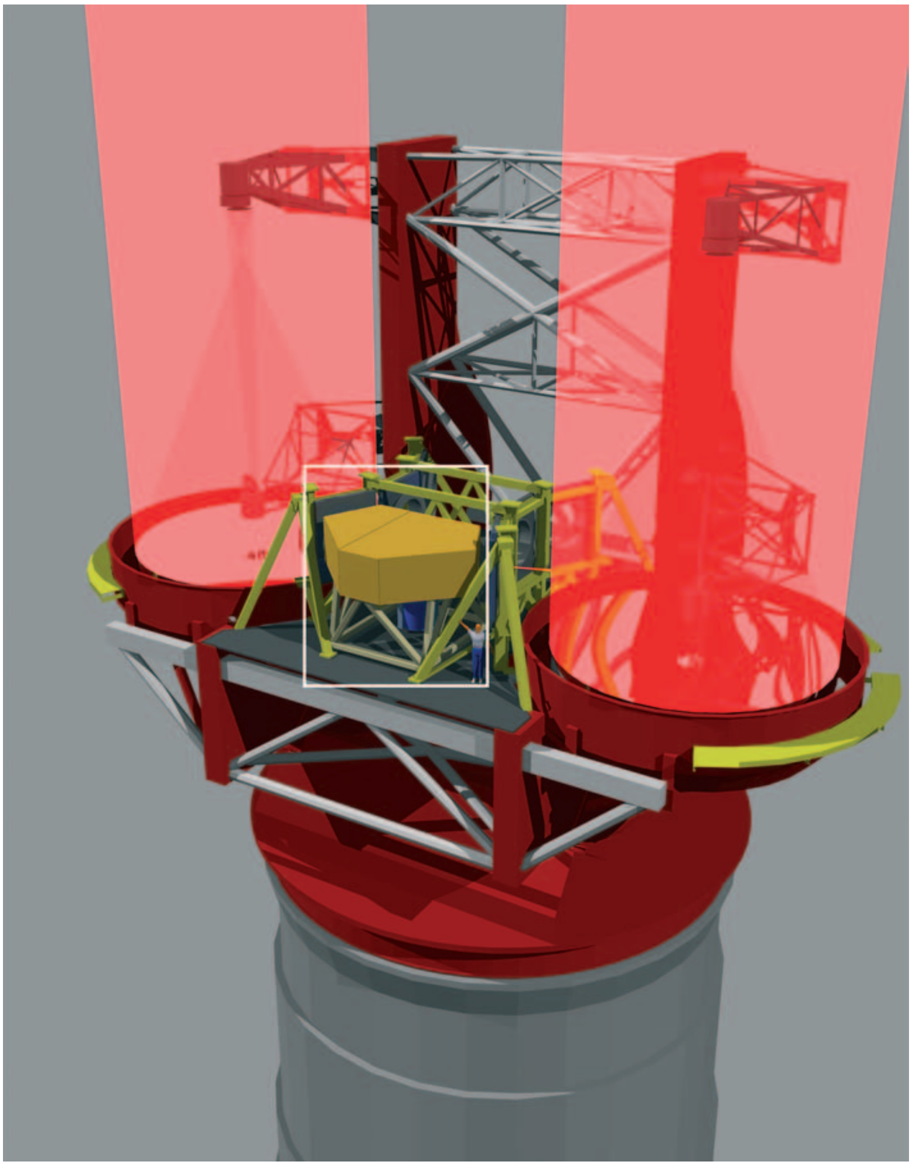


Fig. IV.11: Overview on the Gregorian instrument platform at the LBT. The location of the LINC-NIRVANA instrument is indicated.

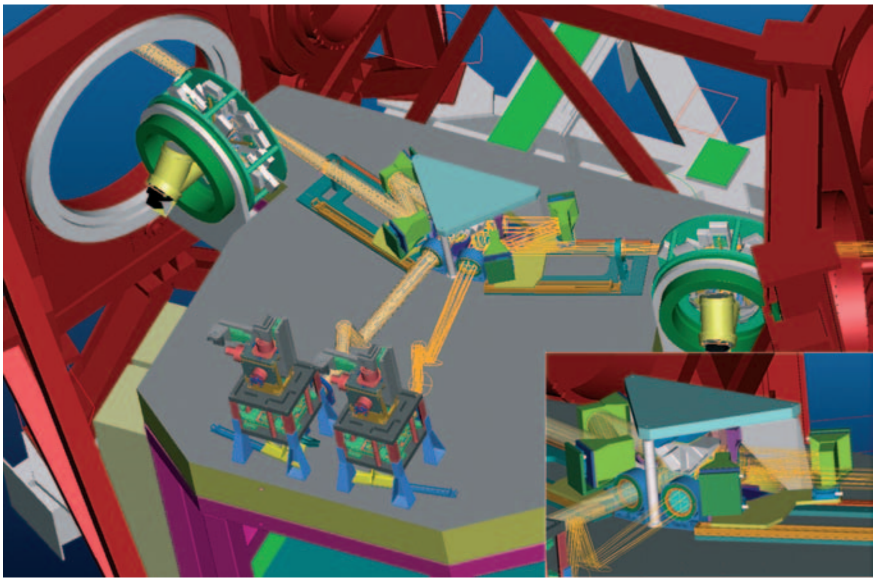
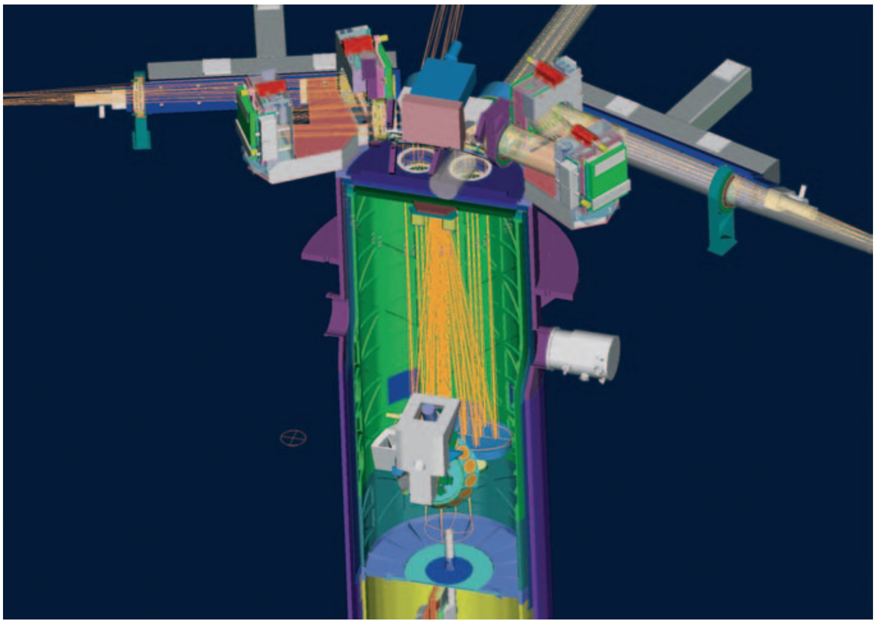


Fig. IV.12: Overview on the light path at the optical bench of LINC-NIRVANA. The insert image shows the ‚crowded area' of the piston mirror that is located in the center of the overview image.

ted in the center of the instrument bench and reflects the light into the dewar underneath (Fig. IV.12). The piston mirror also corrects differences in the length of the light paths to allow the optimum inferometric co-addition of the two beams. The dewar optics combines the incoming light paths of the homothetic telescope pupil through a Cassegrain system plus dichroics onto the 2K × 2K detector where the interference occurs. A fringe tracker at the bottom of the dewar controls the light path differences through displacements of the piston mirror (Fig. IV.13).

LINC-NIRVANA is equipped with two wavefront sensing systems (Fig. IV.12) that allow to measure and correct the wavefront distorsion of up to three layers in the atmosphere: the Ground-Layer Wavefront System GWS is located just at the entrance of the light path on both sides of the instrument. The GWS corrects the atmospheric ground-layer turbulences through the adaptive secondaries of the telescope. The Mid/High-Layer Wavefront System MHWS is contained in two towers at the edge of the instrument bench. The visible light of the two instrument arms is decoupled by two dichroics just below the piston mirror and directed to the MHWSs via an *f*/20-optics and two fold mirrors at the bottom of MHWS towers. The MHWSs sense the mid (4-8 km) and high (8-14 km) atmospheric layers in the respective telescope beams and optimize the

Fig. IV.13: A cross-cut view of the instrument cryostat mounted to the instrument bench.



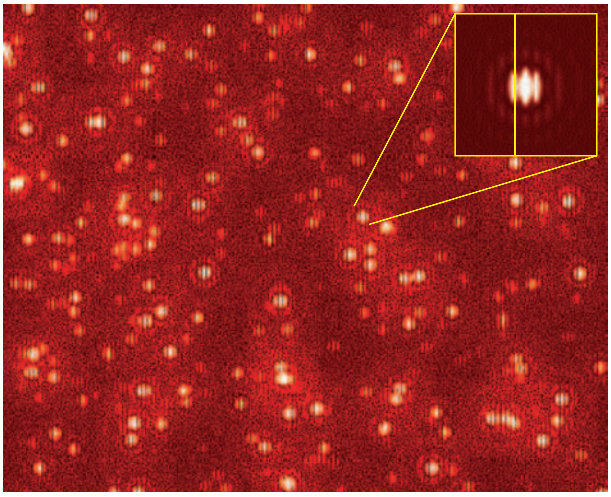


Fig. IV.14: Simulated image of a star field as seen by the LINC-NIRVANA instrument. The insert image shows the interferometric fringe pattern that is folded into each object image in the instrument field of view.

object signal through two deformable mirrors located at the egdes of the folded light paths on the instrument bench. Both the GWSs and the MHWSs use light of natural stars (12 for the GWS in an annular field 2-6 arcmin from the field center and 8 for the MHWS in the central 2 arcmin field of view) for wavefront sensing. The light of the respective stars is amplified by optical co-addition to improve the signal-to-noise ratio.

Fig. IV.14 shows a simulated image of a star field as seen by LINC-NIRVANA: the interferometric fringe pattern (see insert of Fig. IV.14) modulates each object image as it is delivered by the adaptive optics of the instrument. The pixel resolution varies with wavelength from 3.5 marcsec in J, over 4.6 marcsec in H to 6.0 marcsec in K band. The field of view of the science detector is 10.5 × 10.5 arcsec. The estimated limiting JHK magnitudes for point sources in one hour exposures are well beyond 25 mag. The large science detector field of view together with the light collecting power of the LBT and the use of MCAO will make LINC-NIRVANA a unique instrument for high-resolution interferometric imaging exploration for all research areas of astronomy.

LINC-NIRVANA is a joint project between the MPIA, the MPI für Radioastronomie Bonn, the 1. Physikalisches Institut der Universität zu Köln and the Astronomical Observatory of INAF in Arcetri (Italy). PI of the instrument is Tom Herbst (Heidelberg). The instrument ist scheduled for installation at the LBT during the second half of 2006.

(T. Herbst, D. Andersen, H. Baumeister, P. Bizenberger, H. Boehnhardt, F. Briegel, S. Egner, W. Gässler, W. Laun,S. Ligori, L. Mohr, R. Ragazzoni, H.-W. Rix, R.-R. Rohloff, R. Soci, C. Storz, K. Weiss, Y. Xu)

IV.6 CHEOPS – an Instrument for Imaging Extrasolar Planets

CHEOPS (Characterizing Exo-planets by Opto-infrared Polarimetry and Spectroscopy) is an ambitious project to perform direct imaging of extrasolar Jupiter-like planets. It concerns planning and construction of a second-generation instrument for one of the four 8-m telescopes of the ESO Very Large Telescope that will be able to image planets being separated only half an arc second from their central stars whose brightness exceeds that of the planets by at least 18 magnitudes.

CHEOPS is intended to detect the planets, measure their magnitudes and (over the course of time) determine their orbits. In addition, the polarization of the light scattered off the planetary surfaces will be measured. From this the presence and properties of potential dust particles in the planetary atmosphere can be derived. The built-in spectrograph of CHEOPS will allow to determine the chemical composition of the atmospheres. Finally, knowledge of the total emission of the planets in combination with atmospheric models will yield an estimation of their sizes. If the radial velocity variations of the central stars are known too, information on masses, densities and inner structure of the planets can be obtained.

MPIA is the leader of a European consortium currently conducting a feasibility study on this instrument after a preliminary proposal was submitted in 2002. The study phase runs from May 2003 to November 2004. After the study ESO will make a decision whether to continue with the planned instrument and which consortium – a consortium led by French astronomers is currently undertaking a similar study – should actually carry out the project.

The current conceptual design contains a new adaptive optics system for the VLT, called XAO, having about 1500 actuators behind its deformable mirror and a control-loop frequency of about 2 kHz. The instrument will be equipped with a low-resolution integral field spectrograph operating in the spectral range between 0.9 and 1.6 μm as well as with a differential polarimeter named ZIMPOL, operating at 0.8 μm.

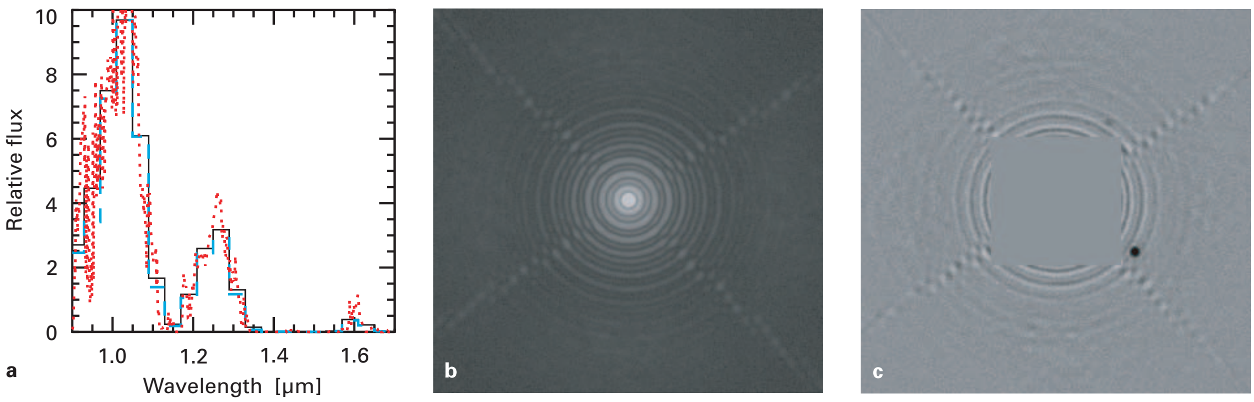
While the adaptive optics XAO will be designed to image point sources as sharply as possible with an 8-m telescope and with 90 percent of the theoretically achievable central peak intensity, the two imaging instruments, spectrograph and polarimeter, will perform so-called differential imaging. This method yields the difference of two images taken at the same time – and with ZIMPOL also on the same detector element –, one of which carries the linearly polarized light of the central star scattered off the planet and one does not. This way, the inevitable background noise caused by residual image distortions can be subtracted. If a contrast of at least 18 magnitudes could thus successfully be overcome across a separation of half an arc second the detection limit of CHEOPS for direct imaging of extrasolar planets in Sun-Jupiter twin systems could be pushed beyond distances of about 20 light years.

To optimize the chances of detection by means of the two differential images, detailed knowledge on the properties of planetary atmospheres – of young and warm planets as well as of mature ones like our own Jupiter – is required. Therefore, model atmospheres have to be developed and their spectral and polarization properties be verified.

Detection of a planet will proceed as follows (see Fig. IV.15). Unlike their central stars, Jupiter-like planets have characteristic spectra cut up by strong absorption bands due to the opacities of molecules residing in their cool atmospheres. So, at certain wavelengths (so-called atmospheric windows) they can appear ten times brighter than at neighboring wavelengths. As an example, Fig. IV.15a shows the spectrum of the Jupiter-like extrasolar planet Epsilon Eridani b in the wavelength region between 0.8 and 1.6 µm. On a direct image the planet does not stand out against the prominent diffraction pattern of the central star that is brighter by a factor of 15 million (Fig. IV.15b). However, if two images taken in neighboring wavelength regions within and outside a molecular absorption band are subtracted from one another the diffraction pattern of the star cancels out almost perfectly (as it exhibits practically the same brightness in both wavelength regions) while the image of the planet is hardly diminished by the subtraction because it shows up only in one of the two windows (Fig. IV.15c). CHEOPS will not only take images in two neighboring wavelength regions but also record a spectrum for each point in the image plane. This will increase the detection sensitivity still further allowing to discover even fainter and less massive planets (Fig. IV.15d). Finally, Fig. IV.15e shows the simulated image of a planet detected with CHEOPS. For recording the spectra the image plane is subdivided by a lens array (a so-called lenslet) into small hexagons, causing the hexagonal shape of the point spread function.

The number of candidate stars that can be searched for planets using CHEOPS is limited to a few hundred because of the guide star limitations for the adaptive optics system XAO (the guide stars have to be sufficiently bright and close to the target star). On the other hand the demanding XAO system will achieve its top performance only under the best seeing conditions given in about 30 percent of all clear nights. Therefore, the survey for nearby exoplanets will require a detailed planning of the observing program.

(M. Feldt, W. Brandner, Th. Henning, S. Hippler; Astrophysikalisches Institut der Universität Jena, ThüringerLandessternwarte, Sterrewacht Leiden, Astronomisches Institut der Universität Amsterdam, Astronomisches Institut der ETH Zürich, Universität Lissabon, Dipartimento di Astrofisica e Osservatorio dell'Università di Padova, Osservatorio di Capodimonte, Napoli)



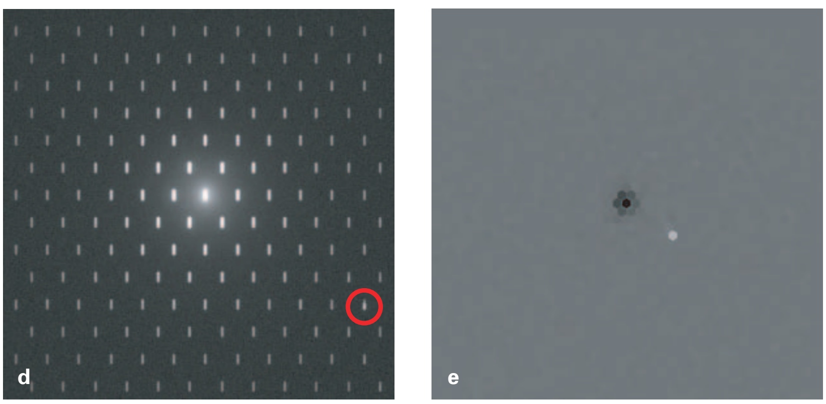


Fig. IV.15: a) Characteristic spectrum of the Jupiter-like extrasolar planet Epsilon Eridani b in the near-infrared region; **b)** direct image of a star with Jupiter-like planets; **c)** difference between two images taken within and outside a molecular absorption band; **d)** image obtained with the integral-field spectrograph; **e)** simulated image of a planet and its central star obtained with CHEOPS.

IV.7 SDI – an Optics System for Simultaneous Differential Imaging of Jupiter-like Gas Planets

At present, a little over 100 extrasolar planetary systems are known but no planet orbiting another star than the sun has yet been detected directly. This will require an extreme contrast sensitivity in addition to an angular resolution as high as possible.

Highest optical angular resolution can presently be achieved with the large telescopes of the 8-m class if they are equipped with an adaptive optics system. However, because of the incompletely corrected images such AO systems suffer from rather low contrast ("speckle noise"). The contrast needed can be lowered, though, by a suitable choice of the stars observed: The intrinsic luminosity of young (about 100 million years old) extrasolar planets in the near-infrared range is 100 000 times higher than that of mature (about 5 billion years old) planets whereas the luminosities of their central stars differ only by a factor of 2 to 5 in the same sense. Nevertheless, even Jupiter-like planets still appear fainter by at least 4 to 5 magnitudes than the central star – too faint to be detected in the speckle noise. In order to suppress speckle noise, the high-resolution infrared camera CONICA at the VLT, which in combination with the AO system NAOS allows diffraction-limited imaging, was supplemented with a differential imaging system.

Unlike their central stars, the atmospheres of cool (300 K < T_{eff} < 1200 K) brown dwarfs and Jupiter-like gas planets (Fig. IV.16) display strong methane (CH_4) absorption bands beyond a wavelength of 1.62 μm. If an image of the star and its planet taken outside the methane absorption is subtracted from one taken within the absorption band, the image of the central star completely cancels out in the differential image while the image of the planet is hardly diminished. However, when images are subtracted that were taken subsequently, a strong so-called speckle noise remains which is due to the incomplete elimination of the seeing by the adaptive optics system. For this reason, CONICA was equipped with additional optics allowing to simultaneously take diffraction-limited narrow-band images in three closely neighboring infrared spectral regions (Fig. IV.17). Since the single images are taken simultaneously the time-dependent speckle noise also cancels out in the differential images.

The photo of the Saturnian satellite Titan (Fig. IV.18), whose dense atmosphere contains methane, is a test to demonstrate the power of the method. To the left, it shows an SDI image at 1575 nm (outside the CH_4 absorption band, filter 1 in Fig. IV.16), and to the right, at a smaller scale, an SDI image at 1625 nm (within the absorption band, filter 2 in Fig. IV.16). Outside the absorption bands Titan's atmosphere is transparent so that extensive structures are visible on the moon's surface.

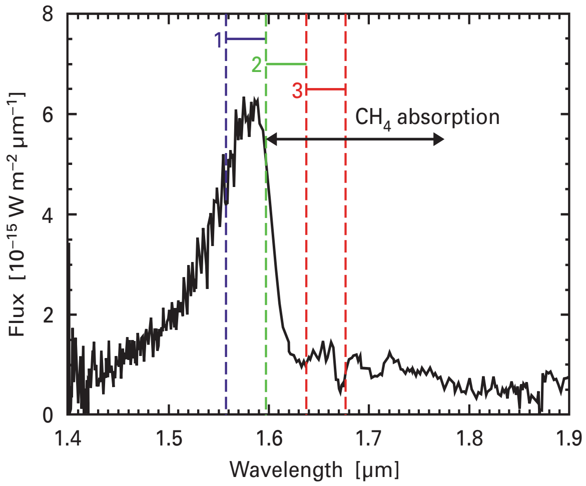


Fig. IV.16: Spectrum of the brown dwarf G 1229B (T_e = 900 K, M = 25 $M_{Jupiter}$) after Legget et al., 1999. Cool atmospheres (300 K < T < 1300 K) show strong methane (CH_4)-absorption bands in the near-infrared range. The position of the narrow band filtersused in SDI is indicated. used in SDI is indicated.

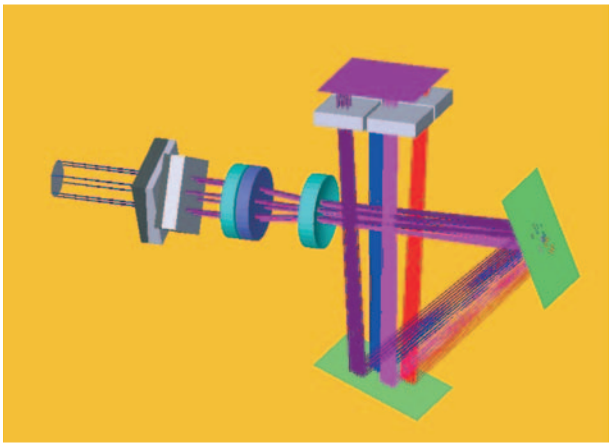


Fig. IV.17: Supplement of the CONICA optics for observations in the SDI mode. Major components are the two Wollaston prisms, the lens system and the quadrant filters.

Angular resolution of the differential image is 0.02 arc seconds or about 200 km per pixel on Titan. It is thus significantly more detailed than images of Titan obtained with the HUBBLE space telescope.

(R. Lenzen, W. Brandner; L. Close, B. Bille, Steward Observatory, M. Hartung, ESO)

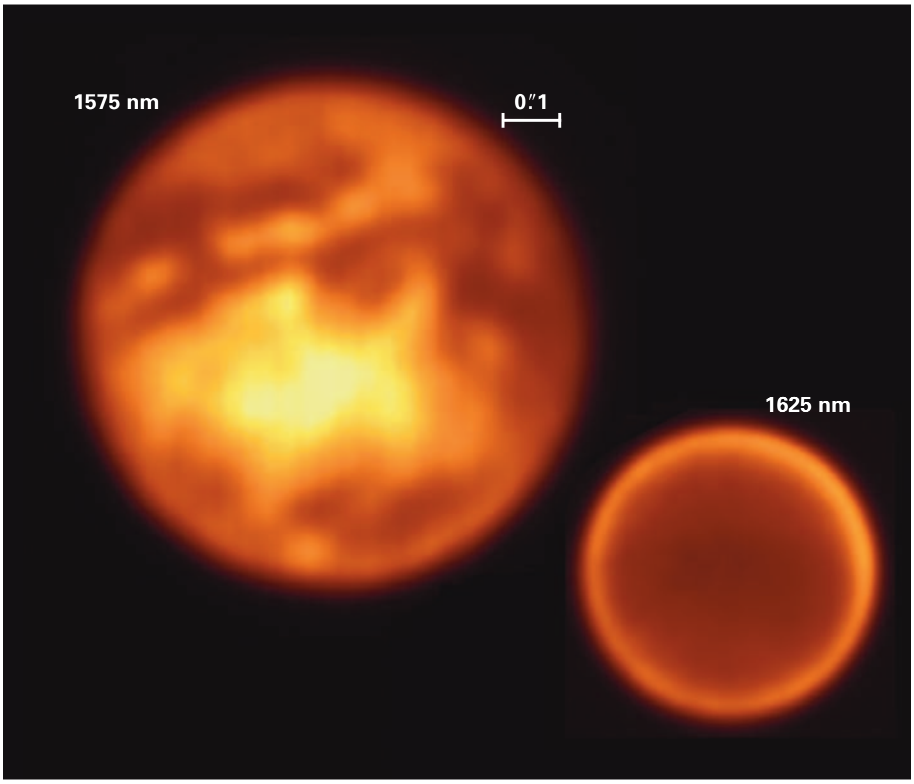


Fig. IV.18: [Picture of the month 5/04 (Titan)]: left - Titan, photo taken at $\lambda = 1575$ nm (Filter 1); right - photo taken at $\lambda = 1625$ nm.

IV.8 PACS – Far-Infrared Camera and Spectrometer for the HERSCHEL Satellite

During HERSCHEL's three months's journey to the Lagrangian Point L2, 1.5 million kilometers "behind Earth" in anti-solar direction, the primary mirror of the HERSCHEL telescope measuring 3.5 m will cool down to $T = 70$ K. This mirror consisting of several segments made of silicon carbide as well as the mirrors of the PLANCK satellite will be vacuum coated with several layers at the Calar Alto Observatory for the ASTRIUM company in order to minimize their intrinsic emission and maximize their reflectivity. The mirror vacuum coating facility at Calar Alto is one of the largest and most efficient in Europe.

The focal-plane chopper developed by MPIA in collaboration with the C. ZEISS company completely qualified for space flight: it stood cold vibration tests simulating the rocket launch, it ran through more than 650 million cycles at $T = 4$ K and it survived 15 cooling cycles (from 330 K to 4 K) and baking procedures to reduce molecular emission without any damages. Its excellent properties regarding optical setting accuracy and minimum energy demand were maintained even after completion of the hard tests. Together with extensive test-, assessment- and product-safeguard-documents, the chopper was handed over in June to the PI institute MPE in Garching as the first external contribution from the PACS consortium and subsequently installed in the focal-plane unit of the qualification model of PACS at the Kayser-Threde company. Another chopper model together with extensive advice was made available to the Belgian space-flight center in Liège for further development of the control programs of the on-board electronics.

Late in summer, MPIA and C. ZEISS started to manufacture the components of the focal-plane chopper for the flight model and the spare flight model. All coils for the SPIRE beam steering mirror (another HERSCHEL instrument) built after the PACS-chopper prototype were delivered to the ATC Edinburgh.

The calibration unit for characterizing the Ge:Ga photodetector arrays in the far-infrared range (wavelengths ranging from 60 to 210 μm) was put into operation. It allows to simulate the beam of light of the HERSCHEL telescope and its low photon background as well as to cool the camera read-out electronics to 4 K and the detectors to 1.5 K. The detector modules for the qualification model delivered by the ASTEQ company each consisted of six lines with 16 pixels each; so the test modules each represent only 24 percent of the area of the final camera (25 × 16 pixels). These low-stressed detectors with a long-wave sensitivity limit of $\lambda < 130$ μm were tested regarding dark current, noise, current sensitivity and homogeneity. While the current sensitivity already attains acceptable values the remaining parameters still have to be improved for the flight models of the camera.

The read-out circuits CRE (pre-amplifier and multiplexer) from several production processes delivered by the IMEC company and intended for operation at $T = 4$ K were characterized in warm and cold. The warm test, which can be conducted always and easily, should possibly allow an assessment of the behavior of the CREs in cryo-vacuum. In extensive test reports MPIA was able to make suggestions to the manufacturer for further development of these important components of the flight models.

Program packages for controlling, calibrating and testing the instrument during the mission were developed for the PACS- Instrument Control Center (ICC) of the HERSCHEL ground-based observatory. MPIA is responsible for this activities. The procedures will already be used for the ground-based-calibrations with the PACS qualification and flight models, thereby testing them. The development of standardized observing procedures has also been started that will offer electronic forms for the execution of observations (astronomical observing templates, AOT) to future PACS users.

MPIA will be granted 300 hours of guaranteed observing time during the HERSCHEL mission for which several observing projects have been defined: These concern studies of star formation regions, quasars, active galaxies and interacting galaxies. Numerous objects selected for these observations had turned out to be very interesting during the Iso mission and will now be studied in greater detail with higher spatial and spectral resolution. In PACS science team meetings common key projects are also defined for the open time in order to gain maximum knowledge.

(D. Lemke, S. Birkmann, K. Eberle, U. Grözinger, M. Haas, Th. Henning, R. Hofferbert, U. Klaas, M. Stickel, R. Vavrek)

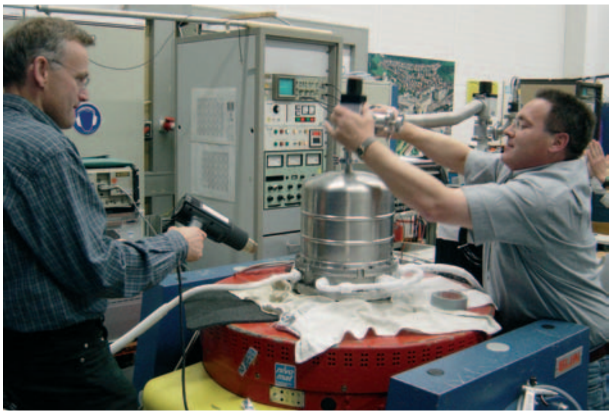


Fig. IV.19: Cold vibration test of the focal-plane chopper for PACS in the cryostat on the vibration table at C. ZEISS .

Fig. IV.20: Last inspection of the focal-plane chopper for PACS in the cleanroom cabin of the C. ZEISS company before it is handed over to the MPIA/MPE team.

Fig. IV.21: The Ge:Ga detector arrays for PACS are installed in the test chamber at MPIA.

IV.9 MIRI and NIRSPEC – Instruments for the James Webb Space Telescope

The James Webb Telescope (JWST) is scheduled for launch in 2011 as the successor to the legendary HUBBLE Space Telescope. With its radiatively cooled 6.5-m mirror it will work in the near- and mid-infrared spectral region, thus being able to explore the highly redshifted early universe. Europe participates, among other things, in two focal-plane instruments, and MPIA will contribute major components to both of them.

The MIRI instrument for the mid-infrared range (5 – 28 μm) will play a key role in the identification of the first galaxies in the early universe. The visible spectral range of these galaxies that formed only a few hundred million years after the big bang is now shifted to the mid-infrared range. In nearby objects within our Milky Way system the high angular resolution of the large telescope allows direct imaging of very young stars with their dusty disks and probably even the large planets forming within them.

NIRSPEC, the spectrometer for the near-infrared range (0.6 – 5 μm) allows to determine the chemical composition and physical conditions such as temperature and pressure in distant celestial objects. In particular, by measuring the redshift of certain spectral lines in the spectra of the most distant supernovae it will be possible to determine the latter's distance. Supernovae always reach the same maximum brightness and therefore are the brightest standard candles in the universe.

Both instruments are equipped with several filters, spectral gratings and prisms, and, depending on the observing mode, a certain combination of them has to be inserted into the light path. For this purpose, these optical components are mounted on wheels in the instrument that have to be moved reliably with highest accuracy and minimum energy expenditure for the entire ten-year duration of the mission. These mechanisms are being developed at MPIA. In addition to filter and grating wheels these mechanisms include a tilting mirror for inserting an internal calibration light source and a linear drive for focusing.

For both instruments, the manufacturing of prototype wheels, their drive units and positioning systems has begun. In addition to the general space-flight requirements of an infrared mission (high vibration loads, extremely low power consumption in order to save coolant, extreme service lifetime and reliability…), for the JWST there will be also the launch in a warm environment on a ARIANE 5. The instruments will have to function both under laboratory conditions at the launch site and in a space vacuum at –265°Celsius under all environmental conditions encountered during their three-month journey to the Lagrangian Point L2 and during the entire mission.

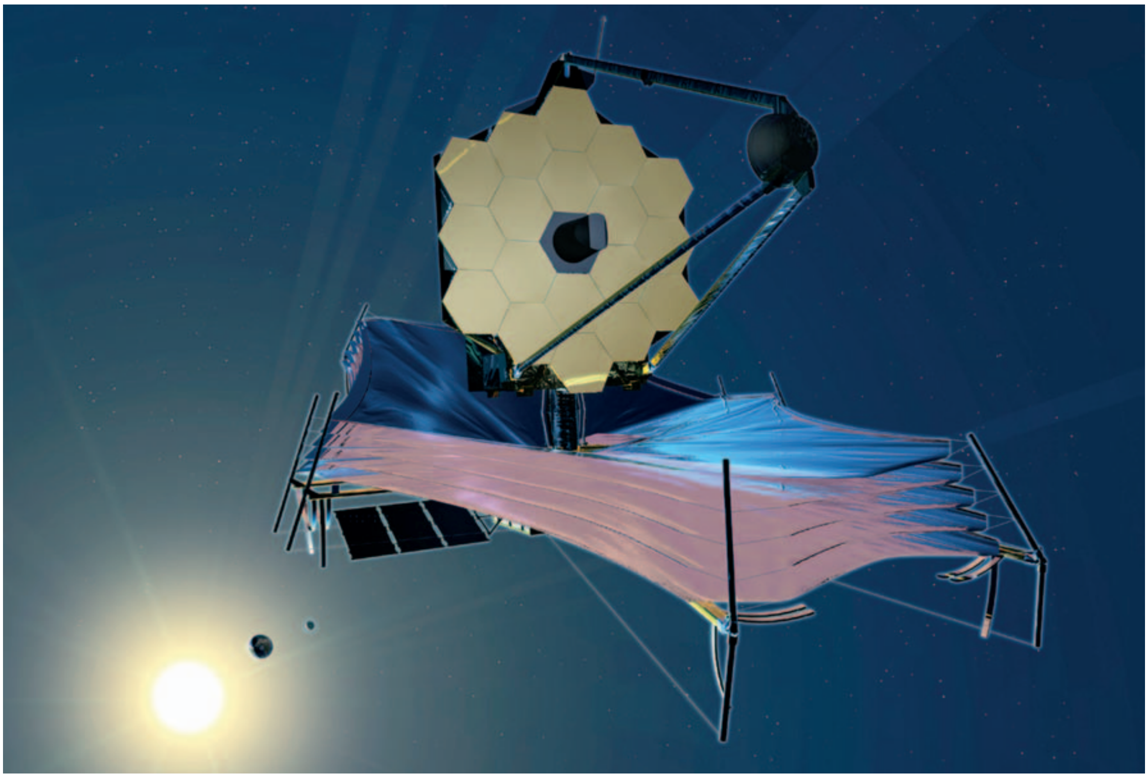


Fig. IV.22: The JWST at the Lagrangian Point L2. The earth (together with the moon) and the sun are always seen in the same direction; the earth is 1.5 million km away. The multi-layer shielding of radiation from the earth and the sun allows a passive cooling of the 6.5 m primary mirror to $T = -230$ °C.

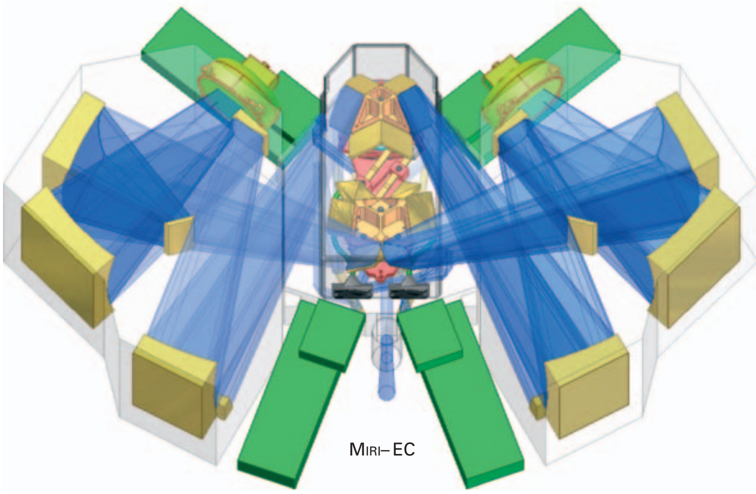


Fig. IV.23: Two wheels bearing gratings and dichroic mirrors are arranged in the spectrometer section of the MIRI instrument. Exact positioning of these wheels is done with electric mechanisms developed at MPIA. The grating wheels are surrounded by imaging mirrors, integral field units for multiplexing of spectral and spatial information, and by detectors. MIRI is operated at a temperature of –265°Celsius. The camera and coronagraph section of the instrument is not shown in this Figure. (MIRI European Consortium).

Fig . IV.24: The prototype of a filter wheel for NIRSPEC is tested at MPIA with regard to the dependence between achievable position accuracy and electric power dissipation.

MPIA is a member of the European MIRI consortium that has started the development phase B (detailed design) in May 2003. In a memorandum, DLR has promised to ESA and the MIRI partners from ten further countries the funding of the German part in MIRI. In the two industrial consortia (ASTRIUM und ALCATEL) competing for the development of NIRSPEC, MPIA has participated in studies for phase A+ and now applies for the subsequent phases B/C/D in both consortia. The parallel development of similar components for MIRI and NIRSPEC means mutual gain of experience and minimization of expenses. All work is based on the successful preparatory work for ISO and HERSCHEL at MPIA.

(D. Lemke, A. Böhm, U. Grözinger, R. Hofferbert, Th. Henning, A. Huber, C. Ramos, R.-R. Rohloff)

People and Events

Commemoration for Hans Elsässer

The founding director of the Max Planck Institute for Astronomy in Heidelberg, Hans Elsässer, died on June 10th, 2003. At a commemoration ceremony held on the Königstuhl colleagues and students remembered the work of this outstanding astronomer who contributed decisively to restore a leading global position in astronomy for Germany after a crisis lasting more than 50 years.

The Symposium

On November 25th, 2003, about one hundred guests gathered at the Institute‘s large auditorium in order to pass the most important stages of Hans Elsässer’s life in review. They had been invited by the two current directors of MPIA, Thomas Henning and Hans-Walter Rix. Elsässer‘s children Gisela and Albrecht had come as well as colleagues and fellow combatants of the very first hour and high-ranking representatives of astronomy, among them Reimar Lüst, former president of the Max Planck Society (MPG) and the European Space Agenca ESA; other representatives of MPG were Hugo Fechtig, Peter Mezger, Joachim Trümper and Reinhard Genzel, the former and officiating directors of the Institutes for Nuclear Physics, Radioastronomy and Extraterrestrial Physics, as well as Günter Preiß, the former legal advisor and head of the institute’s advisory panel of the MPG. Also present were representatives of the University and City of Heidelberg, of the Heidelberg Academy of Sciences, of other universities and astronomical institutes and of the German industry, among them two former presidents of the Astronomical Society, Hans-Heinrich Voigt, Göttingen, and Werner Pfau, Jena, as well as Karl-Heinz Schmidt from the Astrophysikalische Institut Potsdam and Horst Skoludek, former president of the board of the Carl Zeiss company, Oberkochen.

Kalevi Mattila, one of Elsässer’s first students and now a professor at the observatory of the University of Helsinki, had arrived from Finland. Steve Beckwith, director of MPIA from 1991 to 1998 and now director of the Hubble Space Telescope Science Institute in Baltimore, had come from USA to recall Elsässer’s early work on infrared astronomy. Immo Appenzeller, director of the Heidelberger Landessternwarte, who had been acting managing director of the Institute from 1998 to 2000, gave a review of Elsässer’s professional stages in Heidelberg. These guests as well as several of Elsässer’s students and colleagues, among them Dietrich Lemke, Klaus Meisenheimer and Josef Solf, gave their quite personally colored talks. The following record is based on all these contributions.

Hans Elsässer‘s Career

Hans Elsässer was born on March 29th, 1929, in Aalen, Württemberg. At the age of 19, he began to study physics and astronomy in Tübingen and obtained his Ph.D. in 1953. In the same year, he published two papers that had been the basis of his doctoral thesis. In that, he had dealt with the spatial distribution of the zodiacal-light particles and the scattering by a mixture of dielectric spheres. His main interest here was to understand the distribution and properties of the micrometer-sized particles in the interplanetary dust cloud.

During the following years Elsässer stuck to the topic of zodiacal light but soon began to work on a new subject – the structure of the Milky Way. At the Boyden station in Southern Africa, he surveyed the entire southern Milky Way using the Tübingen night-sky photometer. The study based on these observations had been pioneering in many respects: It formed an important basis for the optical exploration of the overall structure of our Galaxy, for detailed studies of the spiral structure towards certain directions and for an extensive photometric and polarimetric survey of bright O and B stars in the southern Milky Way.

In 1962, Elsässer was appointed director of the Landessternwarte Heidelberg. He considerably increased the scientific productivity of this institute and extended its research program by relevant issues, such as Galactic structure.

MPIA and its Calar Alto Observatory

When taking over the management of the Landessternwarte Heidelberg it was Elsässer’s one aspiration to fundamentally improve the desolate situation of observational astronomy in Germany. At that time, observing programs on an international level were practically impossible. The 1-m telescope in Hamburg-Bergedorf dating from 1910 was then the largest telescope in the

Federal Republic of Germany, followed by the even older 72-cm reflector on the Königstuhl. In this situation, the memorandum On the Status of Astronomy issued in 1962 on behalf of the Deutsche Forschungsgemeinschaft, to which Elsässer had made significant contributions, brought about the decisive turn of events. This memorandum particularly recommended, in addition to other measures, “the establishment of national institutions of supra-regional character, such as an optical observatory in a favorable climate with larger instruments”.

Negotiations with Federal authorities taken up in 1962 with the goal to establish a Federal institute for astronomy very soon met with considerable difficulties. In May 1964, the Max Planck Society attended to the project after first talks to its president Prof. Butenandt. In 1967, the Senate of the MPG decided to establish the new Max Planck Institute for Astronomy (MPIA) of which Elsässer was appointed founding director. Early in 1969, MPIA commenced its work with a staff of about ten in rooms at the Landessternwarte and in office barracks on the Königstuhl.

Now an abundance of far-reaching decisions and difficult tasks lay in the hands of Elsässer: the design conception of the new institute building on the Königstuhl as well as the choice of the sites for two observatories planned for the northern and southern hemisphere. For the southern site, the Gamsberg in Namibia was chosen. But this project had to be abandoned later for political reasons. The 2.2-m telescope intended for the Gamsberg was instead loaned to ESO for operation on La Silla.

The northern observatory was built on Calar Alto in southern Spain. Between 1975 and 1986, four telescopes were put into operation there; in 1988 the construction of the observatory was completed according to plans. The efficient institution for astronomical research in Germany set up there is the lasting legacy of Hans Elsässer.

Astronomy from Space

Elsässer very soon realized the great chances offered to astronomy by the development of space research. When the extraterrestrial research in Germany started to receive broader support in the mid-1960s, Elsässer immediately got in. In the course of the years, calibration standards and novel light sources for increasingly shorter wavelengths were built that were used in rocket experiments for measuring the zodiacal light in the ultraviolet spectral region.

The next success was the participation in the HELIOS solar probe to which the Institute contributed a zodiacal-light photometer. In 1974 and 1976, the probes HELIOS A and B were launched for a mission of several years‘ duration during which they repeatedly approached the sun to 0.3 AU, providing unique data on the spatial structure of the zodiacal cloud.

While the rocket and HELIOS programs still were in progress, Elsässer prompted another development at the Institute: the building of a balloon-borne telescope called THISBE. From 1970 on, it allowed observations of the zodiacal light from the mid-ultraviolett to the near-infrared spectral region. With these and the extensive HELIOS data, the Institute had achieved great authority in this field by the mid-1970s.

At that time, however, Elsässer had already directed his interest to something else: Star formation, which he had begun to study from the ground, became a new field of research calling for infrared observations from space. So the Institute was charged to design a telescope and measuring instrument for the SPACELAB mission. In collaboration with several other German institutes and the MBB company, a team at MPIA started to design and develop the first prototype instruments for GIRL, the German Infra-Red Laboratory. But in 1985, the German Federal Ministry of Education and Research stopped the project for financial reasons. But that was by no means the end for the astronomers at the Institute. For a long time they had been participating actively in preparations for the European satellite ISO and in 1985 the Institute was charged with the project management for the ISOPHOT instrument for this mission.

The course adopted by Elsässer is still continued at MPIA. At present, work on the PACS instrument for the European infrared telescope HERSCHEL as well as on two instruments, MIRI and NIRSPEC, for the James Webb Space Telescope is in progress. A long-term objective is the DARWIN mission for a search for terrestrial planets around other stars.

The extensive experience gained by building measuring instruments for the infrared spectral range had also been decisive for MPIA being awarded by ESO the contract to build a high-resolution camera for the Very Large Telescope (VLT). Since 2001, CONICA is working very successfully in combination with the adaptive optics system NAOS on Cerro Paranal. The considerable participation in the instrumental equipment of the Large Binocular Telescope (LBT) also resulted from this competence. A most recent product of this development is the infrared camera OMEGA 2000 that is operating at the Calar Alto observatory.

Infrared Astronomy – Star Formation and Active Galaxies

Problems of star formation soon became one of the central research fields at MPIA. In 1978, a pioneering paper was published. At that time, Elsässer, together with a Ph.D. student, observed young stars and studied for the first time the polarization of the infrared emission of very young stars. Surprisingly, many of them showed rather strong polarization, which could be interpreted in an astonishing way. Theoretical considerations based on the experience that Elsässer had gained during his study of the zodiacal light suggested that the dust is not distributed spherically around the central star but in a disk or ring. For these cases the stellar light, which can only escape perpendicularly to the disk, is expected to be reflected by the dust particles less densely distributed above the poles of the system, thereby getting strongly polarized.

This interpretation of the data was only based on the analysis of the infrared emission of spatially unresolved sources. Direct imaging of the predicted disks was not possible then. This changed with the observation of an object designated S 106 which for years became the archetype of a bipolar nebula. In this bipolar nebula, the central star embedded within a dense equatorial disk was detected in the infrared spectral range as early as 1979. Thus, fundamental aspects of star formation had been found.

Late in the 1970s, Elsässer expanded the research field of MPIA. Until then, observations were limited to stellar objects in the Galaxy, mainly because of the low sensitivity of the infrared detectors and the restricted power of the telescopes available. When the new 2.2-m telescope was put into operation on the Calar Alto, Elsässer assigned the first doctoral thesis on the study of extragalactic objects.

Here, one specialized in celestial bodies that were very bright in the radio spectral region but had no counterpart on the photographic plates of the Palomar Sky Survey. A number of observations then showed that these objects were so-called BL-Lacertae objects – active galaxies from the centers of which two jets are shooting out in opposite directions that in these special cases happen to be aligned with our line of sight. So we are looking into the jet like into a headlight.

In most cases the jets, that may extend up to one million light years into space, are seen sideways. In the 1980s, the study of jets emerging from active galaxies and quasars became another focal point of research at MPIA. At that time, observations were made that helped to identify the mechanism that accelerates the particles within the jets to almost the speed of light.

Fig. V.1: During the commemoration ceremony for Hans Elsässer.
Left – Simone Bischoff, Steven Beckwith, Josef Solf, Reimar Lüst, Reinhard Genzel, Hans-Walter Rix, Karl-Heinz Schmidt, Albrecht Elsässer, Immo Appenzeller, Werner Pfau, Gisela Elsässer.
Right – Peter Mezger, Josef Solf, Hans-Heinrich Voigt, Joachim Trümper, Joachim Heitze, Ralf Bender, Thomas Henning, Eberhard Grün, Wilhelm Kegel.

Fig. V.2: Hans Elsässer next to the »Astronomer« (1997). This sculpture had been built for Elsässer by the trainees of the Institute's fine-mechanics workshop. (Photo: S. Kresin)

At about the same time, astronomers at MPIA investigated another newly discovered phenomenon. Images taken with the IRAS infrared satellite showed some bright extended sources that had only faint counterparts on the Palomar plates. Could these sources possibly be very distant normal galaxies? Actually, they turned out to be rather nearby interacting galaxies, i.e. stellar systems that either are gravitationally interacting while passing one another very closely or that even are colliding and merging. Infrared observations showed that during these events the dust in the galaxies' interiors is whirled around which may lead to bursts of star formation. Observations made with the ISOPHOT instrument on board of the ISO infrared satellite finally helped to explain to a large extent the processes going on in these interacting galaxies.

Although Elsässer's assumptions in these two fields of extragalactic research were not always correct he kept initiating the revelation of important new fields of research. And, finally, his assumption that some red quasars are at extremely high redshifts proved to be right. In 2001, a quasar of a record redshift of $z = 6.3$ was discovered with the Sloan Digital Sky Survey. It has similar properties as the red quasars Elsässer was searching for in the early 1980s. MPIA had contributed a major part in this discovery: For one thing it is participating in the Sloan Survey, and for another thing it had been scientists of the Institute who had taken a spectrum at the VLT that established the enormous redshift of this quasar.

Public Work

In addition to his scientific, organizational, and science-political activities Hans Elsässer always felt obliged to the scientific recruits and the general public. His two textbooks on the *Physik der Sterne und der Sonne* as well as on the *Bau und Physik der Galaxis* which he had authored together with his colleague from the Landessternwarte, Helmut Scheffler, soon became standard works for university teaching.

In 1961, together with Karl Schaifers, he founded the journal Sterne und Weltraum that is intended for professional and amateur astronomers as well as interested laymen. Even in the fifth decade of its existence, this journal, whose editorial staff is still resident at MPIA, enjoys long-lasting and still growing popularity. This, too, showed Elsässer's farsightedness to which astronomy in Germany owes a great deal.

The Search for the Second Earth: DARWIN/TPF – Conference in Heidelberg

Between April 22nd and 25th, 2003, 240 astronomers from all over the world met in Heidelberg for an international conference organized by MPIA with the title »Towards other Earths: DARWIN, TPF and the Search for Extrasolar Terrestrial Planets«. It concerned the search for and exploration of extrasolar planets, in particular those that harbor life. The meeting also served the purpose to define the extremely demanding space missions DARWIN (ESA) and Terrestrial Planet Finder (TPF, NASA). Both concepts are planned to end up in a common mission scheduled for launch in 2014.

"The discovery of the first extrasolar planets in 1995 resulted in an explosion in this field." With these words Thomas Henning, director of the MPIA in Heidelberg, opened the international conference in the municipal hall of Heidelberg. All exoplanets detected so far are gas giants, more similar to Jupiter than to Earth. An important question discussed by the experts in Heidelberg therefore is: Is our solar system that also contains rocky planets like Earth a typical one in the universe or does it represent a rare exception? And is there life on other planets?

Life based on similar principles as terrestrial life needs liquid water. For this to exist, a rocky planet has to be so close to its central star that its image cannot be separated from that of his central star with earth-bound telescopes and detectors available up to now. From space, however, it should soon be possible to detect numerous dark stellar companions using the so-called transit method. This method utilizes the fact that a planet crossing the stellar disk diminishes the stellar light by about one ten thousandths. At present, two space telescopes are planned that will operate with the transit method. The European Space Agency ESA will be the first to start the COROT mission late in 2005; it will be followed by NASA's telescope KEPLER in October 2007. The European telescope EDDINGTON also discussed at the meeting has meanwhile been canceled by ESA for financial reasons.

The transit method, however, is only successful if the planet happens to cross in front of his star as seen from Earth. Statistically, this occurs only in one out of 200 systems. Therefore, one will also attempt to image planets directly. The crucial problem here is the enormous brightness contrast between planet and star, which is about one to one billion in visible light. Future »planet finders« will therefore work in the infrared spectral region where the intensity ratio is reduced to about one to one million.

The best opportunity to study planets is offered by interferometry whose ability to achieve extreme spatial resolution is of utmost interest for almost all astronomical problems. This was taken into account by establishing the German Center of Interferometry, FRINGE (Frontiers of Interferometry in Germany), at MPIA in Heidelberg. The goal of this institution is to coordinate the efforts of German institutes in this field. As a first success, astr-

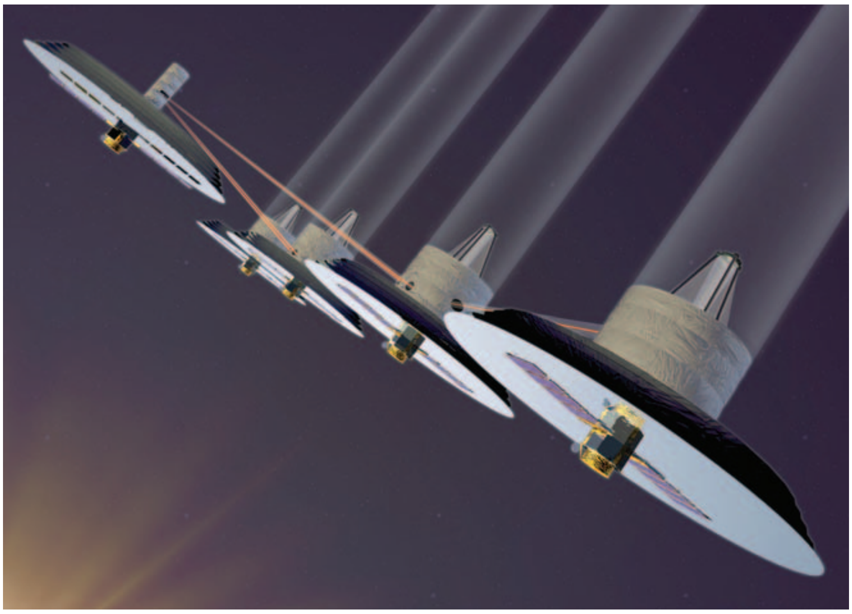


Fig. V.3: Artist's rendering of the free-flying interferometer TPF. (Image: NASA)

Fig. V.4: Press conference at the meeting in Heidelberg. *Left*: Michel Mayor, discoverer of the first exoplanet. *Right*: Malcolm Friedlung and Charles Beichman, project scientists of the missions DARWIN (ESO) and TPF (NASA). (Images: M. Odenwald)

nomers at MPIA could recently celebrate the commissioning of MIDI (Chapter II.4). It is the first instrument worldwide that allows interferometric observations in the mid-infrared spectral range at large telescopes. »We hope to be able with our instrument to detect hot gas planets and directly determine their distances from their central stars«, says project scientist Christoph Leinert of MPIA. Similar efforts will be made by astronomers at the LBT, the Large Binocular Telescope currently being built on Mont Graham, Arizona. Here, too, astronomers at the Institute are participating in the development of scientific instruments that will be used in the search for extrasolar planets (Chapter IV.5).

A European consortium under the leadership of MPIA wants to manage without interferometry by using an instrument called CHEOPS (Chapter IV.6). It would be one of the second generation instruments at the ESO VLT. It would consist of a camera with adaptive optics, an extreme imaging quality and the ability to overcome large brightness contrasts in the immediate vicinity of bright objects. With CHEOPS, astronomers want to image a star simultaneously at several wavelengths and polarization angles. When these images are being subtracted from one another the star's light should cancel out and the planet should become visible.

There was consensus among the astronomers in Heidelberg that these instruments will allow the detection and study of some gas planets. But the much more inconspicuous Earth-sized exoplanets, which are to be searched for traces of life, would not be detectable by them. Here, space telescopes will be needed.

At present, astronomers of ESA and NASA are discussing two projects, called DARWIN and Terrestrial Planet Finder (TPF). The European DARWIN, in which also scientist from Max Planck Institutes are participating, is a space interferometer. According to current plans it will comprise six free-flying single 1.5-m telescopes that will orbit the sun flying in formation at distances to one another of some tens or hundred meters. The six light beams coming from the individual telescopes will be led to a centrally flying satellite and coherently combined there. NASA on the other hand is studying the TPF project. This may also be designed as an interferometer similar to DARWIN. At the same time, NASA is considering the possibility of building a coronagraph – a single 10-m telescope in which a star can be blocked out very precisely with a mask so that a potentially present terrestrial planet would become discernible.

»ESA and NASA plan to conclude their studies by 2006 and then agree on a common concept«, declared Charles Beichman of NASA's Jet Propulsion Laboratory at the Heidelberg meeting. The instrument should be able then to detect Earth-sized planets within the habitable zone. Furthermore, spectroscopy of the planets should be possible in order to search for atmospheres and evidence of life as it is known to us. Molecular oxygen or ozone are regarded as suitable indicators of the presence of life.

If all goes according to the plans the planet-finder machine will be launched in 2015 and then look for terrestrial planets for a period of at least four years. If the dreams of the scientist were to become true thy might find a second Earth in the not too distant future and »complete the Copernican Revolution«, as Thomas Henning put it.

MIDI Conference at Ringberg Castle

The first interferometric observations in the mid-infrared range at the VLT using the MIDI instrument developed at MPIA were the reason for a small meeting on Ringberg Castle with highly qualified international participation.

Among the jewels of the Max Planck Society is the old-fashioned Ringberg Castle built in the early 19th century situated above the Tegernsee. Hardly any meeting place offers such a seclusion in a comfortable, stimulating environment with various opportunities for meetings in small groups and with excellent service and support. The photos shown here capture part of this atmosphere. It is an ideal place for working meetings where participants in new scientific developments can compare their experiences and make new plans.

Early September, 2003, we had the opportunity for one week to get to the bottom of the subject of "Long-baseline interferometry in the mid-infrared". This new method, which concerns the study of the innermost regions of quite different astronomical objects with high angular resolution, had just been inaugurated at the turn of the year 2002/2003 by combining two of the four telescopes of the Very Large Telescope (VLT) on Cerro Paranal, Chile, for interferometric measurements. For this, MPIA had contributed the MIDI instrument (Chapter II.4). So we invited expert colleagues in order to exchange views on first results, prospects for the future, technical difficulties and possibilities and new scientific plans – and everybody came: the Eso representatives responsible for interferometry on Paranal, colleagues from the US working on the corresponding project for the 10-m Keck telescopes on Hawaii, Nobel prize winner Charly Townes who as a man in his middle eighties is still very active – and with his forerunner instrument ISI is the pioneer of this research field, other colleagues from the USA, France, the Netherlands and other German institutes. The entire spectrum of those working in this field was present, from students and post-docs to experienced scientists and directors. The talks conveyed an atmosphere of pioneering, supported by promising results on galaxies and young and evolved

Fig. V.5: The participants of the workshop on the terrace of the castle, grouped around Charles Townes. (photo: H. Zinnecker)

Fig. V.6: Discussions during coffee-break. (photo: H. Zinnecker)

stars. Here, many a person learnt for the first time about the opportunities of this field.

There were also expectations for the near future: When the highly complex infrastructure on Paranal will be completed and the commissioning of the second interferometric instrument (AMBER) at the VLT interferometer will open up also the spectral range of shorter infrared wavelengths, the real strength of the new observing technique will become apparent.

Many of the observations, publications and instrumental developments that will take place in the following months have been initiated during conversations in small circles – enjoying the sun at coffee break or meeting later in the evening on the terrace or in one of- the numerous conference rooms. The meeting program loosely planned at first soon got packed and required all one's efforts. An afternoon trip to the nearby Walberg was welcomed then as a refreshing breather.

What are the results of this successful meeting then? Reliable information about the status of this field, new plans, new acquaintanceships, collaborations, and last not least the very informative collection of the transparencies of the talks held that can be found on the websites of MPIA. A printed proceedings band with its formal requirements would not have matched the quite spontaneous character of this workshop.

Christoph Leinert

Dagmar Schipanski: An important Visit to the Institute

On February 3rd, 2003, Prof. Dagmar Schipanski, Thuringian Minister for Science, Research and Art and a Senator of the Max Planck Society, informed herself about the collaboration between MPIA in Heidelberg, the Friedrich-Schiller-Universität (FSU) in Jena and the Landessternwarte Tautenburg. This cooperation has been intensified by Thomas Henning, managing director of MPIA, who had been director of the Astrophysical Institute of the FSU before changing to the Königstuhl.

Three projects stand out in the cooperation of these institutes. Early in February 2003, a new facility for laboratory astrophysics was opened at the Institute for Solid-State Physics of the FSU which was partly made possible by a cooperation with MPIA. In this laboratory, experiments can be carried out under conditions similar to those prevailing in space. The new institution is part of the Research Group "Laboratory Astrophysics" supported by the Deutsche Forschungsgemeinschaft. In collaboration with the Technische Universität Chemnitz, it is exploring astrophysical problems by means of laboratory experiments. The research concentrates on the formation of dust particles in interstellar space. These data complement observations and theoretical models which mainly deal with the formation of planets in the dusty disks of young stars (Chapter III.2).

In addition, MPIA and FSU are cooperating in the analysis of data obtained by the ISO satellite, the European infrared satellite that yielded a wealth of observational data during a period from 1995 to 1998. MPIA had significantly participated in this mission by developing the ISOPHOT instrument. Finally, the Landessternwarte Tautenburg is participating in the development of the software for the interferometer MIDI built at MPIA that yielded first scientific results in the year under report (Chapter II.4).

Subsequent to her visit at MPIA the minister gave a talk within the scope of the studium generale in the aula of the Ruprecht-Karls-Universität Heidelberg on the subject "Education and Research for the Knowledgeable Society".

Fig. V.7: Thomas Henning and Dietrich Lemke explain the Calar Alto telescopes to the minister.

Paul-Prize Winner Roberto Ragazzoni and the Future of the Adaptive Optics

For a period from 2001 to 2003, the Alexander von Humboldt Foundation got the opportunity within the scope of the Federal Government's "Investing in the Future Program" to invite to Germany top scientist from foreign countries for long-term stays. For this purpose, several scientists were awarded the Wolfgang Paul Prize endowed with two million Euro. One of the prize winners was Roberto Ragazzoni of the Astrophysical Observatory Arcetri near Florence.

In Arcetri, Ragazzoni is head of a working group that develops scientific instruments for modern large telescopes. His group is performing research at the very frontiers in the development of optical instruments. With his know-how and abilities, he is fitting perfectly into a team at MPIA that for many years is very successfully building adaptive optics systems. Together, the team now plans to develop instruments that will be used at the ESO VLT and at the LBT in Arizona. As a long-term objective, the group is dreaming of participating in the giant telescope OWL (Overwhelmingly Large Telescope), whose primary mirror will have an aperture of 100 m and for which a detailed study will be started in the near future.

Here, Roberto Ragazzoni (RR) answers some questions about his research in Heidelberg and elsewhere.

Question: Why are you fascinated by the development of optical instruments?

RR: Simply spoken: Because I enjoy it very much. I am especially interested in developing instruments that will take us a large step forward, breaking technical and scientific new ground.

Could you explain this in more detail?

RR: For me, there are two ways of developing instruments. In the first one, one mainly utilizes the components available, improving them in details, so that the final instrument may be twice as good as its forerunner. I am not very interested in that. I am fascinated by building instruments that are better by a factor of ten and that can be used to detect and study new kinds of objects. The giant leaps are the exciting ones, not the small steps.

In which way did the Wolfgang Paul Prize help you with these "giant leaps"?

RR: The prize acted like a catalyst. With the money, for one thing, we could buy hardware for our project. And for another thing we could use it for funding temporary positions at the Institute for two Ph.D. students and four to five additional team members.

Fig. V.8: The Federal Minister for Education and Research, Edelgard Bulmahn, presents the Wolfgang Paul Prize to Roberto Ragazzoni. (picture: Humboldt Foundation. Lüders)

Which projects are you currently working on?

RR: The focal point is on the LINC-NIRVANA project that will be installed at the LBT (Chapter IV.5). LINC is a Fizeau interferometer in which the light beams of both primary mirrors of the telescope will be coherently combined. With it we will be able to perform interferometry at wavelengths ranging from 0.6 to 2.4 μm. Colleagues at MPIA are designing the beam combiner for this instrument. Its real potential, though, will be utilized only in combination with adaptive optics. For this, we are building NIRVANA (Near-IR/Visible Adaptive Optics Interferometer for Astronomy).

And this instrument will then represent a giant leap in astronomical observing techniques?

RR: I am convinced of that. Up to now, adaptive optics systems correct the smearing of astronomical images due to atmospheric turbulences only in a rather small field of view. Using NIRVANA , we will carry out interferometrical observations in an area six arc minutes across. This is an enormous field of view for this technique.

Fig. V.9: Roberto Ragazzoni during an experiment with PIGS in November 2003 at the William Herschel Telescope.

How will this be achieved?

RR: By using a new technique called multiconjugate adaptive optics (MCAO). With the present-day adaptive optics we correct the telescope image only within a certain area around a star. At larger distances the image gets blurred. With MCAO this technique is applied to several reference stars in several directions. We plan to simultaneously measure about 20 stars over the entire field of view.

How is this done technically?

RR: Before the light coming from the telescopes enters the camera it is split into two sub-beams. One beam is used for analyzing the distortions caused by atmospheric turbulence. In this beam, we install a small glass pyramid at points where a stellar image is formed. If the light beam exactly hits the tip of the pyramid the image is split into four partial images and a zoom lens installed behind produces four pupil images on a detector. If these pupil images differ in their brightness the distortion of the infalling wavefront can be deduced from this difference. This information is needed to correct the image on the detector using an adaptive-optics mirror. If all is functioning well, we will achieve the maximally possible resolution of the LBT. And because we will install pyramids at a total of 20 points we will be able to correct the entire field of view.

Is this technique a novel one?

RR: Yes, I developed it in 1995. The total system is called pyramid wavefront sensor. At present, we develop it at MPIA under the name PYRAMIR (Chapter IV.3). Currently, there is only one pyramid wavefront sensor. It is operating at the Telescopio Nationale Galileo on La Palma. PYRAMIR would be the first wavefront sensor with a pyramid working in the infrared regime, and the second one worldwide.

How does the experiment proceed?

RR: The first prototype will be tested by the end of 2004 on Calar Alto.

You have initiated another experiment recently.

RR: Yes, we call it Pseudo Infinite Guide Star, or PIGS for short. In some cases an „artificial star“ has to be created in the sky that is used by the adaptive optics system for image correction. For this we shoot a laser beam into the sky which produces a luminous spot in the upper atmosphere. The problem with these laser guide stars is that they are not at an „infinite“ distance like the real stars but are formed at an altitude of 10 to 100 kilometers. The PIGS wavefront sensor, however, looks at the laser star as if it were – like the stars – infinitely far away. This is achieved with the help of a tricky optical configuration. We have tested PIGS in late 2003 at the William Herschel Telescope on La Palma.

The developments made at MPIA and in Arcetri will enormously increase the efficiency of large telescopes like the VLT and the LBT. But you are thinking even further?

RR: Yes. For some years, astronomers in Europe and the USA are discussing the possibility of building a telescope with a mirror of 30 to 100 meter diameter. Such an „Overwhelmingly Large Telescope“ (OWL) would depend on adaptive optics.

What is the present status of OWL?

RR: The European Union probably will grant 20 million Euro for a detailed study. The study could begin in 2005 and last for three or four years. If Europe decides to build such a telescope it might see first light in 2015. That would be another giant leap forwards!

(The questions were asked by Thomas Bührke.)

An Apprentice on the Königstuhl

In our ultra-modern fine-mechanical workshop, the scientific instruments used at ground-based telescopes or on board of research satellites are built in direct collaboration with the observing astronomers. Precision mechanics are also being trained in this workshop, who later will find it easy to get along in their jobs. We talked to one of our trainees.

In the year under report, the fine-mechanical engineers worked, e.g., on components for the interferometer for the LBT and on the chopper for the PACS instrument that will be used in the ESA satellite HERSCHEL (Chapter IV.8.). In addition to seven precision mechanics in permanent positions, five trainees are currently employed at MPIA. Thus the Institute also meets its social commitment to offer qualified professional training to young people. „So far, all 42 apprentices trained at the Institute have found a job with other companies or even at MPIA when a position was vacant“, says the head of the workshop, Armin Böhm. „And we also get positive reports from the companies that have employed apprentices trained by us“, completes Wolfgang Sauer, head of practical training.

Frank Sauer (FS) is in his third year of practical training as an precision mechanics and therefore on the verge to take his final examination. Here, he answers our questions.

Question: Frank, the Institute is located somewhat remote from the city on a mountain. How did you decide to accept a position as an apprentice here?

FS: In our school days we had to do a practical training course that had been offered here. I enjoyed working at the machines very much from the beginning, and I also liked the atmosphere here.

What do you like best here, after 2 1/2 years of experience?

FS: The variety is most exciting for me. I am able to work at different machines, even at ultra-modern ones. The computer-controlled machines are programmed in advance and then automatically cut the workpieces from a metal blank. Moreover, from our second year of training on we are fully participating in the work the staff colleagues are doing. I also like the team work. We all know one another and almost feel like a family.

Since recently you also are youth representative of a total of eight trainees at the Institute. Which are your tasks here?

FS: The other trainees appeal to me if there are any problems, with their superiors, for instance. Then I have to talk to the superior.

Fig. V.10: Armin Böhm, head of the workshop, and trainee Frank Sauer at the new computer-controlled milling machine.

Fig. V.11: View of the fine-mechanical workshop at MPIA.

Aren't you afraid that you might get in trouble standing up for others?

FS: No, not at all. For one thing, such cases hardly occur anyway and for another thing, I am legally protected against any disadvantages arising from my work as youth representative.

Is your activity as a youth representative limited to MPIA?

FS: No. Three times a year all youth representatives of all Max Planck Institutes meet to talk about their experiences. This is supported by the Max Planck Society. And from time to time I participate in seminars supported by the labor union Ver.di.

So, in addition you are learning some political work?

FS: Yes, you could say so.

The workpieces you are manufacturing are partly inserted into instruments that are among the best of the world. Does this motivate you?

FS: Yes, this is of course more interesting than building the same component over and over again for machines that are working somewhere in thousands.

Did you become interested in astronomy by working at MPIA?

FS: No. I have never been interested in astronomy, and that did not change. But recently I saw a report on the LBT on television. I watched that to the end which I normally would not have done. But this is not important for my work. I just enjoy working with the machines.

What would you like to do after your training?

FS: To stay here at the Institute.

(The questions were asked by Thomas Bührke.)

Girl’s Day at the Institute

May 8th, 2003, was declared “Girls’ Day” in the Federal Republic of Germany: Thousands of girls were given the opportunity to get to know the working world of alleged “men’s professions” – among these the variety of professions practiced at our Institute. Here is a report given by the organizers of this eventful day.

Often it is a singular event that determines our professional course. For one of us (A. Borch), it had been the technology exhibition “Exhibit” in 1985 in Berlin. A thermal transfer printer was continuously producing prints showing strange subjects. Among those was a so-called Mandelbrot image. “This image immediately fascinated me”, she recalls. “I had to know how it was programmed and I started to be interested in computing time.” Today she is a Ph.D. student at the Max Planck Institute for Astronomy in Heidelberg. Programming is routine work for her. For the second one of us (J. Costa), it had been a vacation practical in a chemical laboratory she did in her school days. “It had been a key experience, rousing my enthusiasm for experimenting”, she recalls. She too is a Ph.D. student at the Institute in Heidelberg.

Experiences like these have led to the establishment of the Girls’ Day, a nation-wide action intended for schoolgirls of grades 5 to 10 that is to allow insights into the world of “male” occupations. In addition to exhibitions, “Open House Days”, and practical training courses, this special day, too, is intended to extend the spectrum of professions girls might choose.

The Girls’ Day is supported by the Federal Ministry for Education and Research, the Ministry for Family and Youth Questions, the Federal Agency for Labor, the

Fig. V.12: In the experiment hall of the Institute Tom Herbst explains with the help of simple experiments the working principle of large telescopes.

Fig. V.13: In the CCD laboratory there are a lot of interesting things to discover. Here Karl-Heinz Marien explains how a CCD camera works.

German Federation of Labor Unions as well as associations of industry and commerce. While in 2002 already 42 000 places had been offered, in 2003 even 100 000 girls had the chance to take a look at "men's occupations" in more than 3500 companies, research institutions and public departments.

And that is just fair since 50 percent of the girls still select from only about ten different occupations, thus choosing from a smaller spectrum than boys do. And these generally are so-called "typical women's occupations" whereas technical or scientific professions are seldom chosen – although girls on average are more successful in school than their male schoolmates. 54.8 percent of those who meet the general matriculation requirements are female pupils while their fraction of those who leave the upper division of elementary school without any final examination is only 34.5 percent. This is reason enough for the Girls' Day to point out interesting professions to girls. In 2003, Girls' Day took place for the third time and MPIA participated for the first time in it.

A variety of experiences

The staff of MPIA readily agreed to partake in Girls' Day. Thus many different projects had been prepared in advance. Finally, on May 8th, a total of 53 schoolgirls at ages from 11 to 16 got to know the workshops and technical departments where the instruments are being built that are used for observing by astronomers from Heidelberg.

In many projects the girls were allowed to do things themselves. In the workshops they learnt how to mill stickers and to solder circuits. In the computer department they had the opportunity to totally dismantle older computers. From the Ph.D. students who presented their work to them, demonstrating the absolute necessity of computers, they got an insight into the working day of a scientist. They also were shown how to program a Mandelbrot image. The Institute's telescopes were on view, and group photographs were taken with a CCD camera; the girls could do optic experiments in the adaptive optics laboratory, technical drawings in the construction department and even control the 3.5-m telescope on Calar Alto from a computer terminal in Heidelberg. Astronomers told about their observations with the HUBBLE Space Telescope, cosmological surveys, search-projects for planets beyond Neptune in our solar system and much more.

For each girl there was something exciting to learn. At noon they were rewarded for their efforts with almond ice cream that had quickly been frozen in a cheerful liquid-nitrogen demonstration – and soon was completely eaten up. Finally, somewhat exhausted, the girls commented positively on this day on which they had discovered a lot of new and interesting things. And the staff of our Institute had also enjoyed this day very much.

(Joana Costa, Andrea Borch)

Staff

Heidelberg

Directors: Henning (Managing Director), Rix

Scientists: Andersen, Barden, Bell, Birkle (until 30.4.), Böhnhardt, Brandner, Burkert (until 30.6.), Feldt, Fried, Gässler, Graser, Grebel (until 31.8.), Haas (until 30.6.), Herbst, Hippelein, Hippler, Hofferbert, Kiss (since 1.9.), Klaas, Klahr, Kniazev, Köhler, Krasnokutski (until 14.11.), Krause (since 15.8.), Launhardt, Leinert, Lemke, Lenzen, Ligori, Maier (until 31.5.), Marien, Mathar, Meisenheimer, Mundt, Odenkirchen (until 31.8.), Pentericci (until 14.2.), Pitz, Röser, Schmitt (1.1. – 28.2.) Setiawan (since 1.6.), Staude, Steinacker (since 1.3.), Stickel, Toth, Vavrek, Weiß, Wilke (until 30.6.), R. Wolf, Xu

Ph. D. Students: Apai, Berton (since 1.5.), Bertschik, Birkmann (since 15.7.), Borch, Büchler, De Matos Costa, Dib, Dirksen (1.1. – 31.10.), Dumitrache (1.5. until 31.7.), Eberle (1.5. – 31.10.), Egner (1.11.), Falter (since 1.4.), Harbeck (until 31.8.), Häring, Hartung (until 31.5.), Häußler (since 1.9.), Hempel, Jesseit (until 30.4.), Kautsch (14.4. – 31.8.), Keil, Kellner, Khochfar (until 30.6.), Koch (27.2. until 31.8.), Kovacs, Lamm (until 31.10.), Mühlbauer, (until 30.6.), Pascucci, Przygodda (until 31.10.), Puga, Ratzka, Rodmann, Rüger (until 15.8.) Schartmann (since 1.12.), Schütz (ab 1.3.), Semenov (since 15.11.), Stolte (until 31.5.), Umbreit, Walcher, Wetzstein

Diploma Students and Student Assistants: Mertin (since 1.12.), Scharlach (5.8. until 30.9.), Stumpf (since 1.7.), Tristram (until 30.11.), Würtele (since 1.10.)

Diploma Students (FH): Brunner (1.3. – 31.8.), Kinder (until 31.3.)

Scientific Services: Bizenberger, Grözinger, Hinrichs, Laun, Neumann, Quetz, Schmelmer

Computers, Data Processing: Briegel, Hiller, Rauh, Richter, Storz, Tremmel, Zimmermann,

Electronics: Alter, Becker, Ehret, Grimm, Klein, Mall, Mohr, Ramos (since 1.3.), Ridinger, Salm, Unser, Wagner, Westermann, Wrhel

Fine Mechanics: Böhm, Heitz, Meister, Meixner, Morr, Pihale, Sauer

Drawing Office: Baumeister, Ebert, Huber (since 1.11.), Münch, Rohloff

Photo Shop: Anders

Graphic Artwork: Meißner-Dorn, Weckauf

Library: A. Dueck (20.2. – 19.3.), M. Dueck

Administration: Apfel, Gieser, Heißler, Hölscher (since 1.2.), Kellermann, Papousado, Schleich, Voss, Zähringer

Secretariate: Bohm, Janssen-Bennynck, Koltes-Al-Zoubi, Meng (until 31.10.), Seifert (since 15.11.)

Technical Services: Behnke, Herz, Jung, Lang, Nauß, B. Witzel, F. Witzel, Zergiebel

Trainees: Baungärtner, Bender (until 20.1.), Maurer, Müllerthann (since 1.9.), Resnikschek (since 1.9.); Rosenberger, Sauer, Schmitt (since 1.9.), Stadler

Free Collaborator: Dr. Th. Bührke

Scholarship Holders: Alvarez, Bailer-Jones, Bouwman (1.9.), Butler, Chesneau, Ciecielag (1.2. – 31.10.), De Bonis (15.5. – 31.8.), D'Onghia (until 31.8.), Farinato (since 15.2.), Gouliermis (since 1.5.), Heymans (since 22.9.), Hujeirat, Khanzadyan, Kleinheinrich, Lee (until 15.9.), Martinez-Delgado (since 1.12.), Masciadri, Prieto, Soci, Trujillo, Wang (since 1.3.), Zucker (since 1.10.)

Guests: Acosta-Pulido, Spanien (November), Aarseth, Norwegen (November), Ábrahám, Ungarn (June, July, October), Arcidiacono, Italien (April–July), Bacmann, Frankreich (November), Bakker, Holland (July), Bergin, USA (February), Bershady, USA (October), Boeker, ESTEC/NL (October), Bouy ESO (January, June, September), Bik, Holland (November), Bodenheimer, USA (March/April), Borgani, Italien (January), Van den Bosch, MPA Garching (January), Bouwmann, Holland (January, July), Bromm, USA (June), Brunotti, Italien (February), Cappellari, Leiden (November), Carmona, Linkop University (July), Caubillet, Arcetri (December), Cho, USA (November), Correia, AIP Potsdam (November), Courteau, British Columbia (May), Delplancke, ESO (January), Diolaiti, Italien (April-July), Ferguson, MPG (September), Franx, Holland (September), Gawryszczak, Polen (May/June), Gallagher, USA (June), Garaud, Cambridge (April), Garcia-Berro, Spanien (January-February), Ghedina, Italien (June), Gomez-Flechoso, Spanien (July), Hartung, ESO-Chile (September), Hartmann, USA (May), Heymans, Oxford (February, August), Hoekstra, Toronto (July-August), Huelamo, ESO (April), Ida, Japan (April-May), Johansen, Dänemark (September), Karachentsev, Russland (June), Karachentseva, Ukraine (June), Kasper, ESO (December), Kim, USA (May), Klein, Jena (February), Klessen, Potsdam (June), Krivov, Potsdam (April), Kürster, Tautenburg (November), Kroupa, Kiel (January), Lehnert, MPE (December), Lindner, England (July), Linz, Tautenburg (June), Lin, Lick Observatory (April), Lopez-Aguerri, Spanien (July), Maier, ETH Zürich (December), Mikkola, Finnland (November), Merritt, USA (June), Meyer, USA (October), Marco, ESO Chile (July), Mac Low, USA (July), Martin-Hernandez, Genf (Februar-März), Menshchikov, MPIfR (June-July), Munteann, UPC Barcelona (March), Mack, Holland (February), Mazeh, Israel (February), Mikkola, Finnland (November), Ocvirk, France (October), Naab, Cambridge (February, April, June-August), Osmer, USA (August), Phleps, Edinburgh (December), Popowski, MPA (November), Parmentier, Belgium (July), Pavlyuchenko, Russia (February-April), Pizagno, USA (April-May), Plewa, USA (June-July), Powell, USA (January-June), Pramski, Russia (October-November), Pustilnik, Russia (July-August), Rudnick, USA, (November), Raga, Mexico (June), Reunanen, Finland (July), Ribak, Israel (January), Sarzi, England (August), Smith, England (January-February, September-October), Shields, USA (August), Swaters, USA (May), Stuik, Holland (May), Szameit, Jena (November), Schinnerer, NRAO (November), Schreyer, Jena (February), Sterzik, ESO-Chile (July), Swaters, USA (May), Thomas, MPE (November), Torres, Spain (January-February), Tsevi, Israel (February), Verheijen, Potsdam (May), Vernet, Frankreich (June-July), Voshchinnikov, Russia (May), Walter, NRAO (November), Wasla, Japan (June), Wetzstein, München (July), Wiebe, Russia (September-November), Wiedermann, Hamburg (November), Williams, USA (May), Wolf, Oxford (January), Wolf, USA (May), Wünsch, Tschechien (November-December), Zeilinger, Wien (May)

Due to regular international meetings at the MPIA further guests stood at the Institute for shorter periods, who are not listed here.

Co-operative Students: Boxermann (until 28.2.), Heß (10.3. – 5.4.), Konya (1.9. – 31.12.), Leledis (1.9. – 31.12.), Naranjo (since 1.10.), Steinmann (1.3. – 31.8.), Urner (18.2. – 10.3.), Wiehl (25.8. – 3.10.)

Calar Alto/Almeria

Local Directors: Gredel, Vives (until 31.12.)

Astronomy, Coordination: Thiele, Frahm

Astronomy, Night Assistants: Aceituno, Aguirre, Alises, Cardiel, Guijarro, Hoyo, Pedraz

Telescope Techniques: Capel, De Guindos, García, Helmling, Henschke, Hernández L., Hernández R., Raul López, Marín, Morante, Müller, W., Nuñez, Parejo, Schachtebeck, Usero, Wilhelmi

Technical Services: Aguila, A., Aguila, M., Ariza, Barón, Carreño, Corral, Domínguez, Gómez, Góngora, Klee, Rosario López, Márquez, Martínez, Romero, Sánchez, Tapia

Administration, Secretariate: Hernández, M., Hernández, M.J., López, M.I.

Jena

Local Group Head: Huisken

Scientists: Colder (until 31.5.), Diegel (since 15.8.), Rouillé, Staicu

Ph.D. Students: Krasnokutski, Sukhorukov

Guests: Alexandrescu, Roumania (January/February), Dumitrache, Roumania (June/July), Guillois, France (June), Marino, France (June), Morjan, Roumania (January/February), Voigt, Germany (July and November)

Working Groups

Department »Planet and Star Formation«
Director: Thomas Henning

Space Astronomy in the Infrared
Dietrich Lemke, Stephan Birkmann, Ulrich Grözinger, Martin Haas, Csaba Kiss, Ulrich Klaas, Stefan Mertin, Oliver Krause, Roland Vavrek, Manfred Stickel, Viktor Toth, Karsten Wilke

Star Formation
Christoph Leinert, Carlos Alvarez, Daniel Apai, Jeroen Bowman, David Butler, Markus Feldt, Rainer Köhler, Tigran Khanzadyan, Ralf Launhardt, Rainer Lenzen, Ilaria Pascucci, Elena Puga, Thorsten Ratzka, Oliver Schütz, Dmitri Semenov, Hongchi Wang

Brown Dwarfs, Extrasolar Planets
Reinhard Mundt, Coryn Bailer-Jones, Wolfgang Brandner, Markus Lamm, Elena Masciadri, Jens Rodmann, Johny Setiawan

Theory
Hubertus Klahr, Bernhard Keil, Jürgen Steinacker, Stefan Umbreit

Laboratory Astrophysics
Friedrich Huisken, Olivier Debieu, Serge Krasnokutzki, Gaël Rouillé, Angela Staicu, Oleksandr Sukhorukov

Frontiers of Interferometry in Germany
Christoph Leinert, Olivier Chesneau, Uwe Graser, Ralf Launhardt, Frank Przygodda

Adaptive Optics
Wolfgang Brandner, Carlos Alvarez, Joana Büchler, Alessandro Berton, David Butler, Markus Feldt, Dimitrios Gouliermis, Stefan Hippler, Elena Masciadri, Micaela Stumpf

Department »Galaxies and Cosmology«
Director: Hans-Walter Rix

Structure and Dynamics of Galaxies
Andreas Burkert, Hans-Walter Rix, David Andersen, Michael Odenkirchen, Ignacio Trujillo, Roland Jesseit, Jakob Walcher

Stellar Populations and Star Formation
Eva Grebel, Thomas Herbst, Alexei Kniazev, Henry Lee, David Martinez Delgado, Dan Zucker, Sami Dib, Daniel Harbeck, Andreas Koch, Andrea Stolte

Evolution of Galaxies and Cosmology
Eric Bell, Andreas Burkert, Hans-Walter Rix, Elena D'Onghia, Helmut Hetznecker, Catherine Heymans, Martina Kleinheinrich, Marc Barden, Sadegh Khochfar, Angela Hempel, Andrea Borch

Aktive Galactic Nuclei
Klaus Meisenheimer, Almudena Prieto, Laura Pentericci, Ahmad Hujeirat, Nadine Häring, Marc Schartmann, Konrad Tristram

Sloan Digital Sky Survey
Eva Grebel, Eric Bell, Daniel Zucker, Alexei Kniazev, Laura Pentericci, Michael Odenkirchen

Deep Surveys
Klaus Meisenheimer, Hermann Röser, Hans Hippelein, Christian Maier, Zoltan Kovacs, Siegfried Falter, Boris Häußler

Instrumentation
Thomas Herbst, Hermann-Josef Röser, Josef Fried, Roberto Ragazzoni, Wolfgang Gäßler, David Andersen, Roberto Soci, Sebastian Egner

Collaboration with Industrial Firms

ABB (formerly Hartmann + Braun), Alzenau
Additive, Friedrichsdorf
ADR, Paris
Agilent Technologies, Böblingen
Almet-AMB, Mannheim
Amphenol-Tuchel Electronics, Heilbronn
Analyt-MTC, Mühlheim
Angst+Pfister, Mörfelden
APE Elektronik, Kuppenheim
Arthur Henninger, Karlsruhe
asknet, Karlsruhe
Auer Paul GmbH, Mannheim
Baier Digitaldruck, Heidelberg
Barr, USA
Barth, Leimen
Bechtle, Heilbronn
Bectronic GmbH, Derschen
Best Power Technology, Erlangen
Beta Layout, Arbergen
Binder Magnete, Villingen-Schwenningen
Blaessinger, Stuttgart
Bohnenstiel, Heidelberg
Böllhoff, Winnenden
Börsig, Neckarsulm
Bubenzer Bremsen, Kirchen-Wehrbach
Bürklin, München
CAB, Karlsruhe
Cadillac-Plastic, Viernheim
C&K Components, Neuried b. München
Cancom, Frankfurt
C.A.P. CNC+Coating Technik, Zell. a. H.
Carl Roth, Karlsruhe
Cherry Mikroschalter, Auerbach
Christiani, Konstanz
Coating-Plast, Schriesheim
Com Pro, Stuttgart
Compumess Electronik, Unterschleissheim
Comtronic GmbH, Heiligkreuzsteinach
Conrad Electronic, Hirschau
Creaso, Gilching
Cryophysics, Darmstadt
Dannewitz, Linsengericht
DELL, Langen
Delta, Wuppertal
Deltron Components GmbH, Neuried b. München
DEMAG, Nördlingen
Deti, Meckesheim
DMG-Service, Pfronten
Dürkes & Obermayer, Heidelberg
Dyna Systems NCH, Mörfelden-Walldorf
e2v technologies, GB
EBARA Pumpen, Dietzenbach
EBJ, Ladenburg
EBV-Electronik, Leonberg
EC Motion, Mönchengladbach
Edsyn Europa, Kreuzwertheim
EFH, Neidenstein
Eldon, Büttelborn
Elna Transformatoren, Sandhausen
elspec, Geretsried
ELV Electronik, Leer
ERNI, Adelberg
eurodis Enatechnik, Quickborn
EWF, Eppingen
Faber, Mannheim
Fairchild Imaging Syst., USA
Farben Specht, Bammental
Farnell Electronic Components, Deisenhofen
Farnell Electronic Services, Möglingen
FCT Electronic, München
Fels Spedition, Heidelberg
Fisba, St. Gallen

Fischer Elektronik, Lüdenscheid
Flash Computer, Guentersleben
FPS-Werkzeugmaschinen GmbH, Otterfing
Franke, Aalen
Fritz Faulhaber, Schönaich
FPS-Werkzeugmaschinen GmbH, Otterfing
Franke, Aalen
Fritz Faulhaber, Schönaich
Future Electronics Deutschland, Unterföhring
Ganter, Walldorf
Geier Metalle, Mannheim
GENOMA Normteile, Hameln
GLT, Pforzheim
Gordion, Troisdorf
Gould Nicolet Meßtechnik, Dietzenbach
Grandpair, Heidelberg
Grulms-Pneumatik, Grünstadt
GRW, Würzburg
Gummi Körner, Eppelheim
Gummi-Plast Schild, Gernsheim
Gutekunst, Pfalzgrafenweiler
Halm+Kolb, Stuttgart
Heidenhain, Traunreut
Heraeus, Hanau
Hilger und Kern, Mannheim
Hilma-Römheld GmbH, Hilchenbach
Helukabel, Hemmingen
Hema, Mannheim
Herz, Leister Geräte, Neuwied
Hewlett-Packard Direkt, Böblingen
Hinkel Elektronik, Pirmasens-Winzeln
HM Industrieservice, Waghäusel
Hommel-Hercules Werkzeughandel, Viernheim
Hormuth, Heidelberg
Horst Göbel, Ludwigshafen
Horst Pfau, Mannheim
HOT Electronic, Taufkirchen
HTF Elektro, Mannheim
Huber + Suhner, Taufkirchen
Hummer+Rieß, Nürnberg
Häcker, Weinsberg
Häfele Leiterplattentechnik, Schrießheim
IBF Mikroelektronik, Oldenburg
Infrared Labs, Tucson, USA
Ingenieurbüro Steinbach, Jena Inkos, Reute/Breisgau
INMAC, Mainz
iSystem, Dachau
ITOS GmbH. Mainz
Jacobi Eloxal, Altlussheim
Janos, USA
Jarmyn, Limburg
Joisten+Kettenbaum, Bergisch Gladbach
Kaufmann, Crailsheim
Kerb-Konus-Vertriebs-GmbH, Amberg
Kippdata, Bonn
Kniel, Karlsruhe
Knürr, München
Korth, Hamburg
Lambda Electronics, Achern
Layher, Güglingen
Lemo Electronik, München
Leybold Vakuum GmbH, Köln
Lineartechnik Korb, Korb
Loedige, Paderborn
LPKF CAD/CAM Systeme, Garbsen
Macrotron, München
Mädler, Stuttgart
Mankiewicz, Hamburg
Matsuo Electronics Europe, Eschborn
Matsushita Automation, Holzkirchen
Maxim Ges. f. elektronische integrierte Bausteine, Planegg
Menges electronic, Dortmund
Mentor, Erkrath
Metrofunkkabel-Union, Berlin
Micro-Optronic-Messtechnik, Langebrück
Mitsubishi-Electric, Weiterstadt
Mizzi, Brühl
Mönninghoff, Bochum
Moxa, Laudenbach
MSC Vertriebs-GmbH, Stutensee
MTI, Baden-Baden
Munz, Lohmar
Nanotec, Finsing
Neust Schaltungselektronik, Ehringshausen - Katzenfurt
Newport, Darmstadt
Nickel Schalt- und Meßgeräte, Villingen-Schwenningen
Niedergesess, Sandhausen
Nies Electronic, Frankfurt
Noor, Viernheim
Nova Electronik, Pulheim
Oberhausen, Ketsch
Otto Faber, Mannheim
Otto Ganter, Furtwangen
OWIS GmbH, Staufen
Parametric Technology, München
Parcom, CH-Flurlingen
pbe Electronic, Elmshorn
Peltron GmbH, Fürth
Pfeiffer, Mannheim
Pfeiffer Vacuum GmbH, 5614 Asslar
Physik Instrumente, Waldbronn
Phytec Meßtechnik, Mainz
Phytron, Gröbenzell
Plastipol, Runkel
PROUT, Darmstadt
ProLogic, Wuppertal
PTC, Mannheim
PSI Tronix, Tulare, California, USA
Püschel Electronik, Mannheim
R.E.D. Regional-Electronic-Distribution, Rodgau-Jügesheim
Radiall, Rödermark
RALA, Ludwigshafen
Rau-Messtechnik, Kelkheim
Räder Gangl, München
Reeg, Wiesloch
Reinhold Halbeck, Offenhausen
Reith, Mannheim
Retronic, Ronneburg
Rexim, Maulbronn
Riekert & Sprenger, Wertheim
Rittal-Werk, Herborn
Rockwell, USA
Roland Häfele Leiterplattentechnik, Schriesheim
Roth, Karlsruhe
RS Components, Mörfelden-Walldorf
RSP-GmbH, Mannheim
Rudolf, Heidelberg
Rütgers, Mannheim
Rufenach Vertriebs-GmbH, Heidelberg
Sartorius, Ratingen
Sasco, Putzbrunn
Scantec, Planegg
Schaffner Elektronik, Karlsruhe
Schott Mainz
Schulz, München
Schuricht, Bremen
Schuricht, Fellbach-Schmiden
Schweizer Elektroisolierungsstoffe, Mannheim
Scientific Computers, Aachen
SCT Servo Control Technology, Taunusstein
SE Spezial-Electronic, Bückeburg
Seifert mtm Systems, Ennepetal
Siemens IC-Center, Mannheim
Spaeter, Viernheim
Spindler & Hoyer, Göttingen
Spoerle Electronic, Dreieich
Steward Observatory, USA
Straschu Leiterplatten, Oldenburg
SUCO-Scheuffele, Bietigheim-Bissingen
Swiss Optik, Schweiz
Synatron, Hallbergmoos
Tafelmeier, Rosenheim
Tandler, Brauen
THK, Düsseldorf

Thorlabs, Gruüberg
TMS Test- und Messsysteme, Herxheim/Hayna
Tower Electronic Components, Schriesheim
Transtec, Tübingen Rutronik, Ispringen
TreNew Electronic, Pforzheim
TS-Optoelectronic, München
TWK-Elektronik, Karlsruhe
Vacuumschmelze, Hanau
VBE Baustoff+Eisen, Heidelberg
Vero Electronics, Bremen
VisionEngineering, Emmering
Vision Systems, Norderstedt
W. & W. Schenk, Maulbronn
WIKA, Klingenberg
Wikotec, Bramsche
Wilhelm Gassert, Schriesheim
Winlight, Frankreich
Witter GmbH, Heidelberg
WS CAD Electronik, Berk Kirchen

Teaching Activities

Winter Term 2002/2003

Bönhardt, H.: The Solar System, Univ. Erlangen-Nürnberg (Bloc Course)
Burkert, A., Rix, H.-W.: Struktur, Kinematics and Dynamics of Stellar Systems (Seminar, with B. Fuchs, A. Just, R. Spurzem, R. Wielen)
Lemke, D., Röser, H.-J.: Introduction to Astronomy and Astrophysics, III (Seminar, with J. Krautter)
Meisenheimer, K.: Particle Acceleration and Radiation Processes in Radio Galaxies (Seminar, with J.G. Kirk, S. Wagner)

Summer Term 2003

Bönhardt, H.: The Solar System, Univ. Erlangen-Nürnberg (Bloc Course); The Rio de Janeiro Astronomy Winter School, Nat. Obs. Rio de Janeiro (Bloc Course)
Burkert, A., Rix, H.-W.: Stellar Dynamics (Seminar, with B. Fuchs, A. Just, R. Spurzem, R. Wielen)
Fried, J.: Galaxies (Lecture, with B. Fuchs)
Henning, Th.: Star Formation (Lecture)
Meisenheimer, K.: Group Work Physics II
Haas, M., Lemke, D., Leinert, Ch., Mundt, R., Röser, H.-J.: Introduction to Astronomy and Astrophysics III (Seminar)

Winter Term 2002/2003

Henning, Th.: Physics of Star Formation (Seminar)
Leinert, Ch., Lemke, D.: Introduction to Astronomy and Astrophysics, III (Seminar, with H.-P. Gail)
Meisenheimer, K.: Radio Galaxies at High Redshifts (Seminar, with J.G. Kirk, S. Wagner)
Rix, H.-W.: Observing the Big Bang and its Aftermath (Lecture)
Rix, H.-W.: Structure, Kinematics and Dynamics of Stellar Systems (Seminar, with B. Fuchs, A. Just, R. Spurzem and R. Wielen)
Röser, H.-J.: Clusters Of Galaxies (Lecture)

Practical work for advanced students: During Winter and Summer Terms, for students of Physics and Astronomy laboratory exercises on »Adaptive Optics« are offered at the Institute.During four afternoons, they can build up an analyzer to determine the deformation of wave fronts als well as optical aberrations like coma and astigmatism. The experiment takes place in the Adaptive Optics Laboratory at MPIA. (Responsible: Stefan Hippler, Wolfgang Brandner; Tutors: Stephan Kellner, Oliver Schütz, Alessandro Berton). A second experiment is devoted to the technology of CCD Cameras.

Conferences, Talks and Public Lectures

Conferences organized

Conferences organized at the Institute

Meeting of the Working Groop »Baden-Württemberg – center for Adaptive Optics« at MPIA, 2. April (S. Hippler)
Conference »Toward other Earths – DARWIN/TPF and the search for extrasolar terrestrial planets«, Conference Center Heidelberg, 22.-25. April (R. Launhardt, D. Apai, H. Boehnhardt, Th. Henning, I. Pascucci)
Calar Alto Colloquium, Heidelberg, 28.–29. April
GEMS Workshop, May 2003, MPIA (E. Bell)
Ringberg Workshop on long baseline interferometry in the mid-infrared, 1.-5. September (U. Graser, C. Leinert, T. Ratzka)
Meeting of the »EU research and training network for adaptive optics for extremely large telescopes«, MPIA, 16.–17. October (S. Hippler)
Meeting of the Research Group »Laboratory Astrophysics«, MPIA, 21. November (J. Steinacker)

Other Conferences

Bönhardt, H.: First decadal review of the Edgeworth-Kuiper-Belt – towards new frontiers, international ESO-UCN workshop, Antofagasta, March 11-15 (SOC chair); Synergies from widefield imaging surveys, JENAM, Budapest, August 25-29 (SOC); The new ROSETTA targets, ESA science workshop, Capri, October 13-16 (SOC);

Brandner, W.: ESO workshop on science with adaptive optics, Garching, September (Co-chair and LOC)

Feldt, M.: CHEOPS kick-off meeting, Padua, 3.-4. February; CHEOPS progress meeting, Zürich, 6-7 October

Gässler, W.: AO Mini-school, München, 19-23. February

Haas, M.: »Evolution of quasars«, AG-Tagung, Splinter Meeting, Freiburg, 15. – 19. September

Henning, Th.: SOC-Mitglied bei »Astrophysics of dust«, Estes Park, USA; IAU – Symposium »Star formation at high angular resolution«, Sydney, Australia; AO-Meeting »Science with adaptive optics«, Garching, September; IRAM Meeting, Star Formation, Grenoble, France, December (Chairman)

Hippler, S.: Mini-school »Multi-conjugate adaptive optics for extremely large telescopes«, ESO-Garching, 19-21. February

Martinez-Delgado, D.: »Satellites and tidal streams«, INGIAC Joint conference, 26-30 Mai, La Palma (Spain)

Meisenheimer, K.: Formation and early evolution of galaxies, SFB 439 Workshop, Kloster Irsee, 30. June – 4. July (with S. Phleps)

Ragazzoni, R.: National school of astrophysic Isola d'Elba, I telescopi di nuova generazione 11.–17 Mai, »LBT and VLT/VLTI«; Mini school in Munich; RTN workshop La Palma; 2nd Baeckaskog workshop on exteremely large telescopes, Baeckaskog Castle, Sweden, 9.–11. September (SOC Chair)

Steinacker, J.: Splinter meeting »Interferometry with large telescopes«, Annual Meeting of the Astronomische Gesellschaft, Freiburg i. Br. 15.–20. September

Umbreit, St.: N-body events, mini workshop, Heidelberg, 25.– 28. November (with R. Spurzem)

Partecipation in Conferences, Scientific and Public Talks

Scientific Talks and Poster Contributions

Apai, D.: Towards other Earths: DARWIN, TPF and the search for extrasolar terrestrial planets, April 22-25, Heidelberg (poster); IAU Symp. 221: Star formation at high angular resolution, 22-25. July, Sydney (poster)

Bailer-Jones, C.: GAIA photometry working group meeting, MPIA, 10.–11. March (talk); GAIA science team meeting no. 7, ARI, Heidelberg, 12.–13. March; University of Heidelberg, July (invited talk); Meeting of the American Astronomical Society, Nashville, USA, 25.–29. Maiy (Poster); GAIA Data Processing Meeting, Barcelona, April (talk); GAIA Science Team Meeting no. 8, ESTEC, 25.–26. June; GAIA Science Team meeting no. 9, ESTEC, 7. – 8. October; GAIA photometry working group meeting, Leiden, 9.–10. October (talk)

Bell, E.: The baryonic Universe, Aspen USA, January (talk); Spectroscopic and imaging surveys in cosmology workshop, Oxford, March (talk); The multi-wavelength Universe, Venice, October (talk); Spectroscopic and imaging surveys in cosmology workshop, Neapel, September (talk)

Berton A.: General meeting of the CHEOPS project group, Zurich, 6.–7. October; Informal meeting of the CHEOPS project group, Padua, 4. Dezember (talk)

Boenhardt, H.: »First Decadal review of the Edgeworth-Kuiper-Belt – Towards New Frontiers«, International ESO-UCN workshop, Antofagasta, 11.–15. March (invited talk); »The ESO large programs«, ESO workshop, Garching, 19.–21. May (invited talk); ESA science workshop »The new ROSETTA targets«, Capri, 13.–16. October (invited talk); Physikalisches Kolloquium, Universität Braunschweig, 24. June (invited talk); MPI für Aeronomie Katlenburg-Lindau, 25 June (invited talk), Physikalisches Kolloquium, Universität Erlangen-Nürnberg, 3. November (invited talk)

Brandner, W.: The solar system and extrasolar planets, Weimar, February (talk); Towards other Earths: DARWIN, TPF and the search for extrasolar terrestrial planets, Heidelberg, 22.–25. April, (talk); IAU Symp. 221: »Star formation at high angular resolution«, Sydney, July (invited talk); CHEOPS Meetings, Zürich, October (eingeladener Vortrag); Astronomical colloquium at the University of Florida at Gainesville, November (invited talk)

Butler, D.: Stellar populations, MPA, Garching, 6.–11. October (poster); Science with »Adaptive Optics«, ESO Workshop, Garching16-19 September (talk)

Chesneau, O.: JEMAN Mini-symposium on young stars, August (invited talk)

Feldt, M.: Towards other Earths: DARWIN, TPF and the search for extrasolar terrestrial planets, (invited talk); IAU Syposium 221, Sydney, 22-25 July (invited talk); Extrasolar planets: today and tomorrow, Paris, 30.6.–4.7. (poster)

Gässler, W.: 2nd Baeckaskog workshop on extremely large telescopes, Baeckaskog Castle, Sweden, 9.–11. September (talk); ESO Workshop on Science with AO, München. 16.–17. September (poster)

Gouliermis, D.: ESO workshop »Science with adaptive optics«, Garching, 16.–19. September (poster); RTN meeting »Adaptive optics for extremely large telescopes«, 16.–17. October, Heidelberg (talk)

Graser, U.: Ringberg workshop on long-baseline interferometry in the mid infrared, 1.–5. September (invited talk)

Grebel, E.: Fourth Carnegie centennial symposium on origin and evolution of the elements, Pasadena, 16.–21. Februar (invited talk); Calar Alto Colloquium, Heidelberg, 28.–29. April (invited talk); Kolloquium der ETH Zürich, 29. April (invited talk); ING-IAC Joint conference, Santa Cruz de la Palma, 26.–30. Mai (invited talk); 2nd AIP Thinkshop »The Local Group as a cosmological training sample«, Potsdam, 12.–15. June (invited talk); Workshop on the formation and evolution of massive young star clusters, Cancun, Mexico, 17.– 21. November (invited talk)

Gredel, R.: 250 years of astronomy in Spain, Cadiz, September (talk)

Haas, M.: The Promise of ALMA, Elba 26.-30.Mai (talk); AG-Tagung 2004, Freiburg, 15.–19. September (talk); Multiwavelength AGN surveys«, Cozumel/Mexiko 8.–12. Dezember (invited talk)

Häring, N.: ESO workshop Science with adaptive optics, Garching, 16.–19. September (talk)

Häußler, B.: GEMS meetings in Baltimore (19.–20. January), Heidelberg (12.–14. May), Oxford (22.–26. October); SISCO Meeting, Neapel (3.–6. September); IAU Genaral Assembly, Sydney, 13.–26. July (poster)

Henning, Th.: Colloquium for the inauguration of the Laboratory Astrophysics Branch, Universität Jena, February; Astrophysics of Dust, Estes Park, Colorado, USA, May (invited talk); International Astronomical Union XXV. General Assembly, Sydney, Australia, July (poster); Ringberg Workshop on long baseline interferometry in the mid-infrared. Schloss Ringberg, Tegernsee, September (invited talk); 4th Cologne-Bonn-Zermatt-Symposium on the dense interstellar medium in galaxies. Zermatt, Schweiz, September (talk); DESY-HS Workshop »Astronomie mit Großgeräten«, AIP Potsdam, September (invited talk); University of Arizona, Tucson, USA, November (colloquium talk); Universität Heidelberg, November (colloquium talk); Universität Freiburg, December (colloquium talk)

Hippler, S.: NAOMI workshop on adaptive optics, La Palma, 9.–10. January (talk); Colloquium der Justus-Liebig Universität Gießen, 8. Februar (invited talk); ESO Mini-school on multi-conjugate adaptive optics for extremely large telescopes, Garching, 19.–21. February (talk); CHEOPS progress meeting, ETH Zürich, 6.–7. October (talk)

Huisken, F.: Royal Astronomical Society Meeting on Polyatomics and DIB's in diffuse interstellar clouds, Manchester, England, 8.–9. January (poster), Workshop »Nanotechnology: avenues of research and technological applications«, Lissabon, 14. April (invited talk, poster); International Conference on »Astrophysics of Dust«, Estes Park, Colorado, USA, 25.–30. May (poster), XX. International symposium on molecular beams, Lissabon, 8.–13. June (invited talk); Autumn school on materials science and electron microscopy, Berlin Adlershof, 27. September – 1. October (invited talk); Colloquium in honour of the 65th birthday of Prof. Dr. Udo Buck, MPI für Strömungsforschung, Göttingen, 24. October (invited talk); Physikalisches Kolloquium der Universität Duisburg, 5. November (invited talk)

Kautsch, S.: Jahrestagung der österreichischen Gesellschaft fuer Astronomie und Astrophysik Innsbruck 24. – 25. April (poster); Astrophysics Conference: Star and structure formation: from first light to the Milky Way, ETH Zürich, 18.–23. August (poster)

Kniazev, A.: AAS meeting, Seattle, January (poster); SDSS collaboration meeting, Flagstaff, 10.–12. April (talk); SDSS collaboration meeting, Fermilab, Chicago, 2.-4. October (invited talk)

Köhler, R.: IAU Colloquium 191 »The environment and evolution of binary and multiple stars«, Merida/Mexiko, 1.– 9. February (talk); Towards other Earths: DARWIN, TPF and the search for extrasolar terrestrial planets, April 22-25, Heidelberg; Astronomisches Kolloquium, Jena, 29. July (invited talk); Ringberg Workshop on Long baseline interferometry, 1.– 5. September; Workshop on Science with AO, ESO/Garching, 15.–20. September (talk); AG-Tagung, Splinter-Meeting »Star and planet formation – the role of binaries and angular momentum«, Freiburg, 18. September (invited talk); Workshop »Spectroscopically and spatially resolving the components of close binary stars«, Dubrovnik/Kroation, 18.– 25. October (invited talk)

Krause, O.: Joint European and National Astronomical Meeting, Budapest (poster); 25th General Assembly of the IAU, Sydney (talk, poster)

Launhardt, R.: IAU Symposium 221: Star formation at high angular resolution, Sydney, 22-25 July (invited talk, poster)

Lee, H.: 201st meeting of the AAS, Seattle, USA, January (poster); Carnegie Observatories centennial symposium IV: Origin and evolution of the elements (poster)

Leinert, Ch.: DARWIN Conference, Heidelberg, April; IAU Symposium 221 »Star formation at high angular resolution, Sydney, Australien, July (invited talk); Astronomisches Kolloquium »Optische Interferometrie«, Bonn, October (invited talk); Jahrestagung der Astronomische Gesellschaft, Freiburg, September (invited talk).

Lemke, D.: Jahrestagung der Astronomische Gesellschaft, Freiburg, September (invited talk)

Lenzen, R.: ESO Workshop on science with adaptive optics, München, 16.–19. September (invited talk, poster); Carl von Ossietzky-Universität Oldenburg, 14. July (invited talk)

Maier, Ch.: Multiwavelength cosmology conference, Mykonos Island, Greece, June (poster); Workshop »The formation and early evolution of galaxies«, Irsee, July, (talk); Tagung der ETH Zürich »Star and structure formation: from first stars to the Milky Way« (talk)

Marien, K.-H.: SPIEs 48th annual meeting, San Diego, 3-8 August (poster)

Martinez-Delgado, D.: Meeting »Satellites and tidal streams«, La Palma, 26-30 May (talk); Meeting »How does the Galaxy work?«, Granada, 23-27 June (invited talk); Stellar population conference, 5-10. October, Garching (poster)

Masciardi, E.: IAP Congress on extra-solar planets, Paris, 30. June – 4. July (poster); ESO Workshop on Science with the AO, Garching, 16.-19. September (poster)

Meisenheimer, K.: Colloquium talk in Groningen, 7. April; SFB 439 Workshop »Formation and early evolution of galaxies«, Kloster Irsee, 30. June – 4. July (review talk); Ringberg meeting on interferometry, 1. September (invited talk); AG-Splinter meeting, Freiburg 16. September (invited talk)

Pascucci, I.: DARWIN Conference, Heidelberg, 22.-25. April (Poster); IAU Symposium No. 221: Star formation at high angular resolution, Darling Harbor, Sydney, 22.–25. July (poster); Ringberg Symposium on Long baseline interferometry in the mid-infrared, 1.–5. September (two talks)

Ragazzoni, R.: Società Astronomica Italiana Trieste, XLVII Congresso Nazionale SAI, Trieste, 14.–17. April (talk); 2nd Baeckaskog workshop on exteremely large telescopes, Baeckaskog Castle, Sweden, 9.–11. September (invited talk, a second talk, two posters); SPIE International Symposium »Optical science and technology«, SPIE's 48th annual meeting, San Diego, California, 3.–8. August (talk); EMBO Workshop on advanced light microscopy 3rd international meeting of the European Light Microscopy Initiative (ELMI) Barcelona, 11-13 June (invited talk); IAU XXV General Assembly, Sydney, July, Joint Discussion 08, Large telescopes and virtual observatory – visions for the future (invited talk)

Ratzka, Th.: DARWIN Conference, Heidelberg, 22.-25. April; Jahrestagung der AG, Splinter-Meeting »Star and planet formation – the role of binaries and angular momentum«, Freiburg, 16.–19. September (talk)

Rix, H.-W.: Seminar on Theoretical Physics, Universität Heidelberg, 13. January (invited talk); Physikalisches Kolloquium der Universität Göttingen, 3. February (invited talk); Astrophysics colloquium at University of Colorado, Boulder, 7. April (invited talk); Colloquium at UC Santa Cruz, USA, 9. April (invited talk); Vatican Summer School at Vatican Observatory, Castel Gandolfo, 30. June – 7. July (six lectures); Kolloquium über Teilchen- und Astrophysik, Universität Heidelberg, 21. July (invited talk); ETH-Konferenz, Zurich, 21. August (invited talk); Astronomy seminar at Cambridge University (UK), 3. September (invited talk); ESO-USM-MPE Workshop on Multiwavelength Mapping of Galaxy Formation and Evolution, Venice, 14. October (invited talk); Workshop »Astronomie mit Großgeräten«, AIP Potsdam, 17. (invited talk); Observatoire de Strasbourg, 21. November, Seminar talk

Rodmann, J.: Workshop »Planet formation: The solar system and extrasolar planets«, Weimar, February (poster); Conference »Toward Other Earths: DARWIN/TPF and the search for extrasolar planets«, Heidelberg, 22.–25. April (poster); PLANETS Network meeting and School »Introduction into the formation of planetary systems«, Heidelberg, October; Summerschool, »Extrasolar planets and brown dwarfs«, Santiago, 15.–19. December (Poster)

Röser, H.-J.: Carnegie Observatories Centennial Symposium »Clusters of galaxies: probes of cosmological structure and galaxy evolution«, Pasadena, 27.–31. January (Poster)

Schartmann. M.: International Summer School »Black holes in the Universe«, Cargese (Corsica), 12.–24. May; Ringberg Workshop »Long baseline interferometry in the mid-infrared«, 1.–5. September (talk)

Schütz, O.: Conference »Toward other Earths: DARWIN/TPF and the search for extrasolar planets«, Heidelberg, 22.–25. April; ESO Workshop »High resolution infrared spectroscopy in astronomy«, Garching, 18.–21. November; ESO Seminar talk, Santiago, 4. August: »Extrasolar planets«

Setiawan, J. Jahrestagung der AG, Freiburg, 15.–19. September (talk); Tagung »Spectroscopically and spatially resolving the components of close binary stars«, Dubrovnik, 20.–24. October (poster)

Staicu, A.: XX International Symposium on molecular beams, Lissabon, 8.–.13 June (poster); 7th International Conference ROMOPTO 2003 on Optics, Constanta, Romania, September 8-11 (poster)

Steinacker, J.: Workshop »Formation of planets: the solar system and extrasolar planets« Weimar, February (talk); Conference »Toward other Earths: DARWIN/TPF and the search for extrasolar planets«, Heidelberg, 22.-25. April (talk); Workshop »Planetary formation: toward a new scenario« Marseille, June (talk); Universität Jena, June: »The significance of radiation transfer for the theory of star and planet formation« (invited talk); XIXth IAP Colloquium »Extrasolar planets: today and tomorrow«, Paris, June (talk); JEMAN »New deal in European astronomy: trends and perspectives«, Budapest, August (talk); Ringberg Workshop »Long baseline interferometry in the mid-infrared«, September (talk); Jahrestagung der AG, Splinter meeting »Interferometry with large telescopes«, Freiburg, September (talk); Workshop »Numerical methods for multidimensional radiative transfer problems«, Heidelberg, September (talk); Universität Graz, December (invited talk)

Stickel, M.: IAU Symposium 216, Maps of the Cosmos, Sydney July 2003 (poster); IAU Symposium 217, Recycling intergalactic and interstellar matter, Sydney July 2003 (talk)

Sukhorukov, O.: Eighteenth Colloquium on high-resolution molecular spectroscopy, Dijon, 8.–12. September (poster)

Tóth, L.V.: New deal in European astronomy: trends and perspectives, August, Budapest. (talk)

Umbreit, S.: Workshop »Planetenbildung: Das Sonnensystem und extrasolare Planeten«, Weimar, 19.–21. February; Conference »Toward Other Earths: DARWIN/TPF and the search for extrasolar planets«, Heidelberg, 22.-25.

Public Talks

Leinert, Ch.: Volkssternwarte Bonn, October: »Optische Interferometrie«

Lemke, D.: Sternfreunde Nordenham, May: »Astronomie mit ISO«

Lenzen, R.: Heppenheim, 6. September: »NACO/VLT – From the First Idea to First Results«

Quetz, A. M.: Rüsselsheimer Sternfreunde e.V., Volkshochschule Rüsselsheim, February.: »Entstehung von Planetensystemen«; Volkssternwarte Darmstadt e.V., May: »Entstehung von Planetensystemen«; Freundeskreis Planetarium Mannheim e.V., Astronomie am Nachmittag, December.: »Entstehung von Planeten-systemen«

Rix, H.-W.: Rotary Club, Bensheim, March: »Wie das Universum interessant wurde«

Staude, J.: Annual meeting of the MPG, Hamburg, June: several school lectures

Further Activities at the Institute

In May, a Girl's Day was organized at the Institute, at which 53 schoolgirls aged from 11 und 16 had the opportunity to visit the technical and administrative departments of the MPIA.

In October, the Institute partecipated in the SWR Uni-Forum in organizing a School Day. About 70 Schoolboys and -girls from secondary schools had the occasion to partecipate in the scientific work done at the Institute.

In the course of the year, a total of 550 visitors in 17 groups were guided through the Institute (A.M. Quetz, S. Kellner u.a.)

At Calar Alto about 1800 visitors, about 75 % of which were spanish School classes and about 10 % members of public spanish organizations, were guided through the observatory.

J. Staude, assisted by A.M. Quetz, edited the 42. annual volume of the magazine Sterne und Weltraum.

Service in Comittees

Bailer-Jones, C.: Member of the GAIA Science Teams and the Senior Advisory Body to the ESA for the development of GAIA; Chairman of the GAIA Classification Working Group; Member of the Organizing Committee of IAU Commission 45 (Stellar Classification)

Böhnhardt, H.: Member of the ESA working group »ROSETTA science« and » ROSETTA dust modelling«

Feldt, M.: Member of the working group »Lessons Learned« of the ESO VLT Instrument PIs

Graser, U.: Technical co-ordinator for FrInGe ("Frontiers of Interferometry in Germany), member of the Board of the European Interferometry Initiative (EII), Chairman of the working groop »Advanced Instruments: Feasibility and pre-design studies« of the European Interferometry Joint Research Activity

Grebel, E.: Member of the SDSS Collaboration Council and the RAVE Executive Board

Gredel, R.: Member of the OPTICON working groop »Future of medium-sized telescopes«

Henning, Th.: Member of the Scientific and Technical Committee of ESO; member of the ESO Strategic Planning Group; member of the ESO-VLT Instrument Science Team for VISIR; member of the Astronomy Working Group der ESA; member of the SOFIA Science Steering Committee; member of the SOFIA Science Council; member of the European ALMA Board; chairman of the German Interferometry Centre FrInGe; member of the finding commission »Director ARI Heidelberg«; TAC HUBBLE Space Telescope; Referee of the Deutschen Forschungsgemeinschaft (DFG); member of the DLR referee commission »Extraterrestrische Grundlagenforschung«; vice chairman of the scientific oversight committee of the Kiepenheuer Institute for Solar Physics, Freiburg; Scientific Member of the ISOPHOT, MIDI (VLT) and HIFI (HERSCHEL) Instrument Teams; Co-Investigator of the infrared instruments FIFI-LS (SOFIA), PACS (HERSCHEL), MIRI (JWST), CHEOPS (VLT), PRIMA-DDL (VLTI); Member of the Deutsche Akademie der Naturforscher Leopoldina.

Leinert, Ch.: member of the ESO OPC panel, member of the ESO Science Demonstration Time Team, member of the IAU Working Group for Interferometry

Lemke, D.: Principal Investigator of the ISOPHOT consortium, Co-Investigator in the HERSCHEL-PACS- and the NGST-MIRI Consortium, member of the referee commission »Verbundforschung Astronomie«, MPIA-coordinator of the POE Network

Klaas, U.: Co-Investigator in the ISOPHOT consortium and the HERSCHEL-PACS consortium, member of the ISO Active Archive Phase Coordination Committee and the HERSCHEL Calibration Steering Group

Launhardt, R.: member of the board of the Scientific Ernst-Patzer Foundation

Lenzen, R.: member of the Phase-A Review Board for ESO Instrumentation HAWK-I

Rix, H.-W.: member of the scientific oversight committee and of the board of trustees of the Astrophysikalisches Institut Potsdam (AIP), member of the Scientific Advisory Board of the Astronomisches Rechen-Institut Heidelberg (ARI), member of the ESO Visiting Committee, member of the VLTI Steering Committee, member of the Board of OPTICON and of the Board of the Large Binocular Telescope Corporation (LBTC); Chairman of the Board of the Large Binocular Telescope Beteiligungsgesellschaft (LBTB)

Staude, J.: member of the panel of judges at the national contest »Jugend forscht«

Awards

Sebastian Jester obtained the Otto-Hahn Medal 2002 of the Max-Planck Society (awarded at the annual meeting 2003) for his scientific work on the physical conditions prevailing in the jets of radio galaxies and quasars.

Sebastian Egner obtained the Otto-Haxel Award of the Heidelberg University for his diploma thesis on »Optical turbulence estimation and emulation«. The prize is awarded for excellent diploma theses in Physics.

Publications

In Journals with Referee System:

Abazajian, K., J. K. Adelman-McCarthy, M. A. Agueros, S. S. Allam, S. F. Anderson, J. Annis, N. A. Bahcall, I. K. Baldry, S. Bastian, A. Berlind, M. Bernardi, M. R. Blanton, N. Blythe, J. J. Bochanski, Jr. , W. N. Boroski, H. Brewington, J. W. Briggs, J. Brinkmann, R. J. Brunner, T. Budavári, L. N. Carey, M. A. Carr, F. J. Castander, K. Chiu, M. J. Collinge, A. J. Connolly, K. R. Covey, I. Csabai, J. J. Dalcanton, S. Dodelson, M. Doi, F. Dong, D. J. Eisenstein, M. L. Evans, X. Fan, P. D. Feldman, D. P. Finkbeiner, S. D. Friedman, J. A. Frieman, M. Fukugita, R. R. Gal, B. Gillespie, K. Glazebrook, C. F. Gonzalez, J. Gray, E. K. Grebel, L. Grodnicki, J. E. Gunn, V. K. Gurbani, P. B. Hall, L. Hao, D. Harbeck, F. H. Harris, H. C. Harris, M. Harvanek, S. L. Hawley, T. M. Heckman, J. F. Helmboldt, J. S. Hendry, G. S. Hennessy, R. B. Hindsley, D. W. Hogg, D. J. Holmgren, J. A. Holtzman, L. Homer, L. Hui, S.-J. Ichikawa, T. Ichikawa, J. P. Inkmann, Z. Ivezic, S. Jester, D. E. Johnston, B. Jordan, W. P. Jordan, A. M. Jorgensen, M. Juric, G. Kauffmann, S. M. Kent, S. J. Kleinman, G. R. Knapp, A. Y. Kniazev, R. G. Kron, J. Krzesinski, P. Z. Kunszt, N. Kuropatkin, D. Q. Lamb, H. Lampeitl, B. E. Laubscher, B. C. Lee, R. F. Leger, N. Li, A. Lidz, H. Lin, Y.-S. Loh, D. C. Long, J. Loveday, R. H. Lupton, T. Malik, B. Margon, P. M. McGehee, T. A. McKay, A. Meiksin, G. A. Miknaitis, B. K. Moorthy, J. A. Munn, T. Murphy, R. Nakajima, V. K. Narayanan, T. Nash, E. H. Neilsen, Jr. , H. J. Newberg, P. R. Newman, R. C. Nichol, T. Nicinski, M. Nieto-Santisteban, A. Nitta, M. Odenkirchen, S. Okamura, J. P. Ostriker, R. Owen, N. Padmanabhan, J. Peoples, J. R. Pier, B. Pindor, A. C. Pope, T. R. Quinn, R. R. Rafikov, S. N. Raymond, G. T. Richards, M. W. Richmond, H.-W. Rix, C. M. Rockosi, J. Schaye, D. J. Schlegel, D. P. Schneider, J. Schroeder, R. Scranton, M. Sekiguchi, U. Seljak, G. Sergey, B. Sesar, E. Sheldon, K. Shimasaku, W. A. Siegmund, N. M. Silvestri, A. J. Sinisgalli, E. Sirko, J. A. Smith, V. Smolcic, S. A. Snedden, A. Stebbins, C. Steinhardt, G. Stinson, C. Stoughton, I. V. Strateva, M. A. Strauss, M. SubbaRao, A. S. Szalay, I. Szapudi, P. Szkody, L. Tasca, M. Tegmark, A. R. Thakar, C. Tremonti, D. L. Tucker, A. Uomoto, D. E. Vanden Berk, J. Vandenberg, M. S. Vogeley, W. Voges, N. P. Vogt, L. M. Walkowicz, D. H. Weinberg, A. A. West, S. D. M. White, B. C. Wilhite, B. Willman, Y. Xu, B. Yanny, J. Yarger, N. Yasuda, C.-W. Yip, D. R. Yocum, D. G. York, N. L. Zakamska, I. Zehavi, W. Zheng, S. Zibetti and D. B. Zucker: The first data release of the Sloan Digital Sky Survey. The Astronomical Journal 126, 2081-2086 (2003)

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Bacmann, A., B. Lefloch, C. Ceccarelli, J. Steinacker, A. Castets and L. Loinard: CO depletion and deuterium fractionation in prestellar cores. The Astrophysical Journal 585, L55-L58 (2003)

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Bell, E. F., D. H. McIntosh, N. Katz and M. D. Weinberg: The optical and near-infrared properties of galaxies. I. Luminosity and stellar mass functions. The Astrophysical Journal Supplement Series 149, 289-312 (2003)

Bell, E. F., D. H. McIntosh, N. Katz and M. D. Weinberg: A first estimate of the baryonic mass function of galaxies. The Astrophysical Journal 585, L117-L120 (2003)

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Burkert, A.: The origin of the correlation between the spin parameter and the baryon fraction of galactic disks. Astrophysics and Space Science 284, 697-700 (2003)

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