Max Planck Institute for Astronomy

Heidelberg-Königstuhl

Annual Report 2004

Max Planck Institute for Astronomy Annual Report 2004

MAX-PLANCK-GESELLSCHAFT

Cover Picture:

The active nucleus of the spiral galaxy NGC 1097 and its surroundings, imaged with the high-resolution infrared camera system NACO at the VLT. At a radius of about 2000 light-years more than 300 starforming regions (white dots in the figure) are surrounding the bright central source, which marks the position of the galactic nucleus. (See p. 58 – 63)

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Contents

Preface

This Annual Report 2004 provides an overview of the research activities at the Max Planck Institute for Astronomy (MPIA) in Heidelberg. It is intended for our colleagues worldwide as well as for the interested public.

Particularly interesting scientific results from the last year are featured as Highlights. They demonstrate the high discovery potential involved in the two research fields that are pursued at the Institute: *Planet and Star Formation* as well as *Galaxies and Cosmology*. This is not least due to new instruments that were built at the Institute or to which major contributions could be made in collaboration.

The construction of the Large Binocular Telescope (LBT) on Mount Graham in Arizona, in which the Institute is partecipating, is making good progress: in the year 2004, after the installation of the first mirror, we could celebrate in Arizona its official dedication. The same is true for the intrumentation 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 Telscope, the successor to HUBBLE, is equally well proceeding. Together with partners, we have just initiated the construction of the “Differential Delay Lines” for the Very Large Telescope Interferometer (VLTI) of the European Southern Observatory (ESO) in order to provide the instrumental capabilities for an astrometric search programme for extrasolar planets.

In addition to brief presentations of current scientific results, we report in more depth 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 showcase important events that took place at the Institute. At the same time, we let visiting scientists and staff members of the Institute get a word in, in order to draw a vivid picture of the working atmosphere at the Institute. Data presented in the last section will give an insight into the structure of the MPIA as well as into its publication activity.

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, May 2005

I General

I.1. Scientific Goals

Since it was established in 1967, the Max Planck Institute for Astronomy (Fig. I.1) is dedicated to the exploration of the universe in the optical and infrared spectral region. Apart from conceiving, conducting, analyzing and interpreting observing programs, MPIA is dealing with the development of telescopes and observing instruments, usually within large international collaborations.

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.

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

Star and Planet Formation

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 that 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 there is also a possibility 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 (see Chapter III.1). 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 Dwarfs had been discovered as late as 1995; meanwhile a little over one hundred are known.

Today, there are many questions: What is the exact mass of these objects? 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. 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 as well as molecules in the gaseous phase. Findings obtained here under controlled conditions can be used to interpret astronomical observations

Galaxies and Cosmology

The galaxies we observe in the pres ent-day universe indeed are magnificent "island universes", consisting of billions of stars as well as of gas, dust, and the mysterious dark matter. As Edwin Hubble already realized 70 years ago, galaxies do not show the variety of qualitative appearance and structure that seem physically possible. For one thing, galaxies as an object class span ten orders of magnitudes in their stellar masses, and the number of newly forming stars varies within the same range; the physical sizes of different galaxies vary at least within a factor of 100. While some galaxies do not have a perceptible black hole at their centers, in other galaxies this central black hole has the mass of more than one billion stars. But for another thing, results obtained particularly in the last years and decades have shown empirically that only a tiny fraction of the possible combinations of the characteristic quantities (stellar mass, stellar ages, size, central black hole etc) are actually realized in the universe. Virtually all quantities strongly correlate with all other quantities: massive galaxies are large; massive galaxies virtually do not contain young stars; the central black hole contains a constant mass fraction of the spherical star distribution that is ten million times its size. While spiral galaxies are the most common galaxy type, no such galaxy is among the most massive ones.

That means that the "realm of galaxies", as Hubble has called it, shows a high degree of order. How this order developed from the arbitrary fluctuations existing after the big bang is the fundamental question of galaxy formation and a central issue of cosmology.

Specific questions arising from this overall picture are, e.g.:

- During which cosmologic epoch did most of the stars form?
- Is cosmic star formation now coming to its end? Why has the star formation rate declined over the last six billion years?
- How did the central black holes in galaxies form and grow? Why is it possible today to predict the properties of the small-sized central black hole from the overall size of a galaxy?
- Which processes determine structure and morphology of galaxies and when does this happen?
- What is the state of the interstellar medium, the raw material from which new stars form?
- Can the various observations be understood ab initio within a comprehensive model?

The methods used at MPIA to tackle these questions comprise three aspects: the detailed study of galaxies in the present-day universe; the direct study of galaxies at earlier cosmic epochs by observing distant (high-redshift) objects; the comparison of observations with physical models.

With its observational capabilities, MPIA is able to enter new territory at the very frontier of our knowledge in this rapidly developing field.

I.2. Observatories, Telescopes, and Instruments

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. Since January 1st, 2004, the observatory is being operated on equal terms with the Spanish Consejo Superior de Investigaciones Cientìficas. 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.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 usually 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 is 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 aboard Iso, was built under the coordinating leadership of the Institute. From 1996 to 1998, Iso provided excellent data, particularly in the so far inaccessible far-infrared range. The know-how gained this way is now used by the Institute's scientists in newly started projects like the Herschel Space Telescope and the James Webb Space Telescope (JWST). At present, scientists at MPIA are actively participating in the US-American Spitzer Infrared Observatory with observing programs that involve a number of exciting discoveries. These include dusty belts around solar like, 1 to 3 billion year old main-sequence stars – similar to the Kuiper belt in our own solar systems about two billion years ago (Chapter II.2); or the proof that supernovae do not contribute significantly to the dust contents of the interstellar medium (as was wrongly claimed in the recent past, cf. Chapter II.3); or the detection of an infrared light echo emanating from the neutron star at the center of the Cas A supernova remnant: the neutron star that had formed during a supernova explosion in 1680 obviously suffered a major gamma-ray burst only 50 years ago that now passes through the dust in the more distant surroundings, heating it for a short time.

Today, the Institute is participating in a number 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 linked 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 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. At the same time the Institute is participating in studies for the instrumentation of next-generation large telescopes, the so-called Extremely Large Telescopes (ELTs).

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

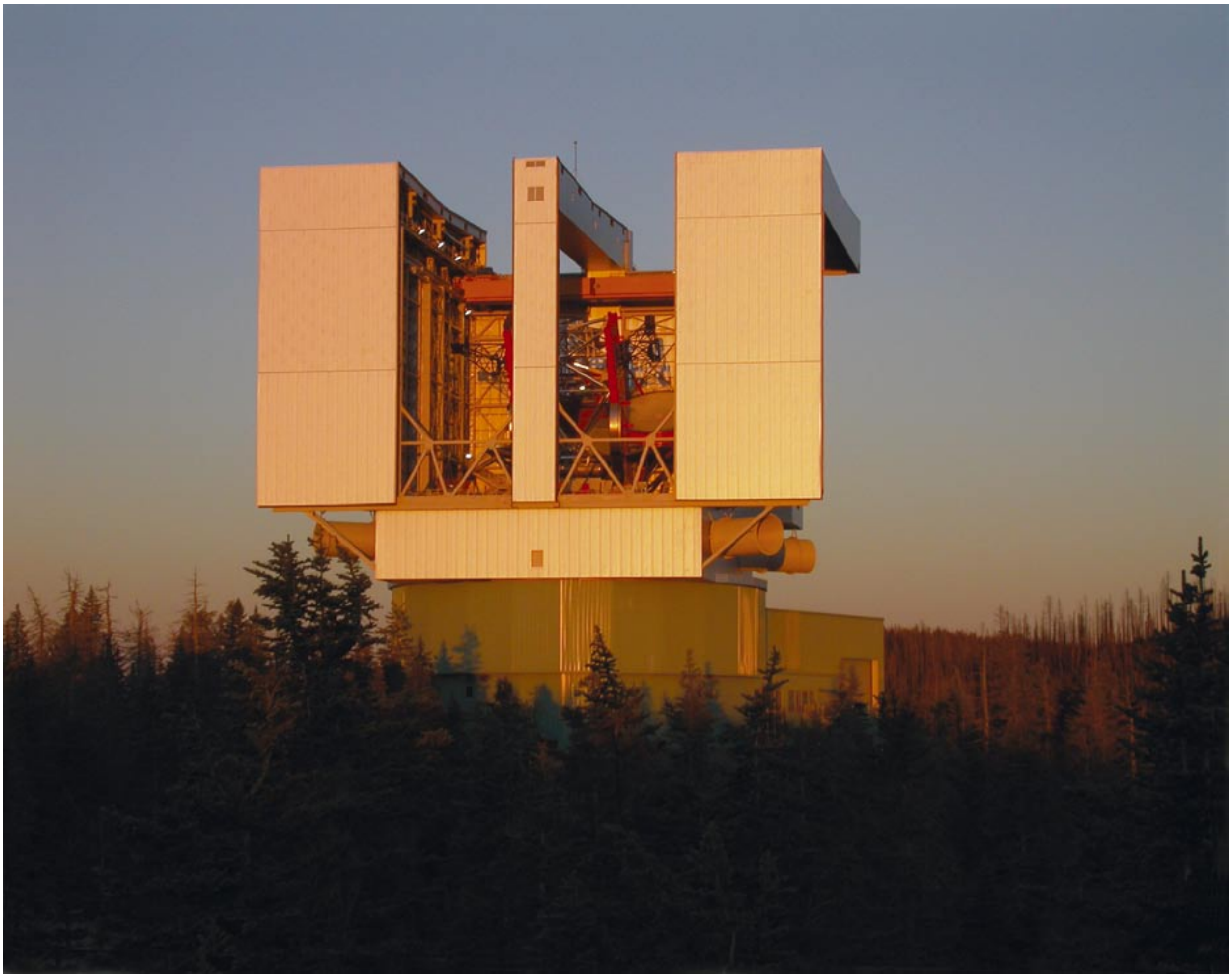


Fig. I.4: The Large Binocular Telescope.

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 is already being incorporated into the development of new instruments for the VLT and LBT (Chapter IV.1). In the adaptive-optics laboratory at MPIA, an experimental set-up of the novel PYRAMIR wavefront sensor has been advanced (Chapter IV.6).

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. It is the first interferometric instrument at the VLT and is used in the mid-infrared range. Meanwhile, this instrument allowed very successful interferometric observations in the mid-infrared with a resolution of only a few hundredths of an arcsecond.

Construction of a common Laser Guide Star Facility (LGSF) that will be used at the NACO and SINFONI instruments at the VLT, both of which are 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 of the total LGSF consisting of PARSEC, a special fiber optics, and the projection telescope took place in the first half of 2005. Installation on Paranal is slated for the fall of 2005.

At MPIA, the development of the second-generation VLT/VLTI instruments is already in the works. The Institute is participating in the PLANET FINDER project for searching and characterizing extrasolar planets using extreme adaptive optics and additional ancillary equipment. The CHEOPS project (Chapter IV.4) is also part of this complex. At the same time, MPIA, together with institutes in Geneva and Leiden, is developing the so-called differential delay lines for the PRIMA system intended for the astrometric search for extrasolar planets. Another project – in collaboration with the Observatoire de Nice – is APRÈS-MIDI, the extension of MIDI combining the light of the four main telescopes of the VLTI, thus allowing image reconstruction.

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 design of the double mirror will allow interferometric observations. In this mode, spatial resolution of the LBT will correspond to that of a single mirror 22.8 m in diameter. First "scientific" light with only one primary mirror is planned for the fall of 2005. One year later, the complete telescope should be put into operation.

Under the leadership of the Landessternwarte Heidelberg, the German partners are building the LUCIFER near-infrared spectrograph for the LBT (Chapter IV.2). 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. At the same time, 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 LINC beam combiner (Chapter IV.1), 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 Astronomy – Instrumentation

Today, MPIA is still participating significantly in the ISO project of the European Space Agency ESA: ISOPHOT, one of four scientific instruments aboard 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.

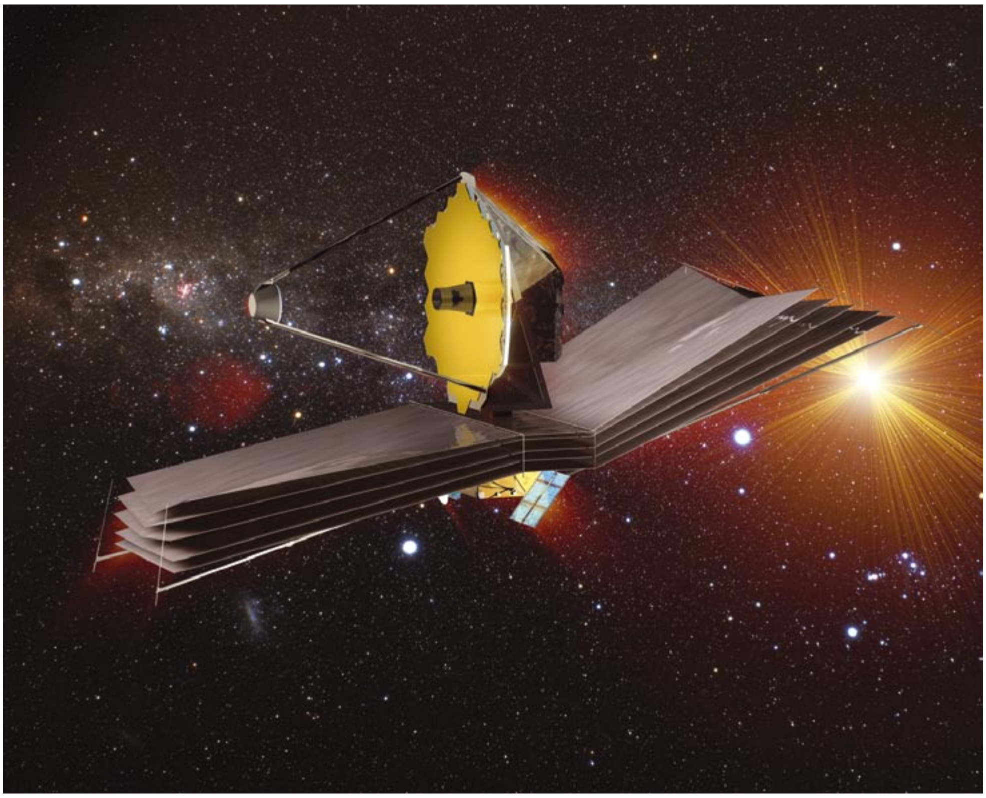


Fig. I.5: Possible design of the JWST, with the large primary mirror and the characteristic solar screen.

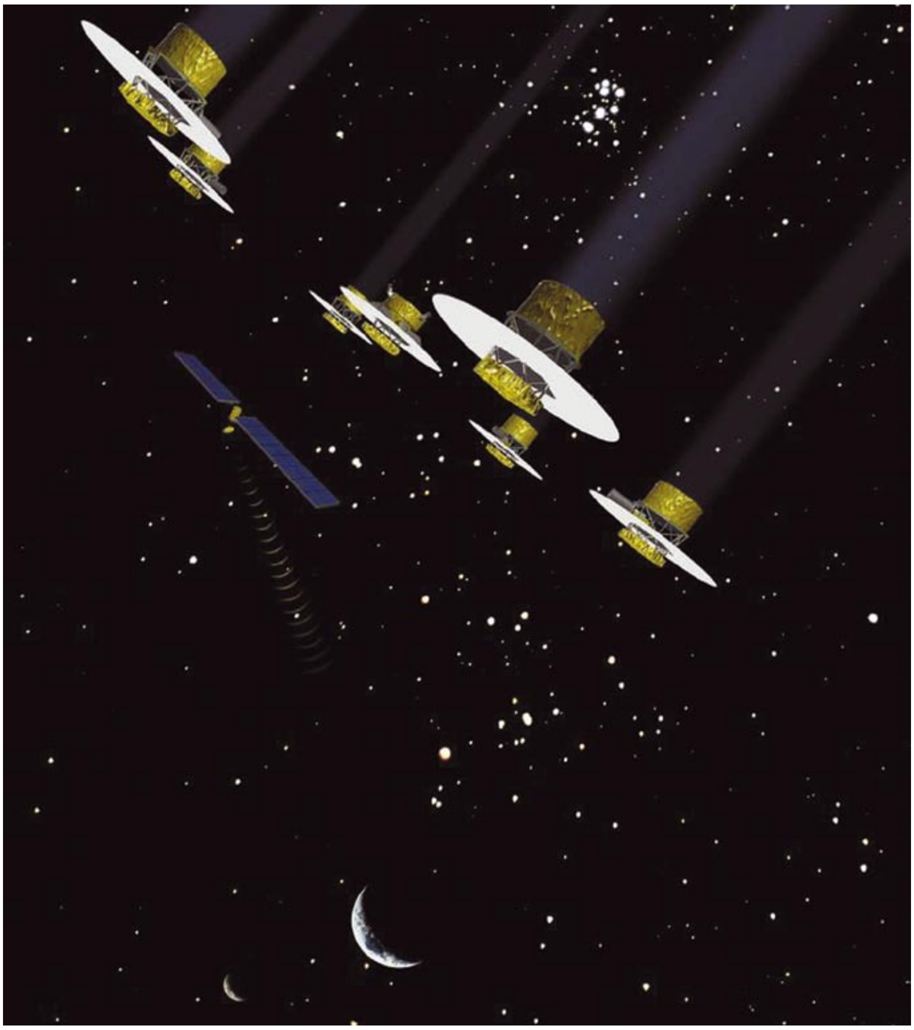


Fig. I.6: Possible concept of the DARWIN space interferometer consisting of six free-flying individual telescopes.

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 aboard the European HERSCHEL 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. A 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 six telescopes orbiting the sun at the Lagrangian point L2 in 1.5 million kilometer 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

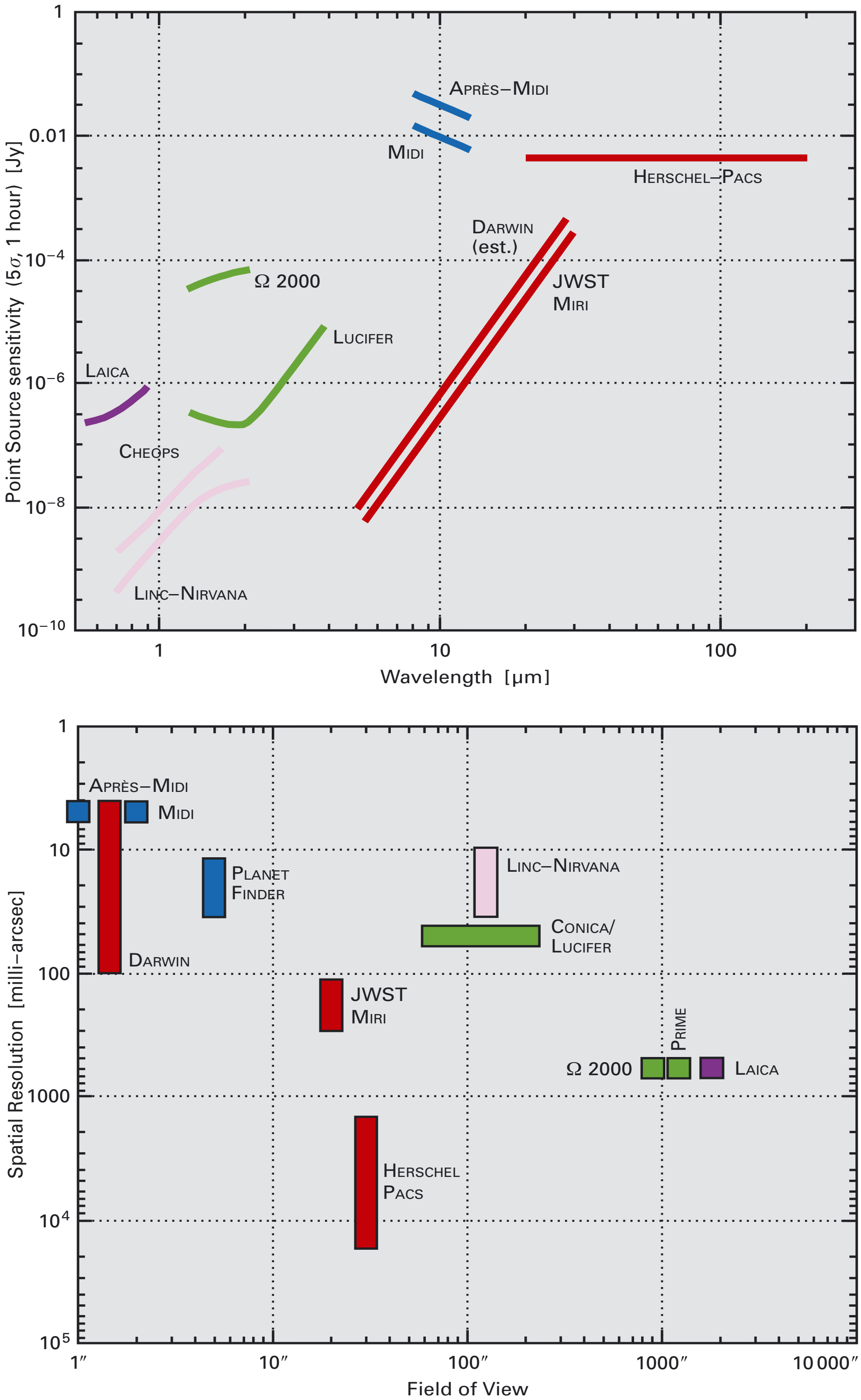


Fig. I.7: The Institute's major instruments. *Above:* sensitivity as a function of wavelength; *below:* spatial resolution as a function of the field of view.

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. Sensitivity is shown as a function of wavelength (above), and spatial resolution as a function of the size of the field of view (below).

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 Institute for Theoretical Astrophysics of the University or the department Cosmophysics of the MPI for Nuclear Physics 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 for extraterrestrial Physics in Garching and the MPI for Radio Astronomy in Bonn as well as with numerous German institutes 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 design of APRÈS-MIDI – an extension of MIDI to an imaging interferometer using 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. Physikalisches Institut der Universität zu Köln.

MPIA is participating in a number of EU networks and worldwide collaborations, partly in a leading position. These include:

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.

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.

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

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.1).

OPTICON is also supporting a so-called Joint Research Activity (JRA) of the Max Planck Institute for Astronomy 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.

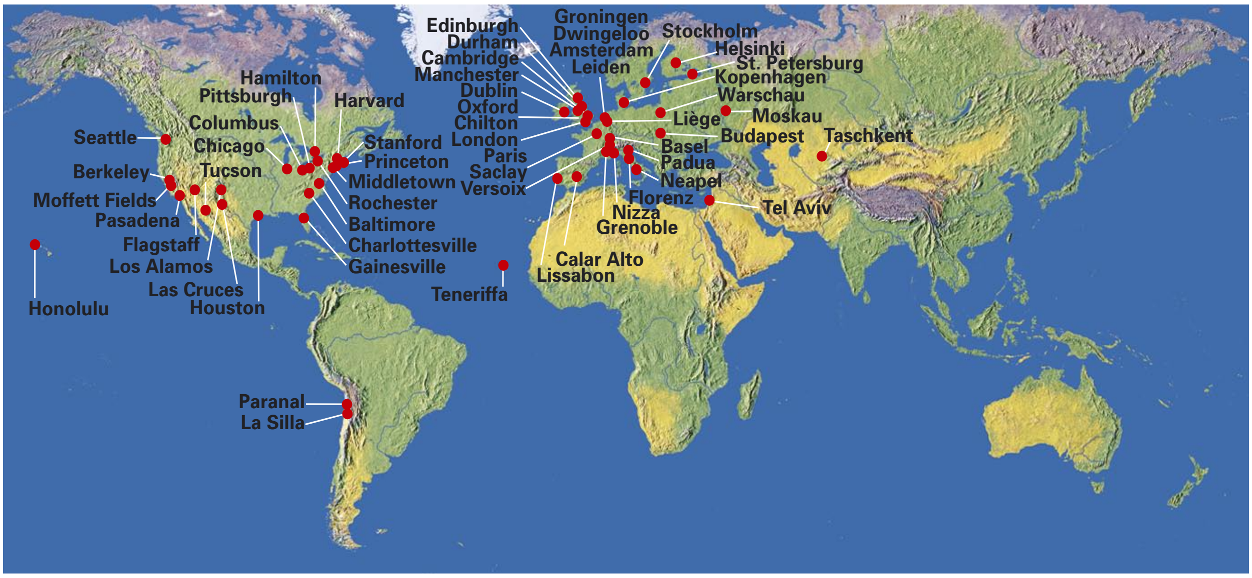


Fig. I.9: Diststribution of the international partner institutes of MPIA.

Together with the universities of Braunschweig, Chemnitz, Dresden, Jena, and Leiden, MPIA is participating in the DFG Research Group „Laboratory Astrophysics". This field of research is being pursued at the MPIA branch in Jena.

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 FEPS: The NASA infrared telescope SPITZER (formerly SIRTF) has started its planned 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 a program to study the evolution from protoplanetary disks to planetary systems.

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. 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 Max Planck Institute for Astronomy in Heidelberg is the University of Tel Aviv, Israel. Moreover, a wide field camera for the Wise Observatory is being built that will be used to search for planet transits.

The Sloan Digital Sky Survey (SDSS): At the international level, participation in this project is of major importance. It 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, Max Planck Institute for Astronomy in Heidelberg and the Max Planck Institute for 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.

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. Also staff members of our branch in Jena have teaching duties at the Jena University. 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. And the experiment "Stellar CCD photometry" is offered at the Institute's 70 cm telescope on the Königstuhl.

In July, 2004, the Max Planck Society and the University of Heidelberg established a common "International Max Planck Research School for Astronomy and Cosmic Physics". In the beginning, the school will offer a three year education under excellent conditions in experimental and theoretical research in the field of astronomy and cosmic physics to 40 PhD students from all over the world. It is sponsored by the five institutes doing astronomical research in Heidelberg.

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. In cooperation with the Landessternwarte, 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 the Königstuhl.

At the invitation of the Klaus Tschira Foundation, MPIA and all other astronomical institutes in Heidelberg participated in a symposium on "The Planets of the Sun and Distant Stars – Astronomy Meets Earth Sciences". The symposium took place on October 26th in the studio of the Villa Bosch. In addition to scientific subjects, scientists, journalists and media experts were discussing the optimum way of imparting scientific results to the general public.

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

In cooperation with the Academy of Advanced Training of Teachers of the Land Baden-Württemberg at Donaueschingen, and with the support of the Klaus Tschira Foundation, a school project has been initiated in the year under report with the following intentions: For selected articles published in SuW, detailed didactic materials will be developed each month and made freely available in the internet. In their regular physics lessons, teachers and students will thus be able to deal with current research issues presented in generally comprehensible terms in SuW. Teachers and students nationwide showed great interest in this project.

II Highlights

II.1 Dust Growth in Protoplanetary Disks

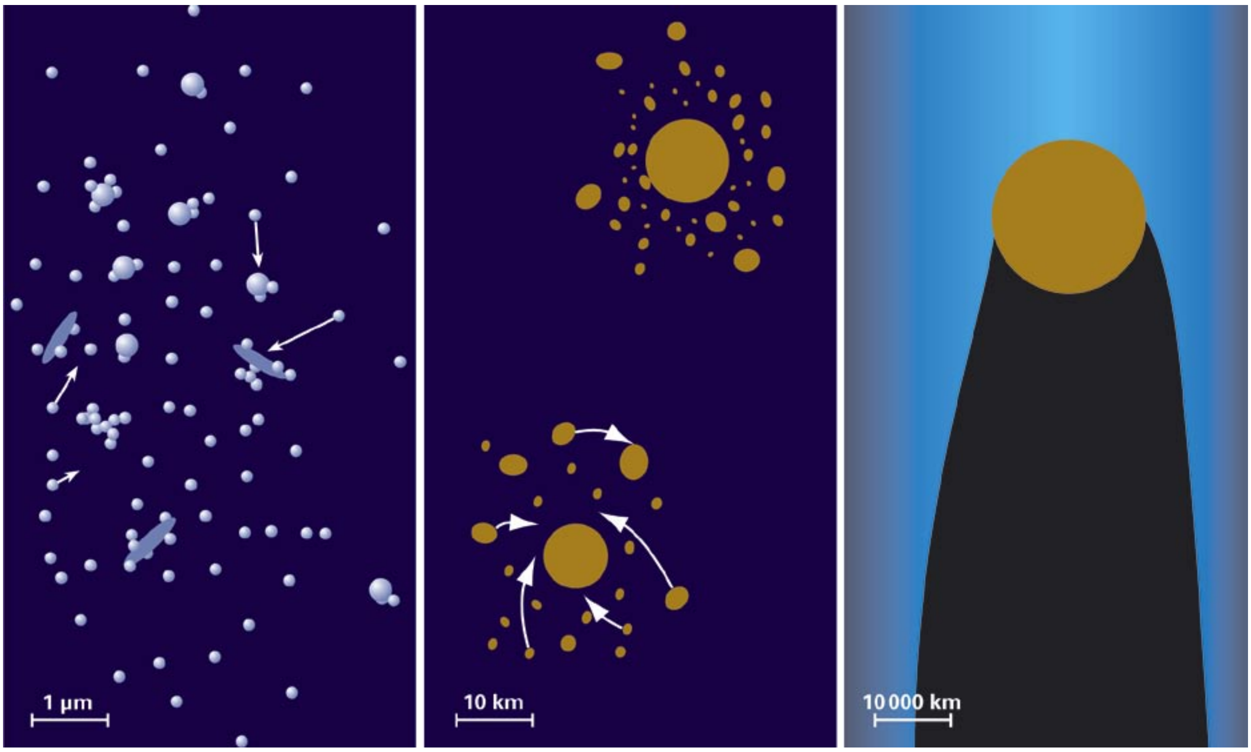
Protoplanetary disks are formed from interstellar-cloud material. Thus initially the dust particles are even smaller than a micrometer. They then grow by coagulation to form grains some millimeters or centimeters across – this being the first stage of planet formation. However, so far there is only very few convincing evidence for the existence of particles of this size. But recently a German-American team led by MPIA observed several young stars in the Taurus-Auriga star formation region using the Very Large Array (VLA) and their data demonstrate that millimeter-sized particles are forming already within one million years.

Astronomical observations have shown that the infrared emission of protoplanetary disks is decreasing significantly within a period of about ten million years (cf. Chapter II.2). The reason for this is not known unequivocally: Either the dust disappears from the system, or the particles grow to form small grains that no longer emit so intensely in the infrared region (Fig. II.2.1).

In order to detect millimeter- or centimeter-sized dust particles it is necessary to observe at larger wavelengths that are of the same order of magnitude than the particles themselves. But here, too, the observational results are still ambiguous when the disks are spatially unresolved: optically thick dusty disks with very small particles cannot be distinguished from optically thin disks with larger particles. This ambiguity can only be resolved with the help of high-resolution observations in the millimeter- and sub-millimeter regime.

Since recently, such observations are possible thanks to technical upgrades of the Very Large Array at Socorro, New Mexico. In the year under report, astronomers at MPIA and colleagues from the USA observed 14 low-mass pre-main sequence stars (so-called T Tauri stars) at a wavelength of 7 mm. They are located in the Taurus-

Fig. II.1.1: Three stages of planet formation. *Left*: The coagulation of dust particles up to diameters of some micrometers. *Middle*: Further growth of the particles to the size of planetesimals under the influence of gravity. *Right*: Coagulation of planetesimals to form planets that accrete gas from their environs, thereby building up an atmosphere.



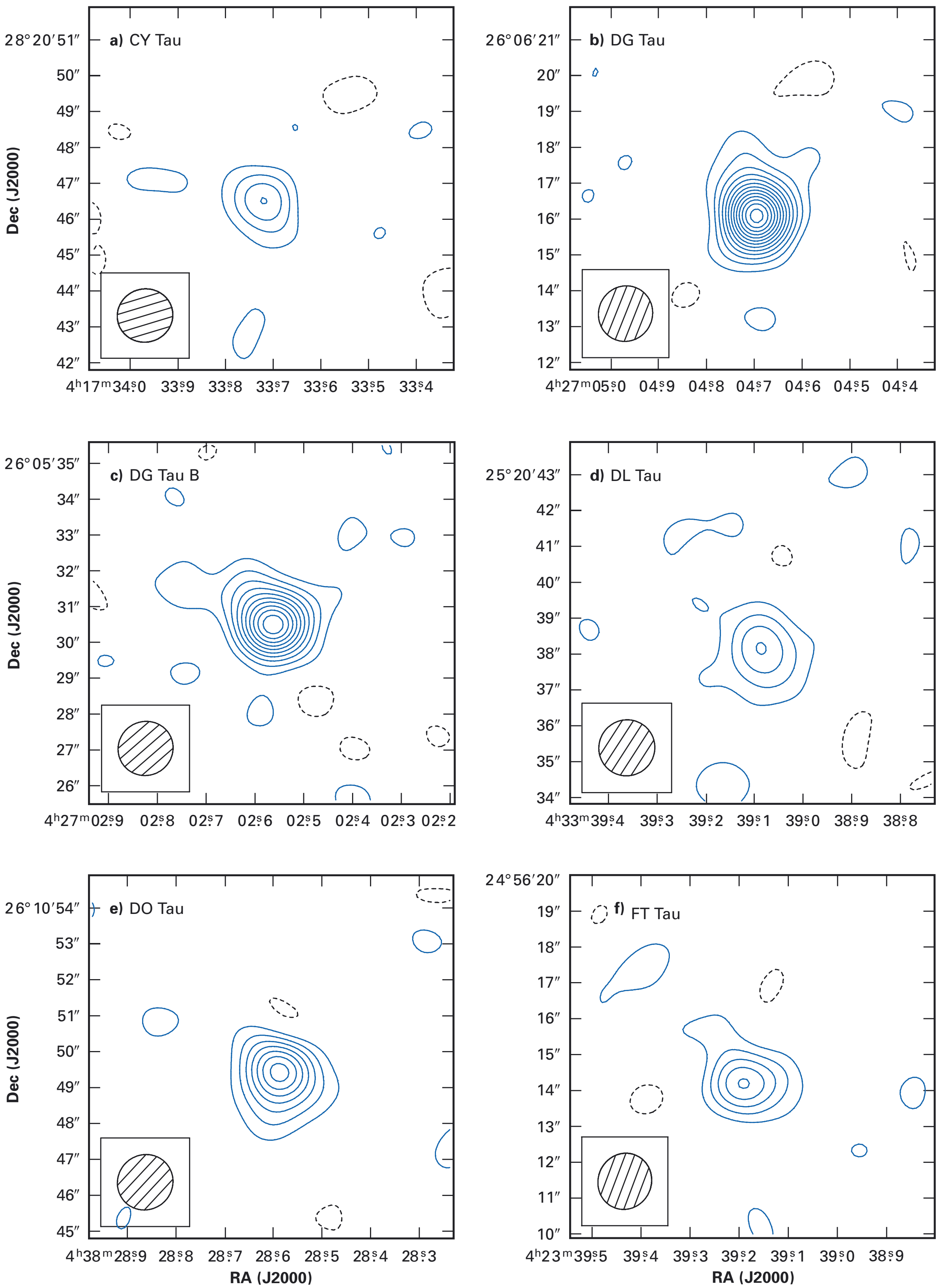
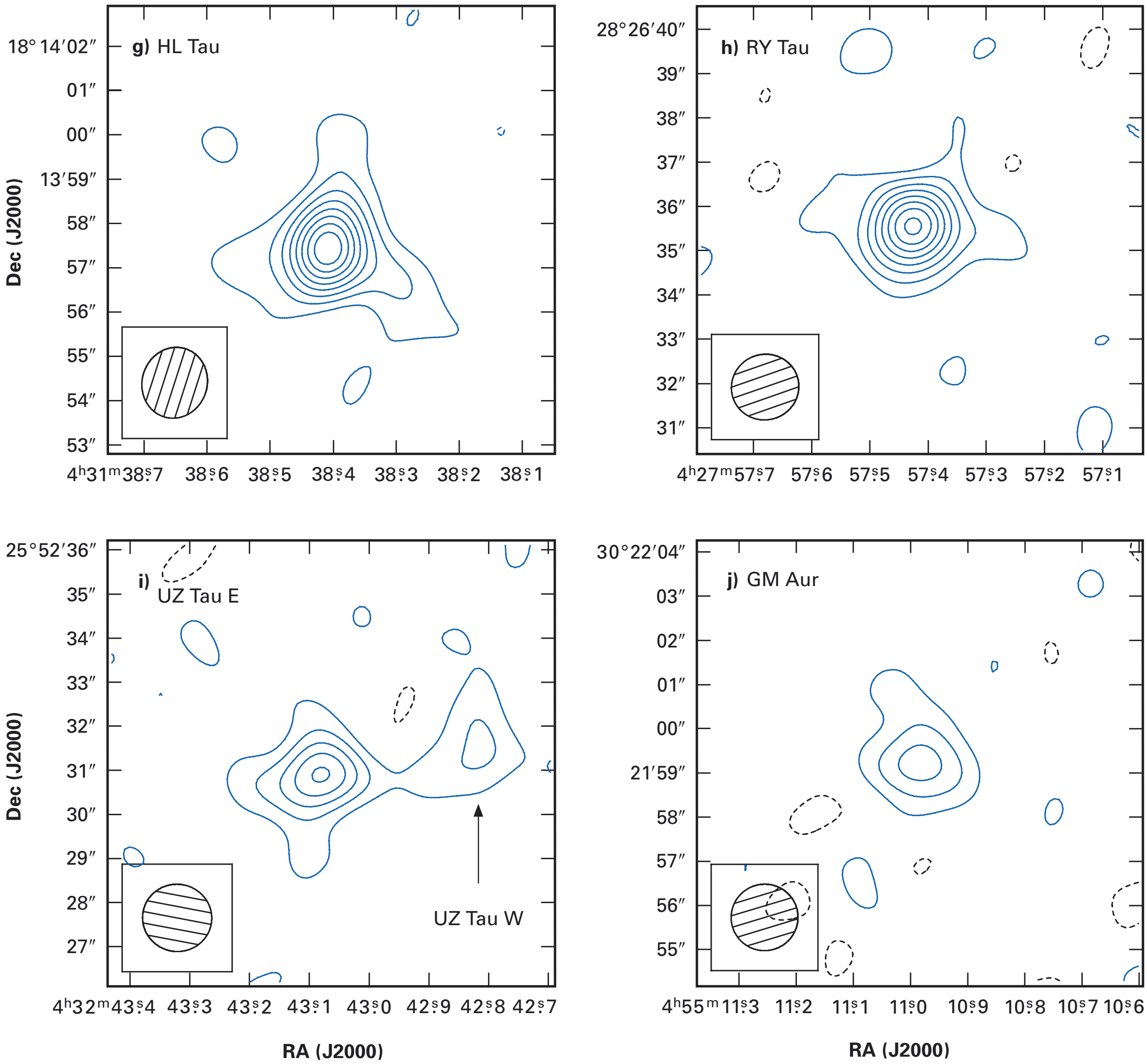


Fig. II.1.2: Ten T Tauri stars whose disks could be spatially resolved at a wavelength of 7 mm.



Auriga complex at a distance of 140 pc (460 light years), their ages ranging between 100 000 and 3 million years. 13 stars from this group have masses between 0.5 and 0.7 solar masses; only one star (RY Tau) is significantly more massive, having 1.7 solar masses. In all 14 stars emission at 7 mm wavelength was detected; in ten of them the disks even could be spatially resolved, as it was hoped for. Their sizes range from 100 to 200 AU (Fig. II.1.2).

Before the data could be interpreted, however, an interfering effect had to be considered: T Tauri stars exhibit strong stellar winds generating bremsstrahlung in their environs. Although this radiation occurs mainly at wavelengths in the cm-regime, it also contributes to the millimeter emission thereby interfering with the emission of the dust. In order to determine the percentage of this contribution, five objects were observed additionally at the longer wavelengths of 1.3, 2.0, and 3.6 cm; in four of them the bremsstrahlung was detected. It was shown to contribute an average of about 60 percent to the millimeter emission. This fraction was allowed for in the subsequent data analysis and interpretation.

To start with, given the size of the disks, the 7-mm-emission can be assumed to be essentially optically thin. Only a small fraction from the optically thick inner region of the disk adds to this. The emission measured at 7 mm and further observations in the millimeter regime were used to determine the spectral energy distribution of the circumstellar disk. From its shape the so-called opacity index could be established (Fig. II.1.3), which is a measure of the size of the particles. For interstellar particles of sizes in the submicrometer range its value is about 2; for very large bodies absorbing almost all of the light it decreases to 0.

For almost all objects observed the opacity indices turned out to be smaller than 2; for half of these ob-

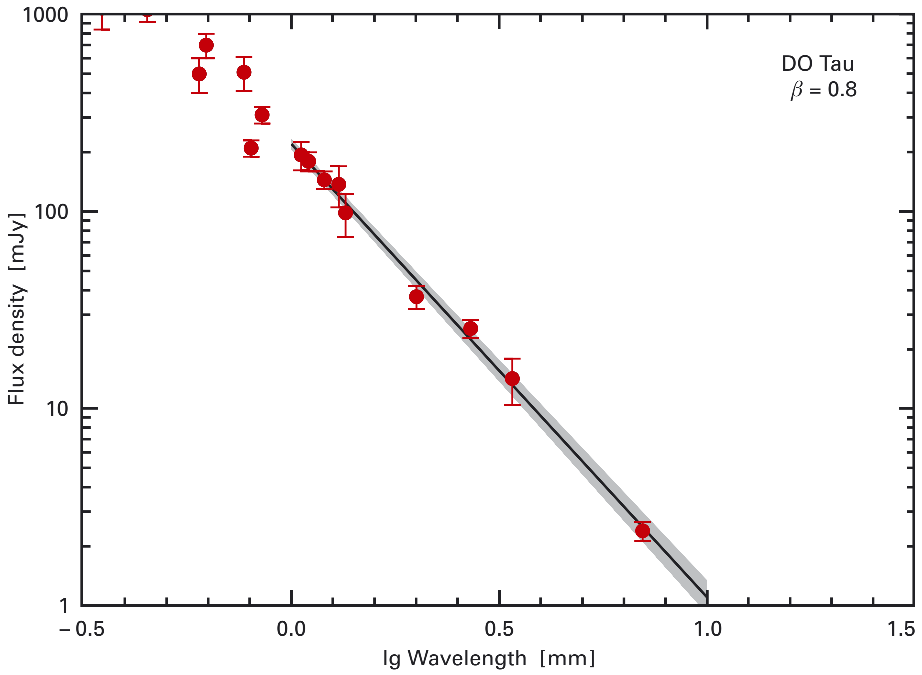


Fig. II.1.3: Spectral energy distribution of the T Tauri star DO Tau. From the slope of the curve an opacity index of about 0.8 was determined.

jects the values indicate the presence of particles in the millimeter-size range. So there is clear evidence for the growth of dust particles in protoplanetary disks around T Tauri stars.

The study of the particle size is an important step towards an understanding of the formation of planetesimals. These chunks about 10 kilometers in diameter are providing the "building blocks" for the formation of large planetary bodies. How the sub-micrometer sized dust particles manage to grow relatively fast to such dimensions is unclear yet. With observations, model calculations and laboratory experiments, MPIA is actively partaking in the exploration of this question.

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II.2 The Evolution of Protoplanetary Disks – Observed with the SPITZER Space Telescope

During their formation phase, most solar like stars are surrounded by dusty disks – this is now considered a well established fact. At least in some of those disks also planets will form eventually, as is demonstrated by our solar system and more than 130 extrasolar planets discovered since 1995. However, many questions about the growth of planets from the tiny dust grains within circumstellar disks are still open. Since recently, the US-American SPITZER Space Telescope (Fig. II.2.1 and II.2.2) allows to observe such objects in the far infrared regime. SPITZER is used to conduct the Legacy Science Program of Formation and Evolution of Planetary Systems in which astronomers at MPIA are partaking. First results show the disks to dissolve within ten million years. But in older stars, too, dust is present, presumably contained within a kind of Kuiper belt.

According to present notions the formation of planets takes place in several stages. At first, dust and gas in the protoplanetary disk are mixed. The solid particles then grow by colliding and sticking together. This way, the particles get heavier and heavier and gravitationally sink towards the center plane of the system where they form a comparatively thin dusty disk. Since the dust density increases by this process the particles now collide more often and evolve into planetesimals several kilometers in diameter. These bodies are then able to merge gravitationally to form planets.

When a large planet has formed in the outer regions of the dusty disk it continues to accrete gas from its environs, thereby surrounding itself with a huge atmosphere. Computer simulations show how a large planet sweeps up all the disk material along its orbit, thus creating a

Fig. II.2.1: The SPITZER Infrared Telescope in April 2003 during its integration into the launch vehicle.

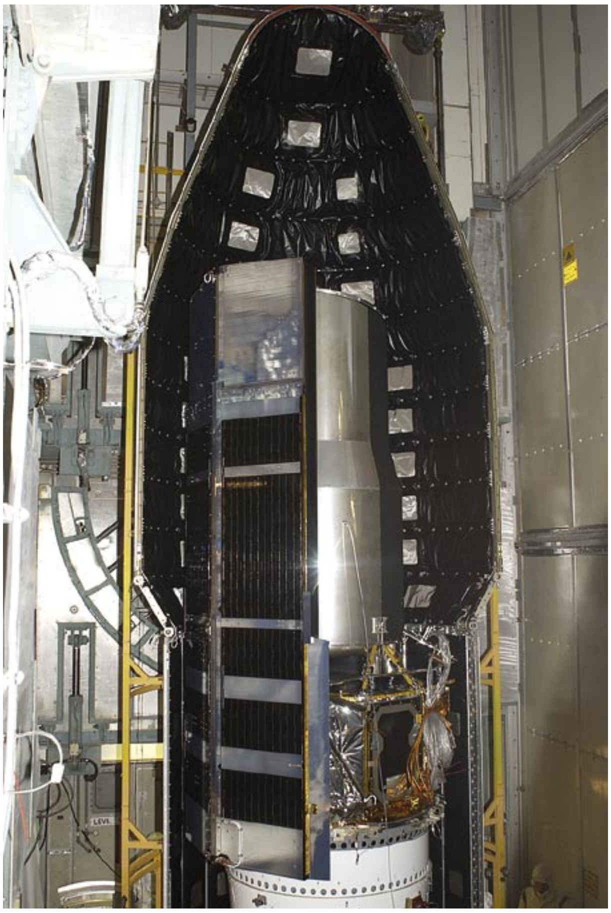


Fig. II.2.2: Cape Canaveral on August 25th, 2003: Launch of the SPITZER Infrared Telescope on a Delta 7920 H.

ring-like gap. Gas giants such as Jupiter and Saturn probably have formed this way.

However, even older systems like our own solar system still contain substantial amounts of dust, which is continuously supplied by collisions of planetoids. A thin dusty disk in the inner solar system makes itself conspicuous by scattering sunlight that can be seen as zodiacal light in the sky.

So far, the possibilities to observationally verify the evolutionary stages described above are very limited. The main problem is the central star outshining the disk. Therefore many questions are still disputed, e.g. for how long the disks exist and on which time scales the planets form.

These questions will purposefully be studied within one of the six "Legacy Science Programs" using the US-American SPITZER Space Telescope launched in August 2003. These programs offer the opportunity to tackle particular problems systematically and with great effort, the telescope being available for them usually for a hundred hours and more.

Within the program "The Formation and Evolution of Planetary Systems: Placing Our Solar System in Context", 330 stars of spectral types F8V to K3V and ages ranging from about 3 million to 3 billion years will be observed. This will be done with three imaging and spectroscopic instruments aboard SPITZER working at wavelengths from 3 to 160 µm.

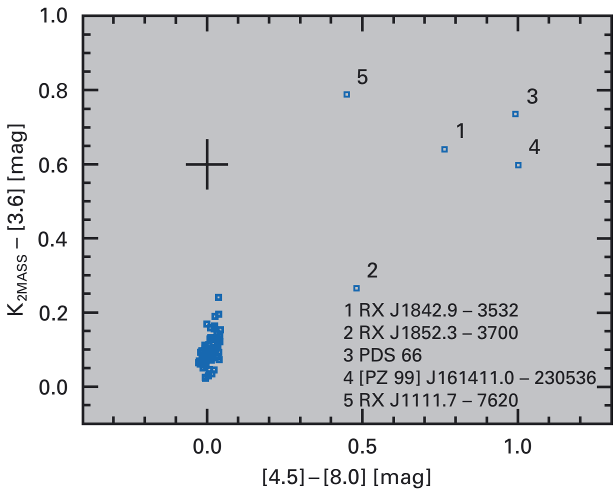


Fig. II.2.3: Color diagram of the stars studied. K_{2MASS} denotes data from the infrared survey at a wavelength of 2 µm. The five stars surrounded by dusty disks stand out by their strong emission at 3.6 and 8.0 µm.

Young Stars with Dusty Disks

How large is the fraction of young stars with protoplanetary disk, and for how long do these disks exist? These questions are being investigated by astronomers at MPIA and their colleagues in the USA. For this purpose, they selected a group of 74 stars with masses ranging from 0.8 to 1.2 solar masses and distances between 125 and 550 light years, which are not older than 30 million years. More precisely: 29 stars are 3 to 10 million years and 45 are 10 to 30 million years old. So with a certain scatter in mass, this group represents the evolution of our young sun.

For these stars, photometric data from the Infrared Array Camera (IRAC) in the wavelength range from 3.6 to 8.0 µm are available. Hot dust in the inner zones of a potential dusty disk within about 3 AU distance to the star will emit in this spectral range. As is shown in Fig. II.2.3, five stars of this group exhibit an increased infrared emission indicating a dusty disk. Fig. II.2.4 shows a plot of the spectral energy distribution in which additional data of the IRAS and ISO infrared satellites as well as from (sub-)millimeter telescopes have been incorporated.

Interestingly, four out of the five stars belong to the young group (3 to 10 million years old) and only one to the older group (10 to 30 million years). So the fraction of stars with disks decreases from 14 % to 2 %. Other studies had reached similar results, stating that the relative proportion of disks in 1 million year old stars is over 80 % while in stars 5 to 10 million years old it is only 10 %.

Despite the poor statistics, this finding supports the theory according to which the fine dust has almost disappeared after ten million years. This effect can be specified in yet another way. Due to its high sensitivity, the IRAC camera aboard SPITZER would be able to even detect dust with a total mass of about 10^{-10} solar masses at a distance typical for this group of stars. For comparison: sub-millimeter observations have shown that solar like stars with ages of a few million years are surrounded by $^1/_{1000}$ to $^1/_{10}$ solar masses of dust. This, too, indicates the disappearance of the bulk of the disk within the first ten million years.

However, this interpretation should be considered with care since there might be large amounts of cool dust in the outskirts of the disks emitting beyond the maximum wavelength of 8 µm. Nevertheless it is quite obvious that the disks are dissolving rather quickly. How do these findings fit into the theories of the formation of our solar system?

According to some models, planetesimals up to one kilometer across can form within a period of one million years in dense disks. When colliding, these bodies destroy each other due to the high relative velocities, thereby releasing large amounts of fine dust which emits infrared radiation in the near vicinity of the star. There is no way to judge whether this "second generation of dust" or still the original material has been observed by SPITZER. Additional observations of stars of the age class up to about 100 million years are needed to obtain further information on this.

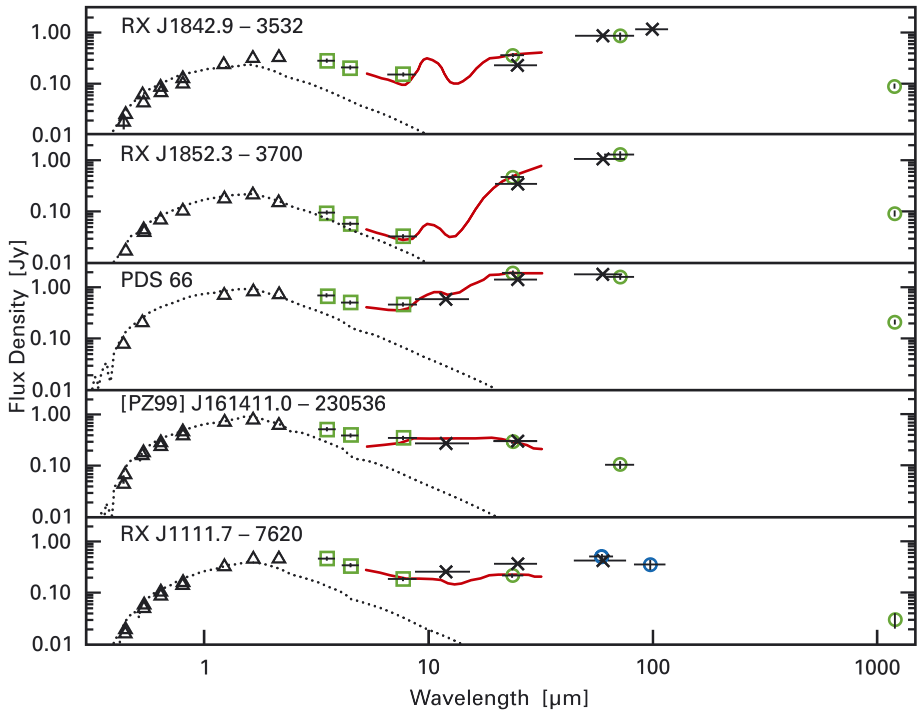


Fig. II.2.4: Spectral energy distribution of the five stars surrounded by dusty disks. The dust makes itself conspicuous at wavelengths beyond 3 µm.

Kuiper Belts in Solar Like Stars

When larger bodies as planetesimals or planets have formed within a protoplanetary disk, the remaining dust quickly disappears. Very small particles up to 1 µm across are blown out of the system by radiation pressure within several hundred years. Larger particles are slowed down by the so-called Poynting-Robertson drag and fall into the star. (This drag is caused by the fact that an orbiting particle experiences a net radiation pressure opposite to its flight direction; thereby it looses energy and spirals towards the central star.) Dust grains up to a size of 10 µm therefore remain within the system no longer than a few million years. If older stars, like our sun, are surrounded by dust, it has to be supplied continuously. As already mentioned, this happens by collisions of planetoids.

In our solar system, there are two major dust zones – the asteroid belt lying between the orbits of Mars and Jupiter and the Kuiper belt located beyond the orbit of Neptune at a distance of about 30 to 50 AU from the sun. Such dusty disks could only be detected in very few nearby luminous stars, such as Beta Pictoris and Wega. Using SPITZER, astronomers were able to detect dust in several solar like stars, which probably resides in regions comparable to the Kuiper belt.

Photometric data up to 70 µm wavelength and spectroscopic data of low spectral resolution in the range between 5.2 and 38 µm were available. In total, clear evidence of cool dust was found in seven stars, making itself conspicuous mainly by its significant emission at 70 µm (Fig. II.2.3). Six of these stars are solar like main-sequence stars with ages between 1 and 3 billion years. Only one of them, HD 105, is considerably younger, being about 30 million years old.

From these data alone the disk cannot be modeled unambiguously. There is no information about the chemical composition of the dust grains and, above all, none about their size distribution. Anyway, the disk of HD 105 has a large central hole. If the grains are assumed to be, e.g., 5 to 1000 µm across and consisting of silicate and graphite, the inner radius of the disks results to be 45 AU. The smaller the smallest particles are, the further out the inner edge wanders from the star. Also for the other, significantly older main-sequence stars, the best match of the data is with models in which the disks display a central hole with radii between 20 and 50 AU.

How can the central opening in the disks be accounted for? Sublimation of the dust particles or the Poynting-Robertson drag are not very probable explanations. The most simple one is: there are one or several big planets orbiting their central star within 10 to 20 AU, keeping their environs "dust-free" by means of their gravity. Beyond these planetary orbits, a planetoid belt similar to the Kuiper belt should exist, where colliding bodies continuously are supplying dust.

How do the observed dusty disks compare quantitatively to our Kuiper belt? The disk around the star HD 105 contains about 10^{-7} solar masses while in the other, older stars the values typically are only around 10^{-10}

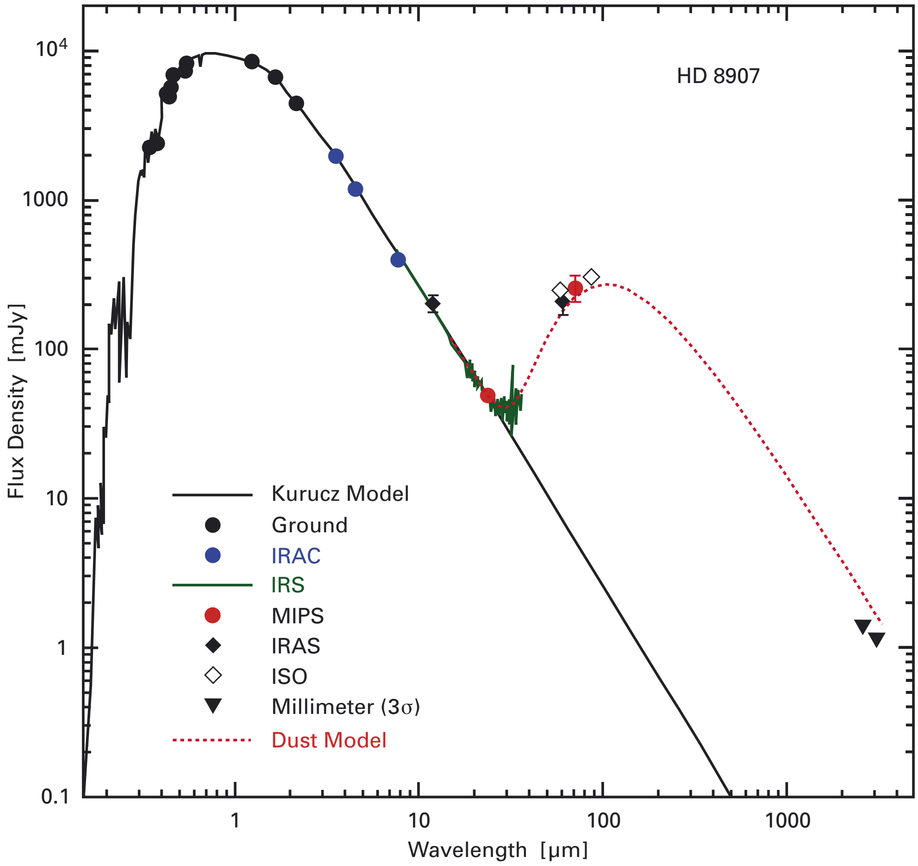


Fig. II.2.5: Spectral energy distribution of the star HD 8907. The strong emission in the mid- and far-infrared regime comes from a cool dusty disk.

solar masses. The dust particles in the Kuiper belt have been estimated to contain a total of about 10^{-11} solar masses. That is less than in the stars observed, but our solar system is older than the objects studied. Evolutionary models of the Kuiper belt suggest that the dust mass has decreased in the course of time, e.g. by the formation of big planetoids. So it is quite possible that the dusty belts of the stars observed show properties very similar to those the Kuiper belt had maybe two billion years ago.

An object named HD 12039 turned out to be particularly interesting. This solar like, about 30 million year old star exhibits a strong infrared excess at wavelengths from 14 to 40 µm, but is not detectable at 70 µm. The observational data can best be interpreted by a thin dusty ring of particles with sizes mainly between 3 and 10 µm surrounding the star at a distance between 4 and 6 AU. So HD 12039 reminds us of the asteroid belt in our solar system. And in that star, too, the dusty disk might be an indication of invisible planets.

If the models of HD 12039 are correct, the disk of the star, which is 140 light years away from us, should be observable with high-resolution instruments such as NICMOS aboard the HUBBLE Telescope or with adaptive optics systems such as NACO at the VLT. Such images should provide further information whether HD 12039 is been orbited by a planet or not.

(Jeroen Bouwman, Thomas Henning, Jens Rodmann, Sebastian Wolf. Participating institutes in the USA: Steward Observatory, The University of Arizona, California Institute of Technology, Pasadena, NASA –Ames Research Center, Moffet Field, Space Telescope Science Institute, Baltimore, University of California, Berkeley, Space Science Institute, Boulder, Lunar Planetary Lab, The University of Arizona, Tucson, SPITZER Science Center, Caltech, Pasadena, National Optical Astronomy Observatory, Tucson, Univ. of Rochester, Rochester, Planetary Science Institute, Tucson, Johns Hopkins University, Baltimore, Princeton University, Princeton, Smithsonian Center for Astrophysics, Cambridge)

II.3 Mysterious Stellar Dust in the Early Universe

In 2003, large quantities of dust were detected in the most distant quasars. So the question arose how this dust could possibly have formed within only about 700 million years after the big bang. The mystery soon seemed to be solved: a team of astronomers claimed to have detected enormous amounts of dust in the Cassiopeia A (Cas A) supernova remnant. The scientists concluded from this that type II supernovae were the first to produce dust in the universe. When astronomers at MPIA followed up this issue they came to a different conclusion: The dust detected at Cas A has nothing to do with the supernova remnant but actually belongs to an extended dust complex lying between Earth and Cas A. Thus the question about the origin of the dust in the early universe is still open.

Dust plays a significant role in the universe as it constitutes the raw material from which stars and planets continually form. The solid particles can only form, however, when heavy elements, carbon in particular, are present. According to current cosmology, only the light, volatile elements hydrogen and helium as well as small amounts of lithium and beryllium were created in the big bang. All heavier elements were synthesized later by nuclear reactions within the interiors of stars and subsequently blown into interstellar space by supernova explosions or stellar winds.

Only when the interstellar medium had been enriched in this way with heavy elements, dust could also form and only then the prerequisites for planet formation were given. As observations made over the last two years have shown, large quantities of dust already existed no later than 700 million years after the big bang. About one hundred million solar masses of dust were detected in the vicinity of the most distant quasars. How could these enormous amounts of dust have been created in such a short period of time?

The only possible early sources of dust are supernova explosions. The stars of the first generation consisted of hydrogen and helium only and therefore were significantly more massive on average than present-day stars. Massive stars explode as supernovae and in their explosion envelops, so the speculation, dust might form. But do supernovae really produce that much dust? So far, supernova remnants were considered to be dust poor, since only small amounts of warm dust had been detected within them in the infrared regime at short wavelengths. This seemed to be changed with an observation made in 2003.

A British team had studied Cas A in the sub-millimeter regime, detecting strong emission in the region of the supernova remnant. This was supposed to come from the amazingly large amount of three solar masses of cool dust, which would correspond to a major fraction of the total mass of the collapsed precursor star. So the conclusion was that apparently type II supernovae (to which the supernova of Cas A belongs) indeed produce enough dust to account for the enrichment in the early universe.

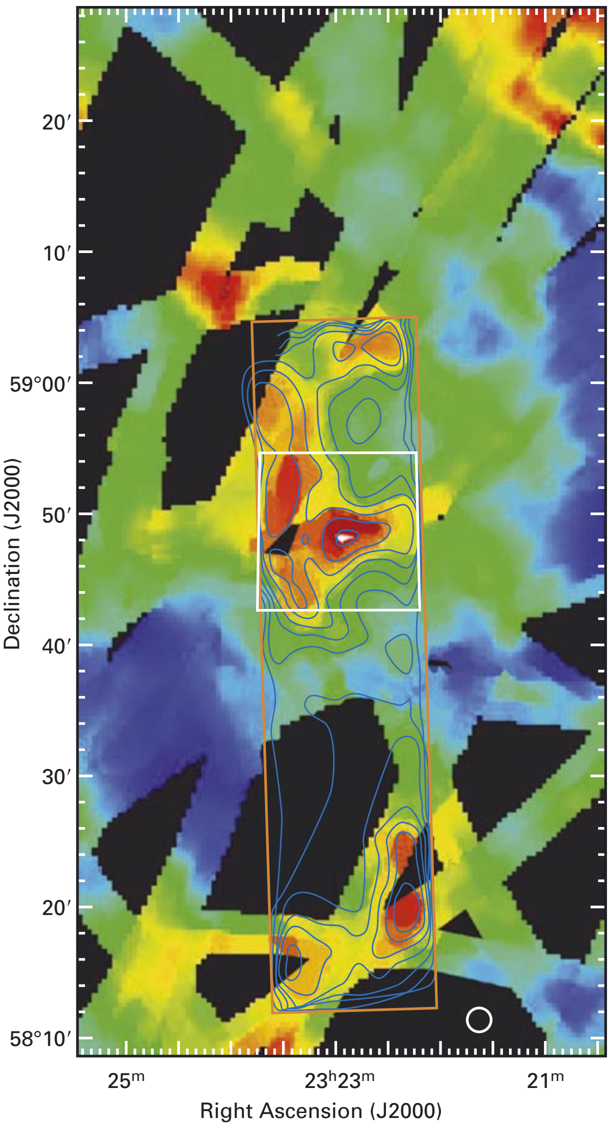


Fig. II.3.1: The surroundings of Cas A as seen in the ISOPHOT Serendipity Survey at a wavelength of 170 µm. The emission of very cold dust can be recognized here. Cas A (center) is obviously covered by an extended dust cloud in the foreground. The contours within the white rectangle show measurements taken by SPITZER at 160 µm that are in excellent agreement with the ISO data.

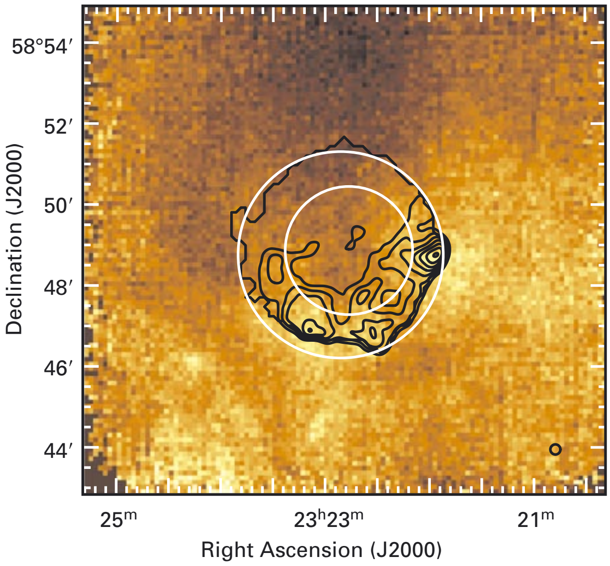


Fig. II.3.2: Distribution of OH gas in the vicinity of Cas A. The region shown corresponds to the white rectangle in Fig. II.3.1.. Since the OH cloud has been observed in absorption against the bright radio source Cas A, the interstellar cloud has to lie in the foreground of the supernova remnant.

But only one year later this conclusion was being refuted. Astronomers at MPIA suspected that the dust indeed exists but is located much nearer in the foreground, not being associated with Cas A. It has been known for a long time that Cas A is lying at a distance of about 11000 light years beyond the dust rich Perseus spiral arm. Dust clouds lying in the foreground presumably made it impossible for astronomers on Earth to observe the supernova explosion that should have taken place around 1680. Cas A is so close to Earth that the supernova would have appeared as the brightest star in the whole sky, if it were not obscured by the dust clouds in the Perseus arm. So it appeared likely that the newly discovered sub-millimeter emission originates from that dust in the foreground and not from Cas A itself.

In order to test this hypothesis, astronomers at the Institute first analyzed infrared data found in the archives of the ISO infrared satellite. The region around Cas A had been observed within the so-called ISO Serendipity Survey in the far infrared at a wavelength of 170 μm (Fig. II.3.1). In this spectral range, very cold dust of temperatures between 10 and 20 Kelvin (–250 to –260 °C) does emit its thermal radiation. The ISO map showed three emission regions that corresponded very exactly in their location and extent with the emission found in the sub-millimeter range. The dust responsible for this has a temperature of 14 K, a value typical for dark clouds.

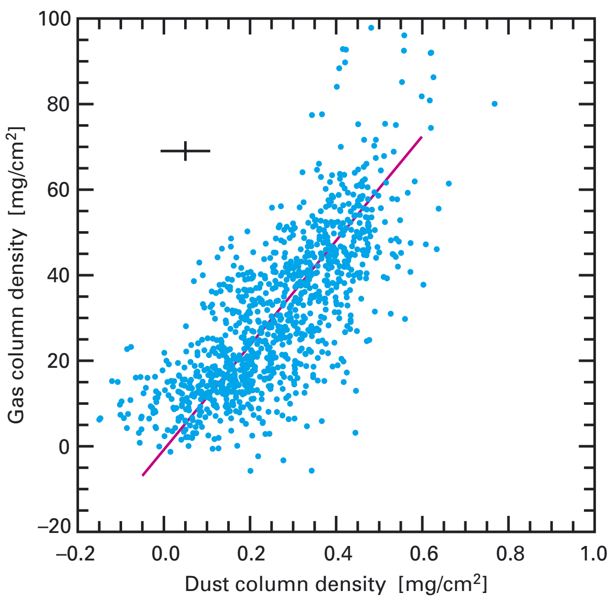
Interestingly, molecular gas had been found before in the region of this dust cloud (Fig. II.3.2). Since this gas had been detected in absorption against the bright radio emission of Cas A it has to be located between Earth and the supernova remnant. On account of its kinematics it can be associated with the Perseus arm. The column density of the OH molecule and the sub-millimeter flux also showed a good correlation between the gas and dust. To sum up: the measured gas to dust ratio is typical for our galactic environment (Fig. II.3.3).

Quantitative comparison of the distribution of this gas with the dust emission shows that the dust within the interstellar clouds virtually produces the entire emission in the infrared and sub-millimeter regime.

This analysis included new observations of Cas A made with the SPITZER Space Infrared Telescope. For these, astronomers at the Institute together with colleagues from Steward Observatory in Tucson, Arizona, and the Space Science Institute in Boulder, Colorado, used the imaging photometer at a wavelength of 160 μm. The dust clouds detected in the infrared range actually extend far beyond the boundary of the supernova remnant. So there are no significant amounts of dust associated with the supernova remnant Cas A (Fig. II.3.4).

So the question about the first sources of dust in the universe is open again. It is closely linked with the search for the first stellar generation of which no sign has been detected yet. The search for it is one of the top priorities in astrophysics. New information on this topic is expected from future space telescopes such as HERSCHEL or PLANCK.

Fig. II.3.3: Correlation between gas and dust, determined from the column density of the OH molecule and the sub-millimeter flux. The measured gas to dust ratio is typical for our galactic environment.



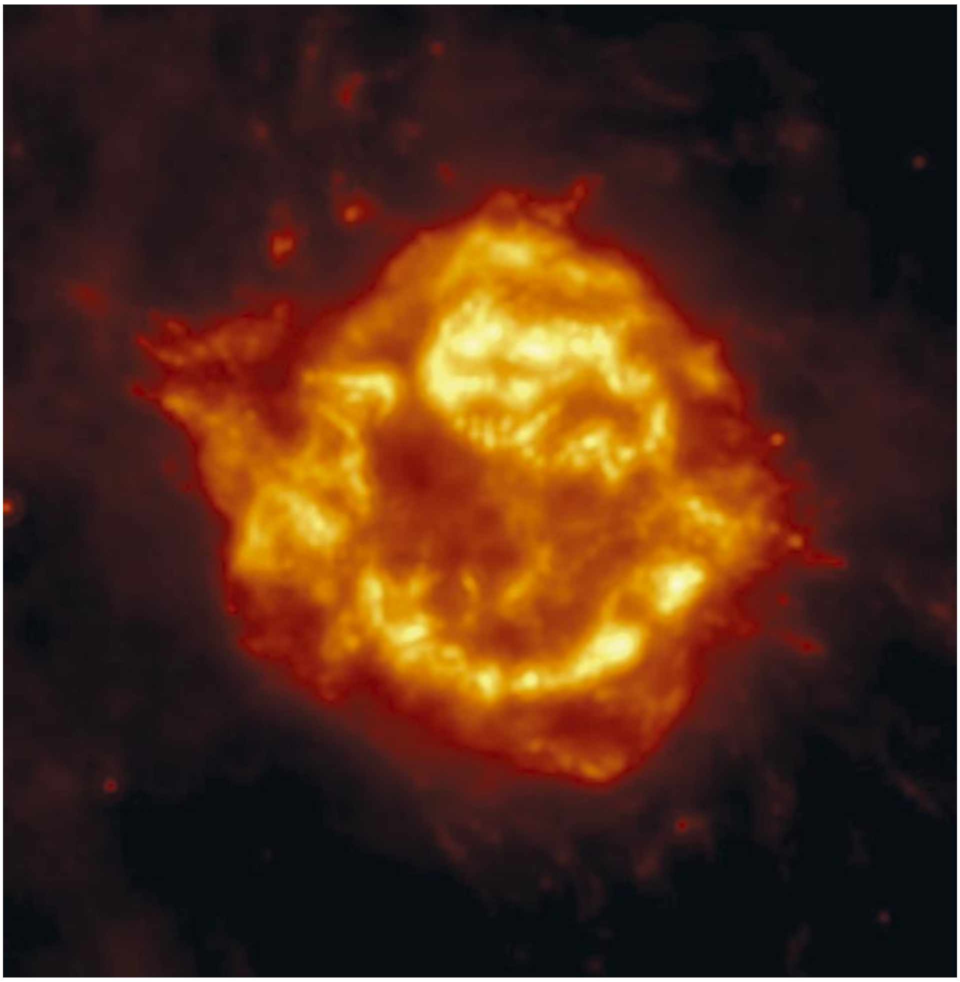


Fig. II.3.4 : Supernova remnant Cas A imaged with SPITZER at a wavelength of 24 μm. This infrared image shows the emission of the warm dust generated by the supernova; its total mass is only 0.002 solar masses. (JPL/NASA/O. Krause, UoA)

(Oliver Krause, Stephan M. Birkmann,
Dietrich Lemke, Ulrich Klaas.
Participating institutes:
Steward Observatory, Tucson Arizona,
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II.4 The Monoceros Tidal Stream in Our Milky Way System

Three years ago, a ring-like structure extending over about 100° in the sky was found in the data of the Sloan Digital Sky Survey. It turned out to be a tidal stream of stars that had been ripped off from a dwarf galaxy during a merger with the Milky Way. Astronomers at MPIA combined all observational data available to construct a comprehensive model of this so-called Monoceros stream, thereby also obtaining information about the suspected association of globular clusters and other star groups with this tidal stream.

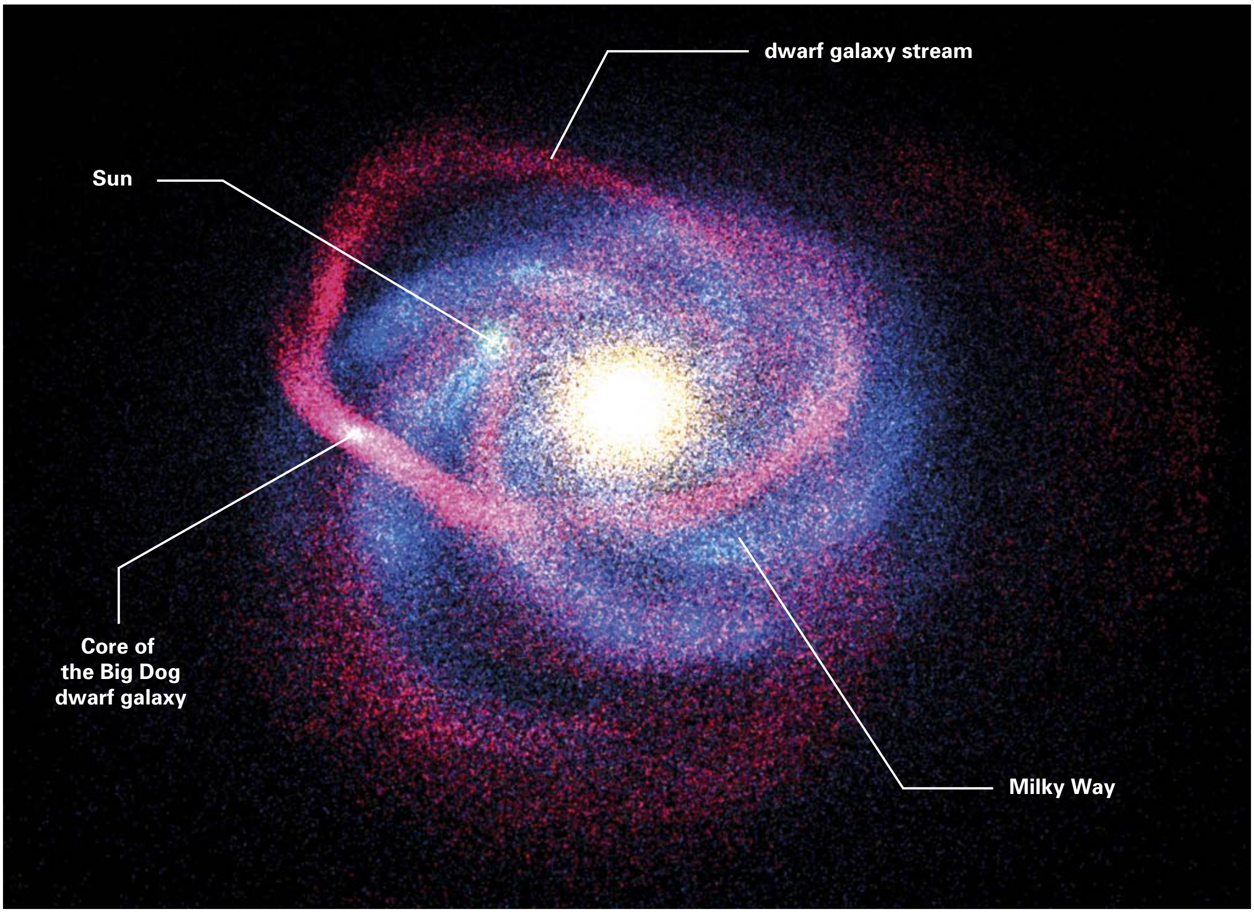
According to modern cosmology, the present-day large galaxies have grown by mergers of smaller galaxies. Even in the recent cosmological past of several billion years it probably happened now and then that satellite galaxies would dive into their central galaxies and then get dispersed therein. By interaction with the gravitational potential of the large galaxy the stars of the satellite presumably were able to sink towards the disk of a spiral galaxy, adding significantly to the stellar population there.

Even today the »fossil« remnants of such mergers can be detected within our Milky Way system. The most prominent example is the Sagittarius dwarf galaxy, whose tidal stream warps itself completely around the center of the Galaxy.

For ten years this was the only known example of a satellite galaxy merging with our Galaxy. In 2002 then, a ring-like structure extending over about 100° in the sky was found in the Sloan Digital Sky Survey. This stream of stars was named after its central constellation, Monoceros. The stream is coiling twice around the center of the Milky Way and essentially contains metal poor stars. Fig. II.4.1 shows a qualitative sketch of the structure.

Much less is known about the Monoceros stream than about the Sagittarius stream. One reason for this is the fact that for the most part it lies within the Galactic plane, the light being absorbed by dust. So far, its distance to the Galactic center was constrained only very roughly to be

Fig. II.4.1: Schematic representation of the Monoceros tidal stream.



between 15 and 20 kpc (50 000 and 65 000 light years), and the real source of the stream has not yet been identified definitely. A possible suspect is a dwarf galaxy in the constellation Canis Major. It is perceptible particularly by an over-density of more than 60 M giants lying in an elliptical region. Fig. II.4.2 illustrates the location of this dwarf galaxy close to the Galactic plane.

Moreover, four globular clusters are found in the surroundings of the Canis Major dwarf galaxy, having the same radial velocity as the dwarf. So it was suspected quite early that these objects had been invading the Galaxy together as a joint group. Furthermore, another hardly discernible star stream was discovered in 2004. It was named after its position in the constellations Triangulum and Andromeda Tri/And stream and actually may be part of the Monoceros stream.

Astronomers at the Institute used the observational data available to construct a spatial model of the Monoceros tidal stream. The goal was first to determine its kinematics and dynamics and then to reconstruct the disintegration process from that information. In addition, it was planned to clearly identify the progenitor galaxy and to study the potential members mentioned above.

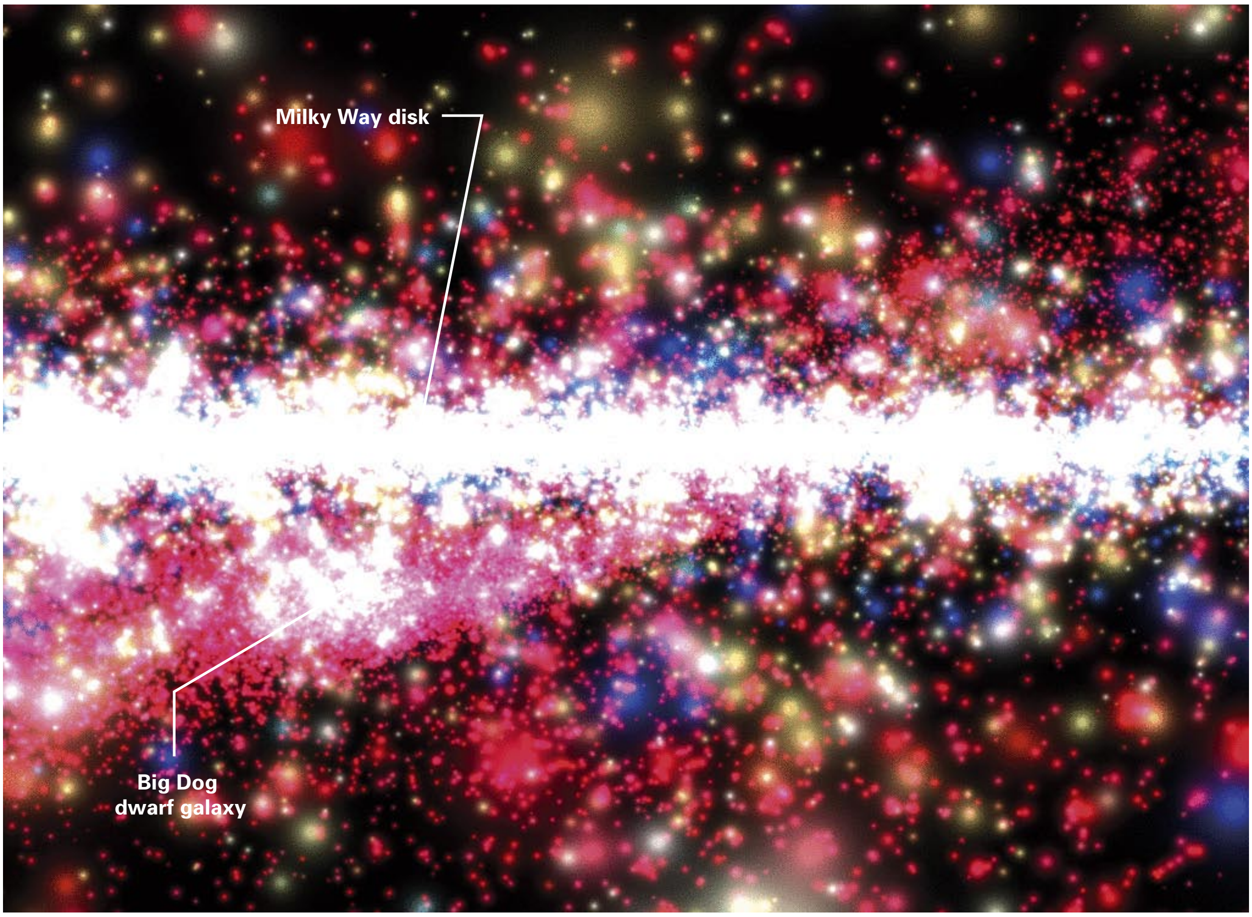
Fig. II.4.2: Position of the Canis Major dwarf galaxy directly below the Galactic plane.

Observational Data and Model of the Monoceros Tidal Stream

There are several criteria in order to establish the membership of stars in a common stream. Photometrically, an overabundance of a particular stellar type can be recognized; similarities can also be found in the abundances of elements as well as in radial velocities and proper motions. Observational data like these have been used for modeling the stream. In the model, the Milky Way system is subdivided into three components: dark matter halo, disk, and central bulge. For these regions gravitational potentials are designed in which the dwarf galaxy then is moving.

It would have taken too much computing time to calculate complete numerical simulations of all possible scenarios within a large range of physical parameters (e.g., distance to the Galactic center and inclination to the Galactic plane). Therefore, in a first step, the theoreticians developed a semi-analytical model, thereby constraining the possible parameter range for which pure numerical models were calculated subsequently.

In these models, the three components of the Galaxy were represented by a total of 1.3 million particles and the dwarf galaxy by 100 000 particles. The movement of the dwarf within the potential of the Milky Way was then followed over a period of three billion years. In the



process, the parameters were being varied in order to find those solutions which fitted the observational data best.

The first question to be investigated was in which direction the stars of the Monoceros stream are moving around the Galactic center. Here, only the proper motions in galactic longitude finally tipped the balance in favor of a prograde orbit (Fig. II.4.3). Merely the data of two stars do not fit the model. Hence a prograde orbit was assumed in all subsequent models.

Fig II.4.3 clearly shows that the Monoceros stream consists of two almost concentric rings with radii of about 12 kpc (40 000 light years) and 22 kpc (70 000 light years), respectively. Both rings are inclined by about 25° to the Galactic plane. This unusual shape may be caused by an anisotropic mass loss of the dwarf galaxy while passing through the Galaxy.

Using the best model of the stream (prograde orbit) the astronomers looked into the question whether the CMa dwarf galaxy is indeed the progenitor of this stream. Since the dwarf is located close to the Galactic plane it is difficult to observe. Several astronomers only vaguely estimated its mass at 10^8 to 10^9 solar masses and its distance at 7.2 kpc (24 000 light years). Using the known radial velocities and proper motions of the M supergiants within the CMa dwarf galaxy its orbit was calculated back in time and subsequently compared to the model. The result confirmed the CMa dwarf galaxy

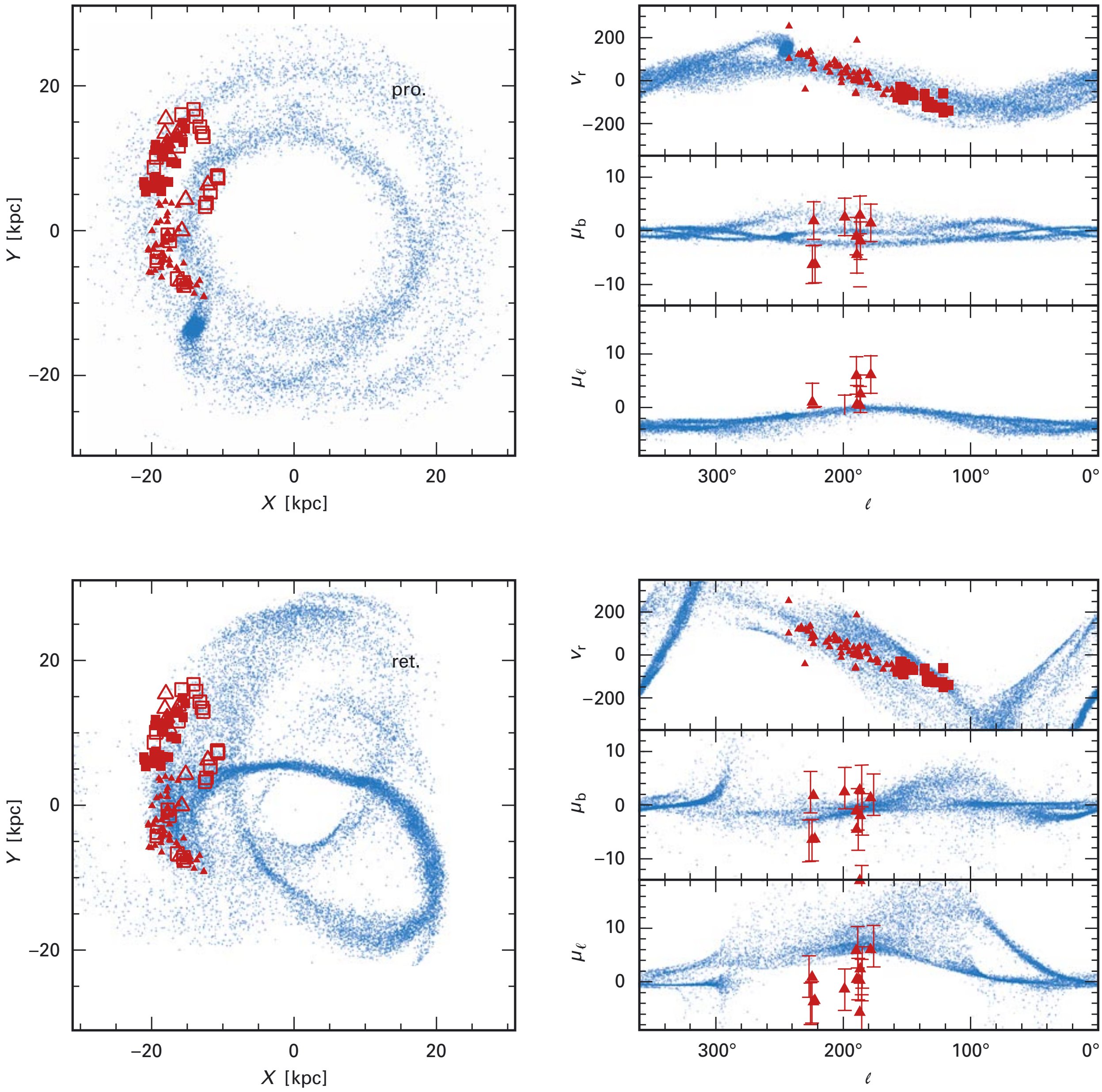


Fig. II.4.3: Models and observational data of the Monoceros stream – above for a prograde, below for a retrograde orbit. The proper motions in Galactic longitude μ_ℓ were the deciding factor in favor of the prograde orbits.

as the progenitor of the Monoceros stream. The best agreement was achieved with a large initial mass of 1.8 $\times 10^9$ solar masses.

The next interesting question was whether the globular clusters, associated by some astronomers with the CMa dwarf galaxy, do fit into the model, too. The analysis showed that this is not the case. Two of the globular clusters (NGC 1851 and NGC 1904) have too high radial velocities and their orbits are much more eccentric than that of the Monoceros stream. The third cluster (NGC 2298) even moves around the Galactic center on a highly eccentric, retrograde orbit. For the fourth globular cluster no proper motions were available. But there are other star clusters which may be connected with the CMa dwarf galaxy. Whether this is the case will only be settled when proper motions of these objects become available.

For the recently discovered Tri/And stream, however, the model suggested a possible connection with the Monoceros stream. Its kinematics indicate that the Tri/And stream extends from 120° to 150° of galactic longitude. It even might constitute a link to another stellar stream stretching from 110° to 140° of galactic longitude that, too, was discovered only recently within the data of the Sloan Digital Sky Survey. The entire stream would then be visible over a region reaching from 110° to 240° of galactic longitude.

Future measurements, especially of proper motions, should permit further improvements of the spatial kinematic model. It would be possible then to reconstruct the past evolution of the CMa dwarf galaxy after it had invaded our Milky Way system, now getting dispersed in it.

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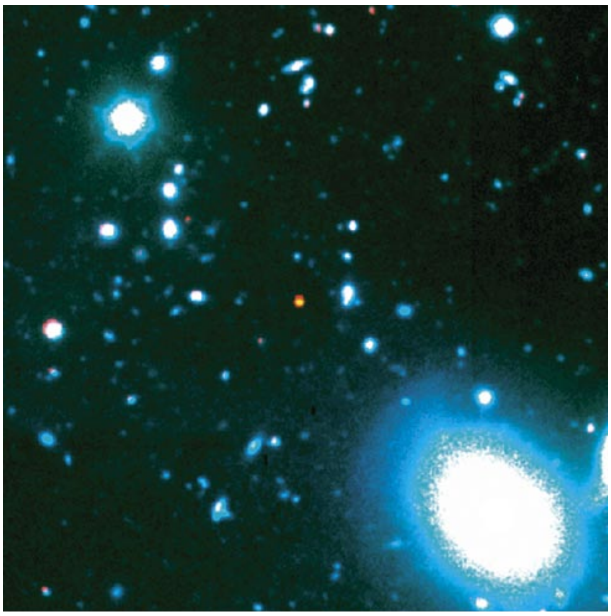
II.5 Dust and Gas in the Most Distant Quasar

The most distant quasar known, designated J1148+5251, has a redshift of $z = 6.42$. The light we receive from it today was emitted when the Universe was about 870 million years old. Last year, using the Very Large Array, large amounts of carbon monoxide gas were detected within this object. This finding sheds new light on the creation of heavy elements in the early Universe, providing new topics for discussion on the question: Which existed first, galaxies or their central black holes?

The object with the catalogue designation J1148+5251 was discovered early in 2003 in the data of the Sloan Digital Sky Survey (SDSS). The SDSS, started in April 2000, is the most extensive digital sky survey so far. It uses a 2.5-m-telescope specifically built for this purpose on Apache Point, New Mexico. The project is conducted by a consortium of US-American, Japanese, and German institutes. In Germany, MPIA in Heidelberg and the MPI for Astrophysics in Garching are involved.

The source J1148+5251 was noticed in the SDSS data because of its conspicuous red color. Additional images and follow-up spectroscopy with the Keck telescope confirmed the assumption that it is a very distant quasar (Fig. II.5.1). With $z = 6.42$ it even holds the present redshift-record. Together with a handful of other quasars it belongs to those objects we observe in the transitional period between the neutral "dark ages" and the era of re-ionization.



According to modern cosmology, the gas cooled down after the big bang, becoming neutral after about 300 000 years (Fig. II.5.2). Subsequently, the first stars and quasars formed, their UV radiation starting to re-ionize their surrounding medium. First the universe resembled a Swiss cheese, the neutral gas being interspersed with "holes" of ionized plasma. These plasma bubbles expanded until finally the whole medium was ionized. As far as we know today, this phase ended barely one billion years after the big bang.

As can be inferred from its spectrum, the quasar J1148+5251 has created a plasma bubble 9.6 Mpc (30 million light years) in diameter around itself. The size of this bubble indicates that the quasar activity up to then had lasted for about ten million years. The radiation comes from a hot gaseous disk (accretion disk) surrounding a central black hole of 1 to 5 billion solar masses. So here one can see an object that is in the process of ionizing its environs.

J1148+5251 is remarkable in yet another respect. Using the IRAM radio telescope on Pico Veleta in Southern Spain, radio astronomers had detected large quantities of dust in this object. The assumption that the dust is being heated mainly by young stars leads to a star formation rate of about 3000 solar masses per year, or one new star every five hours. This rate is about a thousand times higher than that in our present-day Milky Way system.

Another remarkable fact is that obviously large amounts of heavy elements already existed even in this early stage of the universe since without them no dust could have formed. Since carbon, oxygen, and other elements building cosmic dust are only created by nuclear reactions in the interiors of stars, the enrichment of the interstellar gas with heavy elements must have taken place with remarkable speed. How this happened, by supernovae and/or by stellar winds from massive stars, is still unclear (cf. chapter II.3).

Fig. II.5.1: On an image taken with the Keck telescope the quasar J1148+5251 is noticeable by its red color. (S. Djorgovski, Keck)

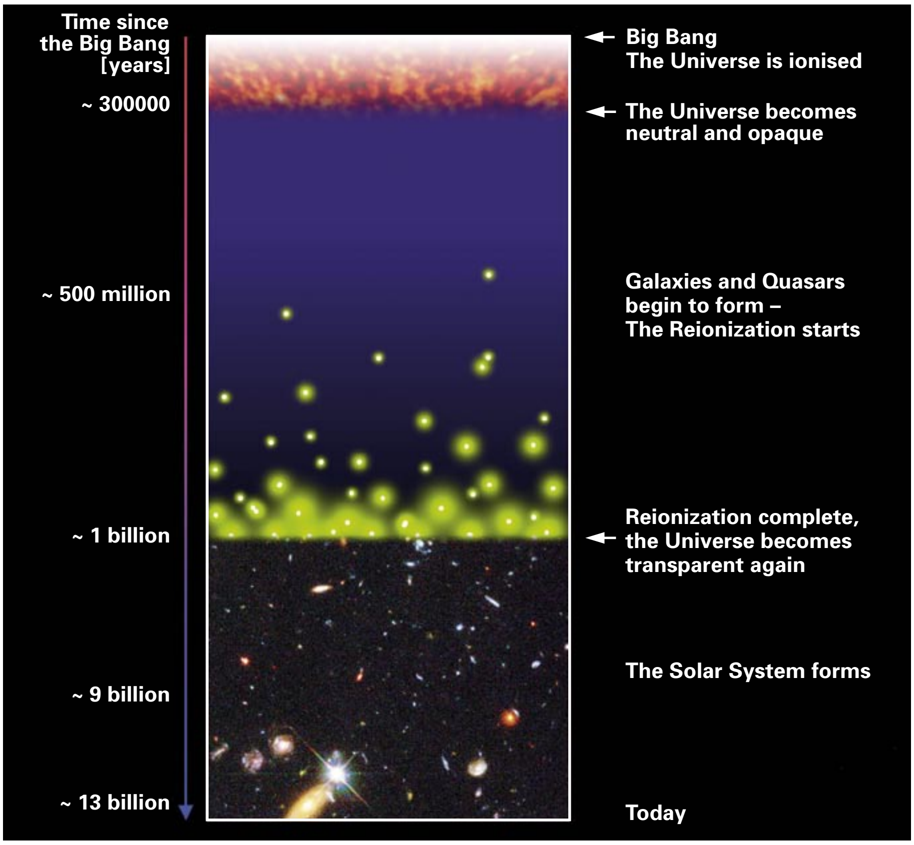
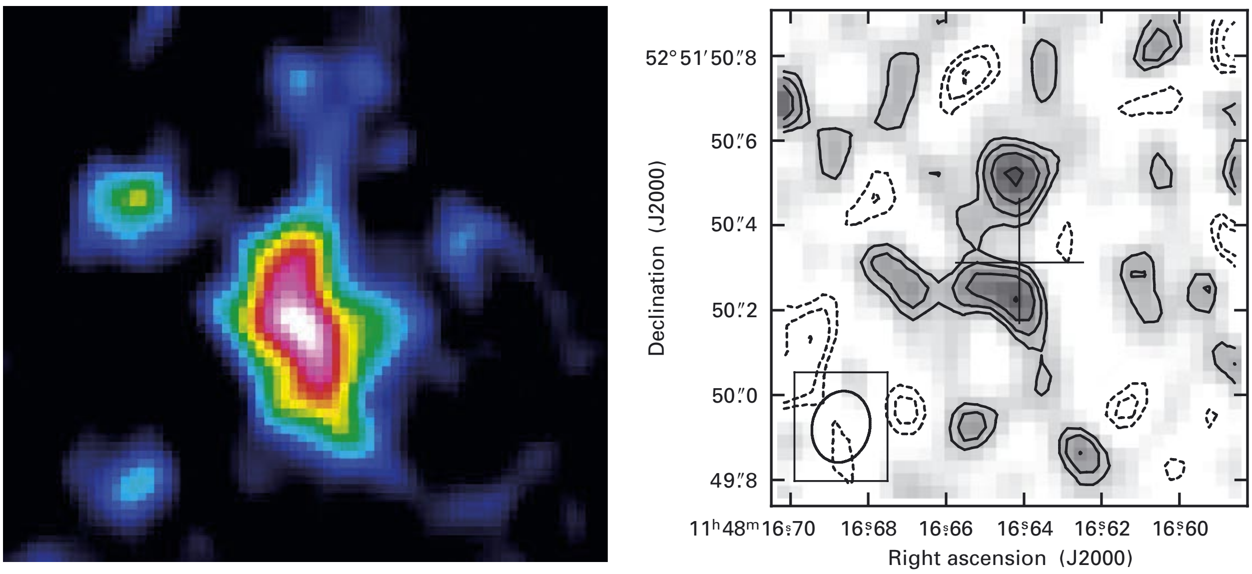


Fig. II.5.2: The evolutionary stages of the Universe. Re-ionization sets in some hundred million years after the big bang. (S. Djorgovski)

Fig. II.5.3: VLA map of the quasar J1148+5251. The position of the optically visible core has been marked on the contours.



Additional spectacular results were obtained from observations made with the Very Large Array in Socorro, New Mexico. With a resolution of 0.15 arcseconds (corresponding to 3000 light years at the site of the quasar), a cloud of CO gas 12 000 light years long and 4500 light years wide was found (Fig. II.5.3). Assuming the normal abundance ratio between CO and the most abundant gas, H_2, a total mass of 1.6×10^{10} solar masses was inferred for this structure that might be a gravitationally bound disk orbiting the quasar center. If this assumption is correct a rotational velocity of 280 km/s can be deduced from the width of the CO spectral line. Via Kepler's law the rotational velocity then gives a dynamical mass of about 5×10^{10} solar masses. This mass is compatible with the molecular gas mass derived from the CO data. But it does not leave much room for additional matter besides the gas. This is very remarkable in a particular way.

Studies of nearby galaxies with central black holes have revealed a very close relation between the mass of the black hole and the mass of the stars within the central bulge of the galaxy surrounding the black hole. Accordingly, the matter contained in the bulge is about 700 times that of the black hole (cf. Annual Report 2003, p. 74). If this relation were to hold already in the early universe, J1148+5251 should contain several 10^{12} solar masses of matter within its bulge. The observations, though, yield a value smaller by two orders of magnitude. How can this result be explained?

In the current cosmological picture, the mass relation between the black hole and the stellar bulge is interpreted as a result of coeval evolution of these two galactic components. The low bulge mass of J1148+5251 could be explained if the black hole formed first, growing to its enormous size prior to the assembly of the bulge. In this case the black hole could be considered the »condensation nucleus« for galaxy formation

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II.6 Why Does the Cosmic Star Formation Rate Decline?

A central issue of modern cosmology concerns the temporal evolution of the star formation rate. Scientific results of the last decade show it to have declined during the second "half of the life" of the universe by an order of magnitude. The cause for this is still mostly unclear. An international team of astronomers led by MPIA recently studied the star formation rate in galaxies at $z = 0.7$, when the universe was half its present age. As it turned out a decrease of tidal interactions between galaxies cannot be the main cause for the rapidly declining star formation rate during the past seven billion years. Other processes taking place within spiral galaxies appear to be responsible.

A number of methods for investigating the star formation rates in distant galaxies have been developed in the past. The intensity of the UV emission of young, hot stars is generally considered a good indicator. Yet, large amounts of dust necessarily being present in star forming regions may absorb most of the UV radiation. Therefore the thermal infrared emission of the dust heated by the young stars is also a measure of the star formation rate. Additional indicators are strong emission lines from, e.g., highly-excited hydrogen and oxygen ions, or radio and X-ray emission.

Studies based on observational data at various wavelength regions are particularly robust but also very time-consuming. Scientists at MPIA chose to follow that way, being able to partly fall back on sky surveys recently conducted under the leadership of MPIA.

The Multi-spectral Data Set

For the visible spectral region, they had at their disposal the data of the COMBO-17 (Classifying Objects by Medium-Band Observations with 17 Filter) galaxy survey. Within this survey carried out at MPIA a large area of the sky had been imaged through 17 filters, measuring the magnitudes of galaxies in as many corresponding color ranges. Thus it is possible to classify galaxies and determine their redshifts up to a brightness of 24 mag in the red spectral region within a few percent accuracy. The crucial prerequisite for this project was the large image field of the Wide Field Imager (WFI), developed under the leadership of MPIA and built together with ESO. It is operating at the 2.2-m-MPG/ESO telescope on La Silla and has a 32 arcminutes × 33 arcminutes field of view, corresponding to about the size of the full moon.

A specially developed software identifies, in addition to stellar types and quasars, different galaxy types such as elliptical and spiral galaxies as well as starburst galaxies with unusually high star formation rates in the COMBO-17 data. A total of about 25 000 galaxies have been recorded, making COMBO-17 one of the most extensive and deepest surveys worldwide.

A second data set available to the astronomers was the GEMS (Galaxy Evolution from Morphology and Spectral Energy Distributions) sky image, the up till then largest color frame obtained with the HUBBLE Space Telescope (cf. Ann. Report 2003, p. 40). The GEMS image field also has a size of 28 arcminutes × 28 arcminutes, being a mosaic of 78 single frames each taken with the Advanced Camera for Surveys (ACS) in two wavelength ranges around 606 nm and 850 nm. In a galaxy at redshift $z = 0.7$, details of 500 and 700 pc (1600 and 2300 light years), respectively, can still be discerned. Thus extended star forming regions and other typical structures with sizes of some thousand light years are discernible with brilliant resolution (Fig. II.6.1).

The GEMS field lies within the CHANDRA Deep Field South (CDFS), observed with the CHANDRA Space Telescope in the X-ray spectral range. Thus for some of the galaxies, these data were also available to the astronomers. Infrared images taken with the SPITZER Space Telescope at a wavelength of 24 μm (Fig. II.6.1) were also added to the multi-spectral data set. This field spanned 90 × 30 arcminutes, covering the CDFS.

The strategy of the new study was to select from COMBO-17 all galaxies within a narrow redshift range of $0.65 < z < 0.75$. This corresponds to an average look-back time of seven billion years, about half the age of the universe, and to a time interval of 500 million years. These objects subsequently were identified within the other surveys and the data combined. Finally, the respective star formation rates and the galaxy types were determined from this, and then these values were compared to those of the galaxies of the present-day universe. COMBO-17 contained 1727 galaxies within the selected redshift or distance interval. Of these, 442 could be identified on both the SPITZER and the GEMS image.

For galaxies in the present-day universe the star formation rate is determined for instance from the total infrared emission in the range between 8 μm and 1000 μm. Since SPITZER only gives a value at 24 μm, astronomers had to apply a known correlation that permits to calculate the total luminosity from this single value. After that the UV fluxes of the objects derived from the COMBO-17 data were also included. This way the radiation emitted directly by young stars as well as the infrared emission

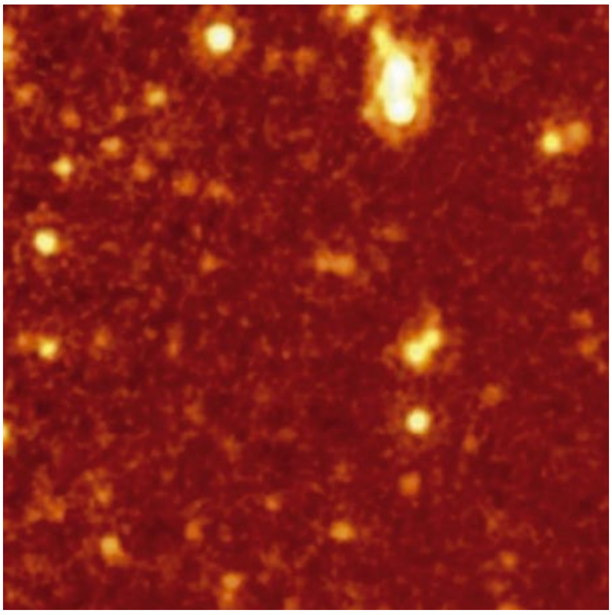


Fig. II.6.1: *above:* Part of the GEMS image used for studying the cosmic star formation rate; *right:* the same area of the sky, taken with SPITZER at a wavelength of 24 μm. The side length of the frames is about 3.5 arcminutes.

re-emitted by dust was obtained. That was the great advantage of this study.

From these data, astronomers calculated the infrared luminosity of all galaxies within the selected redshift interval around z = 0.7 to be 7×10^{13} solar luminosities while the UV luminosity was only 1.5×10^{13} solar luminosities. So the ratio IR/UV = 7 holds at an average redshift of 0.7 (Fig. II.6.2). This means that most of the total emission is in the infrared, as it is known from dust-rich starburst galaxies.

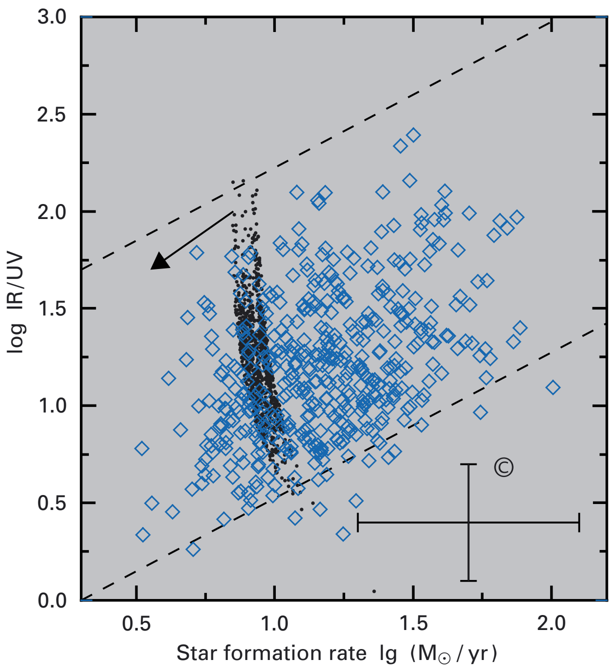


Fig. II.6.2: The ratio of IR- to UV-emission as a function of the star formation rate. Open diamonds denote the galaxies measured with SPITZER, dots are upper limits. The arrow indicates the direction to which the data of the undetected objects can shift. The dashed lines indicate the region of present-day galaxies.

Causes of the Decline of Star Formation

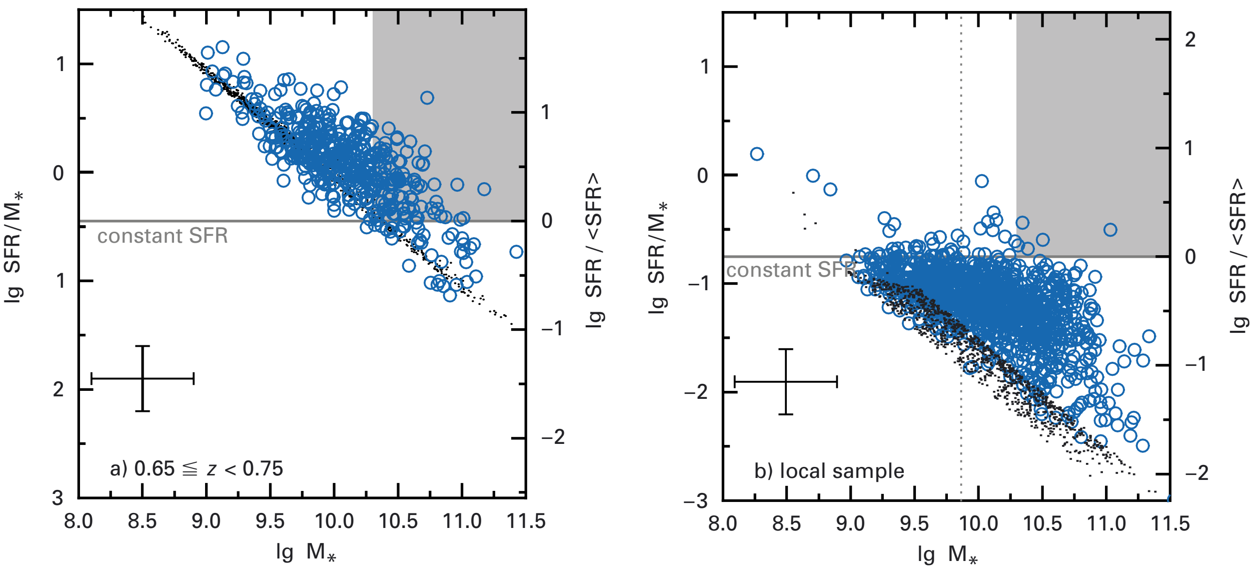
An interesting question now was how much which galaxy types contributed to star formation when the universe was about half its present age. Here the spatially highly resolved GEMS image was of particular significance. The result came as a surprise: The highest contribution to the total IR luminosity came from spiral galaxies; the brightest IR sources showed an increasing fraction of interacting galaxies. Elliptical galaxies played a minor role. The relative contributions to the total IR luminosity were: spiral galaxies (50 %), elliptical and S0 galaxies (10 %), interacting galaxies (30 %), and irregular galaxies (10 %).

The following conclusions were drawn from this result: The rapid decline of the star formation rate during the second half of the evolution of the universe is only partly caused by a decreasing interaction and merger activity between galaxies. So far it was widely assumed that tidal interactions between galaxies were swirling the interstellar gas in the systems, thereby triggering new star formation. As with the expansion of the universe interactions became rarer and rarer, the cosmic star formation rate should decline too. According to the recent studies, this effect exists in principle but is not of crucial importance – at least not during the second half of the life of the universe. Instead, the star formation rate obviously decreases within the large, undisturbed spiral galaxies.

At present, one can only speculate on the cause of this. Perhaps the interstellar gas and thus the raw material for building new stars is dwindling within the spirals, or maybe tidal interactions with small satellite galaxies that are not discernable in the GEMS image are responsible.

The examination of the so-called specific star formation rate (SFR) – the star formation rate normalized to the stellar mass within the galaxy – turned out to be

Fig. II.6.3: Comparison of specific star formation rates: To the left, galaxies of the early universe (z=0.7), to the right, present-day galaxies. The star formation rate at z= 0.7 is distinctly higher.



rather revealing. This quantity is closely related to the past-averaged star formation rate <SFR>. This quantity is obtained by dividing the stellar mass by the period of time that has elapsed since the formation of the first stars in the respective galaxy. In their analysis the astronomers worked on the simplified assumption that in the galaxies observed almost all stars formed at $z = 4$, i.e. 12 billion years ago.

Fig. II.6.3 shows the specific star formation rate (SFR) obtained this way, normalized to the past-averaged star formation rate <SFR>. Due to the sensitivity of the observations only galaxies with stellar masses of at least 2×10^{10} solar masses are included. A value of 1 means the currently measured specific star formation rate equals the past-averaged star formation rate. Galaxies around $z = 0.7$ are plotted on the left-hand, present-day galaxies on the right-hand side. The difference is obvious: Present-day galaxies show a broad distribution with rather low specific star formation rates ranging between 0.03 and 0.2. Not even one percent of all objects have values above 1, where starburst galaxies are expected. The distribution of galaxies in the early universe, on the other hand, is completely different. Here almost 40 % of the galaxies have values above 1 and thus are starbursts that partly are producing considerably more new stars at $z = 0.7$ than indicated by their past-averaged star formation rate. The majority of this starburst population are spiral galaxies and only a minor fraction are tidally interacting systems.

These new results will help to improve current models of cosmic evolution which up till now do not comment on how strongly tidal interactions and mergers of galaxies have influenced the cosmic star formation.

The multi-spectral study presented above is the beginning of a more comprehensive study. For the future it is planned to sum up images taken by SPITZER at wavelengths of 70 and 160 μm, in order to obtain a more global understanding of the average spectral energy density of the galaxy emission. On a longer-term basis new telescopes such as APEX, ALMA, and HERSCHEL are expected to answer the relevant questions.

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III Scientific Work

III.1 Brown Dwarfs – Origins, Disks, Binarity, and Atmospheres

For thousands of years, the stars have been a source of wonder and enquiry. A scientific understanding of them only really began in the 19th century, with the development of spectroscopy by people such as Frauenhofer, Kirchhoff and Bunsen. They were found to have a wide range of spectra, and were organized into increasingly complex schemes of classification. But what were the stars? What were they made from? How did they shine? Why did they show these differences in their spectra?

One of the great successes of 20th century astrophysics was the development of detailed models of stellar structure, based on physical theories of mechanics, thermodynamics, radiative transfer and, later, nuclear physics. Calibrated and refined by detailed observations, these models were found to describe the properties and also the evolution of stars in remarkable detail and accuracy.

Of particular significance was the discovery of the hydrogen-burning Main Sequence: all stars go through a relatively peaceful and stable phase of hydrogen burning, in which hydrogen is converted to helium in the core of the star by thermonuclear fusion, releasing the energy which causes stars to shine. The mass of the star is the major factor in this processes. The most massive stars burn bright but are short-lived, evolving across the Main Sequence in less than a million years. As we go down the Main Sequence to lower masses, the central temperatures are lower and thus the nuclear reactions less energetic, so the stars become fainter and their main-sequence lifetimes longer.

What happens as we keep going down in mass? Theoretically, there is a mass below which hydrogen burning cannot occur; this transition takes place at about 0.075 M_{Sun}, the "hydrogen burning limit". Stars below this limit will essentially just cool and become fainter with time as they radiate away their gravitational energy. Theoretical predictions of the internal and observable properties of these "Brown Dwarfs" (BDs) were made already in the 1960s, with detailed models being presented right up until the first discoveries.

Discovery of Brown Dwarfs

In the 1980s and 1990s, a number of very low luminosity and low temperature objects were found, typically from deep optical and infrared surveys or proper motion studies. However, with all of these BD candidates it was impossible to be sure that they had masses below the hydrogen burning limit. Masses could not be measured directly (i.e. dynamically). Rather we had to rely on models of BD structure and evolution to derive masses from the observed luminosities and effective temperatures. But these models had large uncertainties, so it was not clear if the candidates lay above or below the hydrogen mass burning limit.

An important development came with the so-called "Lithium test", proposed by Rafael Rebolo, member of the Advisory Council of the MPIA, and co-workers at the IAC in Spain. Lithium burns in thermonuclear reactions at temperatures just slightly lower than hydrogen. Most stars have very little Lithium in them, a primordial element produced in the big bang, and so will deplete it entirely over a short timescale (of order 100 million years for the lower mass stars; more quickly for more massive stars).

All but the most massive Brown Dwarfs, however, are too cool to burn Lithium, which then remains undepleted. So, if we can detect Lithium in the atmosphere of a low mass object, i.e. by observing the corresponding absorption line in its spectrum, then we know it must be a Brown Dwarf. Although this test has proven useful in many cases, it is not always decisive. Very young low mass stars will not have had enough time so burn their Lithium, so will not be distinguishable from Brown Dwarfs. In addition, the most massive Brown Dwarfs also burn Lithium, so even if a cool object has no Lithium, it could still be a Brown Dwarf.

The first truly unambiguous detection of a Brown Dwarf was made in 1995 by a team in the USA led by T. Nakajima (Caltech). They discovered a very faint, cool companion to the low mass star, Gl 229 (see Fig. III.1.1). This companion, called Gl 229B, was remarkable because it showed strong methane absorption bands in its atmosphere (Fig. III.1.2). The molecule methane can only form at very low temperatures, much lower than can be achieved in any star, so this had to be a Brown Dwarf. This Brown Dwarf shows such a cool atmosphe-

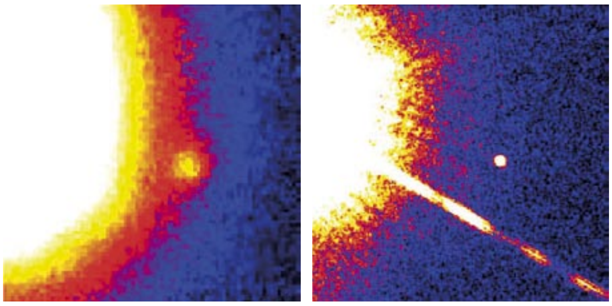


Fig. III.1.1: The discovery of the cool Brown Dwarf Gl 229B. The Brown Dwarf is the faint object to the right of its host star, Gl 229. The image on the right was taken with HST and achieves diffraction-limited imaging, i.e. higher spatial resolution.

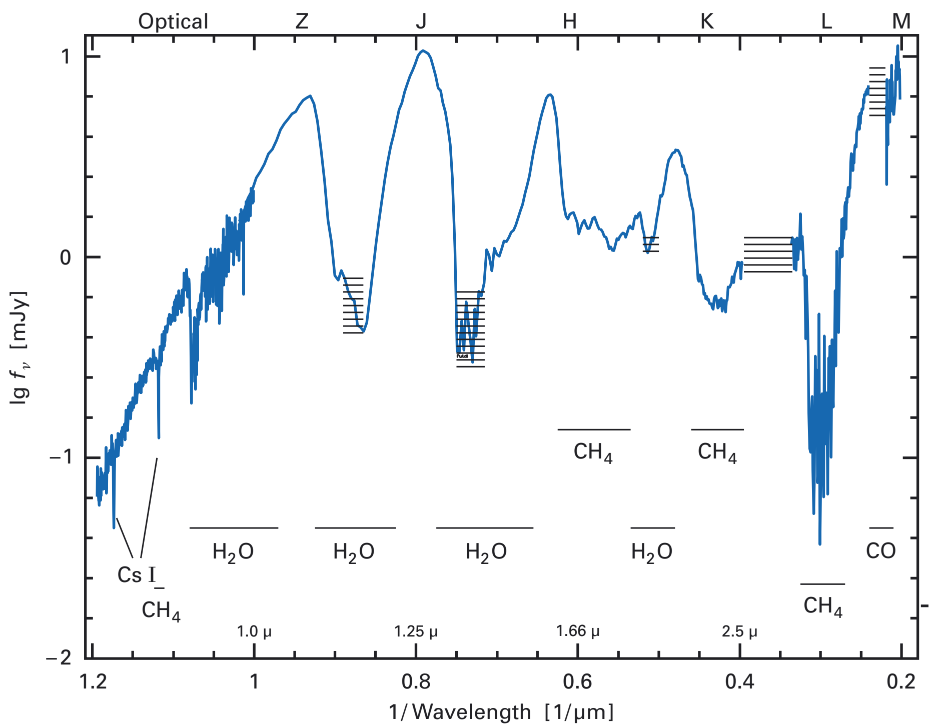
re because it is old (assuming it has the same age as its parent star): Lacking a nuclear energy source, Brown Dwarfs cool and fade with time. This makes them hard to detect at advanced ages, but given their characteristic atmospheres they are easier to distinguish from low mass stars once discovered.

We now know of order hundreds of Brown Dwarfs, and they appear to be as numerous as hydrogen-burning stars in the solar neighbourhood (and presumably in the rest of the Galaxy). Yet, having small masses, they contribute only a small fraction of the total mass in the Galaxy. Thus they are very unlikely to contribute significantly to the “Missing Mass”, or “Dark Matter”.

Fig. III.1.2: Near-infrared spectrum of Gl 229B. Wavelength increases to the right; at the top are marked the locations of standard photometric filters. Spectral bands of methane (CH_4) and water (H_2O) are marked. Reproduced from Oppenheimer et al. (ApJ, 502, 932, 1998).

Cool and faint: properties of Brown Dwarfs

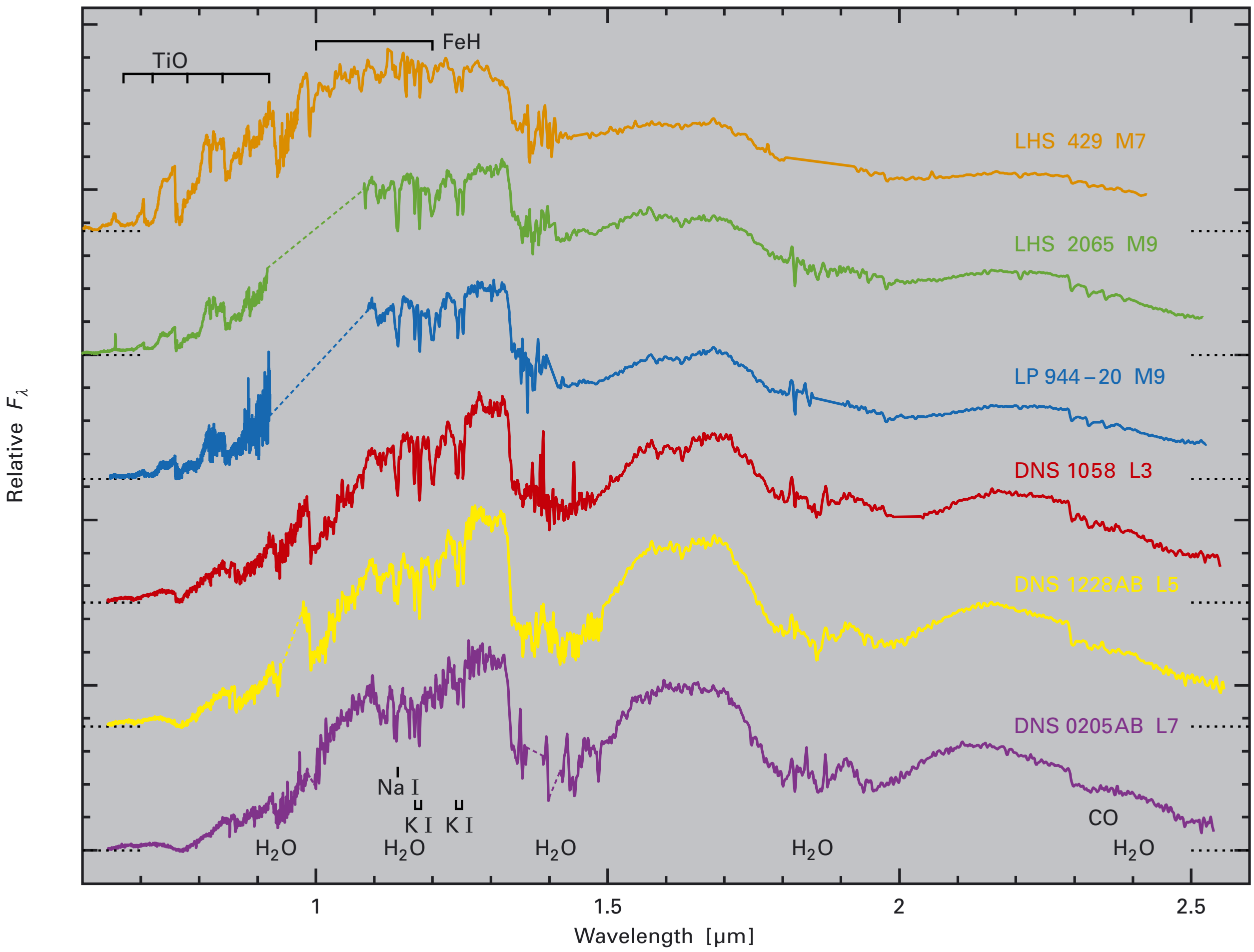
Because of their low masses, BDs are cool, with effective temperatures less than about 2000 K. Regardless of their chemical composition, these objects will appear very red, with most of their emission occurring in the near infrared spectral region (at wavelengths around 1 micron) and very little in the optical bands (Fig. III.1.3). This gives us one of the main ways of detecting these objects, namely their very red optical-infrared colours (e.g. the R-J index) compared to almost any other type of star. Moreover, at these low temperatures, thermochemical equilibrium calculations show that numerous molecules form, as do liquid and solid particles (collectively called »dust«). These dominate the observed spectra of BDs (even though the most abundant chemical is molecular hydrogen). This creates very characteristic spectra which have been split into two broad spectral types. The first type, “L”, is characterized by lines of metallic hydrides (e.g. CrH and FeH) and neutral alkalis (Na, K, Rb, Cs) in their red optical spectra (0.6-1.0 micron). The second ty-



pe, "T", can be identified by strong water and especially methane bands in the near infrared spectrum (1-2.5 micron). Gl 229B is the prototypical T dwarf. Connecting effective temperatures to these spectral types is difficult on account of the complex chemistry and possible dynamics in their atmospheres, as will be discussed later. But very roughly, the L types span the temperature range 2100 to 1300 K, and T dwarfs 1300 to 600 K. "L" and "T" types are therefore the cooler extension of the well-known OBAFGKM spectral type sequence (see Bailer-Jones & Bastian, SuW May 2004, p. 20). (When describing their spectral energy distributions, we refer to M, L and T dwarfs collectively as "ultra cool Dwarfs". What mass a given spectral type corresponds to – i.e. whether it's a low mass star or a Brown Dwarf – depends on the age. This is because Brown Dwarfs cool with time, and thus achieve later and later spectral types as they age.)

By definition of their lack of significant nuclear burning, BDs have masses less than about 0.075 M_{Sun} (which is about 80 Jupiter masses, $M_{Jupiter}$). Going further down in mass we reach the realm of the exosolar planets, of which some 150 have now been discovered with masses between that of Saturn and several times that of Jupiter. Does this mean there is a continuum between planets and stars? Yes and no. Any gaseous object which cannot burn hydrogen we call a "substellar mass object", so both planets and Brown Dwarfs are substellar mass objects. We generally define a planet as something which formed in an accretion disk around a star from the debris left over from the star formation processes. Stars, on the other hand, form during the collapse of gas in the interstellar medium. Objects which formed in this way, but which are too low in mass to burn hydrogen, we would call Brown Dwarfs. Thus the most useful distinction between a planet and a Brown Dwarf is not in its properties or in its mass, but in the way it formed. We do not yet know what the minimum mass of an object is which this star formation process can create: it could well be that some Brown Dwarfs have masses less than the most massive planets, i.e. the mass functions of Brown Dwarfs and planets overlap. Indeed, as we shall now explore, there are many new ideas and theories concerning the formation of Brown Dwarfs.

Fig. III.1.3: Near-infrared spectra of ultra cool Dwarfs. From top to bottom we move through the spectral type sequence from late M Dwarfs (M6) to late L dwarfs (L7). Ultra cool Dwarfs emit most of their radiation between 1 and 2.5 µm. Prominent molecular bands are marked. Reproduced from Leggett et al. (ApJ, 548, 908, 2001).



Origin of Brown Dwarf

At least four different mechanisms have been proposed for BD formation, namely: dynamical ejection of a stellar embryo from its parental molecular cloud core by gravitational interactions; opacity-limited fragmentation of a shock-compressed layer of gas; gravitational instabilities in disks; photoevaporation of small cloud cores in regions of massive star formation. But the formation of BDs is not necessarily exclusive to one process. The removal of accretion envelopes from low mass protostellar cores may be a viable formation mechanism in regions such as the core of the Orion Nebular Cluster, where sufficient massive stars emitting the required intense ultraviolet radiation fields exist. However, photoevaporation will not explain the formation of BDs in regions as the Taurus-Auriga star-forming region where there are no massive stars.

Cast from the nest as a juvenille

The search for a more universal BD production mechanism led Bo Reipurth (University of Hawaii) and Cathie Clarke (University of Cambridge) to propose that BDs are substellar objects because they were ejected from small newborn multiple stellar systems that decayed by dynamical interactions. That is, BDs are "failed" stars because the accretion process was interrupted before a core with a mass high enough to burn hydrogen could form. In a small multiple stellar system, the different members compete for infalling matter and the one that grows slowest is the most likely to be ejected. But even if the members have almost equal masses, these systems are so unstable that one member will invariably be ejected at an early stage when it still has a very low mass. This mechanism has attracted a lot of recent attention because it may explain the rarity of BDs as close companions to normal stars, the absence of wide BD binaries, and the flattening of the low-mass end of the initial mass function. Of course, the substellar cores themselves must still form before this ejection. Hydrodynamical simulations suggest that this occurs in gravitationally unstable disks or collapsing filaments.

As part of his PhD thesis, Stefan Umbreit (MPIA) studied the dynamical decay of non-hierarchical triple systems as a BD formation mechanism using statistical N-body simulations. These studies demonstrate that accretion and subsequent shrinkage of triple systems increase the velocities significantly compared to non-accreting systems and make the ejection process even more probable. Moreover, the simulations are compatible with the observed semi-major axis distribution of a volume-limited sample of binary BDs (Fig. III.1.4).

Dynamical ejection is a violent process, so one would expect BDs produced in this way not to retain massive disks. Likewise, it would be hard to produce very wide BD binaries in this way (as ejection would tend to disrupt such weakly bound systems).

To examine this, the N-body simulations were used to predict the density profiles and lifetimes of Brown Dwarf disks. The issue is whether one can form very tight BD binaries by ejection yet still retain sufficiently large disks around the single ejected BDs to observe them at a typical age of 1-5 Myr. The simulations have shown that just after a close encounter (leading to ejection) the disks are strongly truncated and their sizes are very small, generally below 5 AU. In addition, the disks masses are usually less than the mass of Jupiter. However, due to the generally low accretion rates of BD disks, at least 12 % of these very low mass disks should survive for more than 1 Myr. Thus the fraction of BDs with disks will be low, but not negligible amongst the youngest BDs, and moreover will be larger if wider BD binaries can form. This can be examined observationally.

In addition to disk properties and binary statistics, observational clues for the ejection scenario can be provided by the kinematical behaviour of BDs in young associations and star-forming regions. We would also expect to observe BDs close to low-mass protostars (so-called class 0 objects) if the ejection scenario is the primary production mechanism.

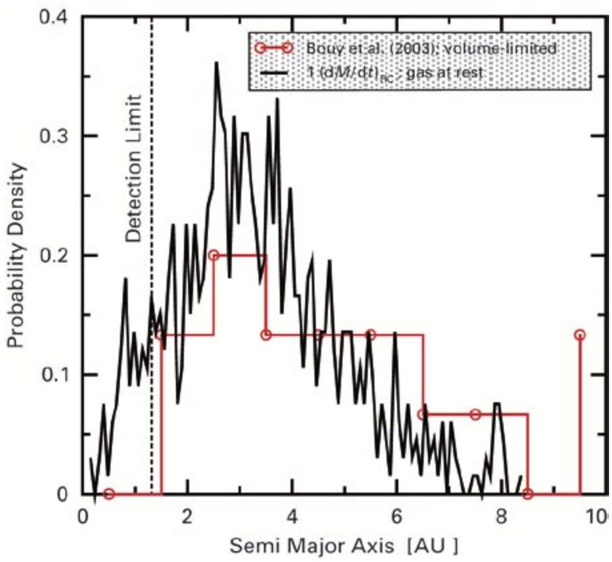


Fig. III.1.4: Semi major axis distribution of the Brown Dwarf binaries obtained in our simulation of decaying triple systems accreting gas at rest. This is compared with the observed distribution of Bouy et al. (2003). These two distribution match very well, as both distributions have a peak at about the same value of a = 3 AU and show about the same degree of asymmetry around the that value.

Disks around Brown Dwarfs

One clue to the nature and formation of BDs could come from the apparent similarity of young BDs to classical T Tauri stars (the pre-Main Sequence phase of low mass stars). Recent spectroscopic surveys indicate that young BDs show T Tauri-like disk accretion down to BD masses close to the deuterium-burning limit (13 $M_{Jupiter}$), emission in the Hα line being used as an accretion indicator. In general, the accretion rate seems to drop rapidly with stellar/BD mass (the accretion rate goes roughly with M^2) and decreases substantially with age. The measured accretion rates can be as low as 10^{-12} M_{sun}/yr. The absence of a discontinuity in the relation between accretion rates and mass across the hydrogen burning limit suggest a common disk accretion process for BDs and classical T Tauri stars, possibly mediated by magnetic fields.

The next step is to search for direct evidence of disks around BDs and to determine their masses. As was the case for T Tauri stars, first evidence for disks around BDs has been obtained from near-infrared surveys, indicating emission in excess over the expected photospheric level. An even better indicator is excess emission at around 10 micron, produced by warm circumstellar dust. The first detection of BDs at these wavelengths came from broadband ISOCAM observations of BDs in the Chamaeleon I and the Rho Ophiuchi star-forming regions with the Infrared Space Observatory. Together with our former students Daniel Apai and Ilaria Pascucci (now at the University of Arizona) as well as Michael Sterzik from the European Southern Observatory, we searched for mid-infrared emission from BDs using ground-based facilities and, in particular, looked for the presence of the 10 micron silicate feature. This feature has enormous analytic potential because it indicates both the optical depth of the emitting material and the dust grain sizes. In the case of the young BD candidate Cha Hα 2, we found clear evidence for thermal dust emission. Surprisingly, the object does not exhibit any silicate feature, either indicating a rather flat disk geometry or considerable grain growth. In the case of the young (~ 1 Myr) bona fide Brown Dwarf CFHT-BD-Tau 4 we had more luck. With the T-ReCS instrument on the Gemini South 8-m telescope, we were able to find a silicate feature in emission which proves the presence of an optically thin disk layer similar to what we see in T Tauri stars. A closer analysis of the spectrum provided first evidence for grain growth and even for dust settling in the disk of this object.

The next challenge was to find millimetre emission from these disks. This is a direct measure of the disk mass with the caveat that the dust opacity has to be known. Using the SCUBA bolometer at the JCMT submillimetre telescope on Hawaii and the MAMBO array on the IRAM 30-m millimetre telescope on Pico Veleta (Spain), we detected, for the first time, millimetre emission from two young BDs at a flux level of a few millijanskys. Assuming similar dust opacities as used in disk mass estimates for T Tauri stars, we derived total disk masses of a few Jupiter masses. This points to the possibility that planets may form even in the disks around BDs.

It is interesting to note that there are a number of sources with infrared disk excess emission which do not show any sign of accretion. This may be another parallel to the T Tauri stars where disks can persist beyond the main accretion phase.

With the sensitive mid-infrared detectors aboard the Spitzer Space Telescope, the detection and spectroscopy of BD disks may become a routine observation. With a spectral type of M9.5 and a mass of about 15 Jupiter masses, OTS 44 is now the coolest and least massive Brown Dwarf observed to have a circumstellar disk. At the time of this writing, we are in the process of obtaining the first spectra of BD disks from SPITZER.

Dynamical mass estimates of Brown Dwarfs: Brown Dwarf binaries

One of the fundamental properties of an astronomical object – whether it be a planet, a star, a stellar cluster or even a cluster of galaxies – is its mass. Weighting a distant object often involves Keplers law. In the case of binary objects, dynamical mass estimates can be derived by monitoring the orbit and computing the orbital parameters.

In 1998, Wolfgang Brandner (MPIA, then at JPL/Caltech) and Eduardo Martín (IAC, then at UC Berkeley) launched a high-spatial resolution study of ultra cool stars and Brown Dwarfs of spectral type L using the Hubble Space Telescope (HST). The idea was to identify binary companions in order to derive dynamical mass estimates for the still elusive class of Brown Dwarfs. Furthermore, binary properties like multiplicity, distribution of binary separations and brightness ratios hold clues on the origin of free-floating Brown Dwarf binaries.

The study was immediately successful, leading to the discovery of the first spatially resolved binary L dwarf DENIS-P J1228.2-1547. As summarized in the PhD thesis of Hervé Bouy (now at IAC), more than 100 L dwarfs have now been surveyed, and more than 20 binaries with angular separations between 0.1 and 0.5 arcsec (corresponding to projected separations between 1 and 10 AU) have been identified in the solar neighbourhood.

Mapping the orbits

Follow-up observations for all binaries were initiated in order to monitor their orbital motion and to derive first estimates on the orbital periods. DENIS-P J1228.2-1547 turned out to be a relatively distant, slow moving binary with an orbital period of approximately 50 yr (Fig. III.1.5). The L-dwarf binary 2MASSW J0746425+2000321, discovered in 2000 with the HST, however, has a much shorter orbital period. Over the past four years, we have tracked the orbital motion with HST, the Gemini North telescope, the ESO VLT, and the Keck telescope. By January 2004, more than 60 % of the orbit, including the periastron passage of the system, had been covered (Fig. III.1.6).

Fitting the orbital parameters indicates that the system has an eccentricity of 0.4, went through its periastron passage in October 2002, and has an orbital period of 10.5 yr. Thus we were quite lucky to catch the binary during its periastron passage, allowing us to cover more than 60 % of the orbit in less than 4 yr.

Combined with the precisely known distance of 12.21+/- 0.05 pc, this yields a system mass of 0.146 times the mass of our Sun. Spectroscopic and photometric measurements of the individual components of the system then provide estimates for each component individually. The primary (spectral type L0) turns out to be a very-low mass star with a mass of 8 % of the mass of our Sun, whereas the secondary (spectral type L1.5) is clearly substellar with a mass of 6.6 % of the mass of our Sun (corresponding of 69 times the mass of Jupiter). Based on the detection of H-α emission in both L dwarfs, the age of the system is estimated to be between 150 and 500 Myr. Comparison to evolutionary models by Isabelle Baraffe and her group in Lyon indicates a good agreement with the observations, although the value for the surface gravity of the Brown Dwarf derived from comparison with DUSTY models appears to be too high.

Recently, researchers at the MPIA, in collaboration with Laird Close from Steward Observatory in Tucson, USA, observed the intermediate age (~ 40 Myr) multiple system AB Doradus. Based on astrometric data from VLBI and the Hipparcos satellite, this was previously known to have a low mass companion. Using high contrast adaptive optics imaging on the VLT, this team was able to directly image this companion – AB Dor C – for the first time, and obtain a spectrum, which indicates a spectral type M8. The combined data indicate a dynamical mass of about 87 $M_{Jupiter}$. When compared to theoretical evolutionary models, this object appears to be subluminous by a factor of just over two. Put another way: at this relatively young age, the models underestimate the mass of an object of given luminosity by a factor of two. Consequently, some very cool objects which have been referred to as »planetary mass objects« may actually have larger masses.

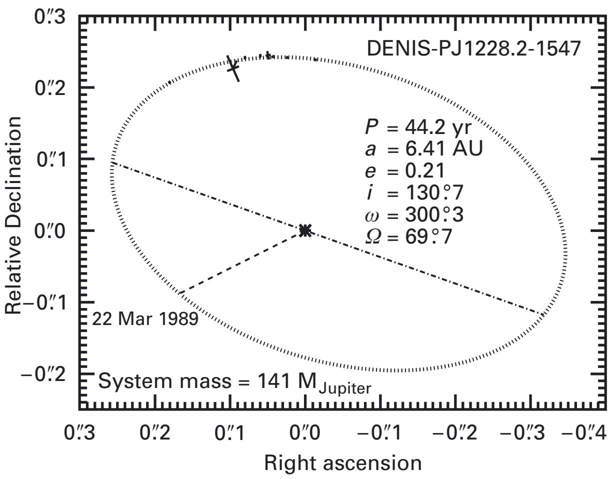


Fig. III.1.5: Measured orbit of the binary Brown Dwarf DENIS–PJ1228.2-1547. The crosses and the star indicate the relative positions of the two binary components in the time span June 1998 to December 2003. Overplotted is a possible orbital solution (dotted) for the astrometric data. The dash-dotted line is the line of nodes and the dashed line indicates the location of periastron.

Any planets out there?

As a by-product of our search for young giant planets using the newly designed Spectral Differential Imager on the NACO instrument on VLT, we, together with Mark McCaughrean (AIP, now at Exeter), discovered that Eps Ind B, the nearest T dwarf, is also a binary. The individual components both exhibit methane atmospheres and have spectral types T1 and T6, corresponding to effective temperatures of approximately 1250 K and 800 K respectively (Fig. III.1.7). The best mass estimates derived from comparison with theoretical evolutionary tracks yield masses of 44 and 28 times the mass of Jupiter. Hence the secondary component of the Eps Ind B binary is less than twice as massive as what is in general considered to be the mass limit between giant planets and Brown Dwarfs.

Our continued monitoring of the orbital motion of Brown Dwarf binaries should yield mass estimates for a larger number of Brown Dwarfs in the near future, and hence provide even more stringent constraints for theoretical models on the structure and evolution of Brown Dwarfs. In addition, we recently started an HST programme to search for planetary mass companions to the twelve most nearby, isolated and young L dwarfs, and also identified the first triple L/T dwarf system DENIS–PJ 020529.0-115925.

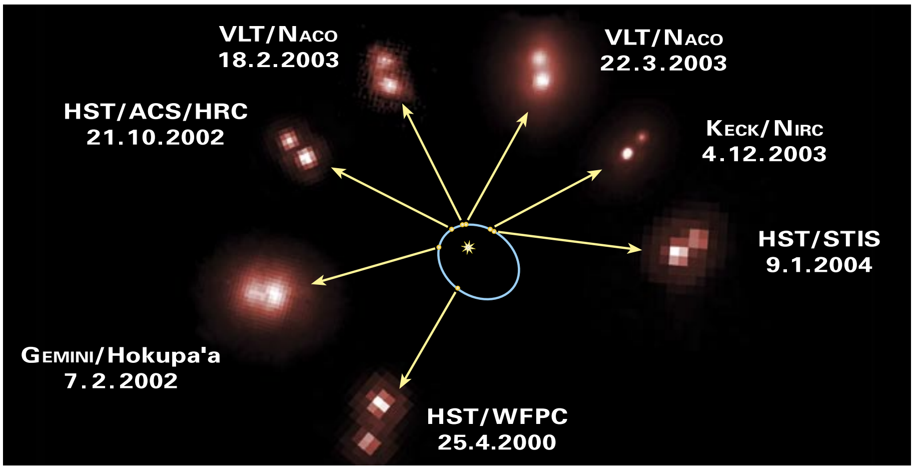


Fig. III.1.6: Observations of the orbital motion of the L-dwarf binary 2MASSW J0746425+2000321 over a period of 4 years. Each point on the ellipse corresponds to one measurement with a ground-based 8 m to 10 m class telescope or the Hubble Space Telescope.

Brown Dwarf atmospheres

The atmospheres of Brown Dwarfs are very cool, with the result that many molecules form and that even solid and liquid "dust" particles condense out of the gaseous phase. This has two dramatic effects. The first is that it changes the equation-of-state of the atmosphere by increasing the mean molecular mass (amongst other things). Second, the opacities are altered, with the result that the spectrum changes quite dramatically. Water (and, at lower temperatures, methane) produce deep absorption bands, while the dust creates a back warming effect which redistributes much of the flux in the near infrared part of the spectrum. Very broad lines of the neutral alkali elements also influence the spectrum. The result is that the optical and near infrared spectrum it is very far from being a black body.

Dusty Brown Dwarfs

The dust, in particular, is of much interest for two reasons. First, a proper self-consistent treatment of the dust is required to correctly model Brown Dwarf atmospheres and to interpret their observed spectra: only if this is done correctly can we infer the correct parameters (in particular effective temperature, abundances and ultimately ages). Indeed, recent work measuring the parallaxes and mid-infrared fluxes of Brown Dwarfs has shown that the L and T spectral types described above are not monotonically related to effective temperature. Generally we think of later spectral types as corresponding to cooler objects (lower effective temperature), and this is the case for main sequence stars. On thermochemical equilibrium grounds, we would likewise expect the sequence L0, L1, L2...T0, T1, T2 ... to correspond to ever lower temperatures. But this now appears not to be the case; specifically an increase in effective temperature is seen when passing from late L to early or mid T types (Fig. III.1.8). Indeed, it seems that these spectral types have as much to do with the properties of the dust as with the effective temperature.

To understand Brown Dwarf atmospheres we must therefore study the dust. In a static atmosphere (in which there is no convection), dust grains will form, grow, and gravitationally settle ("rain out") to regions deep within the star where they will no longer be directly observable in the emergent spectrum (although the absence of the elements locked in the dust grains would be observed). By contrast, in a dynamic atmosphere, upward convection will provide a bouyancy acting against precipitation, and will also act to recycle precipitated elements back into the visible atmosphere, thus retaining a dusty composition. Convection is complex and influenced by rotation, so dust may not be uniformly distributed across the surface of the Brown Dwarf. There may be bands, as we see on Jupiter, or large scale transient clouds, which may themselves be nonuniform in coverage.

Cloud variation monitoring

Although we cannot (yet) resolve the surface of a Brown Dwarf, we could detect such non-uniform features through the variation in the total light emitted by the Brown Dwarf towards us. Dust is a strong opacity source and significantly alters the emitted spectrum. As the Brown Dwarf rotates, the total amount of dust on the visible hemisphere may change, and so the total amount of light emitted from the Brown Dwarf towards us would likewise vary. In other words, we would see a periodic

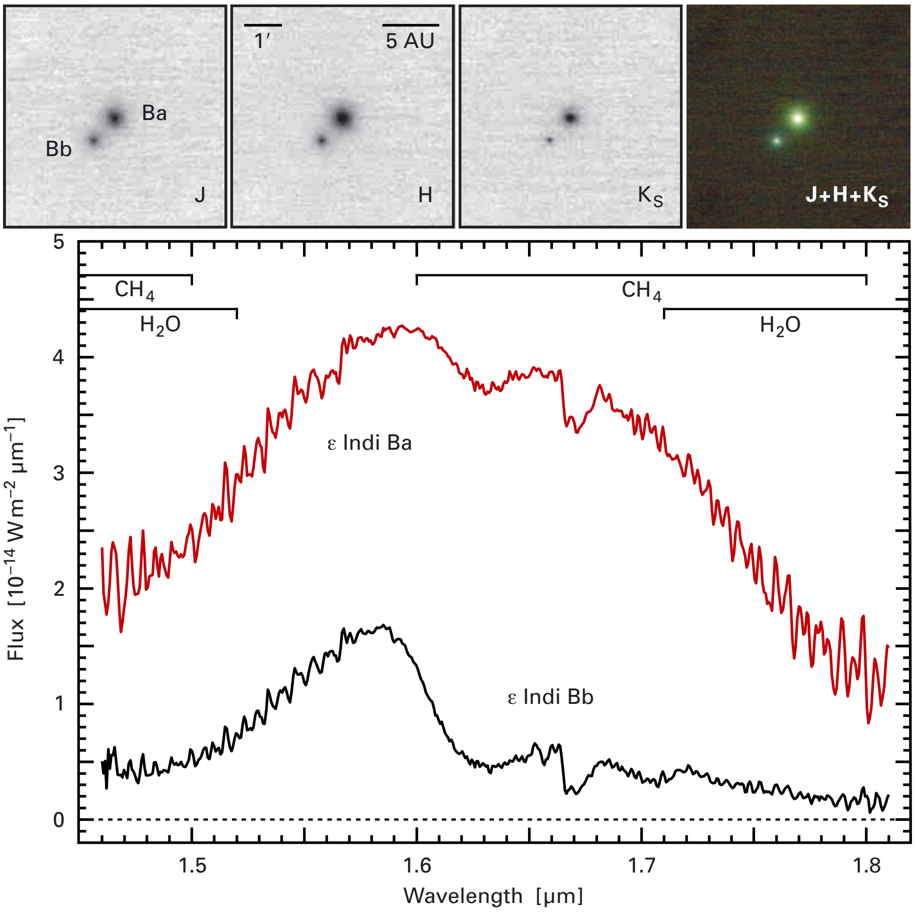
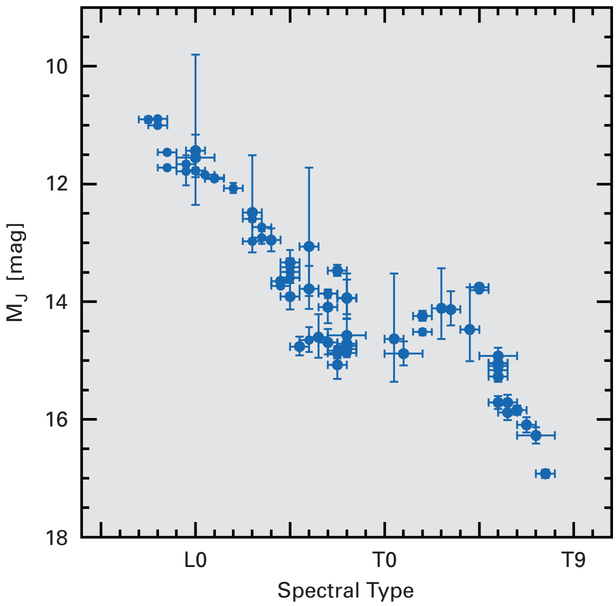


Fig. III.1.7: VLT NACO high resolution infrared imaging and spectroscopy of Epsilon Indi Ba,Bb, the nearest known binary Brown Dwarf, with spectral types T1 and T6 respectively.

Fig. III.1.8: Absolute J-band magnitude (M_J) vs. spectral type. Absolute magnitude were derived from the apparent magnitude using parallax measurements obtained by the US Naval Observatory. We see that as we go down in spectral types, there is an increase in the brightness in the J-band as we move from late L to early or mid T spectral types. This is belived to be related to the removal of dust clouds at these low atmospheric temperatures.



variation in the Brown Dwarf brightness in those parts of the spectrum influenced by dust.

Motivated by this, Coryn Bailer-Jones, in collaboration with Reinhard Mundt (both at MPIA), monitored a number of Brown Dwarfs in very red and infrared filters to look for brightness variations. From an initial sample of 20 objects, we found that half did indeed show statistically significant photometric variations, although with very small amplitudes, between 0.5 % and 8 % (Fig. III.1.9). Some of these variations were periodic, with periods of a few hours. But in some cases they were not periodic. This was curious. Could it be that these Brown Dwarfs were very slowly rotating, such that the limited duration of our observations had not covered even a single rotation period? To check this, we measured the rotational velocities of some Brown Dwarfs using the UVES high resolution spectrograph on the VLT. Rotation broadens spectral lines, so a careful measurement of the line width allows us to measure the rotational velocity. (Actually, since the orientation of the rotation axis is unknown, the observations only put a lower limit a the rotational velocity due to the unknown inclination of the rotation

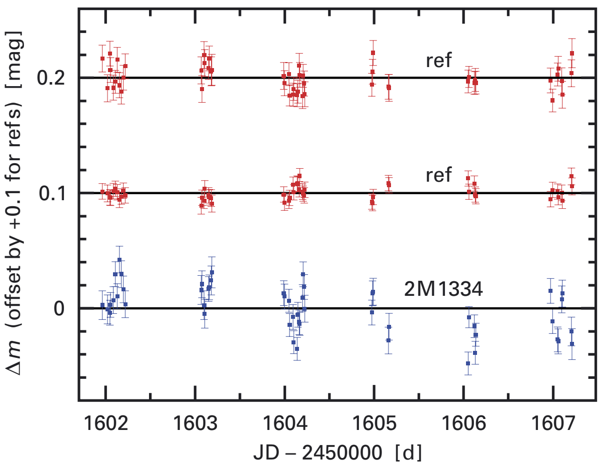
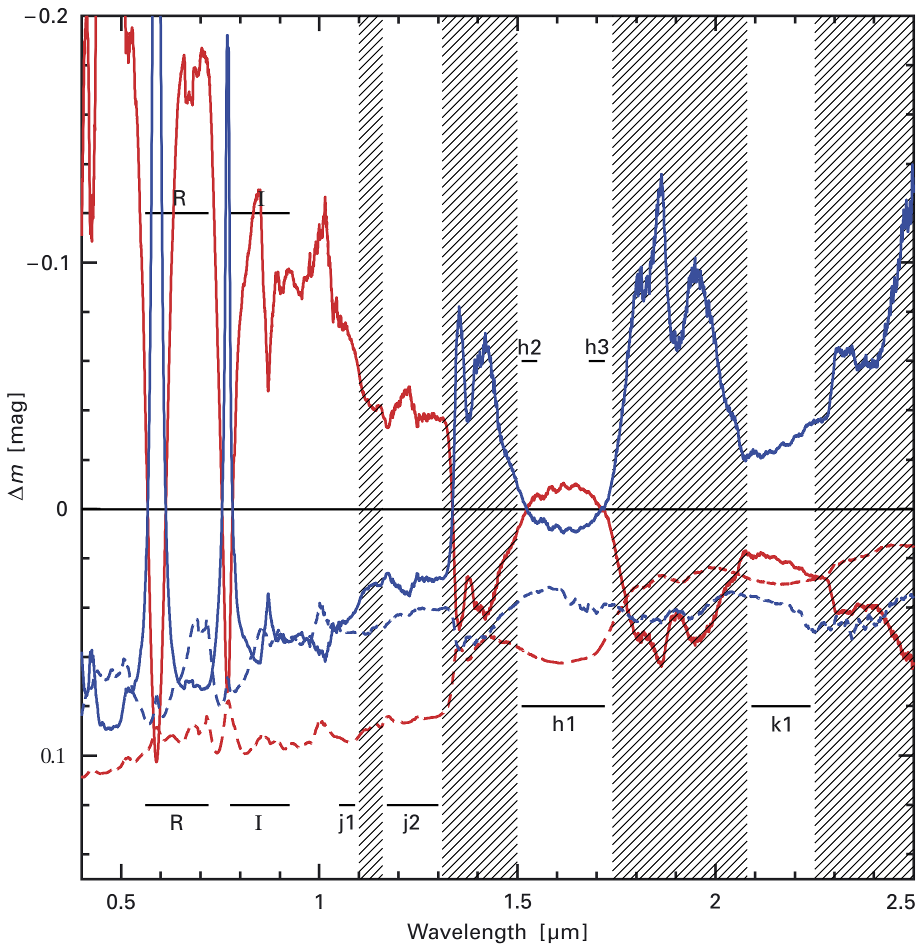


Fig. III.1.9: The blue points show the variation in brightness in the I band of the L1.5 dwarf 2M1334+19. The two sets of red points show the variations of reference stars observed simultaneously (i.e. in the same field). Their light curves have been offset by 0.1 and 0.2 mags respectively. Note that these are relative variations, i.e. the variations relative to a set of (non-variable) stars. This is used to remove spurios variations due to the Earth's atmosphere. Error bars (estimated uncertainties) are plotted for all points. (The lower reference star is brighter than the L dwarf, so has smaller error bars; the upper reference star is similar in brightness to the L dwarf.). We see larger amplitude variations in the L dwarf than in either of these (or any other) reference stars, indicating that the variations are intrinsic to the L dwarf. This is confirmed by statistical tests.

Fig. III.1.10: The solid and dashed lines show the change in the spectrum we would observe due to the variability of different types of dust cloud or cool spots covering 10 % of the surface of an ultra cool dwarf (effective temperature of 1900 K, corresponding very roughly to an early L dwarf). These are theoretical predictions based on atmospheric models and synthetic spectra from France Allard and collaborators. The four lines shown are for the following cases: a dust-free hole on a dusty atmosphere (red solid line) and a dusty but cooler patch on the same atmosphere (red dashed line); a dusty cloud on a dust-free atmosphere (blue solid line) and dust-free but cooler patch on the same atmosphere (blue dashed line). The grey bands show spectral regions hard to observe from the Earth's surface.



axis. However, using simple statistical arguments one can estimate the most likely rotational velocity as well as place constraints on the maximum rotational velocity.) This showed that our Brown Dwarfs were rotating rapidly, i.e. our monitoring should have detected a periodicity in the brightness variations. After all, we had detected a significant variability. So why no period? The most likely explanation is that the variation is nonperiodic. This implies that the features on the surface of the Brown Dwarf are not stable with time, specifically, they would be stable for less than a rotation period. We know that this can happen: on the Sun, the Sun spots change over time, typically only stable for about a rotation period. So could this be happening on Brown Dwarfs? And what are these surface features? Are they really dust clouds?

To study the physical cause of these variations, we have started a program to spectroscopically monitor a number of Brown Dwarfs. Using the latest models of Brown Dwarf atmospheres, we have made predictions of the kind of variations we would see across the spectrum due to the variations in the dust. The most significant variations occur in the near infrared (Fig. III.1.10). However, detecting these is still difficult, because of variations in the Earth‘s atmosphere through which we observe the stars, as well as due to instrumental effects; both of these must be accounted for in the data analysis. Nonetheless, our initial results are interesting. They show evidence for significant variability in a number of parts of the spectrum.

Moreover, some of these variations are correlated with each other, indicating that they are probably intrinsic to the Brown Dwarfs, and not an artefact of the observing. A detailed analysis is still in progress, and firm conclusions must wait for additional observations. It is also difficult to draw unique conclusions, because of the complexity of the physical processes involved. An atmospheric model which includes radiative transfer, dust formation and convective motions is highly complex (indeed, no such self-consistent model yet exists). Thus it is not possible to constrain all parts of such a model with a limited number of observations, so to draw any conclusions we must make certain assumptions. But, tentatively, our data seem to support dust cloud variations in Brown Dwarfs.

Outlook

Brown Dwarf research is going through exciting times. From the first theoretical predictions in the 1960s through detailed modelling and candidate discoveries in the late 1980s and early 1990s, the first bona fide Brown Dwarfs were identified in 1995. Over the past ten years there has been enormous progress in their detection and observational characterization plus theoretical progress in modelling their evolution and atmospheres. Some of the most exciting work is in the mid infrared, for example with the Spitzer Space Telescope, which is invaluabe for probing circumstellar disks as well as Brown Dwarf formation and their very early stages of evolution: this will be vital for assessing how much this has in common with star formation. Likewise, high resolution near infrared imaging is telling us about their binary nature and the statistics of low mass companions, including objects with perhaps just a few Jupiter masses which may well be planets. Deep wide-field imaging surveys will continue to uncover large and fainter populations in the Galactic field and in more stellar clusters, allowing us to look at the evolution of Brown Dwarfs and how this is influenced by their environment. Theoretical advances in the modelling of dust clouds will allow us to better interpret the observed spectra, and more detailed observations, including monitoring and high resolution spectroscopy, will provide more insight into their cool and complex atmospheres.

And as observations push to fainter and lower mass objects, we may soon need a new spectral type beyond the coolest T dwarfs, for those objects with temperatures similar to Jupiter. For Brown Dwarfs, there are exciting times ahead.

(Coryn Bailer-Jones,
Wolfgang Brandner,
Thomas Henning,
Rainer Lenzen,
Stefan Umbreit)

III.2 Dust in the Computer: Numerical Contributions to Planet Formation

Telescopes are the classical tools of astronomers. However, not all cosmic events can be understood by observations alone. Important processes, for instance such as the formation of planets by accumulation of microscopic dust grains, are not accessible to direct observation. Here, computer simulations are brought into play, often called "numerical telescopes" by those who develop them. At the MPIA in Heidelberg, a number of such tools are developed and used successfully for planning and interpretation of planet formation observations.

Astronomy at the Telescope and the Computer

Studying the star formation process has been one of the focuses of astrophysical research during the last two decades. For very massive stars with masses beyond ten solar masses many questions are still open. This is mainly because these stars are relatively rare and form within a short period of time, which seriously limits their observability. For the much more common stars of medium and lower masses, though, a very good understanding of the most important processes of star formation has been achieved meanwhile. Stars in this mass range are of special significance since they are exemplary for studying the evolution of our own solar system and thus the formation of planets such as Jupiter, but also of our home planet Earth.

Astronomy always involves two parts that have to work hand in hand. On the one hand, the observing astronomer has to measure the radiation phenomena of stars and other cosmic objects, while on the other hand, the theoretical astrophysicist tries to explain these observations using laws of nature that have been determined experimentally on Earth. As early as in the mid-20th century it became clear, that the evolution of a star, e.g., cannot be described by the result of a simple equation. Extensive numerical simulations were needed, carried out on mainframe computers then still equipped with electronic tubes, and one was happy when the various evolutionary stages of stars in the computer could successfully be brought into agreement with observations of real stars. Everything we now know about mass, composition and age of a star results from such sophisticated numerical experiments.

In 1995, the discovery of the first extrasolar planet around a solar-like star named 51 Pegasi b came as a real shock to the theoreticians. What was found then was a gas giant the size of Jupiter orbiting closer to its central star than Mercury to the Sun! Up till then models of planet formation had been adjusted to the conditions prevailing in our home system. This new finding now called for some rethinking. In the solar system, terrestrial planets are occupying the inner orbits while gas giants like Jupiter and Saturn are circling the Sun far out at large distances. This seemed to be natural since during planet formation it had been always much warmer close to the Sun than further out. Jupiter, being five times more distant to the Sun than the Earth, is located beyond the so-called "snow line". This defines the distance to the Sun beyond which the gas and dust forming planets are cold enough for molecules such as water to freeze out, thus increasing considerably the amount of material available for the formation of Jupiter. The observational facts – the small planets Mercury, Venus, Earth, and Mars in the inner region and the much more massive planets Jupiter, Saturn und the icy planets Uranus and Neptune far out – were considered to be universal and had been the basis of all attempted explanations, from Kant and Laplace to Weizsäcker and Savronov to the modern models based on recent detailed computer simulations by Pollack and Boss. All these models assume the early Sun to have been surrounded once by a mixture of gas and dust, distributed in a flat disk around the star, similarly to the rings of Saturn. Size and orbiting velocities within this disk corresponded to the present-day solar system. The models only differ in the details of how the planets condensed from this primeval nebula.

Since the discovery of 51 Pegasi b most theoreticians have trouble to explain the existence of massive gas giants on low orbits, so-called "hot Jupiters". But there are at least a few scientist who really enjoy this finding: As early as the 1980s, they had proclaimed a radial migration of young planets. This migration is caused by the planet's gravitational effect on the dusty gas disks as well as by the corresponding retroactive effect on the planet. This theory was more or less ignored at first as no evidence of such a migration was found in our own planetary system. Our planets all seem to be located where they once formed. Since the discovery of many of such hot Jupiters, however, the number of publications on the subject of planet migration has increased exponentially. While in the past these had been papers presenting simple analytic models, nowadays maximum performance computers are used to calculate high resolution three-dimensional models, trying to include all effects ranging from the gas dynamics of the planetary disk to the propagation of radiation within the dusty plasma to the effects of magnetic fields. In recent years, crucial work in this field has been done at MPIA. We will come back to that further below. But first of all, back to the observations!

Planet Formation is Part of Star Formation

Unlike earlier approaches in the field of planet formation, the new ones can now – particularly at MPIA – be based on knowledge gained by studies of star formation. Observing methods can also be adopted from that field since studies of planet formation, like those of star formation before, are profiting from the enormous development taking place in the field of infrared observing techniques since the 1980s.

Why is that so? The answer lies in the nature of the connecting link between star and planet formation – the circumstellar disk. This refers to the disk of gas and dust that develops around the young protostar from infalling matter from the parent molecular cloud as a result of the conservation of angular momentum. According to our observations, these disks typically are a few hundred Astronomical Units in diameter and have a mass of about $^1/_{100}$ the stellar mass. (One Astronomical Unit, AU, is defined as the mean distance between the Earth and the Sun.) Although dust grains – originally sub-micrometer particles – constitute only about $^1/_{100}$ of the total mass of the gas dominated disk, they are of particular importance for observing the structure of the disk because of their optical properties. The gas alone is mostly transparent. So what can be seen is essentially the dust. For one thing, the stellar radiation scattered by the dust enables us to observe the outer shape of the disks. For another thing, the inner structure of the disks can be inferred from the thermal emission of the dust. This radiation can be observed from the near infrared to the millimeter wavelength region, corresponding to the temperature of the dust that ranges from up to 1500 K at the inner edge of the disk, i.e. close to the star, to the cold dust in the outskirts.

The absorption and emission properties of an individual dust grain can be determined experimentally as a function of its chemical and structural composition and its size. But in order to determine the combined properties of all the countless dust grains of various compositions and sizes that comprise the protoplanetary disk, complex calculations using powerful computers are needed. At MPIA, several numerical tools are available for these tasks, like, e.g., the three-dimensional radiative-transfer program by Sebastian Wolf. It uses the so-called Monte Carlo method. This name does not imply that one has to be especially lucky in operating this program successfully but that a random element is included in the algorithm in order to obtain statistically reliable results.

The operating principle of this program is quite easy. Like in "real" stars, photons are emitted from the stellar surface in random directions towards the surrounding disk. The photons can be scattered or even absorbed by dust grains there, thereby heating the disk – exactly as in reality. After following more or less complicated paths through the disk, the photons can leave the star-disk system and be observed by telescopes simulated in the computer. Simulations with millions or even billions of such photons then allow to create images and deduce other observational quantities. Depending on which telescope is simulated in the computer, images can be produced as they would be observed by the HUBBLE Space Telescope or spectral energy distributions as they would be measured by the ISO satellite – partly developed at MPIA – or the SPITZER Space Telescope. In addition to the interpretation of observational data already obtained the computer-simulated telescope is able to study observations expected from future instruments, e.g. the (sub-)millimeter interferometer ALMA (Atacama Large Millimeter Array) currently under construction or the future 100-m-OverWhelmingly Large Telescope (OWL).

Within the computer, the properties of the dust can now be varied and the effects on the observations investigated. By reversing the conclusions the differing of the dust properties from one observed circumstellar disk to the next can subsequently be deduced from the observational data. As with stellar evolution mentioned above, we hopefully will be able to learn something about circumstellar disks evolving into planetary systems.

Dust Grows to Form Planets …

Besides making circumstellar disks observable, the dust there is of great significance in still another respect: It is generally believed today to constitute the raw material for the formation of all planets. In this respect the disks are often called "protoplanetary" instead of "circumstellar"

But how do dust grains less than a micrometer in diameter evolve into planets at least some thousand kilometers across? This process is assumed to run through three qualitatively different stages.

During the first stage, the microscopic dust particles grow into grains with radii in the centimeter range. The dominating process here is called coagulation, meaning the simple and – according to laboratory experiments – very efficient sticking together of small dust particles. Prerequisite for this is the Brownian motion of the tiny particles. Adhesion is accomplished by surface forces, necessitating no special adhesive. Additional important physical processes during this stage of growth are the sinking of larger particles towards the central plane of the disk ("sedimentation"), radial transfer processes (drifting and mixing processes) as well as turbulences within the disk. This entire stage is probably very short, lasting only ten to one hundred thousand years.

The further growth towards bodies several kilometers in diameter by similarly simple coagulation seems to be unlikely. To date, neither experimental data nor theoretical models are able to explain convincingly this phase of growth. We do not know how two stones as big as a fist should stick together, nor do we know to which degree colliding rocks several meters in diameter would disintegrate into dust again. A theoretical and computer-based alternative would be gravitational collapse. Like the star that once formed from a molecular cloud, the kilometer-sized chunks, called planetesimals, also might form during the gravitational collapse of a cloud of meter-sized rocks. The relevant computer simulations are subject of current research, also at MPIA.

A second stage of growth begins as soon as 1 to 10 km sized planetesimals have formed. The biggest of these bodies are able to accrete smaller ones by gravitational interaction. This stage is characterized by rapid growth of a few big bodies and therefore is also called “oligarchic” growth. Terrestrial planets and the cores of future giant planets presumably are formed after several million years. During the third and final stage the latter then accrete gas from the disk – and the gas giants are born.

The formation of planetary cores as well as the accretion of gas have long been simulated in computers. A major problem, however, are the timescales predicted for these processes by the simulations. Under favorable conditions, each process apparently takes ten million years, which seems too long in view of a life expectancy of less than ten million years as it has been estimated observationally for protoplanetary disks. So one tries to feed computers with increasingly detailed models, including more and more relevant physical effects that accelerate the planet formation process. An alternative formation scenario should be mentioned according to which the gas planets, like the central star before, form very rapidly through gravitational collapse directly from the gaseous phase of the primeval nebula. But here, too, numerical simulations did not produce a definite result.

... and is Observed Doing so!

So far the theoretical predictions. What possibilities do we have, besides laboratory experiments dealing with the growth of smallest particles, to test this picture? For one thing, one can simulate how the optical properties of the dust change during its evolution and look specifically for these larger dust grains. For another thing, one can consider the retroactive effects planets already formed would have on the circumstellar disk, rendering them – possibly indirectly – detectable. The second question will be examined separately in the penultimate paragraph.

How can small dust particles, i.e. sub-micrometer grains, be distinguished from those with radii 10 to 1000 times larger? There are several approaches that are shortly presented in the following:

Spectral Energy Distribution in the (Sub-) Millimeter Region

Since only a few images of spatially resolved circumstellar disks are available, the interpretation of the spectral energy distribution plays a pivotal role (Fig. III.2.1). Unfortunately, so many free parameters exist even for simple disk models that a unique model is hard to find. Therefore detailed interpretations, sometimes even predicting the properties of the dust, should be taken with a grain of salt. In particular, the spectral energy distribution in many circumstellar disks was found to decline slower at wavelengths beyond 400 micrometer than that measured in interstellar clouds. In the past, one was easily tempted to attribute this fact to a lower emission exponent caused by growing dust grains. This approach, however, is only justified if the disk is optically thin in this wavelength range. If this is not the case, the visible dust mass increasing towards longer wavelengths alone would explain the slower decline of the spectral energy distribution.

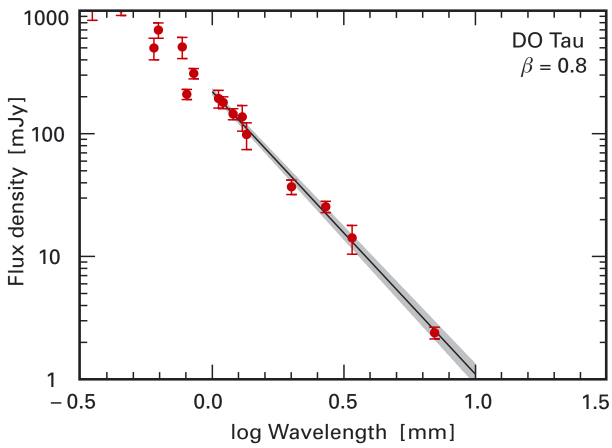


Fig. III.2.1: Spectral energy distribution of the cicumstellar disk around the T Tauri star DO Tau in the millimeter range. The relatively flat decline of the radiation flux in this wavelength region can be interpreted as evidence for dust growth. (Rodmann et al.).

Shape of Characteristic Dust Emission Bands

The most prominent solid-state emission band observable from the ground is the 10-µm-band of astronomical silicate. When silicate grains reach a size of a few micrometer this band has a characteristic plateau shape, while it vanishes completely for still larger grains. Dust growth particularly in the inner regions of circumstellar disks was detected through this effect using the MIDI Mid-infrared Interferometric Instrument.

Polarization of Scattered Radiation

Dust scattering in the upper disk regions polarizes the stellar radiation. Since the degree of the polarization crucially depends on the particle size this method can be used to investigate if particle growth plays a role in the upper disk layers or in the circumstellar envelop.

Spatially Resolved Images in Various Wavelength Regions

The so far soundest method of analyzing dust growth within the disks is to include spatially resolved images of circumstellar disks in addition to a combination of the methods presented above. An important point in doing this is to obtain these images in different wavelength ranges in order to cover various disk regions and physical processes.

As an example we will present here results for the prominent edge-on disk of the "Butterfly Star". High-resolution near-infrared images taken with the NICMOS camera on the HUBBLE Space Telescope, which show the contours of the disk and the circumstellar envelop in scattered light, were used as well as spatially resolved millimeter maps obtained at the Owens Valley Radio Observatory (OVRO), which show the thermal re-emission of the dust within the dense central plane of the disk. In addition, polarization maps in the near-infrared region and the spectral energy distribution ranging from the mid-infrared to the millimeter region were used to interpret the data. The difficulty now was to find a unique model to fit all the observational results.

For such a complicated type of problem the radiative-transfer simulations mentioned above are imperative. Only then images, spectra, and polarization maps can be derived for the disk models developed and then be compared to the observations.

In the case of the Butterfly Star (Fig. III.2.2), the dust within the circumstellar envelop and at the surface of the disk was shown to still resemble the interstellar dust, not having undergone any modifications yet. Dust particles within the dense interior regions of the disk, however, have grown already by several orders of magnitudes – just as it is expected for the first stage of planet formation!

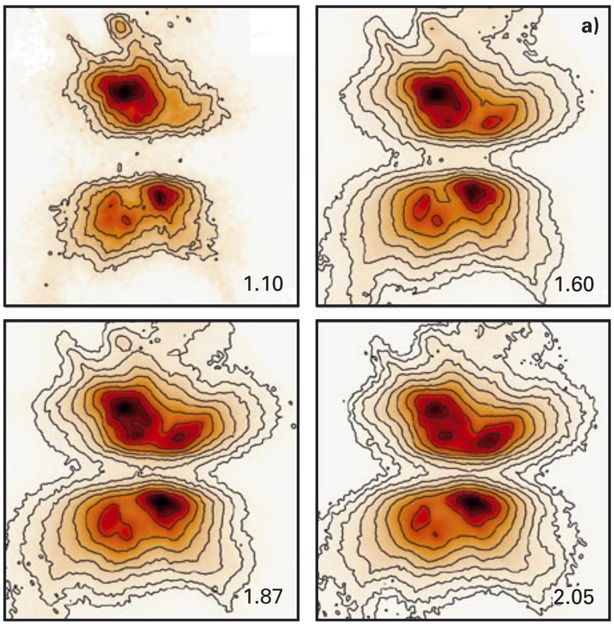


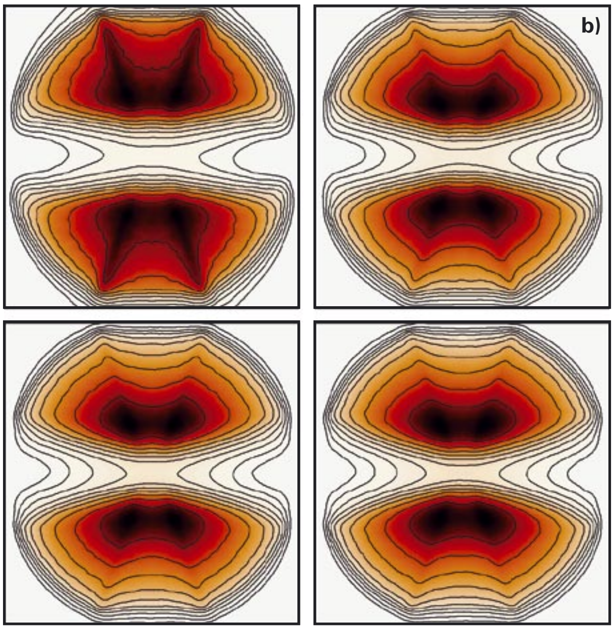
Fig. III.2.2: a) Near-infrared images of the edge-on, prominent circumstellar disk and envelop around the Butterfly Star in Taurus (IRAS 04302+2247). The images were taken with the HUBBLE Space Telescope at wavelengths of 1.10 μm, 1.60 μm, 1.87 μm, and 2.05 μm. The apparent decrease of the thickness of the disk with increasing wavelength is clearly visible. b) Simulated images in scattered light which were compared to the observations in order to deduce the spatial structure, mass and other physical quantities of the circumstellar medium around the Butterfly Star. c) Comparison of observed and simulated millimeter maps of the circumstellar disk around the Butterfly Star. (Wolf, Padgett and Stapelfeldt, 2003).

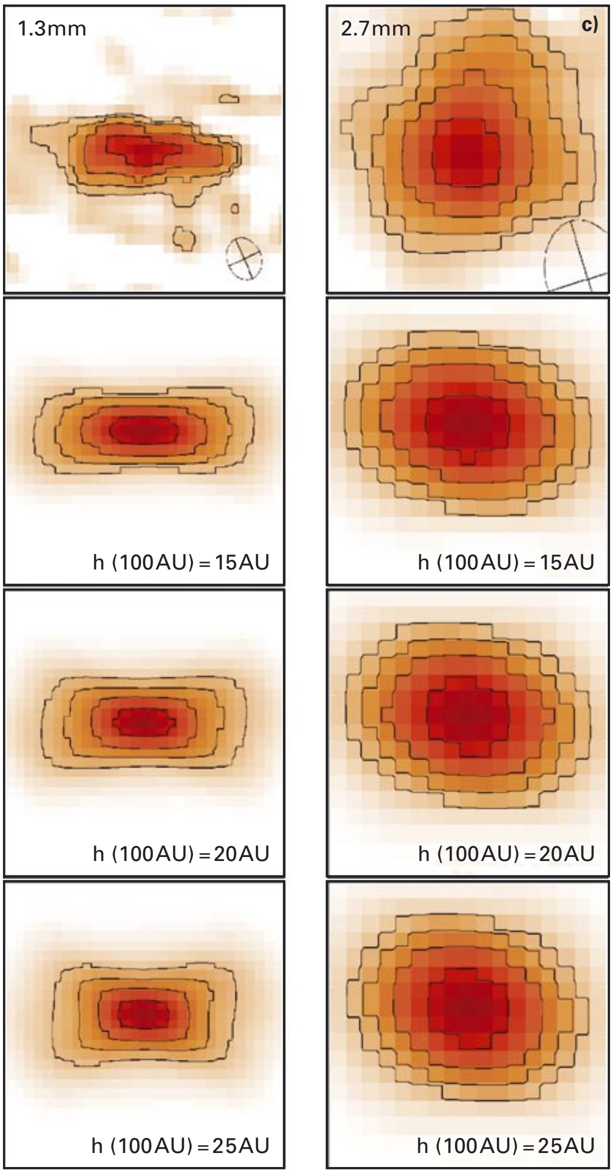
Computer Models of Dust Swirling within a Turbulent Disk

The appearance of protoplanetary disks depends, as we now know, on the distribution of the dust. The distribution of the dust grains, however, is affected by two effects. Firstly these are: growth and transport.

Growth occurs when two microscopic dust particles, driven by Brownian motion, collide. The particles then very easily stick together, forming somewhat bigger grains and thereby changing their optical properties. Expressed in simplified terms, the dust is more and more difficult to detect with increasing size. On the one hand, scattering is only important as long as the size of the dust grains is similar to the wavelength of the light; on the other hand, the opacity, i.e. the shadowing area of a dust grain compared to its mass, is decreasing with increasing particle size. At the same mass, larger grains present less surface area to absorb radiation. So when the dust disappears from photographic images this can be interpreted as growth.

A second explanation for the disappearance of dust, however, is sedimentation towards the central plane of the disk (transport). In a calm study, the house dust is rapidly sinking down, accumulating on the desk and books. A tropical cyclone, on the other hand, can blow sand across the Mediterranean Sea, uproot trees and unroof houses. And dust has no chance at all to settle. So it





is easily appreciated that it makes a big difference for the distribution of the dust and even bigger chunks in the protoplanetary nebula, depending on whether the conditions within the disk are calm (laminar) or stormy (turbulent). Unfortunately, turbulence within a disk cannot be inferred from observations yet. There is only very indirect evidence for the presence of turbulence: the observed mass flow from the disk onto the star. In a laminar disk, the flow is prevented by the fundamental principle of the conservation of angular momentum. Like our Moon that is orbiting the Earth year in, year out, the disk material cannot simply fall onto the star. Only if the disk gas is highly turbulent, angular momentum can be transported outward through turbulent viscosity, allowing the gas to fall inward onto the star. The gas is getting extremely hot when it hits the star, even hotter than the stellar surface, that is already hot as it is. In some young stars with disks, this ultra-hot gas can be observed through an excess of ultraviolet emission, indicating that for these stars at least the inner parts of the disks are turbulent. For the outer parts of the disk, however, we depend on computer modeling. Here, too, a definite answer about the weather conditions within the protoplanetary disk is still missing. At present, conditions similar to that on Earth are assumed. Sometimes it would be calm, and then it would be stormy again. And even if a hurricane were raging in Florida, the sun could be shining and a gentle breeze be blowing in Heidelberg.

Turbulence not only influences the dust to settle or not, it also has an effect on the growth process itself. As the biggest hailstones will come from the heaviest thunderstorms, the dust lumps sinking to the central plane of the solar nebula will be bigger if the disk is turbulent. Chunks not only sink to the central plane of the disk but also drift radially inwards towards the star. In a laminar disk, one will find meter-sized objects virtually raining down onto the parent star. The reason for this is a vertical and radial atmospheric pressure stratification in the disk. This stratification determines the rotational velocity of the disk, which therefore is slightly slower than the Keplerian value. So the rocks moving on Keplerian orbits feel a headwind causing them to spiral inwards until they rain down onto the star. Here, too, as in the picture of the formation of hailstones, the turbulence can delay the precipitation so that the chunks already have grown to larger bodies, i.e. to dimensions where headwind and raining down do no longer play any role. Of course, all these investigations are only possible on the computer. In Heidelberg, we presently study the swirling of dust in magnetic storms (Fig. III.2.3). Our simulations solve the magneto-hydrodynamic equations on a grid, simultaneously calculating the turbulent motion of the dust particles. As a result we get the transport properties of the turbulence for the dust in terms of diffusion coefficients. Calculations of that kind require some weeks of computing time on the fastest mainframe computing systems available to us.

The growth process from meters to kilometers and to planetary cores will continue to be restricted to theoretical models for still a good while as all these objects remain hidden from view. Only its result, namely a young planet, is observable again and can be used to test evolutionary models describing its formation.

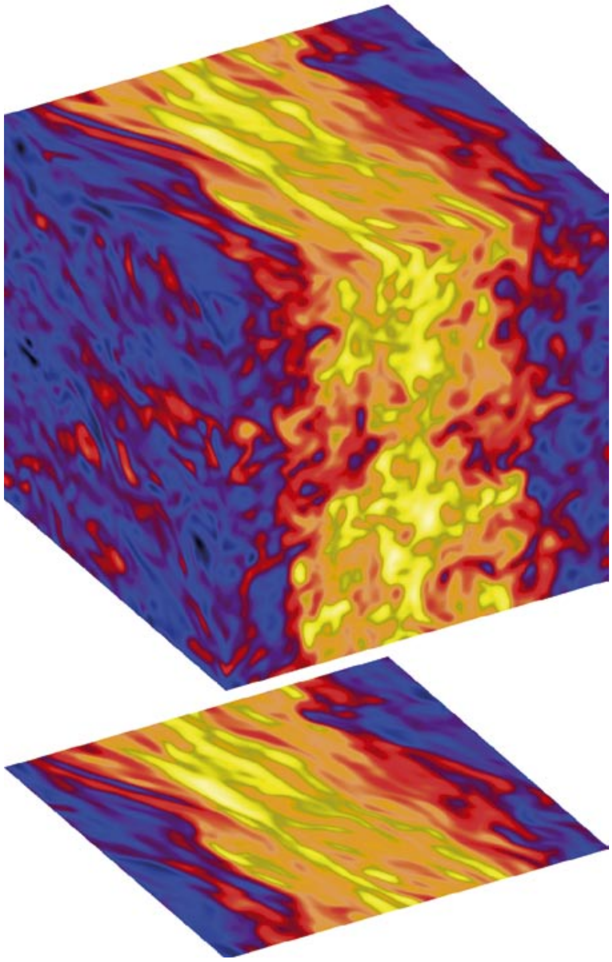


Fig. III.2.3: Diffusion of dust within the magnetically driven turbulence of a protoplanetary disk (yellow – high, blue – low dust density). The figure shows a small cubic section of the accretion disk. From such complicated three-dimensional turbulence simulations the distribution of dust in real circumstellar disks can be deduced.

Images of Newborn Planets. Searching for Planets in Circumstellar Disks

Is there any possibility to detect newborn or also older planets in circumstellar disks? As we have learnt above, circumstellar disks are considered a natural side effect of star formation – at least for lower and medium mass stars, the so-called T-Tauri and Herbig-Ae/Be stars. The disks provide the material and the environment from which and in which planets can form.

In developing search strategies for planets at their place of origin one has to take into account that circumstellar disks and the suspected planets within them are subject of constant evolution. Search methods for planets within disks have to be adapted to the evolutionary stage of the disks.

To come to the point: Present-day observing instruments or those expected for the near future will hardly allow any direct imaging of a young planet in orbit around a star still surrounded by remains of disk material. The disk would outshine an embedded planet in all wavelength regions. Yet numerical simulations show planets to evoke, through gravitational interactions, characteristic large-scale perturbations within the disk structure that can be observed and from which the presence of a causative planet can be inferred. These planets, though, must be sufficiently massive in order to significantly affect the structure of the disk. Evidence of planets within disks will thus be provided most likely by the detection of gas giants.

Gaps within Disks

But what are the characteristic indications of planets within circumstellar disks? Let us start with the youngest planets located in disks which are still optically thick and structurally characterized by the dynamics of the mass dominating gas. Such disks are found around the T Tauri and Herbig-Ae/Be stars mentioned above, having ages between under one million and a few million years. Hydrodynamical simulations of gas-dominated, viscous protoplanetary disks show an embedded planet to be able to open a gap within the disk along its orbit. The width of such a gap depends on the mass and orbit of the planet as well as on the hydrodynamical properties of the gaseous disk. It can be wider than one AU, thus being larger by several orders of magnitude than the planet causing it.

Using radiative-transfer simulations, it was investigated if such a gap would actually be found on high-resolution images. After all, not only the gas but the more easily detectable dust too can be assumed to have a lower spatial density within the gap region than in the surrounding disk material. As it turned out, sub-millimeter and millimeter observations will enable the imaging of such gaps and thus provide indirect evidence of young planets. The masses of planets to be detected indirectly this way have to be at least 1/10 the mass of Jupiter in order to leave a significant "footprint" within the disk.

These observations will be conducted with the ALMA Atacama Large Millimeter Array planned to be put into operation a few years from now in the Atacama desert. In concrete terms, the simulations predict the gaps to be easily detectable in disks around stars located in the nearest rich star formation regions, e.g. in the constellation Taurus at a distance of about 140 pc, provided they do exist and this picture of planet formation and planet-disk interaction matches reality. Numerical simulations thus allow definite predictions making our current notion of the evolution of young planets within disks verifiable.

For the sake of completeness, we should also mention spiral waves excited by protoplanets within the disk (Fig. III.2.4). However, the density contrast produced by these waves is too low to be detectable. Moreover, these waves probably are attenuated very effectively by turbulences in the disk and thus would hardly be recognizable.

Planets, too, Are Accreting Matter – Revealing Themselves by their Warm Surroundings

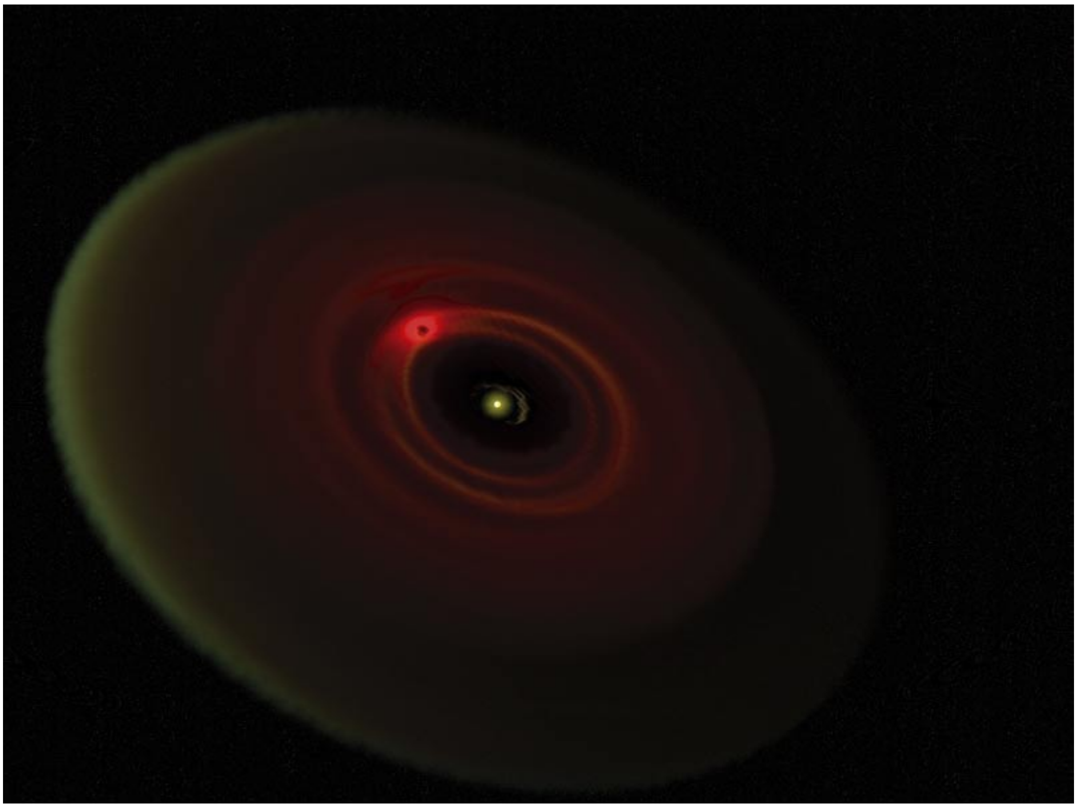
ALMA, though, will allow us to even go one step further. Young planets embedded within gaseous disks can continue to accrete gas, even after having opened a gap. Only when a planet has reached a mass of about ten Jupiter masses, tidal forces will become strong enough to stop any further gas flow into the gap and thus onto the (proto-)planet.

Like accretion onto the central star, accretion of gas and dust onto the planet will occur via an accretion disk. In numerical simulations, such a planetary accretion disk has actually been found in the immediate surroundings of the planet. During the accretion of matter onto the planet the gravitational energy of the infalling material is being released, contributing to the heating of dust around the planet (Fig. III.2.5). Moreover, the young planets themselves are still very hot: Producing energy by contraction, they can reach surface temperatures of several hundred Kelvin or even more than 1000 Kelvin. In any case, one would expect the matter close to the planet to be significantly warmer than the surrounding disk material. The planet and its environment therefore should make themselves conspicuous as a hot spot within the disk.

Here again numerical simulations are needed to quantify the actual order of magnitude of this effect. Only this way we will finally be able to decide whether we should search for "hot spots" in the disk as the most conspicuous indications of planets so far.

The results of the simulations are encouraging: On the sub-millimeter and millimeter images, the warm, dense dust in the region around the planet really stands out clearly against the dust-depleted gap (Fig. III.2.6). And again, this hot spots will be observable with ALMA . The only sour note: The number of objects which sensibly can be searched for hot spots is somewhat more limited since these structures are smaller than the gaps themselves. Young stars at distances up to 100 pc will be on the observing list. Moreover, the sufficiently massive planets have to orbit the star at a distance of a few AU: A young Jupiter (distance from the sun: 5.2 AU) could be found this way.

Fig. III.2.4: A young planet with the mass and at the location of the present-day Jupiter opens up a gap within the protoplanetary disk from which it had formed. This three-dimensional radiative-hydrodynamical computer simulation essentially shows thermal emission of dust. The generation of heat by gas falling onto the planet is clearly visible. (From Klahr and Kley, University of Tübingen)



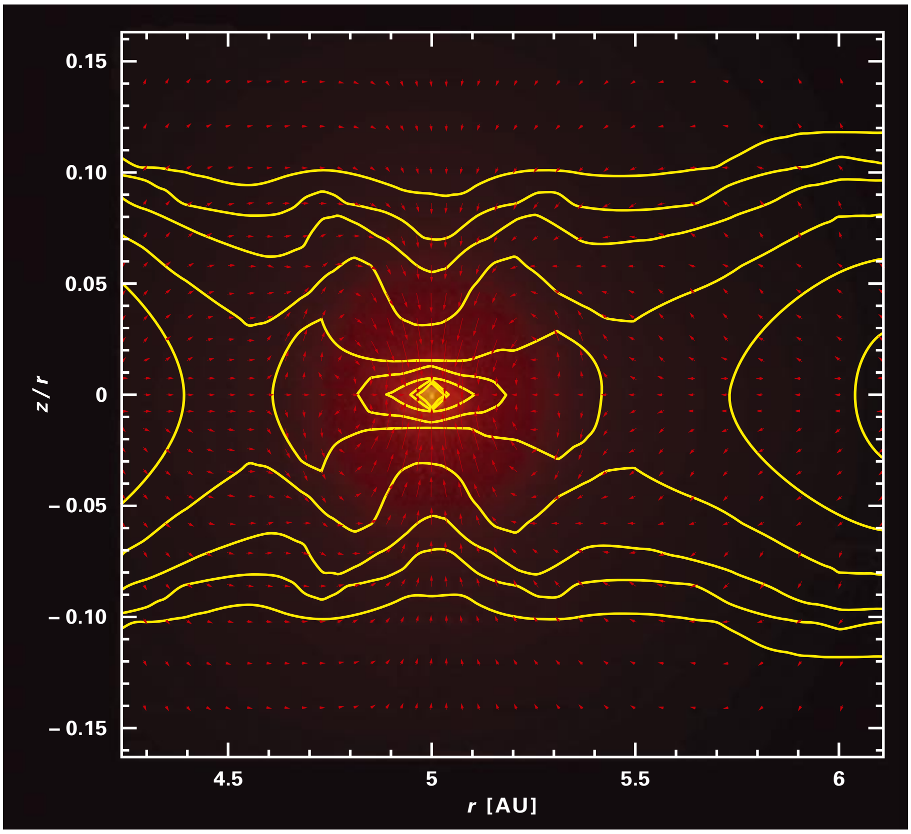


Fig. III.2.5: As in Fig. III.2.4, the young planet within the protoplanetary disk is shown – here in a radial and vertical sectional view through the gas close to the planet. Contour lines mark the gas density, revealing the disk-like structure around the planet. Arrows indicate the gas flow onto the planet. The temperature resulting from accretion is represented by the colors. The planet apparently is surrounded by a huge envelope of warm dust, which probably will be its first observable sign of life. (From: H. Klahr and W. Kley, University of Tübingen)

Planets Within Old, Evolved Dusty Disks

Finally, we will take a look at debris-disks. These are circumstellar disks at the end of their evolution, in which the formation of planetary systems – if extant at all – is already completed. They are called debris-disks since besides the planets they contain only the remains of planet formation – comets, planetesimals, and dust. These disks are optically thin. Apart from gravitation, their structure is therefore determined by the interaction of the stellar radiation with the dust. Our solar system can be considered a representative of this object class.

For the observation and investigation of debris-disks too, micrometer dust particles are of great importance. The dust in these disks, however, is no longer the original one stemming from the parent molecular cloud, the one being discussed as the seeds for planet formation. It is rather a second generation of dust constantly supplied by collisions of planetesimals. Like the original dust, the newly produced dust grains are being continuously removed through the stellar effects described above: The dust grains are either forced into spiral orbits ending on the star by the Poynting-Robertson effect – or they are "blown" out of the disk by stellar radiation pressure. Which effect dominates, essentially depends on the size and the chemical composition of the dust particles.

In debris-disks, too, massive planets cannot move unnoticed along their orbits. But here, in contrast to the gas-dynamical effects describing the interaction of planets with young, gas-dominated disks, it is the effect of the planets' gravitation that forces the dust within the disk into unusually structured distributions. A characteristic feature is the accumulation of inwards drifting dust particles at resonance points along the orbit of the planet. And gravitational scattering of the dust by planets prevents or almost prevents the dust produced within the outer planetesimal belts to reach regions within the orbit of a planet. How dust deficient the region of a planetary system enclosed within the planetary orbit will be, logically depends significantly on the mass of the planet (Fig. III.2.7).

Are the effects caused by planets observable in debris-disks? Yes, since the effects described change the distribution of dust in debris-disks over such large regions that they can be spatially resolved and thus detected even with present-day observing instruments. Again the images obtained in the far-infrared to millimeter-wavelength region are the ones to reveal best the typical resonance structures or dust-depleted inner regions in debris-disks. This is due to the low temperature of the dust in the outskirts of the disk, whose thermal re-emission is observed at these wavelengths.

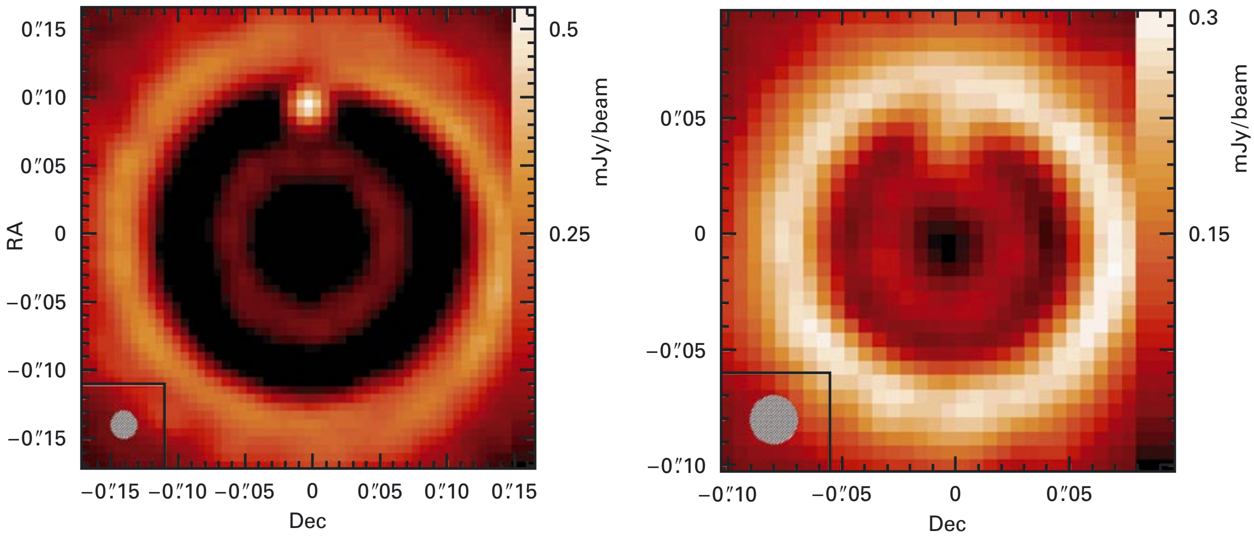
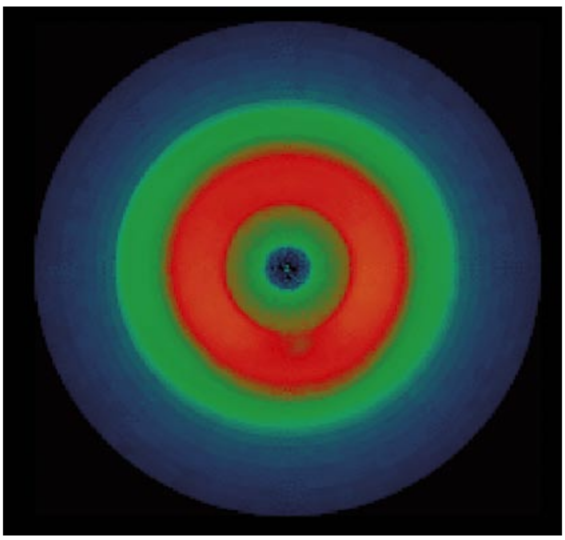


Fig. III.2.6: Young planets in gas-dominated disks will be detectable through the gap along the orbit of the planet. Moreover, young planets are assumed to make themselves conspicuous by the warm dust in their surroundings. These images show how the gap and the warm region around planet of one Jupiter mass at 5 AU distance from the central star would look like if we would observe such a system a few years from now with ALMA. The assumed distances are 50 pc (left) and 100 pc (right). (Wolf and D'Angelo 2005, ApJ)

In addition, it is possible to infer the presence of dust-depleted regions around the star from spectra of debris-disks obtained in the near- to mid-infrared range: The closer the dust is to the star, the warmer it is. Missing dust close to the star is reflected in a lower flux in just this wavelength region.

Numeric simulations of debris-disks can be used for a more detailed analysis of images of debris-disks. Instead of simply stating that the effects of a planet have to be responsible for the observed structure of a debris-disk, comparison with simulations allow to draw conclusions about the mass and the exact orbit of the planet as well as about the dust observed – the site of its formation and its typical size.

Fig. III.2.7: Simulated debris-disk of the early solar system at 1.3 mm wavelength. The position of Neptune is marked. The horseshoe-shaped distribution of dust particles along the orbit of Neptune can be seen. Obviously, Neptune also very efficiently keeps the inner region of its orbit free of dust grains produced by collisions of planetesimals in the Kuiper belt located outside its orbit. (S. Wolf and A. Morio-Martin).



Conclusions and prospects

Numerical simulations show that forthcoming telescopes and observing instruments will allow the detection of planets in cirumstellar disks. Scattering of the stellar light and thermal emission of the smallest dust particles, however, will make direct imaging of planets difficult. But planets do impress characteristic large-scale signatures onto circumstellar disks, which will be observable within a few years time with observatories such as the Atacama Large Millimeter Array (ALMA), the Stratospheric Observatory For Infrared Astronomy (SOFIA), and the James Webb Space Telescope (JWST). Primary signatures are gaps within young disks and asymmetric density distributions in debris-disks.

All these future observations will help to create a clearer picture of planet formation by constraining the large number of free parameters in our numerical models. Thus we hope to get a little closer to the great issue of the origin of our home planet and of the frequency of Earth-like planets around distant suns.

(Hubert Klahr and Sebastian Wolf)

III.3 Even Closer to the Centers of Galaxies

All massive galaxies possess a pronounced center, where both the density of stars and the abundance of molecular gas is increased at least tenfold above the average. But a few percent of the galaxies harbor in their centers a special engine, that is much more powerful than a concentration of stars and gas could explain – we call those centers »Active Galactic Nuclei« (AGN). Profiting from its privileged access to worldwide unique instruments at the Very Large Telescope (VLT) on Cerro Paranal in Chile, the MPIA is carrying out a project to unveil the secrets how the central engine in these AGN could work. To this end we use a combination of high and very high angular resolution, which brings us observationally closer and closer to the very source of action.

The common source of radiation in today's universe are stars which generate their power by nuclear fusion. We know, however, that the extremely energetic processes occurring in the Active Galactic Nuclei cannot be generated by normal stars but have to be related to a more exotic process, which is able to release 10^{35} $–10^{39}$ Watt continuously over periods of about 10^7 years. The most extreme case of such nuclear activity occurs in quasars, where the nucleus itself is so luminous that it outshines the entire galaxy with its billions of stars by orders of magnitude. More than 30 years ago, the British astronomer Donald Lynden-Bell (1969) suggested that active galaxies are fuelled by accretion of matter onto super-massive black holes located at their center. At later time, when the supply of matter is quenched, the activity halts, but the massive black hole remains at the center of the galaxy. Accordingly, these massive dark compact objects should be present in the nuclei of many quiescent galaxies, may be even in all galaxies, as the remnants of a previous quasar phase. And indeed, this seems to be much the case: the observational evidence accumulated in the last years for the presence of a supermassive black hole in our own, now rather peaceful, Milky-Way galaxy is very solid, but it is also so in many other nearby galaxies. Current measurements indicate that these central black holes have masses of 10^6 – 10^9 times the mass of the sun concentrated in a region not bigger than our solar system. The gravitational pull produced by such a high mass concentration must be felt by the stars and the gas in its immediate vicinity. Thus, even if we cannot see the black hole directly, we can infer its presence by studying the stars and gas in its surrounding. Hence, the astronomer's ambition is to investigate the centers of galaxies with the maximum possible spatial resolution.

A difficulty in studying centers of galaxies is the fact that many of them seem deeply embedded in dust, which efficiently absorbs a considerable amount of light from these regions, preventing us to get a clear view onto the central engine. Thus, besides very high spatial resolutions, the study of centers of galaxies requires observations in a range of the electromagnetic spectrum where the effect of dust absorption is minimized. This is indeed possible at wavelengths other than those in the familiar visible range, i.e. at the shortest X-ray wavelengths or at long wavelengths in the infrared and radio ranges. In the near infrared (near-IR), at about 2 μm, the effect of dust absorption is already five times less important than in the optical range; in the mid infrared (mid-IR), at wavelengths longer than 10 μm, it becomes almost negligible. Moreover, the dust is heated by the absorption of ultraviolet and optical light to temperatures of several hundred Kelvin. The emission of this warm dust can be observed at mid-IR wavelengths directly.

Realizing the potential of infrared observations for dust-embedded sources – besides for galactic nuclei also for stars in the early period of their formation – the Max Planck Institute for Astronomy in Heidelberg developed state of the art instrumentation based on adaptive optics and interferometric techniques that allow us to map the nuclei of galaxies at unprecedented spatial scales, down to a few tens of milli-arcseconds (1 mas = $^1/_{1000}$ arcsecond = 2.8×10^{-6} degree). So far, scales well below one arcsecond have only been accessible in the optical, with the Hubble Space Telescope, and in radio, with long base-line interferometry. One of these instruments is NAOS-CONICA (NACO), a near-IR (1 – 2.5 μm) imager and spectrograph which allows to correct the blurring of astronomical images due to the atmosphere, operating at the ESO Very Large Telescope (VLT) at the Paranal observatory (see Annual Report 2002). The second is MIDI, a mid-IR (8 – 13 μm) interferometer, which allows to combine the individual 8m telescopes of the VLT to a giant telescope with an equivalent diameter of 120 m (see Annual Report 2003).

Our group at the MPIA is using these instruments to get images and spectra of the nuclei of the nearest galaxies in the southern sky. For most of our targeted objects, the achieved resolution means, that we are approaching the very center of the galaxy within 1 to 10 parsec (1 parsec corresponds to 3×10^{15} m). For the closest objects, we are resolving the radius of influence of the black hole, for most objects we are just reaching it. Nevertheless, these distances place us a factor between 10 to 30 times closer to the center than it was possible before in the mid-IR.

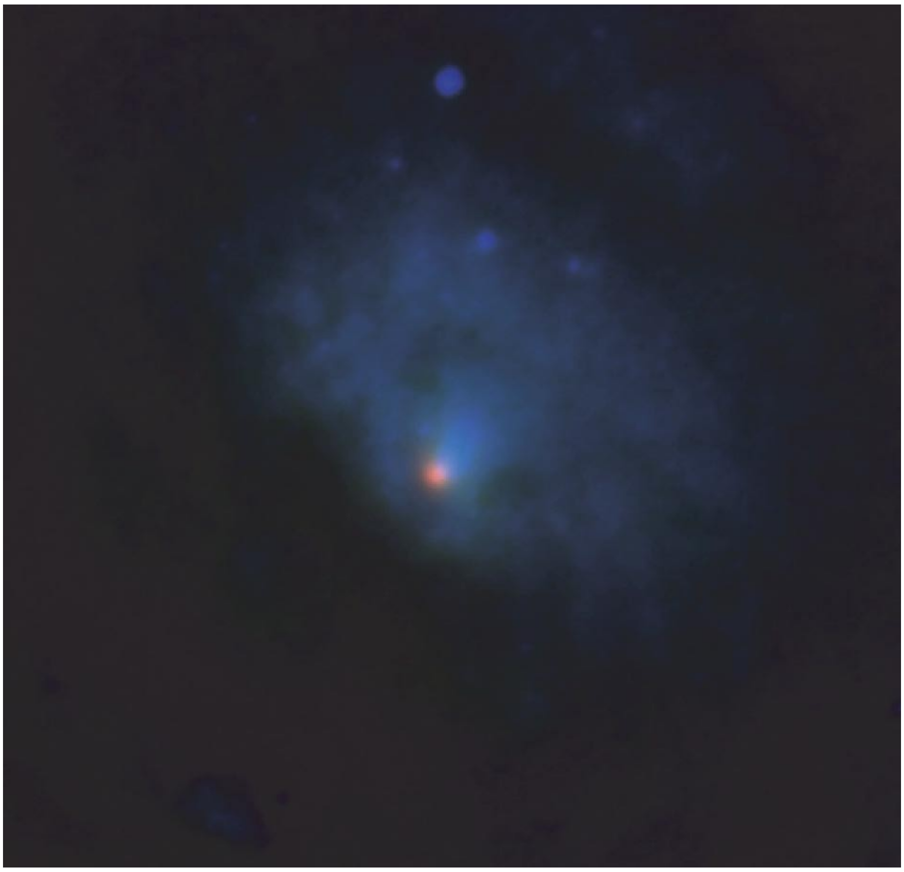
The goal of our project is to collect direct observational evidence for (or against) the now widely assumed picture how the central power-house in active nuclei could work: In its very center sits a super-massive black hole of mass between 10^6 (Milky Way) and a few times 10^9 solar masses (luminous quasars).

Material flowing into the center, because of its associated angular momentum, will not be directly swallowed by the black hole; instead, it will set in an accretion disk around the black hole the size of which may extend up to a tenth of a parsec for a typical black hole mass of 10^8 solar masses.

In the accretion disk the material loses angular momentum by friction, spirals in, heats up to about 100 000 Kelvin due to the friction and is eventually swallowed by the black hole. Most of the generated power is radiated away in a very wide spectral range between short X-rays and IR wavelengths. However, detailed calculations show that friction is not enough to carry away angular momentum but polar outflows from the disk are needed as well.

Models predict that further out gas and dust around an active nucleus should be distributed in a toroidal structure with the active nucleus at the center. The absorption by this dusty structure may, depending on its orientation, hide the nucleus from us but will nevertheless allow radiation from the active center to escape into polar directions. In the simplest model the axes of the accretion disk and of the surrounding gas torus coincide. The escaping radiation will take in general the form of a cone, the opening angle of which is confined by the inner walls of the torus. Often polar outflows of gas or even well collimated jets are observed as well. The torus is expected to have sizes of a few parsecs to several tens of parsec with pronounced gradient in temperatur (hotter than 1000 Kelvin at the inner wall, dropping to several tens of Kelvin further out). Because of its temperature the torus primarily radiates in the mid-IR range. The outward decrease in temperature should result in its apparent size increasing with wavelength.

Fig. III.3.1: The central 100 pc region of the Circinus galaxy (composite image: red – NACO 2 µm, green – NACO 1.3 µm, blue – HST 0.8 µm). The red source can be interpreted as direct or scattered light from the walls of a dusty torus. A rather collimated light beam – bright elongated region at position angle of ~ –45° – points away from the red source. The nature of this continuum light beam is not clear to us; most likely it is scattered light from a collimated beacon similar to the phenomenon of a lighthouse in a foggy night.



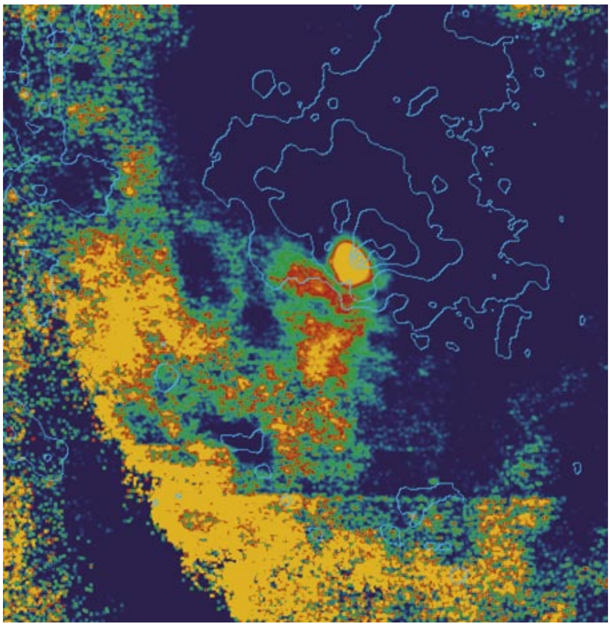


Fig. III.3.2: NACO J-K color map of Circinus showing a slightly elongated central source. The elongation direction is just perpendicular to the Circinus Hα ionization cone which is shown in contours.

The dust-enshrouded active nucleus of the Circinus galaxy

As early results from MIDI, which for the first time resolved the mid-IR emission from the dusty torus of the proto-typical Seyfert II galaxy NGC 1068, have already be presented in last year's annual report, we want to focus on results from the near-IR NACO instrument. Although its spatial resolution is inferior to the MIDI interferometer, it has the advantage that it produces direct images and spectra with a resolution which is three times better than that of the HST in the near-IR.

Fig. III.3.1 shows a NACO composite image of the central region of one of the nearest active galaxies in the southern hemisphere: the Circinus galaxy. Despite its close distance, the nuclear region of this galaxy is unseen at optical wavelengths due to the large amount of dust residing around it. Nevertheless, with NACO we are able to reach close to its center: there appears an unknown bright source at wavelengths longer than 2 μm (red bright source in Fig. 1) of which no traces have been seen at wavelengths around 1.7 μm and shortwards with the HST.

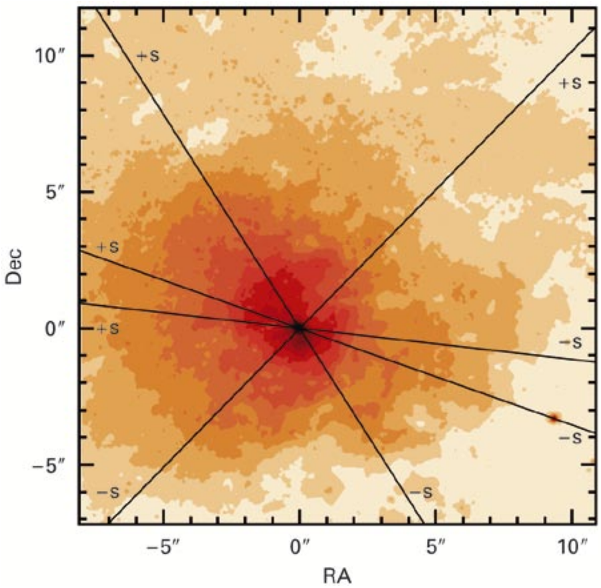
Our NACO images at wavelengths longer than 3 μm and complementary MIDI interferometry observations reveal that the red point-like source in the Circinus galaxy has a size of less than 1 pc radius and an elongated morphology (see Fig. III.3.2). The orientation of the elongated structure is almost perpendicular to the direction where we see the radiation cone emerging from the Circinus nucleus. As shown in Figures 1 and 2, a beam of collimated light emerges from the Circinus nucleus up to distances of about 10 pc from the center. A wide beam is traced by the ionized gas (Fig. III.3.2), but a surprisingly well collimated beam is observed in continuum light shorter than 2 μm (Fig. III.3.1). In the latter, we presumably see light from the nucleus which is scattered by dust above the torus.

Weighing the black hole in Centaurus A

As explained above, angular monentum will prevent circum-nuclear material from falling directly towards the central black hole. The angular momentum transfer is slow and thus the gas will rotate at each radius in nearly Keplerian orbits. This does not only apply to the inner accretion disk, but also to gaseous disks at larger radii.

For Centaurus A, the closest AGN, we measured the circumnuclear rotation velocities with NACO by observing a forbidden line of Fe^{+} at a wavelength of 1.644 μm. We used a slit width of 86 mas and reached a spatial resolution (along the slit) of ~ 60 mas. In order to describe the rotational velocity and velocity dispersion along the four observed slit position angles (Fig. III.3.3 and III.3.4) we constructed a dynamical model in which we assume that the gas lies in a thin disk. If the internal velocity dispersion of the gas is included as a pressure term (»hot disk«), we derive a central mass of 8.6×10^7 solar masses. This value is already 2.5 times lower than that previously deduced by Marconi et al (2005). If

Fig. III.3.3: H-band image of the central region of Centaurus A. The orientations of the slits for the spectroscopic observations with NACO are shown by straight lines.



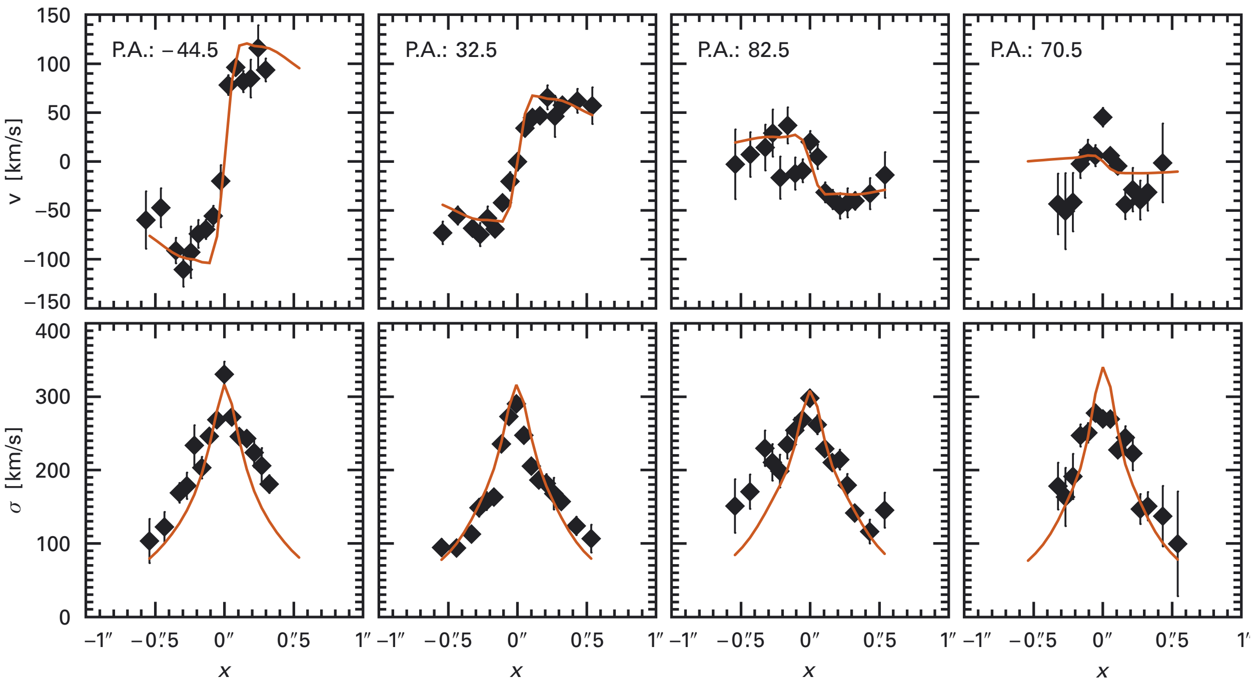


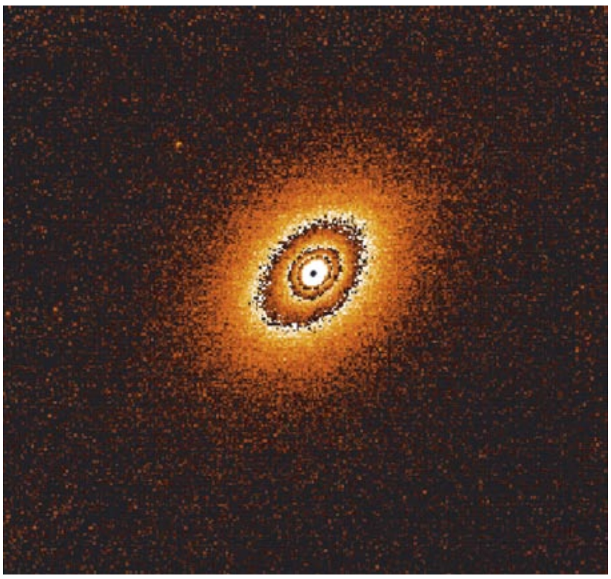
Fig. III.3.4: The NACO rotation curves (upper panel) and velocity dispersion profiles (lower panel) extracted from an Fe^{+} emission line along the four slit positions shown in Fig. 3. Note that the panels show only the very center of Centaurus A within a radius of 0.5 arcsec (19 parsec). The best-fitting disk model (red lines) assumes an inclination angle of 45° and leads to a black hole mass of $(8.6 \pm 0.3)\ 10^7$ solar masses. Here we assume that the gas has an intrinsic velocity dispersion that acts as a pressure term. If we neglect the velocity dispersion in the model (i.e., if we model a cold disk), the resulting black hole mass is a factor of two smaller.

the observed velocity dispersion reflects orbital motions alone ("cold disk"), the black hole mass could be another factor of 2 lower. The difference in central mass estimate is not due to differences in the assumed inclination, but rather reflects the fact that for the first time we resolve the radius of influence of the black hole in the center of Centaurus A. The lower black hole mass derived from our study is much better in agreement with the average correlation between the black hole mass and mass in the stellar bulge seen in other galaxies.

How far out does the influence of the AGN reach ?

As mentioned above, active galactic nuclei often show outflow phenomena and collimated winds. One way to trace the dynamics and energetics of these winds is by studying gas from highly ionized species. The ionization stages in such species require photon energies larger than 100 eV. Photons of that energy are not easily produced by stars but are definitively present during the most active phases of galactic nuclei. The imprint from this highly ionized gas in the optical and IR spectra of active galaxies consists of emission lines from ions like Fe^{+6} to Fe^{+13},

Fig. III.3.5: NACO 2.42 μm continuum emission of the nearby Seyfert type 2 galaxy ESO 428. A repeating color table is used to emphasize the elliptical light distribution. The light profile distribution is characterized by a bright spike at the center marking the nucleus position. This bright spike comes from a region not larger than 13 pc in diameter.



Si^{+5} to Si^{+9}, Mg^{+7}, Ca^{+6}, Ne^{+5}, etc. In the X-rays, ionization levels up to Fe^{+23} have been detected. Because of their high ionization levels, these lines can occur only in gas clouds close to the central source – within a few tens of parsec – which makes them genuine tracers of the gas dynamics and radiation processes occurring relatively close to the central engine.

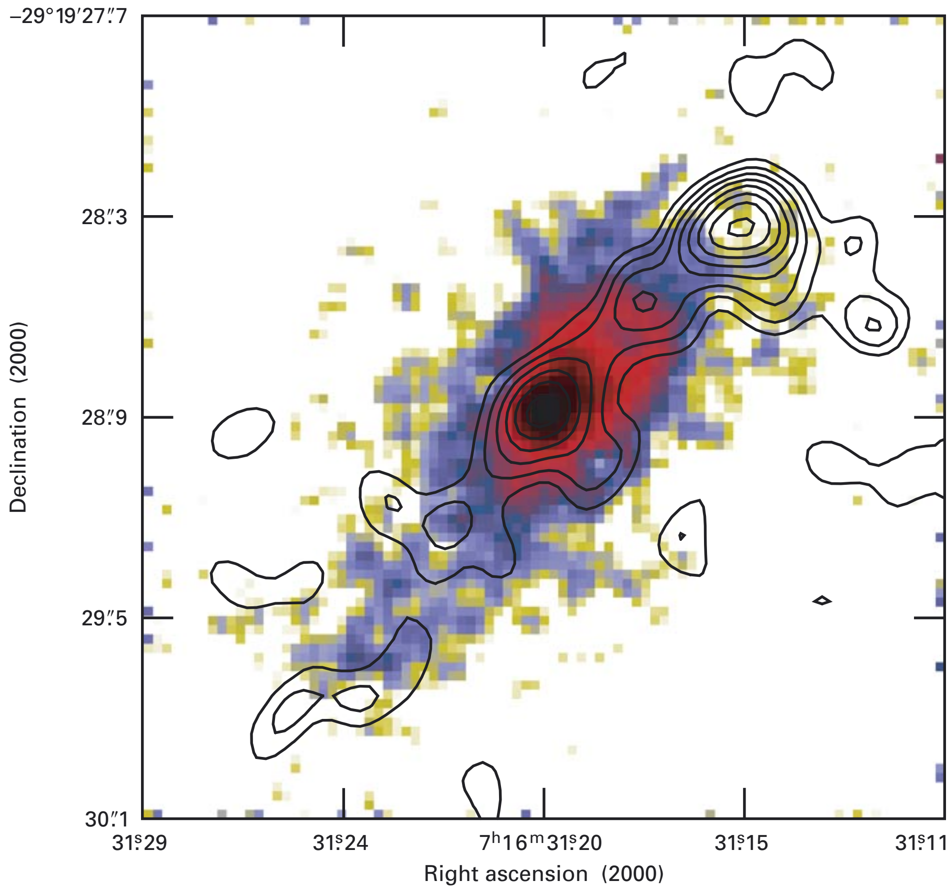
These highly ionized clouds have so far remained spatially unresolved. However the high spatial resolution provided by NACO in the IR, where the strongest high ionization lines are produced, gives us now the opportunity to explore them in detail. Thus, we are conducting an ambitious program at the MPIA aimed at revealing for the first time the size, morphology and kinematics of these high ionization clouds in the nearest active galaxies using NACO and the high spectral resolution provided by spectrographs such as ISAAC at the VLT.

To illustrate the results from this program, we show the case of the near galaxy, ESO 428. Fig. III.3.5 presents a NACO image of this galaxy seen in pure continuum light using a narrow-band filter centered at 2.42 µm. In continuum light, the galaxy shows a very smooth light distribution often seen in normal elliptical galaxies. Yet, when imaging the very highly ionized gas, e.g. a Si^{6+} line at 2.48 µm, the morphology is radically different: Fig 6 shows a bright source at the center, the nucleus, and an extended diffuse emission along a preferential direction. This coincides remarkably well with that of the known radio jets, which propagate in opposite directions from the nucleus.

These radio jets most likely have been launched by magnetically driven winds from the accretion disk. The important discovery with our NACO images is that the high ionization gas either flows out along the same jet direction in an extremely collimated wind, or it is a more local phenomenon, originating in the impact of the plasma jet onto the interstellar medium it encounters on its way out.

Often, the line profiles of this highly ionized gas are indicative of very high velocities, up to 2000 km/s. Even more importantly, they systematically show large asymmetric wings to the blue, when compared to those of lower or intermediate ionization levels, which appear narrower and symmetric. Conventionally this is explained by dust extinction due to the torus, which would affect the nearer approaching part of the bipolar wind less than the distant receding.

Fig. III.3.6: The same galaxy as in Fig. III.3.5, but seen in the light of the forbidden 2.48 µm emission line of Si^{6+}. Only the central 400 pc × 400 pc region is shown. The contours depict the radio jet emanating from a central bright source that is the active nucleus. The alignment between the radio plasma and the high ionization gas can be seen clearly.



However, high spatial resolution images like those of ESO 428 (Fig. III.3.6) show that the high ionization gas is visible at both sides of the nucleus. Therefore, if the picture of a bipolar outflow holds, the line profile should show both blue and red wings. Higher spatial resolution spectrographs, such as SINFONI which recently became available at the VLT, should give us the explanation for these contradictory findings.

How the black hole is fed by the surrounding galaxy

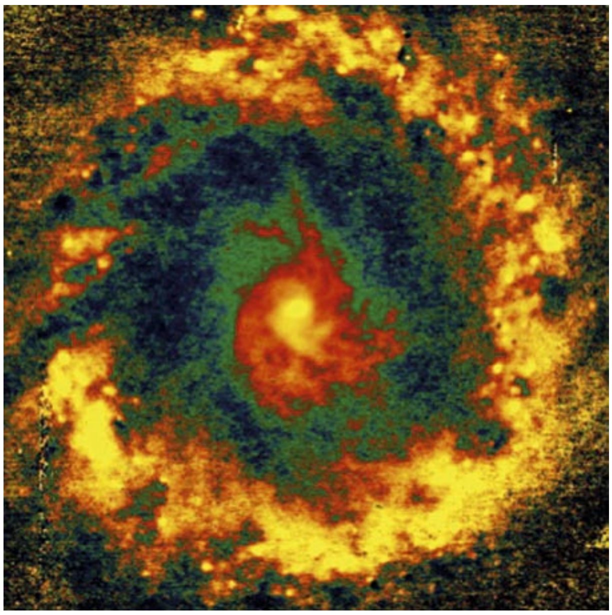
If accretion onto a black hole is indeed responsible for the extremely powerful phenomena at the center of galaxies, it must be fueled steadily via an accretion disk to keep it active. The material that supplies the accretion disk may originate in the body of the galaxy (molecular clouds gas expelled from stars via stellar winds and supernovae), or have an external origin (e.g. gas clouds captured by the galaxy from an interacting or colliding neighbor galaxy), or else it may originate in the galaxy center itself (e.g., stellar mass loss from the nuclear star cluster which might be enhanced by the irritation from the nucleus). A direct impression on how material is delivered to the very center of an active galaxy could be gathered for the first time in near-infrared images taken with NACO of the nearby galaxy NGC 1097.

Fig. III.3.7 shows a NACO 1 µm to 2.5 µm composite image of this galaxy. The figure shows the famous ring of star forming regions of NGC 1097 in their full realm. Because of the high spatial resolution achieved, coupled with the fact of being observing at IR wavelengths, this NACO image reveals more than 300 star forming regions in the ring (white spots in the figure), a factor of four more than were previously known from HST optical images. In the center of the ring, a moderately active nucleus is being slowly fed. In contrast to the situation in extremely active quasars, where the light of the nucleus outshines that of about 10^{11} stars in the host galaxy, moderately active nuclei as NGC 1097 are usually imbedded into the overwhelming stellar light, which can be seen as the bright diffuse emission all over the figure. Some nuclei are additionally obscured by large concentrations of dust enshrouding them. In the case of NGC 1097 it was possible to suppress the stellar light by producing a simple color image: Fig. III.3.8 shows our J-K color difference map obtained with NACO. As the stars appear equally bright in J and K, most of the diffuse stellar light is removed in the difference, thus unveiling a bright nucleus at the center. The ring of dusty star forming regions also has a redder color and thus remains prominent on the color map.

The size of this nucleus, currently limited by the spatial resolution of these images, is less that 10 pc in diameter. The color map shows furthermore a complex network of filaments spiraling around the center. These filaments are the tracers of cold dust and gas being transported to the center in order to feed the central engine.

Fig. III.3.7: NACO composite image of the central 2 kpc region of NGC 1097: red – 2 µm, green – 1.7 µm, blue – 1.2 µm light emission. More than 300 star forming regions (white spots in the image) are distributed in a radius of 700 pc around a bright central source where the active nucleus is located.

Fig. III.3.8: NACO J-K color map of the galaxy NGC 1097. The active nucleus is the bright source at the center, surrounded by a network of filaments through which material is channeled towards the accretion disk, from where it eventually will be swallowed by the central black hole



Conclusions

The examples discussed a bove demonstrate the wealth of information about the nuclei of active galaxies which can be gained with the new generation of high resolution instrumentation built at the MPIA. Starting from resolved images of the gas and dust tori in the inner few parsec of NGC 1068 and the Circinus galaxy with MIDI and NACO, we have guided the reader further out: a gas disk of about 18 parsec diameter is still within the radius of influence of the black hole. Thus we can determine its mass. Jets and outflows of highly ionized gas from the central accretion disk are important tracers of the nuclear activity which can affect tens of parsecs. In order to understand the fuelling process which keep the black hole active, one has to find out how material originating at radii of hundreds or thousands of parsecs from the center is channeled inwards and eventually reaches first the torus and from there the accretion disk. Although our current report focused on IR observations, our study will by no means exclude other ranges of the electromagnetic spectrum. Further theoretical work focused on dynamical models to determine black hole masses and on radiative transfer models to reproduce nuclear spectral energy distributions are also intensively investigated in parallel with the observational work. We are looking forward to further exciting findings in our quest to understand the very centers of galaxies.

(Almudena Prieto, Klaus Meisenheimer,
Nadine Häring, Hans-Walter Rix,
Marc Schartman and Konrad Tristram;
in collaboration with colleagues
from Landessternwarte Heidelberg,
MPIfR / Bonn,
ESO, Sterrewacht Leiden,
Tel-Aviv University,
IAG / Brazil
and Bucknell University / USA)

III.4 Fueling the Central Kiloparsec, or: How to Make Galactic Centers Active?

The central region in a spiral galaxy is a special place. A significant fraction of spiral galaxies show activity in the form of (massive) star formation or even shining galactic black holes. Clearly this activity needs fuel which is thought to be provided in the form of molecular gas. However, how this material is funneled to the very center is not very well understood. Numerous models have been suggested, but only now, with the advent of highest angular resolution observations in the millimeter regime using interferometers, it is possible to test these models.

As part of its multi-wavelength approach in the studies of galaxies and cosmology, MPIA has recently started to play an active role in the combination of NIR, (sub-)millimeter and radio observations in these areas. MPIA astronomers are playing a leading role in large international collaborations to study nearby galaxies. Two surveys with strong MPIA contribution are the "Nuclei of Galaxies project" (NUGA, E. Schinnerer) and the "Spitzer Infrared Nearby Galaxy Survey" (SINGS, F. Walter, J. Cannon), one of the six Spitzer legacy surveys. In addition, MPIA astronomers are leading two of the few "Large Projects" at the National Radio Astronomy Observatory's (NRAO) Very Large Array (VLA) which are linked to multi-wavelength studies of the nearby galaxies ("The HI Nearby Galaxy Survey", THINGS, F. Walter, PI, and F. Bigiel) and the distant universe (VLA-COSMOS, PI: Eva Schinnerer, V. Smolcic). Related studies involve the radio/mm observations of the most distant quasar hosts and sub-millimeter galaxies (F. Walter, K. Knudsen, D. A. Riechers, H. Dannerbauer).

Here, we will give a brief overview of the ongoing effort to understand the fueling processes in nearby galaxies, which is only one aspect of the multi-wavelength research becoming available by adding information from the long-wavelength regime. Updates on the other multi-wavelength observing programs will be presented in the next reports.

What makes galactic centers special places?

In general, the centers of (spiral) galaxies can easily be identified via their excess of stellar light. A significant fraction of nearby galaxies also shows evidence for additional nuclear activity, either in the form of recent or ongoing massive star formation or by having a central Active Galactic Nucleus (AGN). An AGN is understood to result from the feeding of a quiescent, massive black hole by infall of gas from its host galaxy.

These kinds of nuclear activity are quite surprising, since the very centers of galaxies are expected to be inhospitable places for star formation due to strong tidal and sheer forces ripping at molecular clouds, as well as the strong UV radiation fields from the dense stellar populations heating and photo-dissociating the molecular gas. However, recent observations with the Hubble Space Telescope at optical and near-infrared wavelengths have revealed that compact (~ few pc diameter), photometrically distinct star clusters are often present at the photocenter of spiral galaxies of all Hubble types. Surprisingly, the emission from many nuclear star clusters studied in detail turns out to be dominated by a young stellar population with age ≤ 100 Myr. Clearly, these galaxies must recently have had significant inflow of molecular gas – the fuel for star formation – into their very central regions in order to enable such recent star formation.

The connection between the host galaxy and its central engine in active galaxies remains a long-standing dilemma in AGN research. Current models for the fueling of AGN and unification of AGN types imply observable effects in the host galaxy on scales of 10's to about 1000 pc (e.g. nested bars, nuclear disks and dust). AGN activity in galaxies is believed to be closely linked to the availability of (molecular) gas at the very center. From the number density of nearby AGNs a duty cycle of about 100 Myr is deduced and thus the fueling mechanism must be efficient at replenishing the nuclear gas reservoir over this period.

Our current understanding of nuclear fueling

Although a likely scenario for the fueling of galactic centers is beginning to emerge, there remain a wealth of unanswered questions. There is no consensus on the exact mechanisms driving the infall of gas towards the very galactic center. On large scales, it has been proposed that dynamical perturbations – e.g., galaxy collisions, mergers, and mass accretion –, bars, spiral arms, and their gravity torques effectively drive infall of gas to scales of about the central kiloparsec. For example, bars are observed in at least 75 % of all spiral galaxies and are

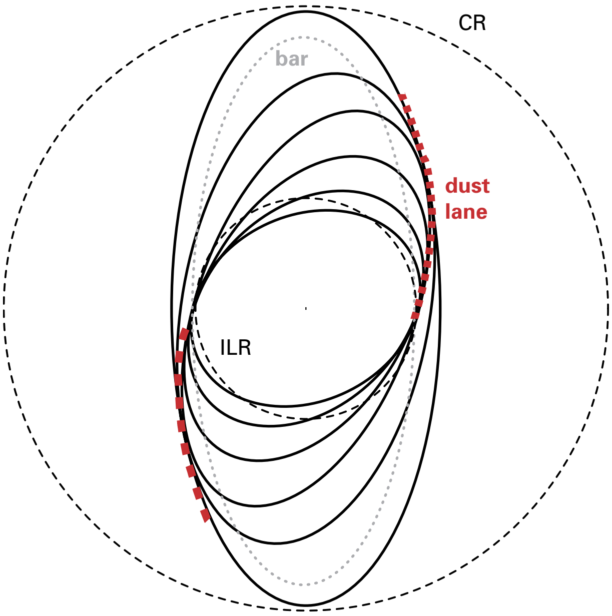


Fig. III.4.1: Schematic view of the gas flow in a spiral galaxy with a large-scale stellar bar (grey dashed line). The rough locations of two resonances important for the fueling of nuclear activity are indicated (black dashed circles): The Corotation Resonance (CR) and the Inner Lindblad Resonance (ILR). Basically, gas located between these two resonances can loose angular momentum and move closer to the nuclear region. Idealized orbits of the gas flow are shown as black ellipses. Where the ellipses come close to each other, gas clouds can very efficiently loose angular momentum via shocks. These regions can be easily observed as so-called gas- and/or dust-lanes (red dashed lines) in the disks of barred spiral galaxies.

believed to play a key role in this process by transporting gas from the outer large-scale disk down to the central kiloparsec. Numerical simulations have demonstrated that bar torques are very efficient at driving gaseous material into the center of a galaxy and detailed comparison of large-scale properties of individual galaxies to dynamical models show quite good agreement.

The overall model for gas flows on large-scale is relatively well understood. However, to explain the efficient mass transfer from the kiloparsec scale to the inner 100 pc, we must deal with the non-trivial problem of angular momentum removal. Secondary or inner bars were first proposed to bridge the last few 100 pc, but recently other mechanisms, such as m = 1 modes like lopsided disks or one-armed spirals, and/or gas density waves have been suggested to be equally or more important. It is also possible that the gas inflow first drives a nuclear starburst, and the tidal disruption of stars of this recently formed nuclear stellar cluster fuels the AGN. Thus the long-standing problem of fuel transport in the central kpc remains unsolved, controversial and vigorously debated. In practice it is rather difficult to test models for gas flow on a few 10 parsec scales due to the high spatial, and thus angular, resolution required. To-date, high-quality data are only available for a few galaxies to test model predictions. However, also models have just started to explore gas flows in the central kiloparsec.

A simplified view of gas flow due to a large-scale stellar bar (of several kpc length) can be described as follows (see Fig. III.4.1): Any rotating pattern (like a bar or spiral arms) in a differentially rotating disk causes the occurrence of resonances. Especially the location of the corotation resonance is important for gas flows. The radius of the corotation resonance is the place where the angular speed of the pattern is identical to the angular velocity due to the gravitational potential. The torques exerted by, for example, a stellar bar will cause the gas to move away from this resonance. Thus all gas inside the corotation resonance will move toward the center.

In the presence of a stellar bar the gas “accumulates” along the leading sides of the rotating bar and forms dust lanes. In such a simple picture (Fig. III.4.1), the orbits of a single gas cloud are therefore no longer circular, but have an elliptical shape. In addition, these elliptical orbits are tilted with respect to each other, causing the gas to loose angular momentum every time the gas cloud enters the region of the dust lanes. Depending on the exact shape of the gravitational potential and the properties of the stellar bar, the gas clouds can accumulate in the central region and form a smooth disk or can be halted at another resonance closer to the nucleus. This so-called Inner Lindblad Resonance (ILR) is believed to be the cause of the beautiful nuclear starburst rings seen in numerous spiral galaxies. In order to move the gas clouds even closer to the very center of a spiral galaxy, the idea of nested bars (or double-bars) has been invoked. In this scenario a smaller inner (or nuclear) bar acts similar to the large-scale (outer) bar: The gas clouds loose their angular momentum due to the elongated orbits and their associated shocks, and move to smaller and smaller radii.

Using mm-interferometers to observe molecular gas kinematics

The study of interstellar gas is a fundamental tool for understanding nuclear activity in galaxies. In the central kiloparsec of spiral galaxies, the gas is dense and molecular, making the millimeter CO lines the best tracers of nuclear gas dynamics. Today‘s millimeter interferometers can easily achieve angular resolutions of a few arcseconds. One of the best instruments available today is the IRAM (Institut für Radioastronomie im Millimeterbereich) Plateau de Bure interferometer (PdBI, see Fig. III.4.2). It is located in the French Alps at an altitude of about 2500 m and operates in the atmospheric windows at 3 and 1mm. When the best observing conditions (i.e. low water vapor and a stable atmosphere) are met in winter

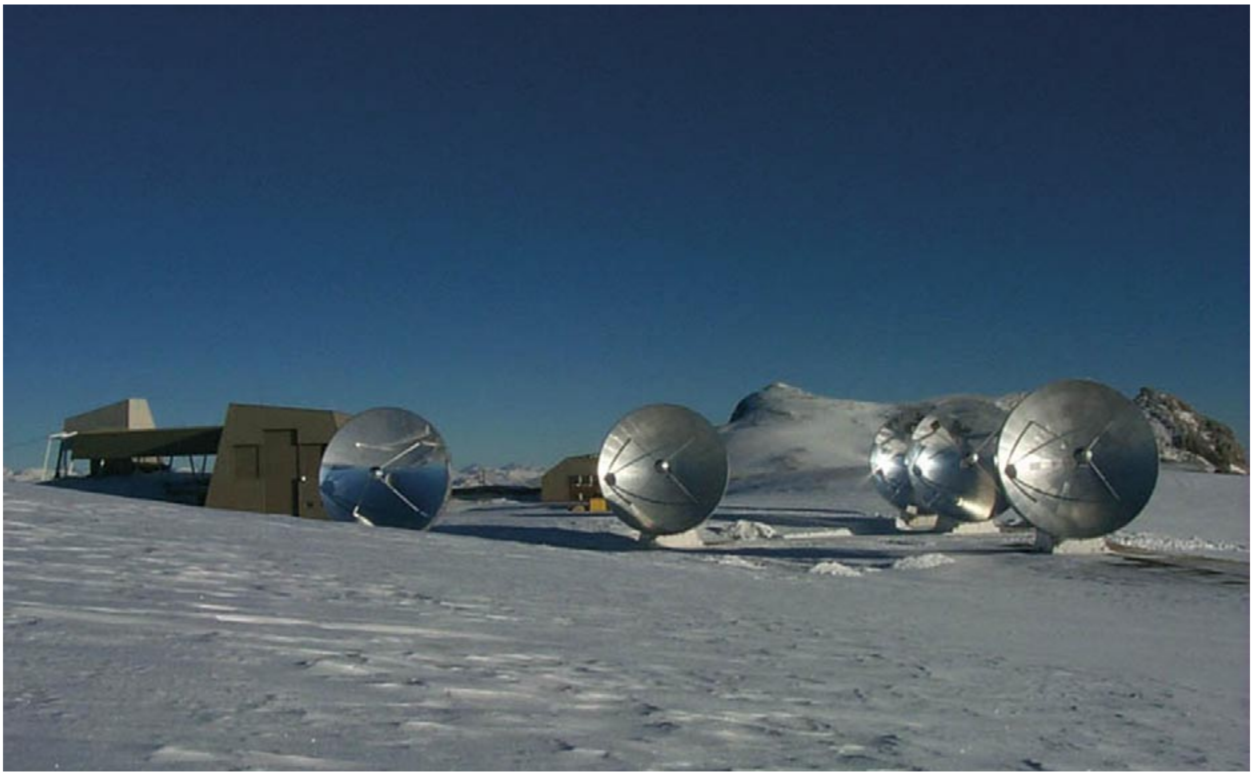


Fig. III.4.2: The mm-interferometer of the IRAM (Institut für Astronomie im Millimeterbereich) on the Plateau de Bure (PdBI). The instrument is located in the South of the French Alps at an altitude of about 2500 m. It currently consists of six 15 m antennas which can be spaced apart as far as 400 m. Observations are obtained in the atmospheric windows at 3 mm and 1 mm. For studies of the gas flow in nearby galaxies, the most important lines are the two lowest transitions of the ^{12}CO molecule at 115 GHz and 230 GHz. Using the largest baselines of up to 400 m length, the corresponding angular resolution that can be achieved at these frequencies is 1.″0 and 0.″5, respectively. (Courtesy of IRAM)

time, observations with even sub-arcsecond resolution are possible at 1mm wavelength. A typical spiral galaxy has abundant molecular gas in its central kiloparsec with a linewidth of the order of 200 km/s. The spectral resolution which can be achieved with mm-interferometers is superb, with typical values of about 5 km/s for the PdBI. This allows an excellent sampling of the CO lines and is instrumental for the study of the molecular gas kinematics in galactic centers.

Observations are crucial for progress

Observations of the molecular gas kinematics in the central kiloparsec of nearby spiral galaxies are crucial to test current models for the fueling of galactic centers. On the one hand they provide the important test which physical properties – e.g. the form of the galactic potential, shocks in the gas component, feedback from star formation or supernova explosions – are shaping the fueling processes. On the other hand, due to the now achievable high spatial resolution with current mm-interferometers, they also allow a direct test of model predictions. In the following, we will present a few examples which highlight the progress which has been made in the past few years.

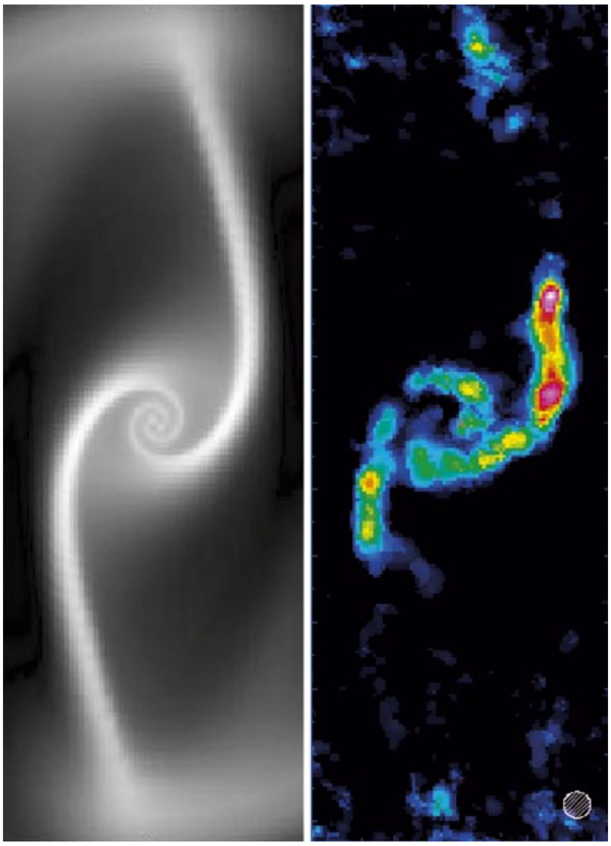
Are Double–Bars the Key? The Case of NGC 4303

NGC 4303 (M 61) hosts a large-scale bar of about 3.1 kpc length which is lying inside prominent spiral arms. In addition to this large-scale bar, a second, inner bar of about 300 pc length has been detected in the near-IR, which is surrounded by a circumnuclear starburst ring/spiral of about 0.5 kpc diameter. Several compact star forming regions inside this starburst ring have been resolved by HST UV imaging.

The previous study of the nuclear molecular gas flow in the double-barred galaxy NGC 4303 by Schinnerer et al. at high (~ 2″) angular resolution provided an important test of the predicted gas flow in this kind of galaxies. The detected emission traces two straight lanes where strong inflowing motions of up to 90 km/s are observed, similar to those predicted by models of galaxies with strong single large-scale bars. In the inner kiloparsec, the gas lanes start to curl and form a spiral structure, which is distorted in the southern spiral arm. Detailed comparisons between the high-resolution models of gas flow in single- and double-barred galaxies and the CO emission from the inner kiloparsec of NGC 4303 show that the observed spiral structure can be adequately explained by a single bar (see Fig. III.4.3). However, the spiral structure may also be consistent with the double-bar model adjusted for the large ratio (~ 15) of bar lengths. Since most of the molecular gas is located in the gas lanes and not in a nuclear ring expected to form in either the single-barred or the double-barred scenario, it seems likely that the circumnuclear molecular gas is probably still settling into the typical ringlike configuration.

The study of NGC 4303 has shown that the overall gas flow in one double-barred galaxy can already be explained – albeit not uniquely – with current dynamical models. However, the observed asymmetry in the galaxy‘s gas distribution cannot easily be explained by current models available, and the impact of star formation on the molecular gas in the central kiloparsec needs further study. In any case, determining whether NGC 4303 is truly representative of all double-barred galaxies makes observations of additional sources essential.

Fig. III.4.3. Comparison of model prediction for the gas distribution in a single barred galaxy (left; courtesy of P. Englmaier) with the observed distribution of the molecular gas in the double barred spiral galaxy NGC 4303 (right). The similarity between the model and the observed distribution of the ^{12}CO (1-0) line emission is striking, suggesting that the gas kinematics are dominated by the large-scale bar even very close to the center. The second inner bar in NGC 4303 is small compared to the outer bar and fits nicely inside the nuclear spiral arms. At the 2″ resolution of our data no clear effect of the nuclear bar onto the nuclear gas kinematics can be seen.



Feeding of the Nuclear Star Cluster in the Late–Type Spiral Galaxies IC 342 and NGC 6946

Understanding the fueling mechanism of star clusters at the very nucleus of spiral galaxies is of great interest. Late-type spiral galaxies are ideal targets, since nuclear stellar clusters can be easily identified due to the lack of a prominent stellar bulge. Two case studies are presented, in which MPIA astronomer Schinnerer in collaboration with T. Böker (ESA, The Netherlands), D.S. Meier (Univ. Illinios, USA), U. Lisenfeld (IAA, Spain) and E. Emsellem (CRAL, France) find evidence for gas inflow toward the very center.

IC 342 is a prime example for a late-type spiral galaxy with a young nuclear cluster. As demonstrated by a number of observations using near-infrared imaging and spectroscopy, it hosts a luminous nuclear star cluster of about 10^6 M_{sun}, which formed in a short-lived burst about 60 Myr ago. Being the nearest (D = 1.8 Mpc) spiral galaxy with intense nuclear star formation, it offers a unique opportunity to study the related gas dynamics on scales of a few parsecs (~ 4.5 pc, corresponds to 0.″5 at the distance of IC 342). The central region of IC 342 has been mapped with intermediate resolution (2.″5 – 4″) in several molecular lines such as the ^{12}CO, ^{13}CO, C^{18}O and HCN(1-0) transitions tracing the physical state of the nuclear molecular gas. The molecular gas ring of about 10″ diameter is evident in all maps, and shows signs of strong streaming motions. Our recent 1.″2 resolution observations of ^{12}CO (2-1) revealed for the first time a 30 pc diameter molecular gas disk coinciding with the nuclear stellar cluster. This disk connects via two faint CO bridges to the circumnuclear ring. Its gas kinematics show evidence for non-circular motion. If interpreted as gas inflow to the center of IC~342, crude estimates of the inflow rate lie between 0.003 and 0.14 M_{Sun}/yr, sufficiently high to replenish the fuel supply for future star formation events. Our latest PdBI observations of the molecular line emission of HCN tracing cold dense molecular gas show that this nuclear gas disk has indeed the properties required for star formation to occur. Further observations with even higher sub-arcsecond resolution of ^{12}CO (2-1) as well as other molecular lines are underway at the PdB interferometer.

NGC 6946 is a prime example for a late-type spiral galaxy with a prominent nuclear starburst. The starburst history of the inner 8″ (~ 230 pc) can be described by two recent events (about 5 Myrs and 15 Myrs ago) that each converted about (5-10) 10^7 M_{Sun} of molecular gas mass into stars. The inferred high extinction of $A_V \approx 10$ towards the nuclear region is surprising given the almost face-on geometry. As one of the closest (D = 5.5 Mpc) galaxies with intense nuclear star formation, NGC 6946 offers a unique opportunity to study the dynamics of ist circumnuclear molecular gas disk. At this distance, the 0.6“ spatial resolution afforded by the PdBI at 1mm samples spatial scales of only 15~pc.

The central molecular gas distribution has been resolved by our new PdBI observations into an S-shape structure (Fig. III.4.4). The CO(1-0) line emission probes the larger scale distribution in the central arcminute, showing that in general the molecular gas distribution is similar to the pattern of young star formation. Although, the molecular gas and the young HII regions are not cospatial. In the central 300 pc the distribution of the molecular gas is very reminiscent of the gas/dust lanes seen along large-scale kiloparsec bars. The nuclear stellar bar detected in the NIR could be a possible explanation for this. Preliminary analysis of the molecular gas kinematics suggests that indeed gas is funneled to the central ~30 pc via shocks along the leading sides of this rotating NIR bar. More analysis is needed to obtain an estimate of the possible inflow rates to the very center. However, the presence of high extinction and several young star forming sites within the central 100 pc make this galaxy an ideal target to study the interplay between gas dynamics and star formation (Fig. III.4.4).

Are all galactic centers similar? The IRAM PdBI key project NUGA

The Nuclei of Galaxies project (NUGA) is the first subarcsecond resolution CO survey of nearby active galactic centers. NUGA is a mainly European collaboration between scientists at MPIA, MPE, MPIfR, University Cologne, National Astronomical Observatory of Spain, Observatoire de Paris, CSIC/Spain, the Institute of Radio Astronomy in Italy and the Astronomical Institute of Basel.

NUGA will systematically study the different mechanisms for gas fueling of active galactic centers. For a carefully selected sample of nearby AGNs covering all stages of nuclear activity (Seyferts – LINERS – starbursts, plus transition objects), the (molecular) gas kinematics at 1 mm and 3 mm were imaged with maximum angular (~ 0.″5) and spectral resolution (3-6 km/s). The improvement in

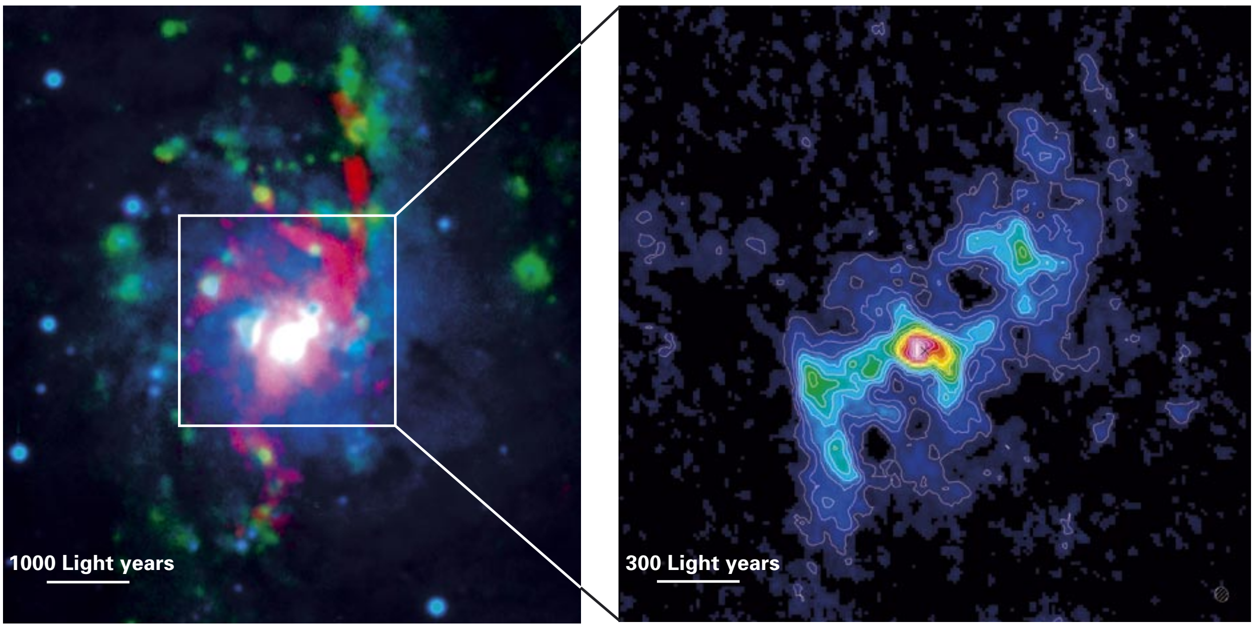


Fig. III.4.4: The distribution of the molecular gas in the nuclear region of the late type spiral NGC 6946. The color composite (left) shows the distribution of the $^{12}CO(1-0)$ line emission (red) in comparison to the light coming from young HII regions as seen in their Hα line emission (green) and the light coming from old stellar populations in the disk (blue). The very nucleus of NGC 6946 is actively forming stars and also shows the presence of abundant molecular material for star formation. The molecular gas distribution in the inner 300 pc as seen in the $^{12}CO(2-1)$ line emission at 0.″6 resolution (right) shows an S-shape reminiscent of the dust/gas lanes seen along large-scale bars. This picture is supported by the recent finding of a small inner bar in the near-infrared. However, model calculations are needed to confirm that this bar has indeed shaped the gas distribution in the inner 300 pc and is transporting gas closer to the very nucleus.

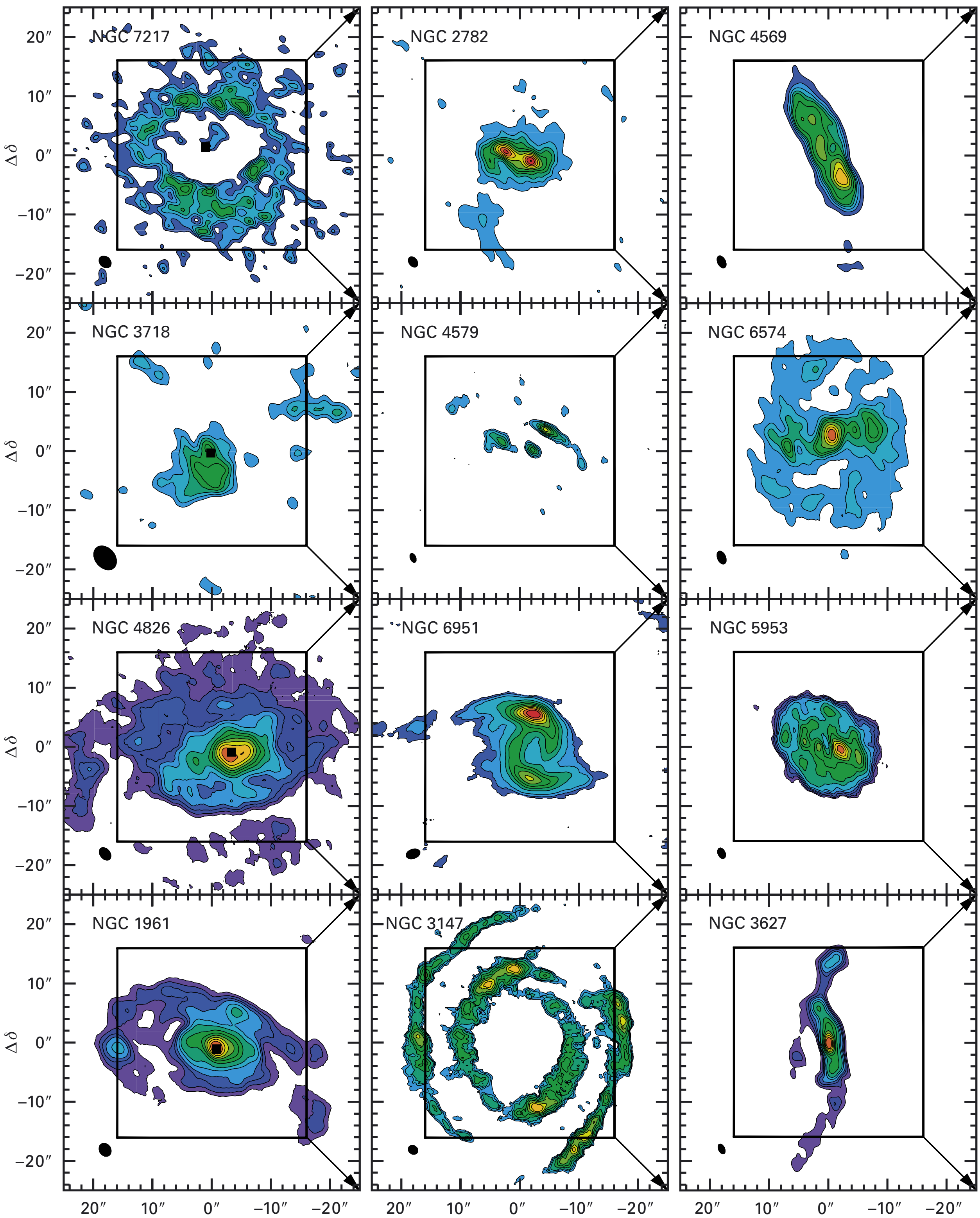


Fig. III.4.5: Examples of NUGA sources as observed in their ^{12}CO (1-0) line emission. The distribution of the molecular gas in the central kiloparsec shows a wealth of dynamical modes from rings (e.g. top left) to $m = 1$ modes (e.g. bottom left, like lop-sided disks or one-armed spirals) and $m = 2$ modes (e.g. top middle, such as two-armed spirals). The beam is indicated in the lower left corner of each sub-image. This clearly demonstrates the necessity to study samples large enough to encompass the variety in nuclear gas kinematics.

sensitivity by a factor of 10 over other mm-surveys makes NUGA data unique in providing unprecedented kinematic information for the inner arcminute of each galaxy.

So far, it has always been difficult to find statistical evidence for the role of large-scale bars and perturbations driven by interactions in AGN feeding. The reason behind this is that these large-scale perturbations have time-scales which are exceedingly longer than the ones which define the AGN duty cycle. Any potential correlation must therefore be sought much closer to the nucleus, in secondary modes embedded in the large-scale (kpc) ones. High-resolution observations (< 1″) are thus required to derive accurately the distribution and kinematics of molecular gas in the vicinity of AGNs.

The first NUGA CO images reveal a rich variety of morphologies in the circumnuclear disks of AGN hosts (see Fig. III.4.5). Various gravitational instabilities have been identified at different spatial scales. Some galaxies host several coexisting perturbations, while other host mainly one type of instability. Most of the nuclear disk perturbations observed in the NUGA targets are related to self-gravitating gas instabilities.

The wealth of nuclear gas kinematics can be broadly classified as:

(a) $m = 1$ gravitational instabilities, which appear as one-arm spirals and lopsided disks and develop on multiple scales traceable from several tens to several hundreds of parsec.

(b) $m = 2$ instabilities that develop the proto-typical two-arm spiral waves (the so-called twin peaks) or gas bars, which are expected to form in stellar bar potentials.

(c) Rings, and stochastic spirals that are related to instabilities.

A key question arising from these results is whether the nuclear/central dynamical characteristics depend on the host galaxy properties, i.e. are large-scale disk properties mirrored in the nucleus (same modes as in the nuclear region), indicating that the nuclear modes depend on large-scale drivers (e.g tidal interaction, warped HI disks), and/or on the overall amount/distribution of the atomic gas.

In order to tackle these questions MPIA scientist Schinnerer and a PhD. student together with colleagues from the NUGA project and C.G. Mundell (ARI, Liverpool, UK) have embarked on a project to map the gas kinematics of the outer disk using the line emission of atomic hydrogen HI at 21 cm. The observations have been carried out using the Very Large Array (VLA) of the National Radio Astronomy Observatory (NRAO; see Fig. III.4.6). Mapping the various spatial scales of the different instabilities (HI: outer, CO: inner) is essential as the instabilities can decouple, and thus prevent further inflow.

Fig. III.4.6: The Very Large Array (VLA) consists of twenty-seven antennas with a diameter of 25 m. It is located in New Mexico, USA, and operated by the National Radio Astronomy Observatory (NRAO). It covers the wavelength range from less than 1 centimeter up to a few meters. The fine-structure emission line of atomic hydrogen, HI, at 1.4 GHz (or 21 cm) can be used to study the kinematics and distribution of the atomic gas in nearby galaxies. HI line emission can usually be detected out to the very outskirts of the disk of spiral galaxies, which are typically larger than the optical disks. In addition, continuum emission at radio wavelengths can be a good tracer of star formation which is obscured by dust and therefore cannot be seen at optical wavelengths. (Courtesy of NRAO)

Preliminary analysis of our low resolution VLA D array HI data suggests that small HI satellites and disturbed HI disks are prevalent in our NUGA sample, thus indicating that, at least, tidal interactions and minor mergers might be possible drivers of nuclear activity. This ongoing systematic study of gas kinematics covering scales from a few tens parsec to the outer few tens kiloparsec will allow us to trace directly the gas flow from the outskirts of the disk to the central kiloparsec scale (see Fig. III.4.7). The combined CO and HI data will be essential to test current and future dynamical models describing the gas flow in disk galaxies.

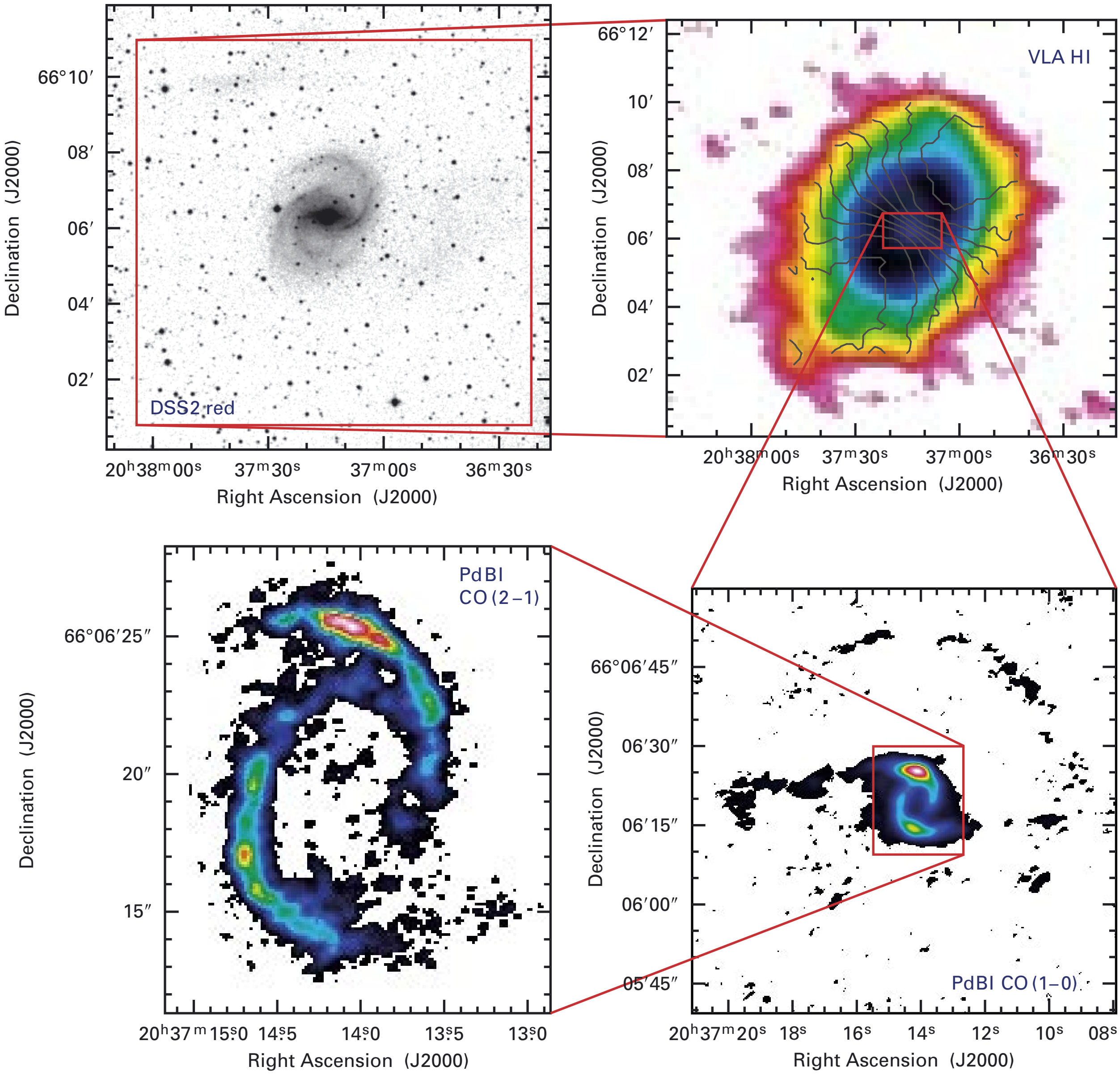


Fig. III.4.7: The example of the NUGA source NGC 6951 clearly demonstrates the importance of combining HI and CO imaging data to probe the gas kinematics over scale lengths of several orders of magnitude. The VLA HI data (top right; intensity map in color, velocity field in contours) clearly shows that the galactic gas disk has a much larger extent than the stellar disk seen in its optical light from the DSS2 red survey (top left). The CO(1-0) emission as observed by PdBI (bottom right) shows gas lanes along the stellar bar and a nuclear ring like structure. Only the 0″.7 resolution CO(2-1) data from PdBI (bottom left) resolves this inner ‚ring' into a spiral-like structure and a small amount of gas located close to the Seyfert 2 nucleus. This demonstrates the power of the HI+CO NUGA sample to test dynamical models.

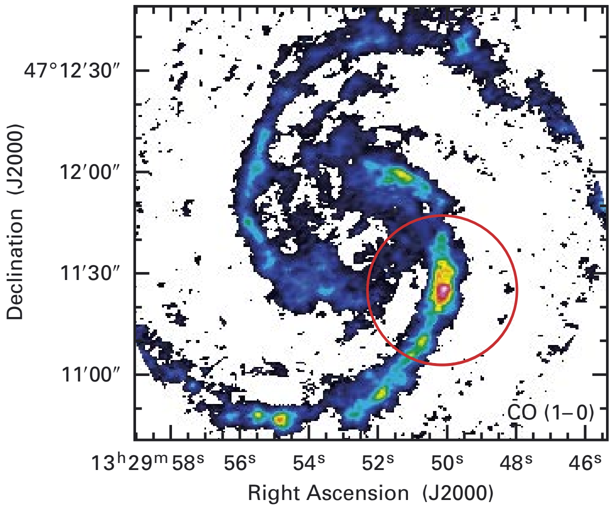


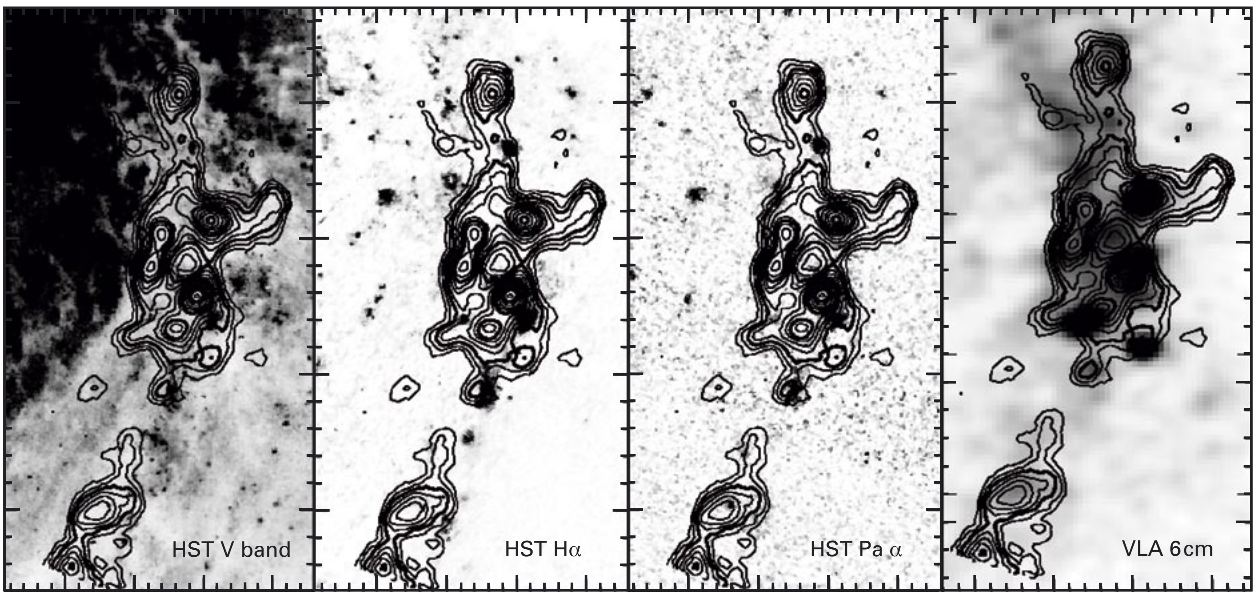
Fig. III.4.8: OVRO 3″ resolution ^{12}CO(1-0) intensity map showing the distribution of the cold molecular ISM in M 51a. The ^{12}CO(1-0) line emission is mainly arising from the molecular gas in the spiral arms. The red circle outlines the area which is shown in Fig. III.4.9.

A Missing Link: How star formation effects gas flows

Most of the star formation in normal spiral galaxies is thought to be governed by spiral density waves. Detailed knowledge of the physical processes associated with spiral density waves is therefore of fundamental importance for understanding the formation of stars in spiral galaxies. The Whirlpool galaxy M 51 is an ideal target for studying spiral structures, because it is nearby (9 Mpc), has well-defined spiral arms, and is almost face-on (Fig. III.4.8). The ~ 10″ (500 pc) wide spiral arms contain a substantial fraction of its molecular gas. The unusually large streaming motions (60 – 150 km/s) found in M 51 imply a very strong density wave whose general features are velocity discontinuities and streaming motions across the spiral arms. Besides the numerous GMCs (Giant Molecular Cloud complexes), a large number of star clusters are associated with the spiral arms, as evident in high resolution Hubble Space Telescope data. Nevertheless, there is no simple correlation between the gas reservoir and the star formation rate, which indicates varying star formation efficiencies and thus varying physical conditions in individual GMCs.

A collaboration lead by MPIA scientists has obtained multi-transition CO emission data of a well-selected region within the disk of M 51. Using the information about the physical conditions of the molecular gas, such as its density and kinetic temperature, in combination with the

Fig. III.4.9: Comparison of the distribution of different star formation tracers to the location of the molecular gas arm. The 1″.5 resolution ^{12}CO(2-1) intensity map is overlaid in contours onto the HST V band showing evolved stellar clusters (left), Hα (middle left) and Paα line emission (middle right) tracing HII regions with different sensitivity to internal extinction and VLA 6 cm radio continuum (right) emission showing young embedded star forming regions as well as the sites of supernova remnants. The molecular gas almost perfectly follows the dust lanes in the HST V band image. As can be seen from the comparison of the HII region line emission and the 6 cm continuum emission, there seems to be significant amount of hidden on-going star formation which is even missed with the NICMOS Paα data. Also there seems to be a spatial offset between the different tracers which may hint at a spatially resolved time sequence.



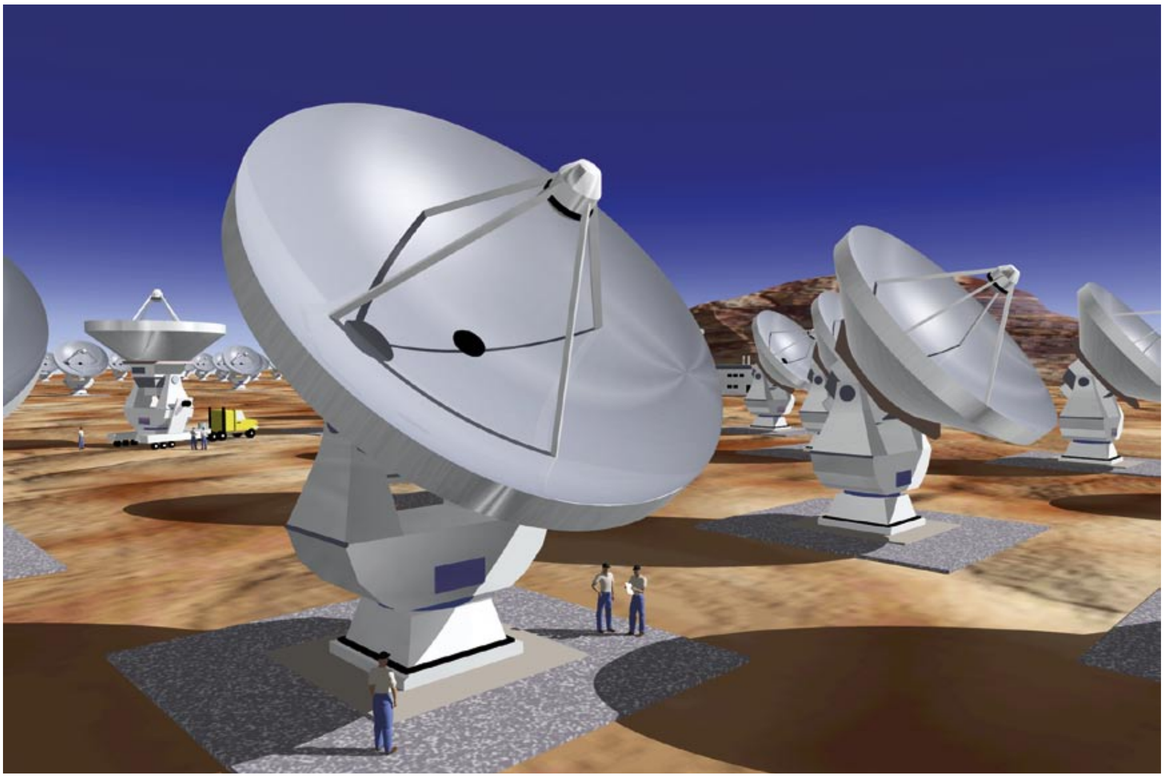


Fig. III.4.10: Artist's impression of Atacama Large Millimeter Array (ALMA). Up to 64 12 m antennas will be placed on the Chajnantor site, a high plateau at an altitude of about 5000 meters amongst the Andean mountains in Chile. (Courtesy of ESO)

information about the location of forming stars, older stellar clusters etc. we can start to understand how star formation might effect in detail the gas flow. Our preliminary analysis suggests the following picture for the spiral arm environment in M 51 (Fig. III.4.9): the molecular gas enters the spiral arm, gets compressed by the density wave shock, and cools. The location at which stars form cannot be identified in optical or near-IR data due to the large extinction (see Fig. III.4.3). Our 3″ resolution radio continuum data obtained with the VLA suggest that star formation occurs still inside the molecular gas arm, well in advance of the HII regions traced in the optical and near-IR. However, the radio continuum is diluted by synchrotron emission from supernova remnants. Adding observations from the thermal infrared is essential to test whether there is in fact a spatially resolved time sequence (molecular gas – embedded star forming regions – HII regions – star clusters), and determine physical conditions in the emerging warm gas.

The future: ALMA

The Atacama Large Millimeter Array (ALMA; Fig. III.4.10) is currently being built jointly by the European Southern Observatory plus Spain, USA and Canada in Northern Chile. This new mm-interferometer will not only have one order of magnitude better sensitivity and spatial resolution than today's mm-interferometers – it will also enable high resolution observations in atmospheric windows in the sub-millimeter regime, where lines from higher transitions of molecules are emitted. Thus studies like NUGA are paramount to explore the parameter space to design the best projects possible for ALMA. Future observations with ALMA will certainly take advantage of the higher spatial resolution. However, observations of different molecular line tracers as enabled by ALMA are essential in order to better understand the interplay between star formation and gas flows as well as the multi-component nature of the molecular gas itself.

All the projects described as well as other radio/millimeter related programs at MPIA are natural paths to prepare for the future use of ALMA.

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H. Dannerbauer, K. Knudsen,
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IV. Instrumental Development

IV.1 Beyond the Fringe: The LINC–NIRVANA Interferometric Imager

LINC-NIRVANA is a near-infrared, interferometric imager with advanced, multi-conjugated adaptive optics for the Large Binocular Telescope (LBT). The LBT is a dual, 8.4 meter telescope currently nearing completion on Mt. Graham in eastern Arizona. LINC-NIRVANA will combine the radiation from the two giant mirrors in »Fizeau« interferometric mode, thereby preserving phase information and allowing true imagery over a wide field of view. The instrument will deliver the sensitivity of a 12 m telescope and the spatial resolution of a 23 m telescope, over a scientific field of view approximately 10 arcseconds square. Guide stars for correcting atmospheric effects can be selected from considerably larger fields: up to six arcminutes in diameter for the visible wavelength MCAO system and up to 1 arcminute in diameter for the near-infrared fringe tracker.

The LINC-NIRVANA interferometric beam combiner is being built by a consortium of four Institutes: the Max-Planck-Institut for Astronomy (MPIA) in Heidelberg, the INAF - Osservatorio Astrofisico di Arcetri in Florence, the University of Köln and the Max-Planck-Institut for Radioastronomy (MPIfR) in Bonn.

The Large Binocular Telescope

The Large Binocular Telescope is an ambitious and innovative undertaking to construct the world's largest single telescope. The LBT promises observational breakthroughs in our understanding of the origin and evolution of our universe and its contents. It also offers a unique opportunity to search for planets outside the Solar System, and it will be an exciting tool to study how stars and planets form. The LBT project is a joint undertaking by the University of Arizona, the German LBTB consortium, the Italian astronomical community (represented by the INAF Arcetri Astrophysical Observatory), the Ohio State University, and the Research Corporation in Tucson.

The LBT Configuration

Figure IV.1.1 shows the configuration of the Large Binocular Telescope. The two, 8.4 meter diameter mirrors are joined on a single, common telescope mount. The secondary mirrors are actually thin glass membranes, whose shape is rapidly controlled by 672 magnetic, voice-coil actuators. These adaptive secondaries can remove distortions introduced by atmospheric turbulence. In order to facilitate diagnostics and efficient operation, the secondaries are concave. This necessitates a Gregorian configuration, with a real, prime focus approximately a meter below the secondary mirrors. The fast, *f*/1.14 primaries keep the overall telescope length small, and hence reduce the size and cost of the enclosure.

Having both mirrors on a single mount lets the LBT operate in three modes:

- As two 8.4 meter telescopes with separate focal planes and instruments. The mount can point the telescopes to fields 1-2 arcminutes apart, and multi-object instruments can either double the effective integration time or double the number of objects observed.

- As a 12 meter telescope, with light from both mirrors combined incoherently in a single focal plane. In practice, this mode is not very useful, since background light is usually the limit to performance. In such circumstances, identical instruments mounted on each individual telescope can achieve the same result with a simpler, more robust design.

- As an interferometer with light from the two mirrors combined coherently. This is the mode which LINC-NIRVANA will exploit.

LBT supports a total of twelve focal stations, including two prime foci, two "direct" Gregorian foci (below the primary mirrors), two auxiliary fiber feeds, and a total of six "bent" Gregorian foci (on the central instrument platform). The two interferometric instruments, LBTI and LINC-NIRVANA, will occupy two pairs of these six, central, focal stations. Reconfigurable swing-arms (see Fig. IV.1.1) allow rapid switching of instruments to respond to different science needs and changing observing conditions.

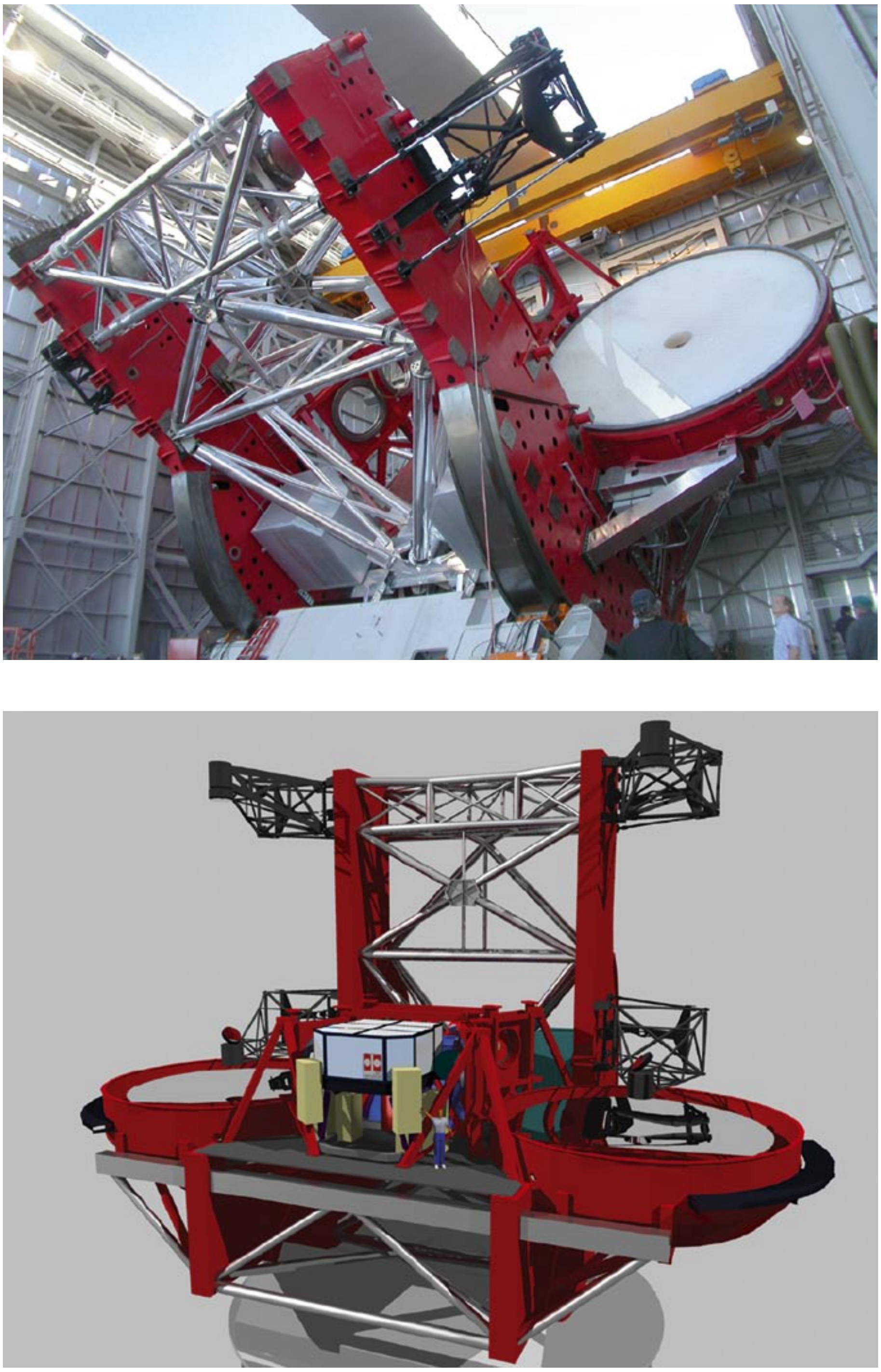
LBT Status and Schedule

At this writing (March 2005), the Large Binocular Telescope is on track to achieve first light, defined as prime focus imagery with a single primary mirror, in late summer 2005. In summer 2006, the first of the two adaptive secondary mirrors will be installed and tested, allowing for the commissioning of the first of the Gregorian focus instruments.

The second primary mirror will arrive in late 2005, with its adaptive secondary mirror following shortly after the first in summer 2006. "Second Light", defined as operation in two-telescope, non-coherent mode, should occur in 2007.

Operating the LBT as a single, coherent telescope will require additional hardware and software infrastructure, as well as a period of thorough commissioning and testing. We anticipate the final phase of LBT

Fig. IV.1.1: a) The LBT in September 2004. b) LINC-NIRVANA on the central, shared-focus instrument platform (light gray box). Note the human figure for scale



operations, known as "coherent combination", to take place after mid 2007. The period between second light and coherent combination also includes commissioning of the bulk of the LBT facility instruments, in addition to the telescope, adaptive mirrors, guider systems, and telescope software.

Fizeau Interferometry on the LBT

LINC-NIRVANA combines the radiation from the two 8.4 m primary mirrors of the Large Binocular Telescope in "Fizeau" mode. Fizeau interferometry offers several advantages over other configurations, particularly when the science program requires sensitive, wide field, true imagery of complex sources. Fizeau beam combination imposes some constraints on the telescope and optical system, but the design of the LBT is ideally suited to accommodate these constraints.

Coaxial versus Fizeau-Interferometry

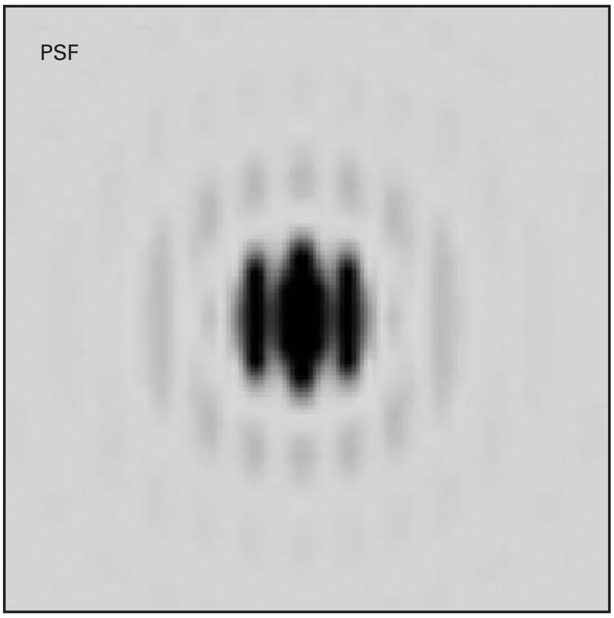
Essentially all current ground-based interferometers are of the coaxial or pupil-plane configuration, in which the beam combiner superposes the two (or more) telescope pupils, and, by scanning a small delay line, produces a modulated signal as the two paths pass back and forth through constructive (zero optical path difference) interference.

Although widely implemented, amplitude interferometry suffers from a number of drawbacks. For example, in its simplest implementation, it does not produce images. In addition, understanding complex sources can consume significant observing time. Field of view (FOV) restrictions are also severe for the pupil-plane configuration.

The Fizeau or image plane configuration overcomes these limitations. In a Fizeau interferometer, the wavefronts interfere in the focal plane, not in the pupil plane. Unlike their pupil-plane cousins, Fizeau interferometers are true imaging devices. In fact, the field of view can be arcminutes in size, limited only by the ability of the adaptive optics (AO) system to deliver aberration-free wavefronts over large sky angles. Perhaps the simplest way to think of a Fizeau interferometer is as a very large telescope (for LBT, 23 meters in diameter), but covered with a mask corresponding to the configuration of the component telescopes placed in front of it. The resulting stellar image, or point spread function (PSF), appears in Fig. IV.1.2.

There are a number of compelling reasons for aggressively pursuing image-plane interferometry on the Large Binocular Telescope:

1. Fizeau interferometry provides high angular resolution over a wide field of view, but only under certain geometric conditions of the optical paths. Achieving this geometry usually requires cumbersome relay optics, but on the LBT, the two mirrors share a common, steerable mount. This means that the telescope always presents the same telescope configuration to the target, drastically simplifying the task of maintaining the needed optical geometry. This simplicity translates directly to cost savings and increased sensitivity. Also, for infrared observations, there will be three, not the typically twenty, warm mirrors required to convey the radiation to the beam combiner.



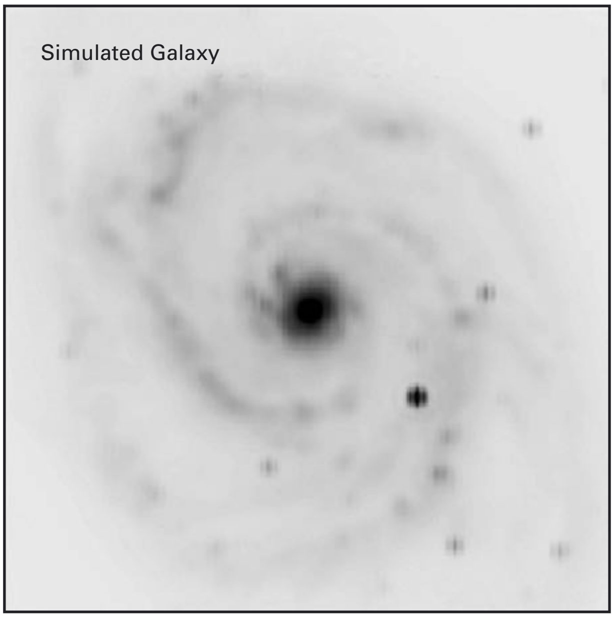


Fig. IV.1.2: The LINC-NIRVANA point spread function and a simulated image of a galaxy.

2. Fizeau imaging works best with compact arrays of telescopes, that is, configurations in which the separation of the mirrors is comparable to their diameter. This ensures relatively uniform coverage of all spatial scales, eliminating difficulties associated with »resolving out« structures with sizes intermediate between that corresponding to the single dish diameter d and the total size (or "baseline") *B*. For example, an interferometer consisting of two 10 m telescopes separated by 100 m and operating at wavelength 2 mm has difficulty "seeing" structure at spatial scales between 5 milliarcseconds (l/*B*) and 50 milliarcseconds (l/*d*). The LBT, with its 8.4 m primary mirrors and 6 m separation, has no such blind spot.

3. There are also strategic reasons for focusing on LBT image-plane interferometry. In addition to being a potentially important technology for future ground and space-based telescopes, Fizeau beam combination on LBT offers a doubling of telescope collecting area and spatial resolution, compared to the largest current facilities. Almost all of the partners in the LBT consortium, and in particular the MPIA, already have access to 8 m class telescopes and state-of-the-art instrumentation. Concentrating on LBT's unique aspects, in particular interferometry, will allow us to outperform these competing facilities.

4. Finally, and most importantly, Fizeau interferometry on the LBT will allow us to significantly enhance the quality and type of science we can do. Specifically, Fizeau interferometry offers a way to deploy our precious mirrors in a way that preserves sensitivity, spatial resolution, and field of view.

The LINC–NIRVANA–Instruments

LINC-NIRVANA began as two projects proposed separately by the MPIA and Italian LBT partners. The original designs called for relatively small field-of-view beam-combination, using the facility-standard adaptive optics system. The two efforts were combined in 2001, and soon thereafter, the team realized the potential of using the LBT adaptive secondaries, in combination with one or two additional deformable mirrors, to allow multi-conjugated adaptive optics. MCAO not only increases the available field of view, but also allows much fainter individual guide stars to be used. This has the salutary effect of significantly expanding the observable fraction of sky.

Since 2001, the team has been refining the instrument design, as well as developing a number of "proof of concept" experiments and prototypes. The University of Cologne joined the effort in 2002, with the aim of providing the fringe-tracking hardware and the science channel cryostat. In 2003, the Max Planck Institute for Radioastronomy in Bonn brought their expertise in image deconvolution and high-speed, low-noise, infrared detector operation to the consortium. Most recently, in 2004, small groups at Roma and Genova joined the LINC-NIRVANA team, with contributions of the optical patrol camera and image processing, respectively.

The first major project milestone took place in April 2003, with the successful completion of the Preliminary Design Review (PDR). The final design review is slated for early summer 2005.

Spatial Resolution

LINC-NIRVANA's point spread function will have an area 400 times smaller than good, seeing-limited images, 100 times smaller than the Hubble Space Telescope PSF, and 10-15 times smaller than the PSF of the James Webb Space Telescope (JWST) or an AO-equipped 8~meter telescope. Such improved resolution translates to direct gains in our understanding of the universe. For example, Figure IV.1.3 demonstrates how this improved resolution affects the observable morphology of distant objects.

For observations limited by background noise statistics, a reduction in the size of the point spread function leads directly to an increase in sensitivity. Table 1 below assumes that the point-source energy is distributed throughout the single-telescope point spread function and that conventional image processing is applied. The LINC-NIRVANA team is currently investigating optimal extraction techniques, which may improve point-source sensitivity, by using only those parts of the PSF which contain source photons.

Detecting diffuse emission has traditionally been a weak point of imaging interferometers, since the time to achieve a target signal-to-noise ratio increases with the ratio of telescope separation to diameter raised to the fourth power. In this respect, LINC-NIRVANA enjoys a significant advantage over other, sparser interferometric arrays such as the Very Large Telescope Interferometer and the Keck Interferometer. Experience has also shown that as spatial resolution improves, many "diffuse" objects break up into the point sources for which interferometers are ideally suited (see, for example, Fig. IV.1.3).

Perhaps the most remarkable thing about the performance outlined outlined in this table is that it represents conventional astronomy goals pushed to the next level via interferometry: increased sensitivity, spatial resolution, and field of view would be on every astronomer's wish list for future telescopes and instrumentation. It is a central goal of the LINC-NIRVANA. project to enable and improve the kinds of science astronomers wish to do.

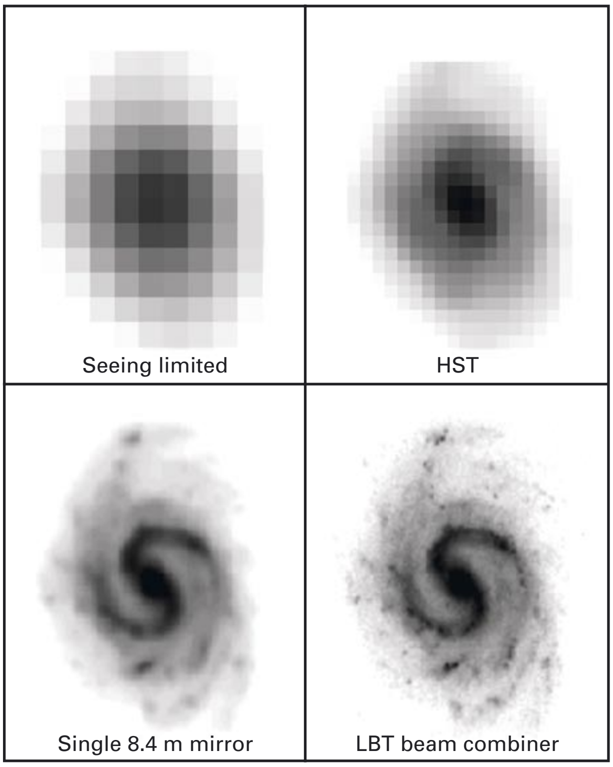


Fig. IV.1.3: Resolution dependence of galaxy morphology. This is an image of the nearby spiral NGC 4535, "moved" to a redshift z ~ 1, and displayed at ground-based resolution (upper-left), seeing limited resolution, (0.4 arcseconds – upper-right), the Hubble Space Telescope diffraction limit (0.2 arcseconds – lower-left), the diffraction limit of one LBT mirror, (0.06 arcseconds), and (lower-right) at the LINC-NIRVANA resolution of 0.02 arcseconds.

Band	Wavelength (μm)	Angular Resulution (″)	Field of View[a]	Sensitivity[b] (mag)
J	1.25	0.011	10.5 × 10.5	28.0
H	1.65	0.015	10.5 × 10.5	26.6
K'	2.12	0.020	10.5 × 10.5	26.0

Table IV.1.1: Spatial resolution, field of view, and point source sensitivity for LINC-NIRVANA

[a] The field of view is limited by the size of commercially available infrared detectors, and could in principle be expanded.

[b] Point source detection with signal-to-noise ratio 5 in one hour, assuming typical sky brightness.

Sample Science Program

As emphasized above, LINC-NIRVANA will enhance the kinds of science that MPIA astronomers currently want to do. This includes targets ranging from the surfaces of nearby planets and satellites to the cores of star forming regions to the faint glimmers of radiation that illuminate the edge of the visible universe. The paragraphs below contain an overview of LINC-NIRVANA's science program.

Imaging of Planetary Surfaces and Atmospheres: For solar system targets, the wide field of view, high spatial resolution, and increased sensitivity of LINC-NIRVANA will allow ground-based monitoring and investigations that rival spacecraft observations. The recent success at imaging the atmosphere and surface of Saturn's largest satellite, Titan, provides an ideal example and taste of things to come (see Fig. IV.1.4). LINC-NIRVANA will enable another leap in spatial resolution, sampling Titan's surface with approximately ten times as many pixels as these striking images from the VLT.

Extrasolar Planets: Current search strategies for extrasolar planets concentrate either on the Doppler shifts in stellar spectral features arising from the reflex motion due to unseen planets, or on the (considerably rarer) photometric changes which occur when the planet passes in front of the star. Both these techniques are biased toward detecting more massive (Jupiter-like) objects close to the host star: the majority of the 130 or so "hot Jupiters" discovered to date have orbits considerably smaller than Earth's. We plan to search for planets using LINC-NIRVANA and a very "old-fashioned" technique: measuring the wobble imposed on the parent star by the gravitational tug of the planet as the two move slowly across the sky.

The astrometric precision offered by LINC-NIRVANA should be sufficient to detect the reflex motion of Jupiter on the Sun out to a distance of 300 light years. The wide field of view increases the likelihood of multiple reference stars, improving the precision of relative astrometry. Formation theories also predict that there may be large numbers of isolated planets either created alone or expelled from binary and multiple systems. Searches for free-floating planets are ideally suited to the greater sensitivity and wide field of view of LINC-NIRVANA .

Energy Balance in Stellar Nurserie: Stellar winds, through their interaction with circumstellar disks and the surrounding media, play a central role in catalyzing and regulating the star formation process. Unfortunately, the small angular scales and the presence of obscuring dust have severely limited our ability to probe the regions where these important interactions take place. LINC-NIRVANA will provide an unprecedented opportunity to study these fundamental processes at angular scales corresponding to less than 1 AU at the nearest star forming regions. The ability to form true images is essential in disentangling these complex regions. A monitoring program of circumstellar emission, coupled with high resolution spectroscopy, can give the full, three-dimensional motions of the gas in the near stellar environment. Note that a shock front travelling at 25 km/s in Taurus will move noticeably during a single, week-long observing run.

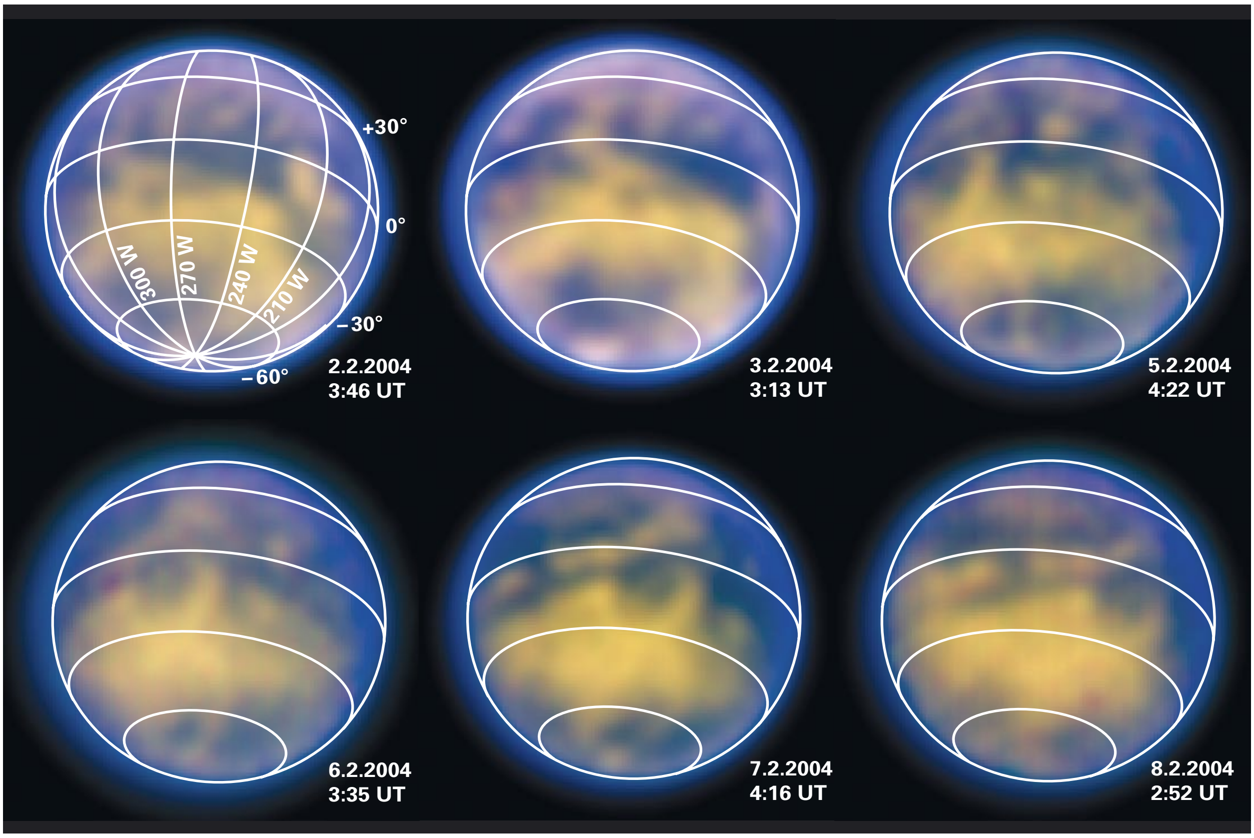


Fig. IV.1.4: Ground-based, adaptive optics images of the surface of Saturn's moon, Titan, using conventional adaptive optics on an 8 meter telescope (using NACO, another MPIA-built instrument). LINC-NIRVANA will permit imagery of such objects with approximately ten times as many resolution elements across the surface.

Stellar Multiplicity: The majority of stars in the Galaxy are found in binary and multiple systems, and the distribution of binary star separations peaks at approximately 50 AU, corresponding to 0.3 arcsec at the distance of the nearest star forming regions. Operating in the near-infrared, LINC-NIRVANA will be able to penetrate the obscuring dust in molecular clouds and resolve young binaries with approximately one thirtieth of this separation. Perhaps more importantly, the exquisite precision possible with relative astrometry over a wide field will enable the measurement and extraction of orbits for a large sample of binaries. The derived dynamical masses can then directly calibrate the mass-luminosity relation and the evolutionary sequence of stars.

Structure of Circumstellar Disks: As mentioned before, circumstellar disks have an important influence on molecular cloud collapse, by either generating or mediating stellar winds. Disks are also of fundamental importance in planet formation, since they act as both a source of raw material and as a shielding envelope to allow the accumulation of the gas and refractory elements which eventually become a planet. Through accretion and resonant scattering, the planet eventually clears a gap in the disk, inexorably altering its structure and dynamics. LINC-NIRVANA can search for evidence of these processes in scattered light. This is another instance where true, panoramic, imagery is an enormous asset. Circumstellar disks are expected to flatten with increasing age during the transition from protostellar to protoplanetary phase, a process that we hope to follow with a large survey.

Supernova Cosmology: Our view of the overall shape and content of the universe has been radically altered in recent years by the results of moderate-redshift supernova cosmology research. The technique takes advantage of the fact that type Ia supernovae have an intrinsic luminosity predictable from the way that their luminosity evolves. Therefore, measurements of this evolution and the spectroscopic redshift give the distance to a given redshift, and hence map out the geometry of the universe. Unfortunately, at the moderate redshifts accessible to the current generation of telescopes, this type of observation cannot measure the fundamentally parameters of the universe independently of each other. Observations of fainter, more distant, supernovae can break the cosmological parameter degeneracy, however. LINC-NIRVANA on LBT has the sensitivity to detect and measure these objects. A dedicated program consuming 25 telescope nights should be able to constrain these important cosmological parameters independently to 5 % accuracy.

Galaxy Formation: The best way to understand galaxy formation is to use the enormous light-gathering capability of large telescopes to look back in time at the era of

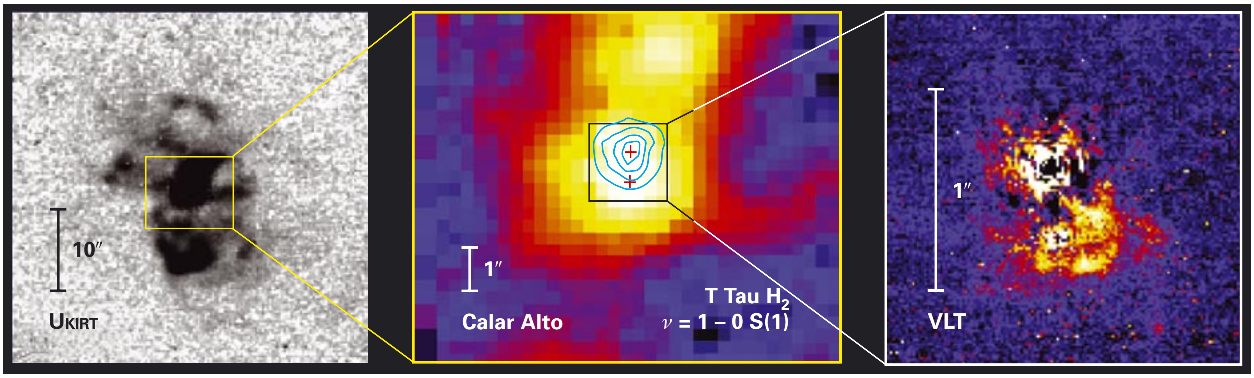


Fig. IV.1.5: Star formation is complex at all angular scales. This sequence of images zooms into the core of the prototypical young stellar object, T Tau. With LINC-NIRVANA, we will finally be able to study the star and planet formation process at scales corresponding to the Earth's orbit.

galaxy assembly. Current models predict that the earliest galaxy fragments are small and faint. Unfortunately, the limited sensitivity of current instruments force us to bias our investigations toward atypically luminous and massive galaxies, and toward galaxies that are undergoing an episode of rapid star formation (Fig. IV.1.6). A deep multi-color, near-infrared survey with LINC-NIRVANA could sample a representative volume of the universe in a dedicated program of 20 nights, detecting galaxy fragments in that volume with only one one-thousandth of the Milky-Way's mass. Until the James Web Space Telescope mission, no other facility will reach this combination of sensitivity, areal coverage, and number of detected objects.

Resolved Extragalactic Stellar Populations: Current technology limits our ability to resolve individual stars in galaxies further than about 15 million light years away, forcing us to assess their stellar content and formation history using the integrated light of millions of stars. In particular, there is not a single giant elliptical galaxy close enough to be fully resolved into individual stars, a situation which has generated a decade-long debate over their star formation history. LINC-NIRVANA will be able to resolve stellar populations in galaxies out to 60 million light years, and can study the age and metallicity of the stars through a combination of narrow and broad-band filters. With LBT, about 100 luminous galaxies will be accessible to this type of study, compared to the current four.

Optical Layout

Figures IV.1.7 and IV.1.8 show an overview of the LINC-NIRVANA opto-mechanical design. The beam combiner sits at one of the shared, bent focal stations on the central instrument platform (Fig. IV.1.1), with the telescope focal planes just inside the instrument enclosure. All of the optical components are mounted to a stiff, carbon-fiber optical bench. This not only supplies mechanical rigidity and minimizes temperature effects, but also can accommodate future experiments and upgrades.

Warm Fore-Optics: Just prior to the telescope focal planes, an annular mirror redirects the field from 2 to 6 arcminutes diameter into the Ground-layer Wavefront Sensors (GWS). This mirror appears as a dashed outline in Fig. IV.1.7, and the GWS are not shown for clarity – they appear in Fig. IV.1.8. The Ground-layer Wavefront Sensors measure the turbulence directly above the telescope by sensing up to 12 natural guide stars in this annular region. The GWS send their correction signals to the adaptive secondary mirrors, each of which has 672 actuators (see below).

Light from the central two arcminutes of the field of view continues further into the instrument to a six-lens "quasi-collimator". This device produces a nearly parallel beam with the characteristic that the ray bundles from the two arcminute field produce an envelope of constant diameter. This strategy allows us to take advantage of all of the (expensive) actuators in the Xinetics deformable mirrors located downstream.

The optical path is folded back on itself twice in a "Z" configuration – one, and eventually perhaps both, of these fold mirrors is a Xinetics 349 actuator deformable mirror (DM). Adaptive optics is most effective when the deformable mirror can optically act directly on the layer of atmospheric turbulence. The Xinetics DM is re-imaged ("conjugated") to an altitude in the range 8-15 km (the second one, if installed, is conjugated to 4-8 km). The entire "Z" structure can be moved back and forth to find and/or track the optimal altitude of turbulence. After the double reflection, the beams from each telescope strike the down-folding beam-combination / piston mirror.

Beam Combination Area: The beam combination or »piston mirror« performs two functions. First, it re-directs the radiation downward toward the science channel cryostat. Second, as its name implies, the piston mirror can be used to remove differential piston (or optical path difference). Differential piston will be present because the adaptive optics systems, although they ensure flat

Fig. IV.1.6: Current state of the art imagery, such as the Hubble Space Telescope Ultra-Deep Field, can reveal the galaxy assembly process back to the epoch ~1 billion years after the Big Bang. The earlier, and more significant era of galaxy building is only accessible to instruments like LINC-NIRVANA which operate in the near-infrared.

wavefronts, cannot control the relative time of arrival of the wavefronts at the two telescopes. Small tilts induced by the atmosphere over the 23 meter baseline will translate, after AO correction, into optical path or piston differences.

The piston mirror removes residual piston by moving back and forth along the line joining the two telescopes, thereby shortening one arm of the interferometer while lengthening the other, effectively doubling the dynamic range for correction. A high-performance piezo-electric stage supplies the necessary stroke and bandwidth.

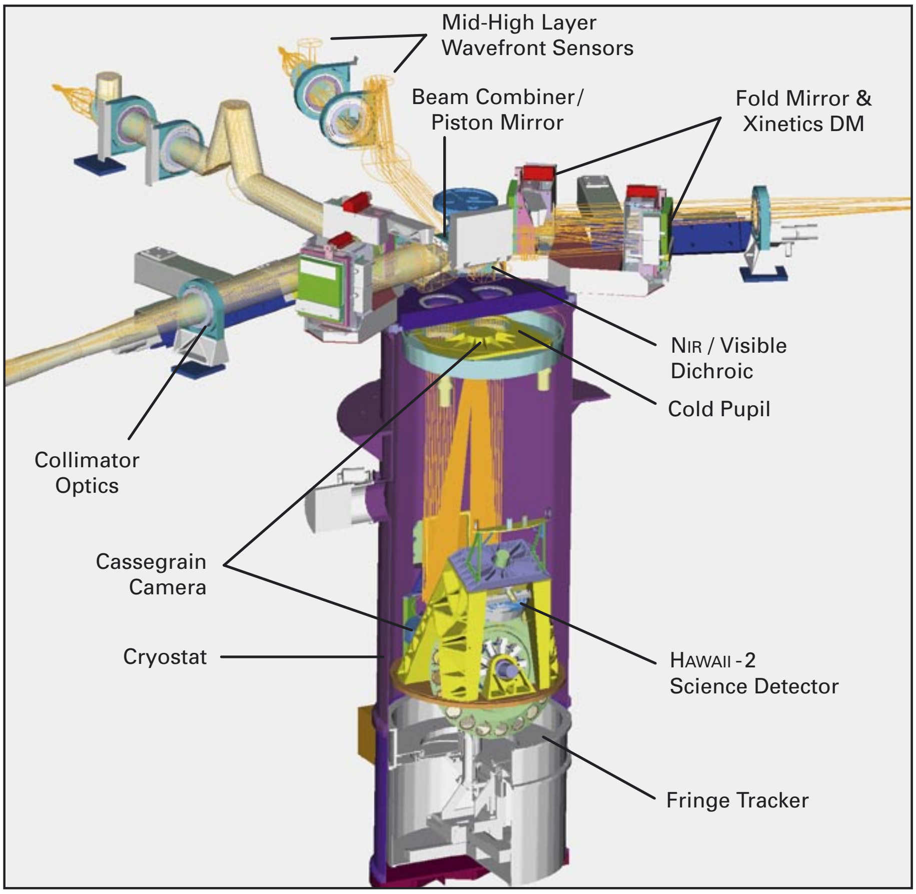
Fig. IV.1.7: The LINC-NIRVANA. optical path. See text for details. The mechanical components are shown in Fig. IV.1.8.

A pair of dichroic mirrors between the piston mirror and the cryostat windows allows the near infrared photons to pass through, but reflects visible radiation through a four-element camera lens to the Mid-High Layer Wavefront Sensors (MHWS – see below).

The Near-Infrared Science Channel

The near-infrared radiation passes through the dichroics and the window of the cryostat, where a cold mask suppresses excess thermal background. A reflective two-mirror camera inside the dewar produces the final interferometric focus (Fig.IV.1.7). The science sensor, a 2048 x 2048 HgCdTe HAWAII-2 array, sees this radiation in reflection off an infrared-infrared dichroic beam splitter. The fringe tracking sensor exploits the near-infrared light outside the reflected band, or from outside the science field, to determine the differential atmospheric piston. The fringe correction signal drives the piezo-electric actuator connected to the down-folding beam combination mirror.

Note that as an interferometer, LINC-NIRVANA must be kept fixed with respect to the "entrance pupil," that is, the



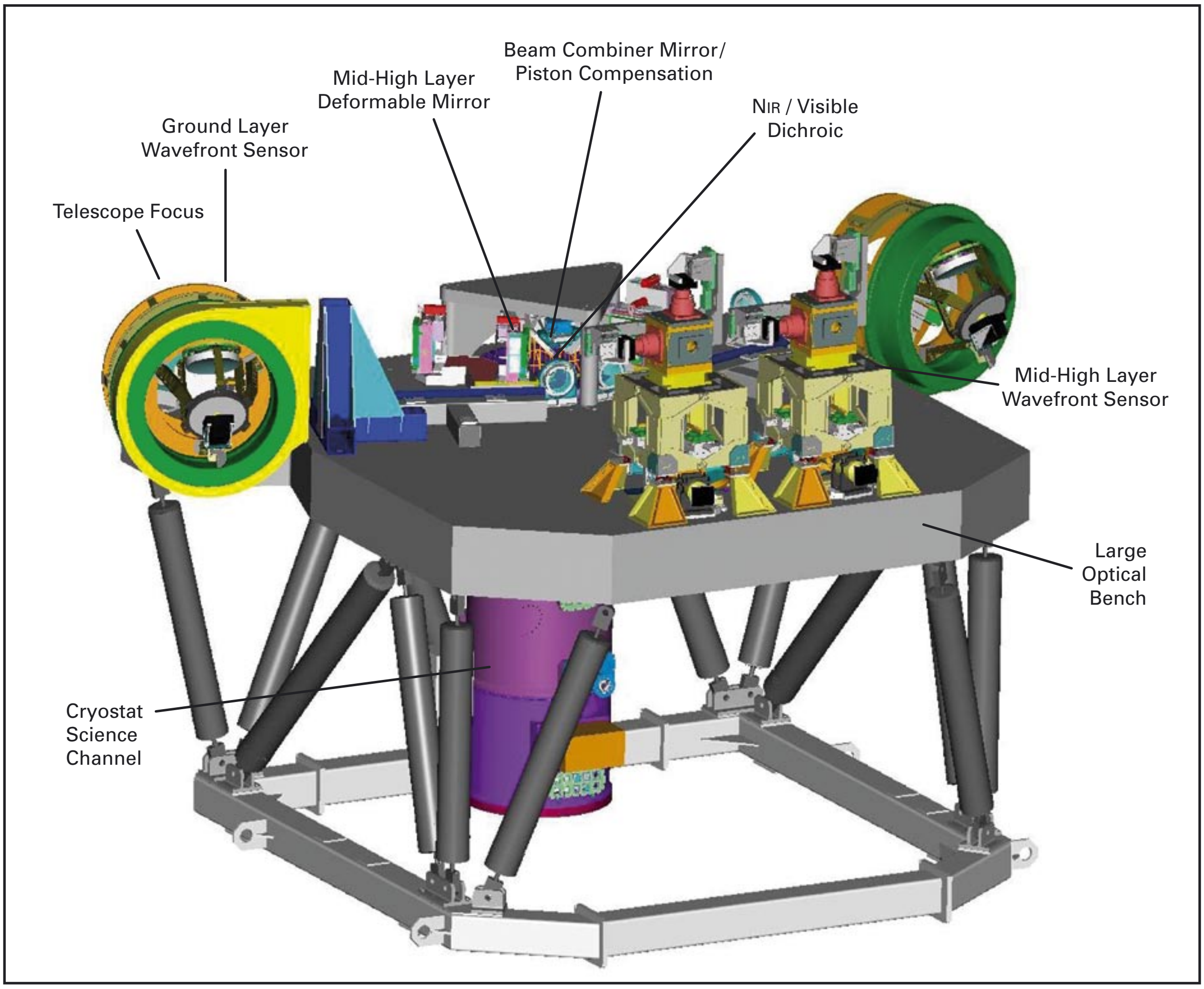


Fig. IV.1.8: Mechanical components associated with the LINC-NIRVANA optical path.

telescope array. Since the LBT uses an altitude-azimuth mount, Earth's rotation will cause the science field to rotate around the optical axis, blurring the image if no corrective measures are taken. The LINC-NIRVANA detector is mounted on a precise rotation assembly, allowing integrations corresponding to sky rotations up to 30°.

The Multi-Conjugated Adaptive Optics System

Multi-conjugated Adaptive Optics (MCAO) takes advantage of the fact that atmospheric turbulence is typically confined to a few distinct layers. By placing optical conjugates, or images, of the deformable mirrors at the altitudes of these dominant layers, very high levels of correction can be achieved over a wide field of view

.In its baseline (so-called "LINC") configuration, LINC-NIRVANA uses a single, on-axis star for wavefront referencing, and a single deformable mirror (either the adaptive secondaries or the Xinetics units) for correction. This is classical adaptive optics, and is essentially equivalent to the LBT facility AO strategy. LINC mode will always be available, even as further capabilities come online.

With the addition of multiple, natural guide stars and "optical co-addition," the final implementation of the instrument (so-called "NIRVANA" mode) uses up to 20 guide stars per telescope over a field up to 6 arcminutes in diameter to correct two, and ultimately perhaps three, atmospheric layers.

LINC-NIRVANA reduces the potential complexity of such an MCAO system by effectively decoupling the loops which control the various deformable mirrors. The Ground Layer Wavefront Sensors sample up to 12 stars each in an annular region between 2 and 6 arcminutes in diameter, and drive the 672-actuator deformable secondary mirrors. The individual star probes consist of an optical pyramid and a field enlarger. The AO secondaries are optically conjugated to a layer approximately 100 meters above the telescope. Light from stars over a fairly large angle on the sky passes through the same portion of such low-lying layers – hence, we can select guide stars from a very wide field.

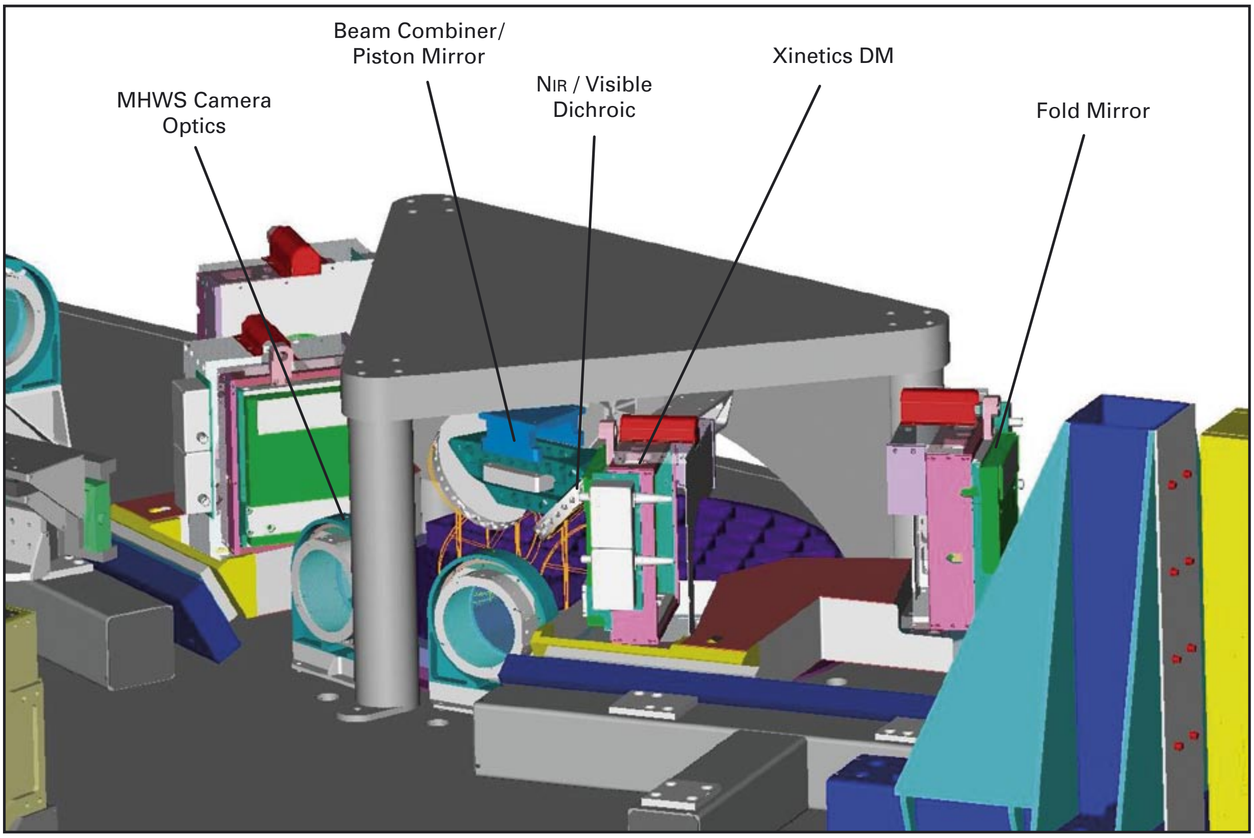


Fig. IV.1.9: Beam combination area, including Xinetics DMs, piston mirror, and the visible / near-infrared dichroic.

The second correction loop uses the two Xinetics deformable mirrors on the "Z" assemblies (described above), and the Mid-High Layer Wavefront Sensors. These devices receive the light that is reflected from the visible/near-infrared dichroic in the beam combination area. The MHWS select up to eight natural guide stars in the central two arcminute field, and measure the turbulence arising at altitudes between 8-15 km (the exact conjugate altitude can be set by displacing the "Z" assemblies). The MHWS star probes are essentially identical to those in the GWS.

As with the science detector, the GWS and MHWS must rotate to follow the sky. For the ground-layer sensors, this is accomplished by rotating the large bearing which holds the wavefront assembly (Fig. IV.1.8). For the mid-high layer sensors, LINC-NIRVANA uses a pair of field-rotation "K-mirror" assemblies (visible in figures IV.1.7 and IV.1.8).

Patrol Camera

To assist in field-finding and placement of the wavefront sensor probes, a visible-wavelength "patrol camera" sits next to each Mid-High Layer Wavefront Sensor (the patrol camera is not shown in Figs. IV.1.7 and IV.1.8). These cameras receive all, some, or none of the visible light, depending on which of several mirrors/beamsplitters are in place below the MHWS.

Future Options

Needless to say, LINC-NIRVANA is a very challenging instrument, and we intend to proceed very methodically in its implementation (see below). Nevertheless, we have included a number of upgrade options in the basic design. These include:

- One additional DM per arm, replacing the second, flat mirror in the "Z" assemblies. This deformable mirror could then be conjugated to layers in the range 4-8 km. A beamsplitter and focus mechanism in the MHWS accommodates the additional layer.
- Enhanced patrol cameras with a larger field-of-view
- Upgraded CCDs in the wavefront sensors. This includes the new generation of "zero read-noise" L3CCDs.

Implementation Plan

Our goal is to bring LINC-NIRVANA to the telescope as soon as it is ready to produce interesting science. Clearly, having all the subsystems and modes working at first light will be too ambitious. We have therefore laid out an implementation sequence, which breaks down the complexity into a series of incremental goals:tific observations.

1. Interferometric near-IR imaging with a pair of single, on-axis wavefront sensors ("LINC" mode). The goal is to achieve scientifically useful data as soon as possible and to aim for performance levels suitable for routine operation.

2. Demonstration of Ground Layer Wavefront Sensors. This phase foresees non-interferometric, diffraction-limited observations with the GWS driving the adaptive secondaries, with a best effort to obtain interferometric measurements.

3. Multi-Conjugate Adaptive Optics using a single telescope aperture (non interferometric). This mode uses the GWS and MHWS simultaneously. The goal is to demonstrate the enhanced field of view and sky coverage afforded by MCAO..

4. Full MCAO. interferometry. This is the final "NIRVANA" mode, with interferometric observations and full MCAO.

Effective exploitation of LINC-Nirvana's capabilities will inevitably involve a balance between engineering and commissioning these modes and performing science observations. We anticipate a timescale of approximately two years for the full implementation sequence, with each step interspersed with significant periods for scientific observations.

Further, up-to-date, news and information about LINC-NIRVANA are available at http://www.mpia.de/LINC

(Dave Andersen, Harald Baumeister, Armin Böhm, Hermann Böhnhardt, Peter Bizenberger, Florian Briegel, Sebastian Egner, Wolfgan Gaessler, Bernhard Grimm, Stefan Hanke, Tom Herbst (PI), Martin Kürster(PM), Werner Laun, Ulrich Mall, Lars Mohr, Vianak Naranjo, Marc Ollivier, Alexei Pavlov*, Hans-Walter Rix, Ralf-Rainer Rohloff, Johannes Schmidt, Roberto Soci*, Clemens Storz, Sebastiano Ligori, Robert Weiss, Wenli Xu*. Collaborating Institutes: INAF-Arcetri, 1. Phys. Inst. Köln, MPIfR)*

IV.2 LUCIFER I/II

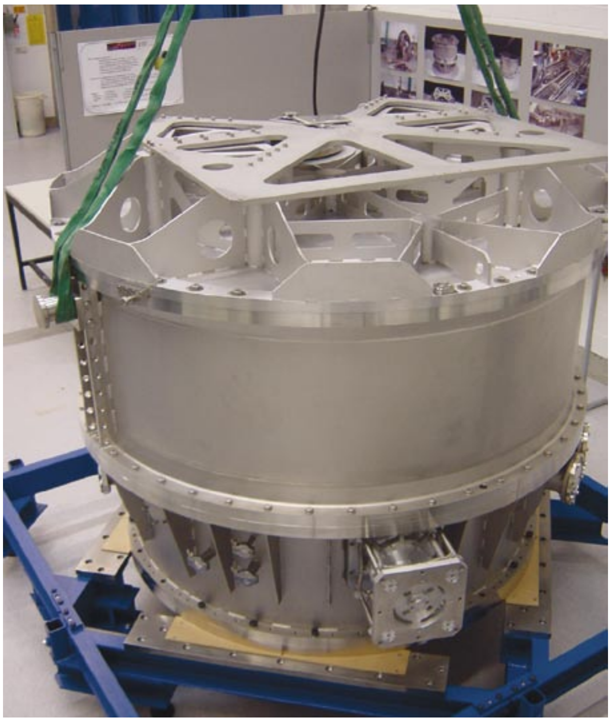
LUCIFER is a near-infrared camera with grating spectroscopy for the Large Binocular Telescope (LBT). The instrument will be used for many purposes, mainly for extragalactic observing programs. It is developed by a consortium of five institutes.

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 for Extraterrestric Physics in Garching is responsible for the development of the MOS unit, the University of Bochum provides the software while the University of Applied Sciences in 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.

In the year under report, the first cryostat has been completed at Bieri (Zurich) and undergone the first evacuation and cooling tests. This cryostat has been accepted and delivered and now is awaiting the integration of the cryogenic components at MPIA. The cryostat for LUCIFER II has been completed too but needs some reworking.

The complex MOS-mask-replacement unit has also been delivered and is presently being tested and optimized in comprehensive functional tests at MPE.

Fig. 4.2.1: The first cryostat (LUCIFER I) is being delivered to MPIA. Showing excellent vacuum- and cryo-characteristics, it is now ready for the integration of the cryogenic components.



The read-out electronics developed at MPIA was expanded to 34 channels, allowing the reference channels to be used. A complete read-out-electronic set was sent to the University of Bochum for software development. A second set is available at MPIA for tests OF LUCIFER . In the fall of 2004 the second HAWAII detector (for LUCIFER II) was delivered.

(Bernhard Grimm, Werner Laun, Rainer Lenzen, Ralf-Rainer Rohloff; Partners: Landessternwarte Heidelberg; MPI for extraterrestrial Physics, Garching; University of Bochum; Fachhochschule Mannheim)

IV.3 MIDI, the Interferometer at the VLT

By the end of 2002, MIDI (Mid-Infrared Interferometric Instrument) had been put into operation at the Very Large Telescope of the European Southern Observatory ESO. After a short testing period it was already used very successfully for scientific observations in 2003. The instrument interferometricly combines the beams of two of the four VLT telescopes.

In 2004, two important milestones took place: in April, MIDI's regular operation at the VLT open to all observers was started and in August, the official commissioning of the MIDI instrument was completed. With that MIDI was de facto handed over to ESO. The formal handing-over act, though, could not take place yet since negotiations with ESO on supplements, mainly in the software and documentation field, were still under way and probably will not be brought to a close until the beginning of 2005.

Although this sounds all very nice, it nevertheless should be mentioned that MIDI cannot be operated with its full capacity yet. The main reason for this is that the external fringe-tracking system is not yet available because the FINITO instrument planned for this task had not passed its functional tests in 2004. This fact as well as the still missing variable curvature mirrors that will image the pupil into the MIDI instrument cause MIDI to work with limited sensitivity, being able to only observe sources brighter than about 1 Jansky. With external fringe-tracking, the sensitivity of MIDI should be increased by up to 5 magnitudes.

At present, the visibility can be measured only to 10 to 15 percent accuracy. By 2005, though, the so-called SCI-PHOT mode will be available for all observations. In this mode, part of the light gathered by each of the two telescopes is coupled out, measuring parallel the photometric flux coming from both telescopes. This method was tested during commissioning in 2004 and also used in some of the guaranteed time observations. It allowed the visibility to be determined with a precision of 3 to 5 percent.

MIDI measurements during science demonstrating time and guaranteed time observations also went according to plan. Because of minor delays in the commissioning of the auxiliary telescopes the commissioning of MIDI with these 1.8-m telescopes had to be postponed to 2005. This commissioning will then be carried out by ESO itself.

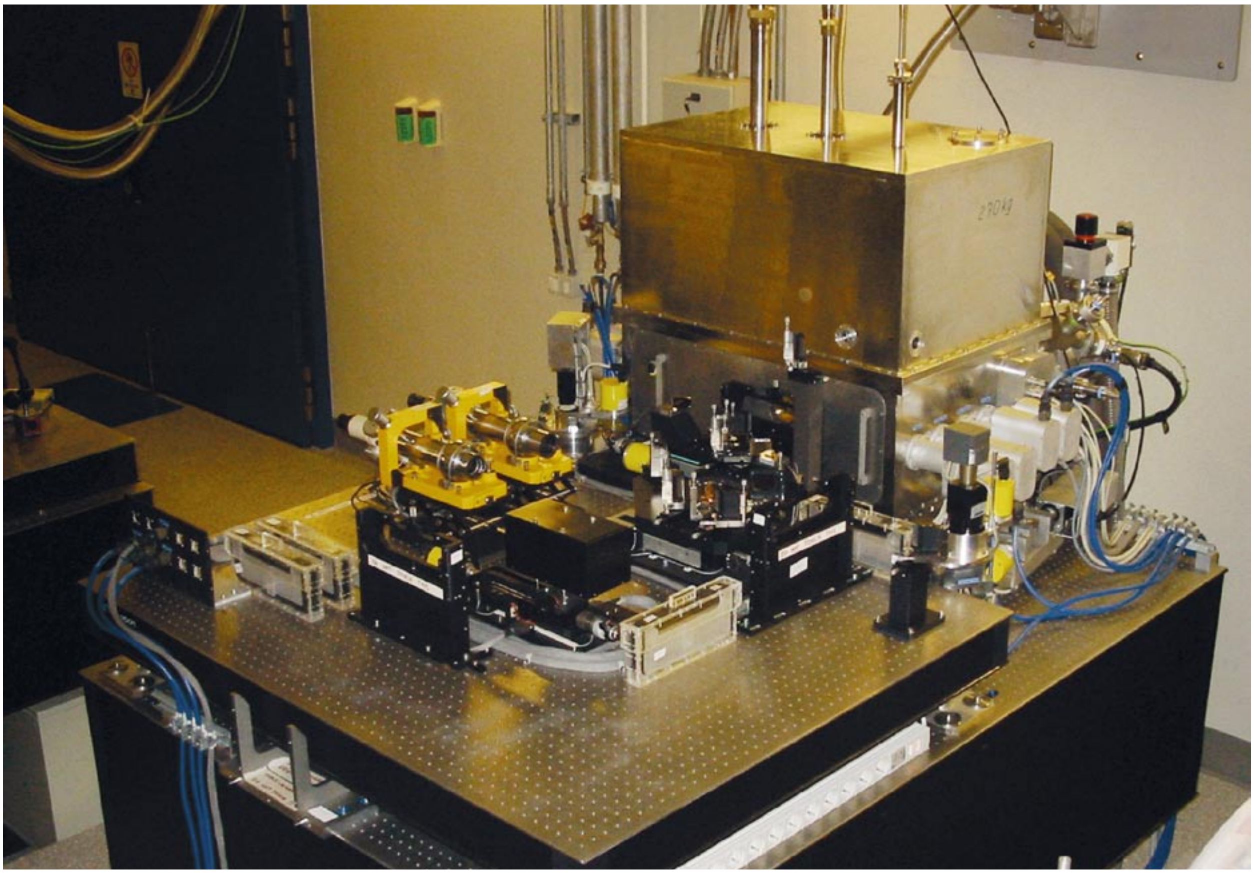
For data analysis, the MIA (MIDI Interactive data Analysis, R. Koehler) software package devised at MPIA was developed to the point where, together with the "Expert Workbench Software" developed at the Sterrewacht Leiden, it could be made available through the internet and used at other institutes.

The planned extension for MIDI into the 20-µm-range (Q band) unfortunately was stopped in September since ESO was not prepared to approve of this extension at short notice. So for our Dutch partners funding was withdrawn and this project had to be cancelled. Another extension, namely the study for developing MIDI into an imaging 4-channel interferometer ("ApreS-MIDI"), was continued vigorously, though. The kick-off for this project – essentially a collaboration between the Observatoire de la Côte d'Azur (PI: B. Lopez) and MPIA with additional contributions from Paris, Lyon, Grenoble, and the MPI for Radioastronomy in Bonn – took place in Heidelberg in January 2004.

In order to link up to four telescopes with ApreS-MIDI (Aperture Synthesis in the MIDI-Infrared), an additional setup will be placed above the optical elements on the MIDI table (i.e. above the "warm optics"), allowing the normal operation of MIDI to be continued without any restrictions. The four beams will be aligned in such a way that they are combined at small inclination angles within the pupil, creating the typical fringe pattern there. This pupil image is then imaged onto the detector using the pupil camera already existing in MIDI. In the year under report, the overall design for ApreS-MIDI was developed while at the same time the hardware design, the software concept, the method of image reconstruction as well as the expected scientific potential of ApreS-MIDI were investigated.

(MIDI: Ch. Leinert, U. Graser, Th. Ratzka, O. Chesneau, R. Köhler, U. Neumann, C. Storz, R. Mathar, N. Salm, W. Laun. Partners: Sterrenkundig Instituut Anton Pannekoek/ Universität Amsterdam, Sterrewacht Leiden, ASTRON/Dwingeloo, Observatoire de Paris/Meudon, Observatoire de la Côte d'Azur/Nizza, Kiepenheuer-Institut für Sonnenphysik, Freiburg. ApreS-MIDI: F. Przygodda, S. Wolf, U. Graser, Th. Henning, U. Neumann, R-R. Rohloff. Partners: Observatoire de la Côte d'Azur/Nizza, MPI for Radioastronomy, Bonn)

Fig. IV.3.1: The MIDI instrument. The rectangular vacuum container at the back houses the beam-combining cold optics and the detector. The "warm" optics is placed in front of it.



IV.4 CHEOPS – an Instrument for Imaging Extrasolar Planets

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

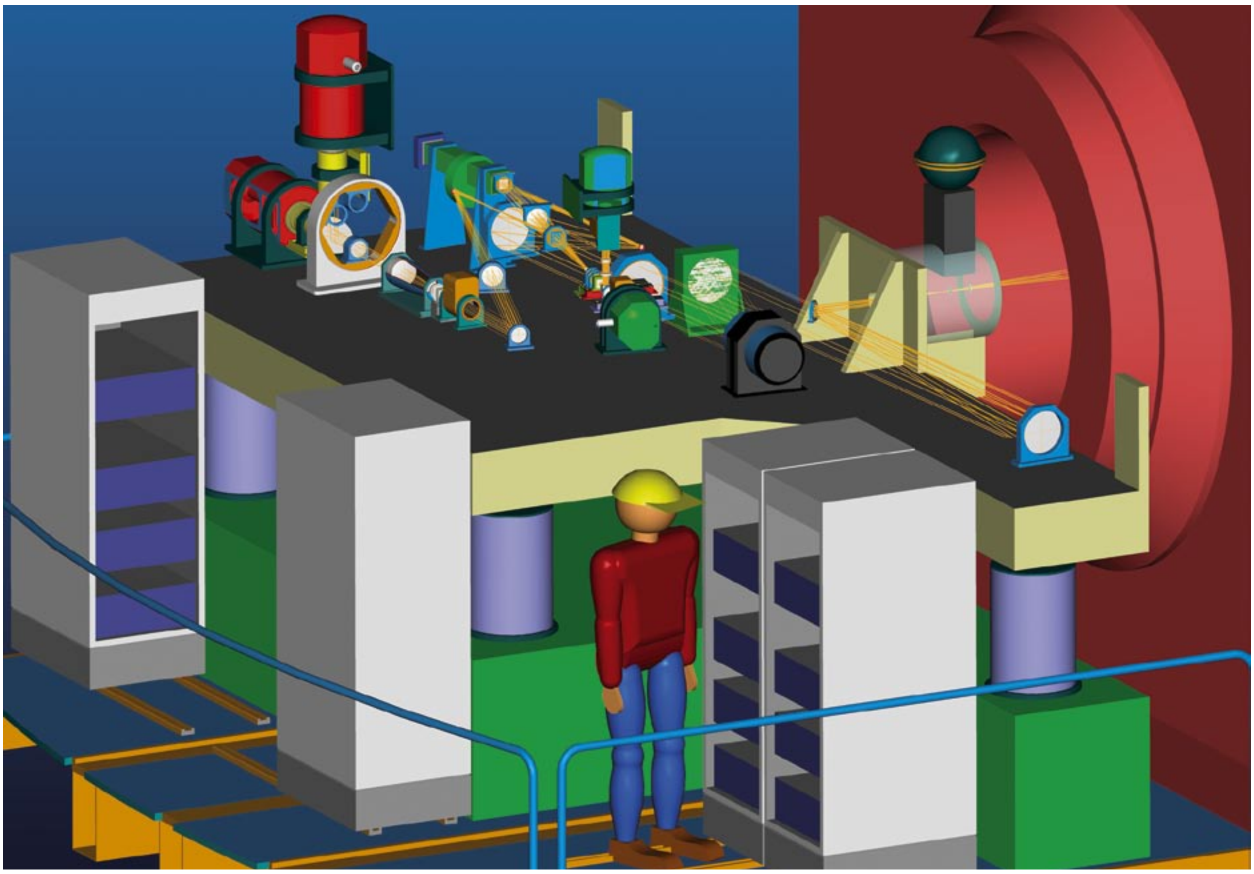
An essential part of the project is to develop an instrument for the VLT that will help to achieve this goal. For this purpose, there was a call for preliminary proposals by ESO in December 2001, picked up by an international consortium led by MPIA. Within a feasibility study beginning in May 2003 and lasting eighteen months a detailed conceptual design was developed for the instrument. The instrument consists of an "eXtreme Adaptive Optics system" (XAO) and two differential imaging components – the ZIMPOL differential polarimeter and a 3D-spectrograph for the near-infrared range. For highest stability, the entire instrument will be securely mounted at the Nasmyth platform of the VLT (see Fig. IV.4.1).

The study phase ended in November 2004. In September, a final meeting of the consortium was held at Ringberg Castle, identifying last problems with the instrumental concept as well as with the overall project. After submission of the documentation in November 2004, ESO made a selection review in December. The result is expected for early 2005.

Within the project, an observing program based on models of planet formation, the spatial distribution of nearby stars as well as their age structure, metallicity etc. will be developed that is intended to yield direct images of several extrasolar gas planets of different ages (10^7 years, 10^8 years, 10^9 years, and older). The observing program will be specified up to the detailed planning of the object list.

(M. Feldt (PI), W. Brandner, Th. Henning, S. Hippler (PM), F. Masciadri, R. Köhler, R. Lenzen, K. Wagner, J. Setiawan, A. Berton, F. de Bonis; Astrophysical Institute of the University of Jena, Thüringer Landessternwarte, Astronomical Institute of the University of Amsterdam, Sterrewacht Leiden, ASTRON Leiden, Astronomical Institute of the ETH Zurich, Dipartimento di Astrofisica e Osservatorio dell'Università di Padova, Osservatorio di Capodimonte, Napoli, University of Lisbon)

Fig. IV.4.1: Design of the CHEOPS instrument.



IV.5 Differential Delay Lines for VLTI-PRIMA

The instrument for "Phase-Referenced Imaging and Microarcsecond Astrometry" (PRIMA) for the Very Large Telescope Interferometer (VLTI) on Cerro Paranal, Chile, is currently being developed at the European Southern Observatory (ESO). MPIA is participating in this project.

With PRIMA, two objects simultaneously can be observed interferometrically in a larger field of view (1 arcminute in diameter). If one of the objects is used as a reference star, perturbations caused by atmospheric turbulences can be compensated for the other object in real time, resulting in an increase of angular resolution and higher sensibility. However, PRIMA will achieve its ultimate goal of astrometric accuracy (measuring positions in the sky) of 10 microarcseconds – corresponding to the apparent diameter of a human hair at 2000 km distance – only after differential delay lines are included.

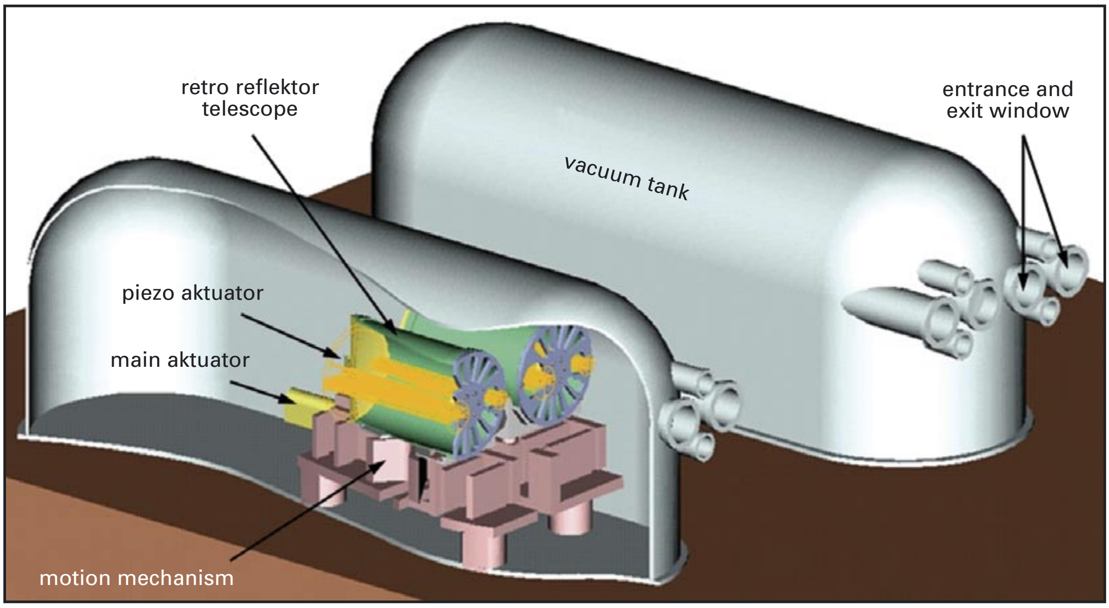
MPIA is leading partner in an international consortium (together with the observatories in Leiden and Geneva) for the development of these differential delay lines as well as the entire astrometric data-reduction software. Work at MPIA focuses on the development of the optomechanical components, a kind of high-precision, movable cat's-eye telescope with an aperture of 20 cm. In connection with a linear motion mechanism and placed in a vacuum, these delay lines will compensate optical path differences of up to 12 cm with nanometer accuracy, corresponding to an accuracy of $1:10^8$.

At present, the project is still in the preliminary design phase. Error budgets and production tolerances for the optical system and various mechanical concepts are worked out. The requirements on the mechanical and optical accuracy are at the limits of technological feasibility. The preliminary design review is planned for the first half of 2005.

The scientific goal of this development is the implementation of an astrometric search-program for planets. By observing small shifts in the position of a star caused by the gravitational interaction with an otherwise invisible planet, Saturn- and Uranus-like planets around stars at distances of up to 60 light years should be detected and their exact masses and orbital parameters be determined. The completion of the instrumentation and the start of the planet-search program are planned for 2007.

(Harald Baumeister, Peter Bizenberger, Thomas Henning (PI), Ralf Launhardt (Project Scientist, PM Optomechanics), Ralf-Rainer Rohloff, Johny Setiawan, Karl Wagner, Partners: Sterrewacht Leiden, Observatoire de Genève)

Fig. IV.5.1: Concept of the differential delay line for PRIMA. Two linearly adjustable cat's-eye reflectors are each placed in a vacuum tank. Optical path differences are achieved by displacements of the entire telescope as well as by displacements of the small tertiary mirror. A laser system measures the displacements with nanometer accuracy.



IV.6 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 that works in the optical range.

Similar to the Shack-Hartmann sensor, 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 design phase for PYRAMIR was completed by the end of 2003. All components – dewar, Hawaii-I detector, read-out electronics, real-time computer, control electronics of the deformable mirror with 2.1 Gbit reflective memory interface, optical components, motors, metrology, software etc. – were procured in 2003 and 2004. Difficulties with the delivery of the cold optics are delaying the conclusion of this phase until probably March 2005.

During the year under report, the cooling vessel was procured and the components that have to be fitted in were manufactured at MPIA. The cooling of the instrument as well as the function of all motors and the detector had been tested at MPIA by the end of 2004. In October 2004, the first implementation into the ALFA optics took place on Calar Alto. Here, also the connection to the real-time computer and to the newly acquired control electronics of the deformable mirror were tested. Apart from minor problems that have been eliminated meanwhile, these tests went satisfactorily. After the delivery of the cold optics – probably in March 2005 –, a test illumination and a trial operation of the real-time system will take place at MPIA. The first operational application on the night sky is now scheduled for June 2005.

(H. Baumeister, P. Bizenberger, W. Brandner, J. Costa, B. Grimm, M. Feldt (PI), Th. Henning, S. Hippler (PM), W. Laun, S. Ligori, R.-R. Rohloff, R. Ragazzoni; D. Peter, N. Salm, C. Storz, K. Wagner)

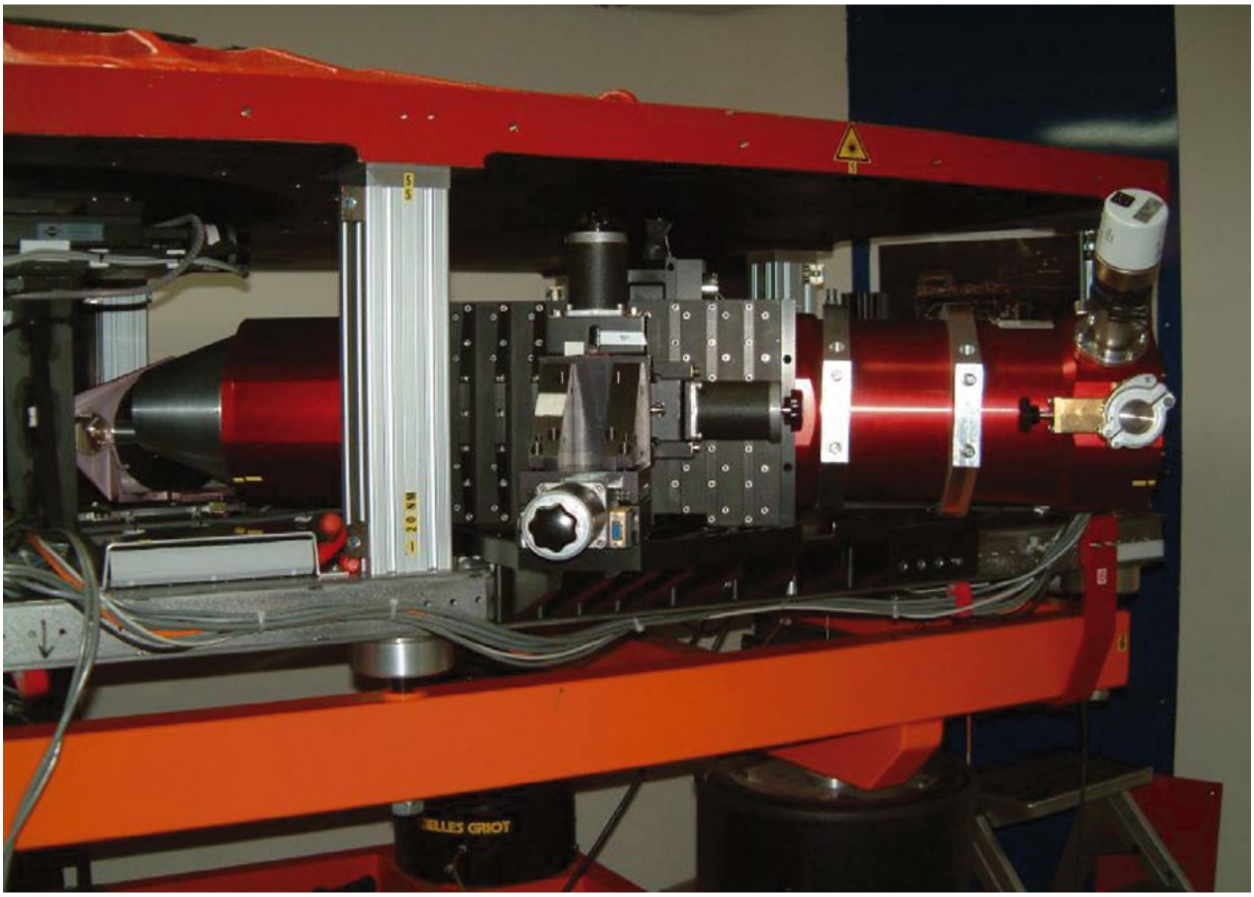


Fig. IV.6.1: The red cylinder within the adaptive optics system ALFA contains the wavefront sensor PYRAMIR.

IV.7 A New Control System for the 3.5 m Telescope at Calar Alto

Reasons for renewal

The 3.5 m telescope went into operation in the early 1980's. While the mechanics are still working nicely, many electronics and computer parts are at the end of their lifetimes. Changes in technology have made replacement of parts increasingly difficult in the last years: many parts – neither original nor equivalent ones – are simply not available anymore. In order to avoid losses of observing time due to technical failures it was decided to renew the telescope control system completely, i.e. to replace computer, bus system and practically all electronics hardware.

The Concept of new control system

The original control system consisted of one central LSI 11 computer which was connected to the various drives and control units with an extended DMA bus system. In contrast, the new concept of the telescope control system, devised by R.Wolf, uses a SUN workstation with standard Solaris operation system as a host for 5 VME computers which control the drives. The workstation also serves as a router to the public Calar Alto network. A linux PC is used for the communication with the operator through a graphical user interface. All computers communicate with each other by a private ethernet network, not accessible directly from the outside. The VME's are located at different places close to the corresponding telescope electronics. These are: main electronics rack (second floor), operation desk (control room), yoke mounting (yoke structure), tube (inside of the telescope tube), and coudé mirror S5 rack (floor of the coudé plant). The linux PC is located in the main desk. The cycletime of the IO-system has been set to 20 Hz for a sufficient realtime response to changes and events triggered from hardware.

The software is organized in several layers. The first layer is the interface to the observer/staff (GUI), which allows the selection of 5 operation modes. The second layer controls the telescope drives which are right ascension, declination, focus, cassegrain flange, coudé S5 mirror azimuth and elevation and dome setting. This task computes 4 times per second all necessary astronomical and internally used data derived from the drivers input like encoder values, universal time, airmass, updates the pointing correction, the refraction etc. The third layer acts as instrument protection. It controls limit switches, stop positions and current state of the drives. It also builds the interface to the drivers, which are found in the layer below the instrument protection. A watchdog monitors all five vme-systems and the tasks running on them and programs running on the SUN by executing a live check every 4 seconds. If all systems respond within the expected time, the watchdog is resetted and repeats the system check 4 seconds later. If not, the electronics of the drives and system power of the vme's is shut down. The system is shut down also in case the watchdog process itself crashes.

Realization and current status

Since the telescope control system is very complex, we decided to split its renewal into two phases. Phase I comprises replacement of the computer and bus system, phase II replacement of the motor controls including the closed loop control of the drives in hour and delta. The problems of phase I are mainly to establish a stable operation of the computer system and furthermore to supply all functionalities of the system. After careful preparation, installation of hard and software for phase I was done in April and May 2004. It became clear very quickly that the concept is a sound one, the losses in observing time due to problems with the telescope control system were on the order of less than an hour per night in the beginning. Logging of telescope actions and analyzing errors and failures quickly led to enormous improvements. As of December 2004, phase I is now in a stable state, all functionalities required for astronomical observations are working. To terminate phase I, we need to incorpate read-out of some telescope parameters and replace the preliminary GUI by the final one. We intend to finish this early 2005. Phase II comprises replacement of the motor control electronics for the drives of the Cassegrain flange, the focus and hour and declination. Usage of modern digital output stages should lead to relatively straight forward solutions. We hope to finish the project in early 2006.

*(Karl Zimmermann,
Rainer Wolf,
Josef Fried)*

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

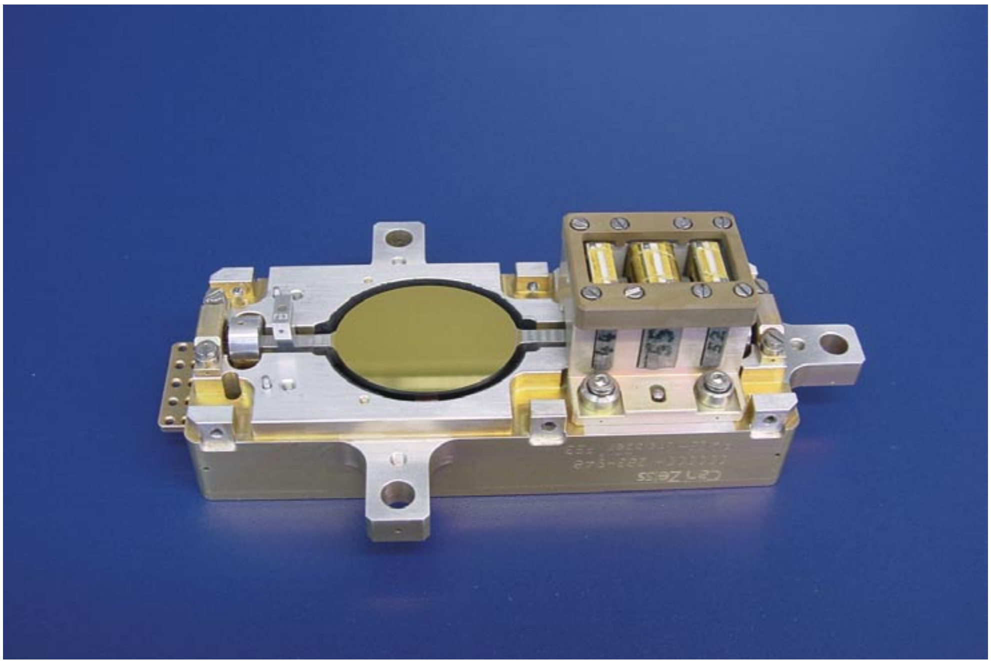
In 2007, the European Space Agency (ESA) will send the HERSCHEL Far-infrared and Sub-millimeter Space Observatory as well as the PLANCK Cosmology Satellite to the Lagrangian Point L2 aboard an ARIANE-5 rocket. At an antisolar distance of 1.5 million km from Earth, HERSCHEL's 3.5-m primary mirror will radiatively cool down to – 200°C. This decrease of the characteristic thermal radiation of the telescope will allow very sensitive measurements in the far-infrared and sub-millimeter range at wavelengths of 60 to 600 μm. Three focal-plane instruments (PACS, SPIRE, and HIFI) will image the infalling radiation from space with high-spatial-resolution cameras and analyze it with spectrometers of medium and high spectral resolution.

The PACS instrument is being developed jointly by eleven European institutes under the leadership of MPE Garching. MPIA is the largest co-investigator institute and responsible for important components and tasks: the development of the focal plane chopper, the characterization of the far-infrared cameras for the spectrometer unit, and the calibration of the instruments during ground-based tests – and later during the flight.

The focal plane chopper is a 30 mm "tipping" ("chopping") mirror comparing most precisely two neighboring sections of the sky with a square-wave modulation with frequencies up to 10 Hz. By subtracting the background radiation identical in both fields, the small signal of the interesting cosmic source can be extracted. Based on the prototype developed at MPIA, C. ZEISS is building the flight model of the chopper (Fig. IV.8.1). This work was almost completed by the end of 2004 when two unexpected problems arose: (1) during cold (– 200 °C) vibration tests with 30 times the gravity acceleration (30 g) simulating the rocket launch, minor shifts between the electrical and mechanical center position of the chopper axis had occurred, (2) after seven cold-warm cycles (– 270 °C → + 300 °C → – 270 °C) the gold-plated mirror surfaces displayed small "pimples" (~ 5 μm height). Although both deviations still would have allowed an application in the PACS flight model, it was decided to conduct a thorough investigation as a precaution in order to ensure that both errors would not increase until launch and thereafter. Shortly before Christmas, a ten-cycle cold-warm test in a helium cryostat with seven different kinds of gold-plated mirrors was started at MPIA.

Differences found during comparative measurements of the sensitivities of the germanium-gallium-infrared cameras carried out at different institutes were followed up in an additional calibration measurement at MPIA (Fig. IV.8.2). Definite and reliable values for current sensitivity and noise were determined. A new generation of pre-amplifiers consisting of integrated cold readout electronics (CREs) were thoroughly characterized at the temperature of liquid helium (– 270 °C). Significant improvements compared to the qualification model were found, so that these new CREs appear usable for the PACS flight model.

Abb. IV.8.1: Flight model of the PACS focal plane chopper. The gold-plated mirror has a maximum diameter of 32 mm. To the left, one of the suspensions in a CuBe flexural pivot can be seen, and to the right, the three coil forms for the 10 μm high-purity Al wires. Within the instrument, the chopper is housed inside an infrared-black enclosure with baffles, which have been removed for this image. (MPIA and ZEISS)



First simulation tests of radiation damages in the detectors, caused by cosmic particles, were started using radioactive gamma sources. As in our ISOPHOT instruments, these damages could be annealed out by intense irradiation with infrared light. Within her thesis, a member of our team will develop methods for a steady operation of the detectors under continuous bombardment by simulated cosmic particles. For this purpose, optimum operating values for the cameras (temperature, bias voltage and photon background) have to be determined and the steady calibration of the camera has to be verified over a long period of time. These studies are so important because the raw data aboard HERSCHEL have to be highly compressed for radio transmission to the ground station. Only the careful removing of disturbing cosmics and the steady current sensitivity of the detectors will allow precise calibration of the astrophysical data.

In the fall, MPIA was participating in the ground-based cold tests of the PACS qualification model in Garching. For this, the instrument was installed inside a large cryostat that also contained a telescope-simulating optics and calibration sources. Furthermore, external calibration sources with spot masks for simulating point sources as well as gas cells for wavelength calibration were used. The instrument was operated with the first version of the control software; real-time and subsequent analysis of the received scientific data was done using the prototypes of the quick-look analysis and the interactive analysis, respectively. In preparation of these tests a number of calibration and control procedures were developed at MPIA. During the tests and the following months, test reports were established and compared to the specifications in order to initiate improvements for the flight model.

For their contributions to the development of the PACS instrument scientists at MPIA are granted 300 hours of guaranteed observing time with HERSCHEL. Most of it will be included in two large high-priority "key projects": 1. quasars at high redshifts, and 2. star formation regions that mostly had been detected with the ISO Serendipity Survey (ISOSS). Further shares in MPIA's guaranteed time will go into the participation in other key projects (luminous galaxies,...). In addition, key projects (with more than 100 hours observing time) will be started for the open observing time; under the leadership of MPIA, an extensive observing team for elliptical galaxies has already been organized.

(Dietrich Lemke, Stephan Birkmann, Helmut Dannerbauer, Ulrich Grözinger, Thomas Henning, Ralph Hofferbert, Ulrich Klaas, Jürgen Schreiber, Jutta Stegmaier, Manfred Stickel, Roland Vavrek)

Fig. IV.8.2: Preparing inspections of a Ge:Ga detector line of the PACS infrared camera. The U-shaped profile is used for the pressure mechanism imposed on the detector line, which can extend the long-wave sensitivity limit up to $\lambda < 200$ µm.

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

The JWST is scheduled for launch under the leadership of NASA in 2012 as the successor to the extremely successful HUBBLE Space Telescope. Goals of this mission are: (1) observing the first stars/galaxies/quasars in the early universe, (2) investigating galactic evolution to the present-day appearance of the universe, (3) observing the formation of stars, planets and the prerequisites for the origin of life. These studies in the high-redshift, dust-enshrouded, and cool universe will be conducted in the infrared spectral region. MPIA is participating in the instrumentation.

The 6.5-m primary mirror of the JWST will be cooled radiatively to – 230 °C in order to avoid blinding of the sensitive cameras by its own thermal radiation. This "passive cooling" is possible at the Lagrangian Point L2 at 1.5 million km antisolar distance from Earth where the JWST will be transported aboard an ARIANE-5 rocket. One and a half of the three focal plane instruments of the JWST come from Europe: NIRSPEC, the multi-object spectrometer (~ 90 percent of it) and the MIRI camera and spectrometer for the mid–infrared range (~ 50 percent of it).

For both instruments, MPIA has designed the filter and grating wheels, based on our successful concept of the ISOPHOT filter wheels: direct drive with a torquer motor, exact positioning with a detent. During operation in cryo-vacuum, this configuration offers maximum reliability and minimum thermal power dissipation since feedbacks and holding currents are avoided. This was demonstrated with three filter wheels in more than one million trouble-free steps during the ISO mission lasting 29 months.

For both NIRSPEC phase-A*-studies of the competing ASTRIUM and ALCATEL company consortia, the wheel concepts were designed at MPIA. After ESA's decision in favor of the ASTRIUM consortium and a renewed call for tenders for the filter/grating wheels, MPIA together with ZEISS and AUSTRIAN AEROSPACE developed a tender in which MPIA as the smallest of the three partners would contribute technical experience gained from earlier missions, the electrical drives and the execution of cold tests. From this contribution strong synergetic effects are expected for the already existing commitment to build the MIRI wheels. A linear drive – originally developed for NASA by the MOOG company, California, for the

Fig. IV.9.1: A 1:1 model of the JWST in front of an exhibition hall in Texas demonstrates the huge dimensions of this satellite observatory. The 6.5-m-primary mirror is a composite of 18 individual 1.3-m-mirrors made of beryllium. The entire satellite including the tennis-court sized radiation shield will be transported tightly folded up within the payload nose cone of an ARIANE-5 rocket to L2. More than 100 mechanisms will then ensure the unfolding and adjusting.

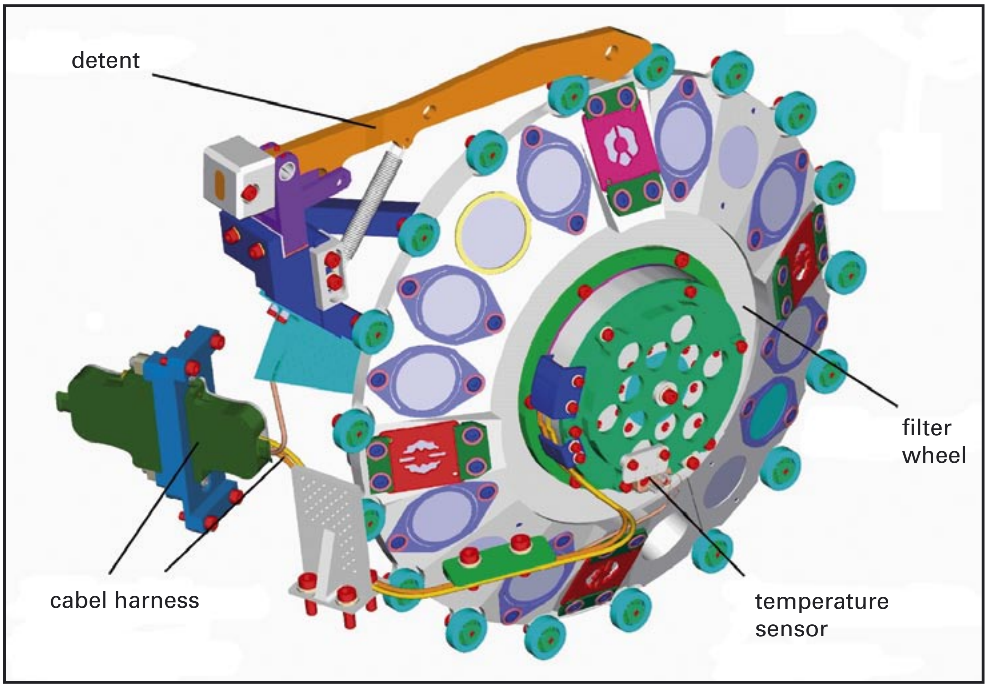


Fig. IV.9.2: The 18 positions of the MIRI filter wheel are equipped with broad- and narrow-band filters, coronagraphic masks and a prism for spectrophotometry. The center of the wheel harbors the direct drive; the index ball bearings and the detent are to be seen at the periphery of the wheel. The wheel is 25 cm across, the positioning accuracy is < 4 arcsec.

alignment of the primary mirror segments of the JWST – was procured in cooperation with ESA as a possible focusing mechanism for NIRSPEC. Detailed cryo-vacuum tests of these components within the MPIA cryostat revealed an unexpected early breakdown of this drive, which therefore had to be sent back for analysis to the manufacturer.

H.W. Rix of MPIA was appointed one of the mission scientists for NIRSPEC against distinguished competition from ESA.

Within the European MIRI consortium MPIA is responsible for the development and delivery of the filter wheel and both spectrometer wheels. As the consortium consists of 21 scientific institutes from all over Europe, the number of interfaces between particular contributions is accordingly large. For MPIA this means, e.g., continuous and exact coordination with (1) CEA, Paris, for the filter wheel disk being equipped there with filters, coronagraphic masks and a prism; (2) ASTRON, Dwingeloo, the manufacturers of the grating wheel disk; (3) AIT, Edinburgh, the manufacturers of the beam divider disk; (4) the PSI, Villingen, where the cryo-harness is manufactured and the cold test chamber is operated; (5) CSL, Liège, the manufacturer of the warm on-board

Fig. IV.9.3: Initial inspection of the cryo-torquer motors in the MPIA cleanroom. The UV-lamp is used to detect possible soiling, a great danger to the central bearings of the filter and grating wheel. All mechanical parts of the motors are manufactured at the MPIA workshops.

electronics; and many more. The preliminary design of the wheel drive mechanism at MPIA was extended by two minor studies on mechanical and thermal issues by ZEISS; useful suggestions were also received from ESA and NASA experts visiting MPIA. Phase B of the MIRI development was successfully completed in the fall with the preliminary design review at ESA. Since then the project is in the building phase C/D that was started with the procurement of the major components (cryo-torquer motors, integrated pre-stressed ball bearings etc.) and the manufacturing of all components for the first "design models". Parallel to this work, a ground-based test instrument (EGSE) for all wheel drive mechanisms is being developed, which can simulate the various operating conditions of the satellite (warm during launch, cold at L2). MPIA will build a total of five of these computer-based test instruments and loan them to different institutes of the MIRI consortium for sub-system and system tests.

Funding of the forthcoming industrial work was granted by DLR shortly before the end of the year. The call for industrial tenders for building the flight models was published shortly before Christmas in the European official gazette. These flight and spare flight models of the filter and grating wheels are planned to be built by a domestic aerospace company according to the preliminary design of MPIA. MPIA will keep the costs relatively low by significant and continuous contributions to the electric section and all cold tests.

Although observations with the JWST will be possible not before 2012, the updated scientific goals of the mission are being compared with already achieved and expected performance data of the MIRI instrument in regular science meetings of the participating institutes. Preparations for the calibration of the instruments on celestial standards and optimized observing experience for the mission are also being discussed here.

(Dietrich Lemke, Armin Böhm, Fulvio de Bonis, Monica Ebert, Ulrich Grözinger, Ralph Hofferbert, Thomas Henning, Armin Huber, Ulrich Klaas, Sven Kuhlmann, Jose Ricardo Ramos, Ralf-Rainer Rohloff, Johanna Rosenberger)

V People and Events

V.1 Dedication of the Large Binocular Telescope

On October 16th, the future largest single telescope in the world, the Large Binocular Telescope on Mount Graham, Arizona, was presented to the public. High-ranking representatives from science and politics were participating in the opening ceremony. For MPIA, leader of the German LBTB consortium, this event was one of the highlights of the year. Both directors, Thomas Henning and Hans-Walter Rix, as well as Tom Herbst, project scientist for the LBT in Germany, and Mathias Voss, head of administration, together with Kurt Mehlhorn, the Vice President of the Max Planck Society, had traveled to Arizona as representatives of MPIA. In Germany, the opening of the LBT was a remarkable media success.

In an obviously cheerful mood, about one hundred guests witnessed the dedication of the double-telescope on Mount Graham near Tucson, Arizona. Within the LBTB consortium, Germany participates at 25% in the project. "Thus we get hold of a quarter of the entire observing time at this unique telescope of superlatives", declared Tom Herbst. At the opening ceremony, only one primary mirror was installed. By the end of 2005, the telescope should also be equipped with its second primary – and thus achieve its full aperture.

A further stage of completion should be achieved by 2007 with the installation of the LINC-NIRVANA instrument built at MPIA in Heidelberg (see Chapter IV.1). This instrument will combine the radiation from the two mirrors with highest precision in a common focal plane, and superimpose it to create an interferometric image. In addition, an adaptive optics system will compensate image perturbations caused by turbulences along the light path through the atmosphere. "With this step, the LBT will achieve a resolving power ten times higher than that of the HUBBLE Space Telescope", said Hans-Walter Rix.

As well as astronomers from MPIA, representatives of the Landessternwarte Heidelberg, the Astrophysical Institute Potsdam, the MPI for Extraterrestrial Physics, and the MPI for Radioastronomy had come to Mount Graham, too. The Max-Planck Society was represented by its vice-president Kurt Mehlhorn and treasurer Michael

Fig. V.1.1: The almost completely mounted telescope in June 2004: The first primary mirror is installed; high above it, the prime-focus camera LBC 1 for the red spectral region is to be seen.

Fig. V.1.2: The LBT building.

Fig. V.1.3: The German delegation in front of the LBT. From left to right, standing: Konstanze Pistor (Ministry of the Land of Brandenburg), Kurt Mehlhorn (MPG), Hans-Walter Rix, Thomas Henning (both MPIA), Matthew Lehnert (MPE), Michael Truchsess (MPG), Markus Schleier (MPG), Matthias Steinmetz (AIP), Olaf Henkel (Leibniz Society), Peter Stolz (AIP). Squatting in front: Günther Hasinger (MPE), Klaus Strassmeier (AIP), Tom Herbst (MPIA).

Truchsess and Markus Schleier, Olaf Henkel, president of the Leibniz Society, and Matthias Schenek, representing the Ministry of Science in Baden-Württemberg, had come as political representatives. Steven Beckwith, former director of MPIA and now an External Scientific Member, also took the chance to visit the LBT.

In Germany, the media expressed a keen interest in the opening ceremony. MPIA had prepared a comprehensive press kit that was sent to numerous editorial offices, and had given a press conference. Everybody was surprised by the response: More than 180 newspapers reported on the event in a total of 770 articles, among them all important national daily newspapers as well as weekly magazines such as "Die Zeit" and "Der Spiegel". In addition, there were 11 TV reports, e.g. in the "Heute Journal" and the "Tagesschau", as well as 18 radio reports. So the event received extensive attention all over Germany, demonstrating once again the intense interest of the media and the general public in astronomical issues.

Germany's Participation in the LBT

After completion, the LBT will be equipped with two huge 8.4-m-mirrors. They are fixed on a common mount and will be pointed simultaneously at distant celestial bodies, thus allowing interferometric observations. The 120 million dollar observatory is located on Mount Graham (3190 m), Arizona.

The LBT was planned and built by an international consortium: Five German institutes under the leadership of MPIA in Heidelberg are participating together with

Fig. V.1.4: About one hundred astronomers and political representatives had come to celebrate the opening of the LBT.

Fig. V.1.5: Günther Hasinger, Kurt Mehlhorn and Hans-Walter Rix in the mirror lab where the second primary mirror is being polished.

one quarter. Their contribution to the realization of the LBT focuses on the technologically most ambitious developments in the instrumental equipment of the telescope. The pioneering experience gained this way on new technological territory will play a pivotal role in the realization of next-generation telescopes.

Both LBT mirrors together span an area of 110 meters square, thus achieving the light-collecting performance of a single 12-m-mirror and the resolving power of a single 23-m-mirror. A single mirror of such gigantic size would currently not be feasible.

The double telescope will be controlled by two guiding systems. They position the telescope and ensure exact tracking with the help of a guide star. The light of the guide star is also used to continuously measure and correct the deformation of the actively supported primary mirror in order to keep its ideal shape in each position of the telescope. These two "acquisition, guiding- and wavefront-sensing units" (AGW) are being built at the Astrophysical Institute Potsdam (AIP), with contributions from INAF-Arcetri, the Landessternwarte Heidelberg, and MPIA.

In the beginning, astronomers will observe with only one of the two primary mirrors, using at first a prime-focus camera and, from late 2005 on, a spectrograph named LUCIFER 1. This spectrograph and its twin LUCIFER 2 are being built in Germany (Landessternwarte Heidelberg, MPI for Extraterrestrial Physics, Ruhr University Bochum, and the University of Applied Sciences in Mannheim). The whole instrument is being tested and assembled in the laboratories at MPIA (see Chapter IV.1).

These instruments will be joined later by a high-resolution spectrograph named PEPSI that is being built at AIP.

The most ambitious of all instruments developed for the LBT is LINC-NIRVANA. It combines two optical methods whose interlocking functions will gradually be extended and tested. With this instrument, unknown experimental territory is being entered. The goal is to get closer and closer to the theoretical resolving power of the double mirror also in reality.

The LBT Interferometric Camera (LINC) will combine the radiation beams from the two mirrors, imaging them in a common focal plane. Extreme precision is required for this process since the two light paths have to be of exactly the same length. NIRVANA (Near-Infra-Red Visible Adaptive Interferometer for Astronomy) will eliminate image perturbations caused by turbulences in the atmospheric layers above the telescope. Only in this way the double telescope will achieve its outstanding spatial resolution.

In addition to its role as a beam combiner and as an infrared camera, LINC-NIRVANA will have a third, very crucial function: adaptive optics. It will give the LBT "space-telescope quality". Here too, MPIA enters new territory with an extended form of adaptive optics, the so-called multiconjugated adaptive optics (MCAO).

If all is going according to plan, the development and implementation of the multiconjugated optics in LINC-NIRVANA will be completed in 2007. Then the LBT will have achieved its full performance.

Fig. V.1.7: The vice-president of the MPG, Kurt Mehlhorn, emphasizes the top position of German astronomy.

Fig. V.1.6: Thomas Henning together with Marco Salvati of Arcetri observatory.

V.2 25 Years of Calar Alto Observatory

On September 28th, 2004, the Calar Alto Observatory located on Calar Alto Mountain (2168 m) in the Sierra de los Filabres celebrated its 25th anniversary. With this branch of MPIA, German astronomers and their Spanish colleagues for the first time had an observatory at their disposal that enabled them to catch up with international astronomical standards after World Wars I and II. Since then, four telescopes of different sizes as well as state-of-the-art cameras and spectrographs are being operated there at the very frontiers of research. These instruments enabled a number of outstanding discoveries in the past. In the future, too, the Calar Alto Observatory will continue to play a major role. On the occasion of the anniversary, a leg of the Spanish cycle race Vuelta a España ended on Calar Alto on September 16th.

A New Beginning after the War

After World War II, observational astronomy in Germany was in a desolate condition. Observing programs on an international level were practically impossible as the largest telescope in the Federal Republic of Germany then was the 1-m-reflector in Hamburg-Bergedorf dating from 1910, followed by the 72-cm-reflector of the Landessternwarte Heidelberg on the Königstuhl, built in 1906.

In this situation, the memorandum "On the Status of Astronomy" issued in 1962 on behalf of the German Research Association (DFG) brought about the decisive turn of events. In this memorandum, the astronomers particularly recommended "the establishment of national institutions of supra-regional character, such as an optical observatory in a favorable climate with larger instruments". Significant contributions to the memorandum were made by Hans Elsässer, the future founding director of MPIA.

In 1967, the Senate of the Max Planck Society decided to establish the MPIA and two observatories, one in the northern and one in the southern hemisphere. While the plans for the southern observatory in Namibia could not be realized for political reasons, the construction of the

Fig. V.2.1: Calar Alto Observatory. A view from the north towards the telescope domes. From left to right: the 2.2-m telescope, the Spanish 1.5-m telescope (in the foreground), the 1.2-m-telescope, the Schmidt-reflector and the dome of the 3.5-m-telescope with a height of 43 m. In the background, the coast of Almería.

northern observatory in Southern Spain was started soon. For the Spanish astronomers, too, the opportunity to build an observatory together with the Max Planck Society meant a new beginning. So an additional, purely Spanish 1.52-m-telescope was also erected on Calar Alto.

The establishment of the Calar Alto Observatory took place in several stages. In the middle of 1975, the 1.2-m-telescope was put into operation, followed by the 2.2-m-telescope in 1979.

The next telescope shipped to the mountain was the overhauled Hamburg Schmidt-reflector. Finally, in 1985, the 3.5-m-telescope (Fig. V.2.2) was tested and then made available to guest observers from July 1986 on. In 1988, the establishment of the Calar Alto Observatory was considered complete.

In recent years, MPIA has built a number of cameras and spectrographs that rank among the world's top instruments of their kind, including, e.g., a near-infrared camera with a large field of view, called OMEGA2000, and the LAICA camera working in the optical spectral range. With its 4096 × 4096 pixel CCD detector it can image an area of the sky larger than the full moon. In addition to these cameras, spectrographs such as TWIN and OMEGACASS are available.

Astronomers and engineers at MPIA have performed technological pioneering work in developing and building an adaptive optics system called ALFA, which also includes a novelty: an artificial "laser guide star". The experience gained with this instrument will be utilized at the ESO Very Large Telescope in Chile and at the Large Binocular Telescope (LBT) on Mount Graham, Arizona.

Scientific Highlights

In the early years of the Calar Alto Observatory, stars and nebulae within our Milky Way system had been the focus of research. A first main research field was star formation. This was followed in the 1980s by, e.g., the discovery of strongly confined gas beams that emerge from young stars, shooting out into space at several hundred kilometers per second. These so-called jets (Fig. V.2.3) are perpendicular to the circumstellar dusty disk and can extend over a length of several light years.

When the 2.2-m-telescope was put into operation on Calar Alto in 1979 astronomers finally also got access to the realm of distant galaxies. A milestone here had been the discovery of interacting galaxies. Today, this research topic is still relevant, also because it is widely assumed that giant elliptical galaxies have formed by mergers of spiral galaxies. Another research focus at MPIA is the phenomenon of extragalactic jets – gas jets emerging from the central regions of active galaxies and quasars and extending up to several million light years into space. Astronomers at MPIA significantly contributed to the deciphering of the acceleration process within jets.

Other highlights were the spectacular images of the impact of comet Shoemaker-Levy 9 onto the planet Jupiter in 1994 (Fig. V.2.4) , and six years later, the detection of free floating planetary objects in a star forming region in the constellation Orion (Fig. V.2.5).

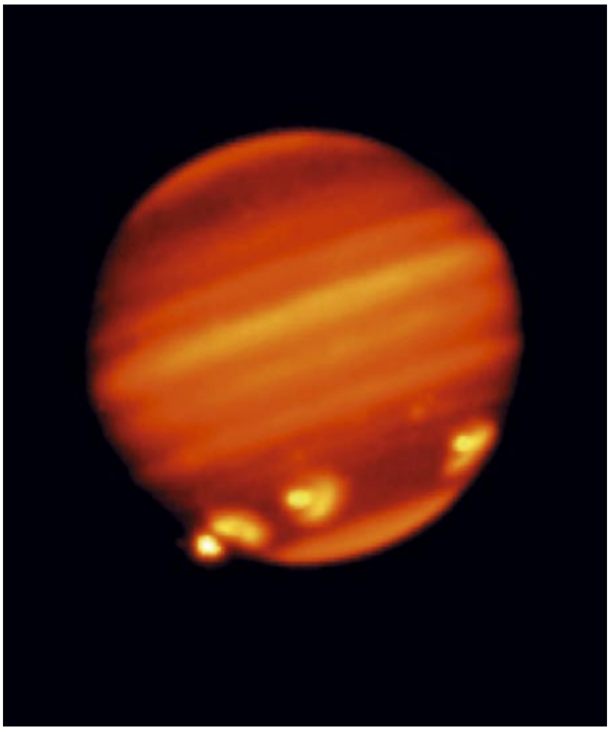
Fig. V.2.2: The 3.5-m-telescope of the Calar Alto Observatory.

Fig. V.2.3: A newborn star (cross) deeply embedded within the molecular cloud L 1551 is visible only in infrared light. It ejects a bright jet of ionized gas, illuminates the extended reflection nebula and lights the structures denoted HH-28 and HH-29.

Fig. V.2.4: Jupiter on July 20th, 1994, imaged with the MAGIC infrared camera at the 3.5-m-telescope on Calar Alto. At the left edge, the explosion cloud produced by the impact of one of the last fragments of comet Shoemaker-Levy 9 can be recognized. To its right, the hot traces of previous impacts.

In the recent past, large sky surveys have become increasingly significant. So, astronomers at MPIA initiated the extremely demanding observing program CADIS (Calar Alto Deep Imaging Survey) at the 2.2- and 3.5-m-telescopes on Calar Alto in order to search for the first galaxies in the universe. Profiting from the experience gained with CADIS is the COMBO-17 survey that is being conducted at the 2.2-m-ESO/MPI telescope on La Silla. A prerequisite for this project is a wide field camera that had been designed by astronomers at MPIA and built together with colleagues from ESO.

Recently, some telescopes have been organized within networks in order to be able to react on short notice to unexpected cosmic events. One of these networks also including the Calar Alto Observatory is the "European Supernova Collaboration". It is supposed to study the brightness changes of supernovae. Calar Alto is also a member of the alert system for gamma ray bursts.



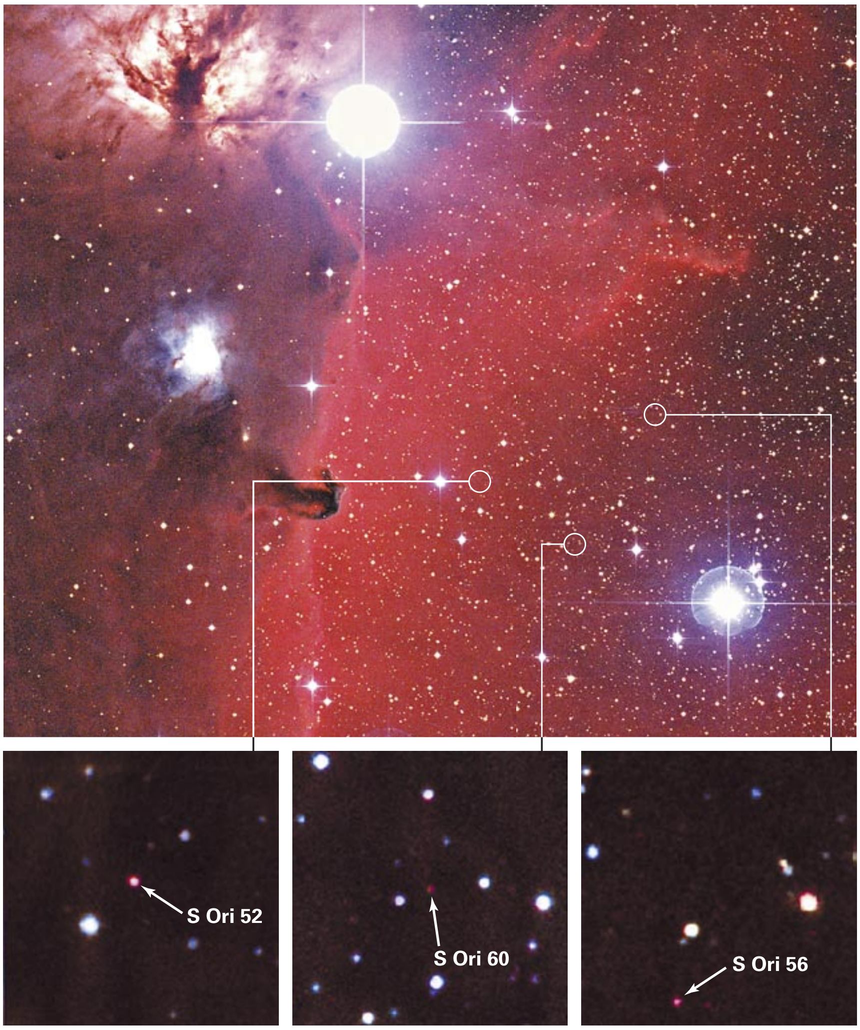


Fig. V.2.5: Free floating planetary objects within the Orion complex.

The Future of the Calar Alto Observatory

The arrival of a new generation of telescopes with mirrors eight to ten meters in diameter has by no means superseded older telescopes of three to four meters aperture. For one thing, the number of the latest observatories is too small in order to conduct all important observing programs. And for another thing, there are also many important projects that do not require large telescopes but sometimes can be very time-consuming. These include the large sky surveys mentioned above. Projects that require regular observations of celestial bodies – variable objects, for instance – will also be of great importance in the future.

Last not least, the telescopes of the Calar Alto Observatory will continue to be used for developing new scientific methods and techniques as it had been the case with the adaptive optics system ALFA.

The operating mode of the Calar Alto Observatory has changed significantly since November 2004. A contract was signed according to which the Spanish Consejo Superior de Investigaciones Científicas (represented by the Instituto de Astrofísica de Andalucía) and the German Max Planck Society (represented by MPIA) will be operating the observatory as concurrent partners. The agreement includes secure funding for the development and building of new observing instruments in order to always ensure the observatory's efficiency and the scientists' competence in the instrumental field.

Fig. V.2.6: In honor of the 25th anniversary of the observatory, a leg of the Spanish cycle race Vuelta a España ended on the Calar Alto peak.

V.3 The European Interferometry Initiative

The European Interferometry Initiative (EII) was created in Heidelberg on January 30th, 2002. The initiators came from Germany, France, and the Netherlands, where considerable efforts in this field of research have already been made and the necessary know-how is available. MPIA takes up a leading position in this initiative insofar as it is the headquarters of the German Center for Interferometry (Frontiers of Interferometry in Germany, FrInGe). Very soon, institutes from 14 European countries as well as the two organizations Eso and Esa joined the EII. In September 2004, representatives of all participating countries met at MPIA in Heidelberg to sign a memorandum of understanding. On this occasion, Thomas Henning was elected president of the Science Council.

The experts agree that interferometric observations will be of great significance in the future. Recent achievements at the VLT interferometer, to which MPIA significantly contributed with the Midi instrument, and at both Keck telescopes have given this technique a great impetus. From 2007 on, the LBT interferometer, too, should be in operation (see Chapter V.1). The goal is now to co-ordinate European research efforts in this field and to direct the know-how of many specialists into joint projects. EII will help to establish optical and infrared interferometry as a conventional method of observational astronomy.

EII was started on January 30th, 2002, when representatives from France (JMMC), the Netherlands (Nova), and Germany (FrInGe) met in Heidelberg. Right from the beginning, the intention had been to also include other European groups. The four main goals of EII are:

- Supporting communication and cooperation between European scientists and institutes.
- Creating synergies within Europe in order to achieve a globally leading position.
- Europe-wide training of observational astronomers as well as students in interferometric techniques.
- Striving to a long-term European vision of interferometry.

The declared objective was also to seek funding from the EU commission. For two projects, this has already been achieved. The “Joint Research Activity” JRA4 is meant to support studies of future European instrumentation projects whereas the “Network Activity” NA5 is funding visits for collaboration in interferometric projects.

In order to utilize already existing structures, these funds were applied for under the roof of Opticon. In January 2004, a kick-off meeting was held for this purpose in Nice, where activities and working packages for JR4 and NA5 were presented and coordinated. The work begun under JRA4 was subdivided into two main sections: for one thing, the work for creating generally usable interferometric software packages, and for another thing, studies into new second-generation interferometric instruments.

The next milestone will be the common Eso/EII workshop “The power of optical/IR Interferometry”, that will be held from April 4th to April 8th, 2005, in Garching. This one-week meeting is dedicated half to science and half to the presentation of studies of future instruments at the VLTI. On this occasion, Eso will select up to three out of the seven proposed projects as second-generation VLTI instruments. Here, MPIA is participating in the Après-Midi instrument, a Midi upgrade allowing Midi to be used as an imaging interferometer by combining three or four telescopes (see Chapter IV.3, Midi).

(Thomas Henning, Uwe Graser)

V.4 The First Emmy Noether Groups at the Institute

With its Emmy Noether Program, the German Research Association (DFG) is supporting promising young post-doc scientists by offering them a way to an early scientific independence. The program enables them to establish a junior research group of their own and to qualify themselves to be university lecturers. Sebastian Wolf was the first participant in the Emmy Noether Program to join MPIA in January 2004. Here, he heads a group for studying protoplanetary disks. Since December 2004, there is an Emmy Noether Group at the Institute, that is working on the formation and properties of sub-stellar objects under the leadership of Coryn Bailer-Jones. We asked Sebastian Wolf (SW) about his experience so far.

Which requirements do you have to fulfill in order to get accepted in the Emmy Noether Program?

SW: You must have got a PhD and already acquired experience abroad. Both held true for me. After obtaining my doctorate at the Thüringische Landessternwarte Tautenburg, I mostly worked at CalTec in Pasadena from February 2002 to December 2003.

Did you focus on planet formation right from the start?

SW: No. In Tautenburg, I developed a method to do 3D-calculations of radiative transfer within any given dust configuration in a particularly easy and fast way. That had been a numeric-theoretical work. At the same time, however, I also observed circumstellar disks in binary stars on La Silla. Within my doctoral thesis, I then applied my model to these dusty disks, among other things, and predicted the polarization of the scattered stellar light. This way, I was able to gain experience in theoretical as well as in observational work.

What was your field of research in Pasadena?

SW: In Pasadena, I had been involved as a postdoc in a so-called Legacy Program of the SPITZER Infrared Space Telescope. I helped to prepare the analysis of data that were expected from a very extended observing program on the formation and evolution of planetary systems – data that have come in meanwhile. That's where I really became aware of the issue of protoplanetary disks.

How come? SPITZER has been launched only in August 2003.

SW: That's right. I had been very lucky to get terrific observational data from the HUBBLE Space Telescope and from the Owens Valley Radio Observatory in the meantime. The data were near-infrared and millimeter images of a protoplanetary disk. My model was perfectly applicable to it, and I was able to derive information on the growth of dust grains – the first step of planet formation – within this disk.

Fig. V.4: Sebastian Wolf, head of a Emmy Noether Program working group for studying protoplanetary disks.

Why then did you join the Emmy Noether Program of the DFG?

SW: Working as a postdoc means to be included within the research project of the group you join. For me, though, it was very important to be able to realize my own ideas. And above all, you can achieve much more in a group than as a loner.

What is the registration procedure at the DFG, what is to be noticed?

SW: Applicants have to describe their research program and goal in great detail. And they have to estimate the prospective personnel and non-personnel costs – which is not quite easy for the latter since one does not know in advance how often one will have to go observing or to conferences. Moreover, applicants must already have chosen an institute and got an offer from there. I had got that from MPIA then.

Now, are you able to realize your ideas within the Emmy Noether Program as you have hoped for?

SW: Definitely! The conditions from my point of view are almost ideal. For four years, the DFG supports my little group to which belong a PhD student and a postdoc. The PhD student Alexander Schegerer primarily works in the observational field, while as theoretician, the postdoc Kacper Kornet is the strong backbone of the group. DFG pays our salaries and provides annual funds, e.g. for observing and conference trips, and also for purchasing a multiprocessor workstation.

A generous support. That probably requires a lot of bureaucratic effort.

SW: Not at all. Means for non-personnel costs are applied for at the DFG, and are paid without any problems within the scope of the promised funds. By the way, I want to praise here the administration of MPIA which kindly takes on the administrative work for me. It's a great advantage to be able to fully concentrate on your research work and that of the group.

Within the Emmy Noether Program, the scholarship holder should achieve the "qualification to be a university lecturer", as the DFG says. So, how are you off for this?

SW: Last semester, I gave my first lecture, and I enjoyed it. Anyway, I would like to be a university lecturer later. The Emmy Noether Program offers a really good opportunity to young scientists – I am 31 years old – to try out if they like dealing with students.

Do you still plan to habilitate, or do you think a junior professorship would be a chance?

SW: In my opinion, the Emmy Noether Program is equivalent to a junior professorship from the qualification point of view. But I would like to habilitate, since if there is any doubt you may be better off with a habilitation than without it.

So, would you recommend the Emmy Noether Program to your younger colleagues?

SW: Definitely. It's really a fantastic thing. For the first time you are responsible for a research program of your own. And it is very instructive to be responsible for colleagues, essentially for PhD students. But above all it is a great chance to pursue over a period of four years a scientific goal you have set yourself.

V.5 Ringberg Workshop on the Structure and Evolution of the Milky Way System and its Surroundings

From December 5 through December 9, astronomers from around the world met at Ringberg Castle to present and discuss their work on the structure and evolution of our Galaxy and its close neighbours, in an environment ideally suited to both scheduled talks and informal conversations. Over 50 scientists and students participated, representing institutes and universities from across North and South America, Europe, and Australia. The meeting, sponsored by MPIA and the Max Planck Society and organized by Eva Grebel (now at the Astronomical Institute of the University of Basel) and David Martinez-Delgado, provided a forum for discussing the latest developments – both observational and theoretical – in our study of this field.

The Milky Way, M 31 (the Andromeda galaxy), and their satellite galaxies play an essential role in our efforts to understand the formation and evolution of galaxies throughout the Universe. Their proximity permits us to observe them in far greater detail than is possible for more distant galaxies, and thus lets us test theoretical scenarios, such as those for the formation of large galaxies via the merging of smaller systems. In recent years, we have witnessed a veritable explosion of new observational information on the structure and development of our Galaxy and other, nearby galaxies, largely due to the advent of large-area astronomical surveys like the Two-Micron All Sky Survey (2MASS), Sloan Digital Sky Survey (SDSS), and the Radial Velocity Experiment (RAVE), the use of both existing space-based facilities (like the Hubble Space Telescope) and new ones (like the Spitzer infrared telescope), and the introduction of 8- to 10-meter class telescopes into common use. Results making use of these resources abounded in the talks and discussions. The topic of the meeting was therefore quite timely.

The scientific topics covered began with our own Milky Way, looking at recent models for its formation and current structure, and the observational evidence confronting these models. A large part of the meeting was devoted to stellar streams and structures in the Galactic disk and halo, evidence for past and ongoing accretion of smaller satellite galaxies onto the Milky Way. Since the first discovery of such a stream (debris from the merging Sagittarius dwarf galaxy) some ten years ago, several additional stellar structures have been found, although controversy still remains as to the true nature of some of these detections. One such controversy was addressed in an organized debate about whether a stellar overdensity measured in the direction of the constellation Canis

Fig. V.5.1: Ken Freeman from Mount Stromlo Observatory and Eva Grebel from the Astronomical Institute at Basel.

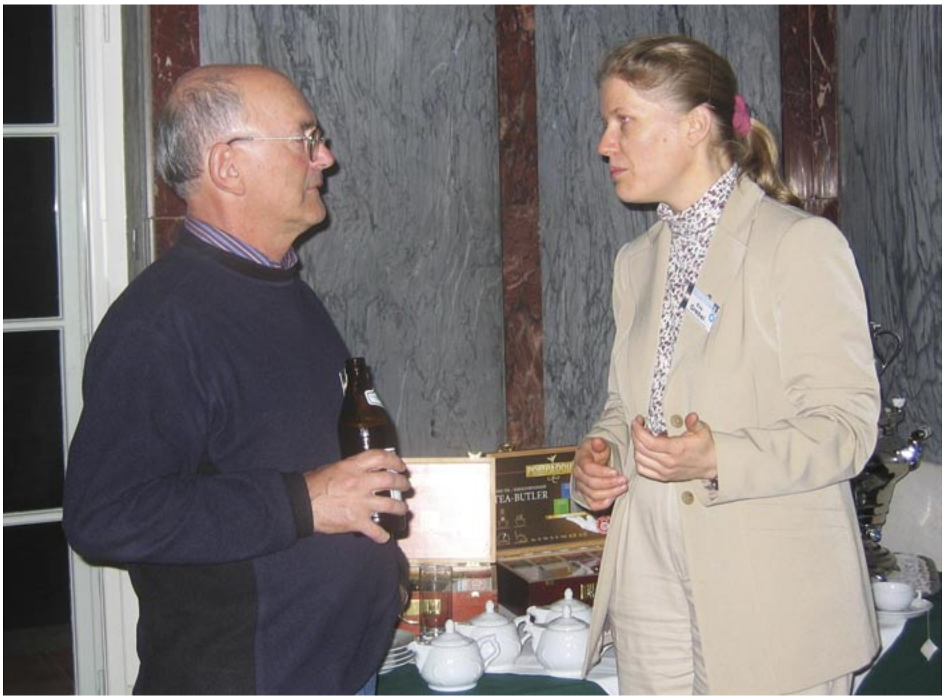


Fig. V.5.2: Gerry Gilmore from the Institute of Astronomy, Cambridge (UK) and Ken Freeman from Mount Stromlo Observatory, Australia. (Picture: Andreas Koch)

Majoris represents a satellite galaxy in the process of accretion, or merely a manifestation of an expected warp in the Milky Way's stellar disk (see also Chap. II.4). By the end of the debate, a strong majority of the participants favored the satellite galaxy interpretation.

The focus of the meeting then moved outward, to the satellites of the Milky Way and to M 31, the nearest large galaxy to our own. Presentations on the history and current state of the Magellanic Clouds, our Galaxy's largest companions, led into discussions of the evidence for past interactions between these satellites and the Milky Way itself, and how such interactions affected the evolution of these smaller bodies. Other participants showed how they are using the smallest Milky Way satellites, dwarf spheroidal galaxies, to model the role of dark matter in the formation and evolution of nearby galaxies. The meeting ended with talks on the evolution of M31, which – at least in its outer parts – appears to be rather different from the Milky Way.

Did our Galaxy have an unusual history, or did M 31? Or perhaps there is no such thing as a »typical« galaxy? While a great many exciting observational and theoretical results were presented at the workshop, quite a few such intriguing questions also arose, indicating directions for future research. Thus the scientists and students attending the meeting found it to be a very informative and productive experience.

(Daniel Zucker, David Martínez-Delgado, Jorge Peñarrubia, David Butler, Richard D'Souza)

V.6 Ringberg Workshop: From Dust Grain to Planet

From December 19th to 22nd, Hubert Klahr and Wolfgang Brandner of MPIA organized a workshop on "Planet Formation – Theory, Observation and Experiment" at Ringberg Castle, the conference location of the MPG. Despite the approaching holidays and a fierce blizzard, about 50 scientists attended the meeting, among them some pioneers of planetary research.

The participants found an almost fairytale winter landscape, inviting to take a walk or to go skiing during leisure time. During the meeting sessions, however, everybody concentrated intensely on the topics discussed. As already indicated by the title, the organizers had planned to bring together experts of different disciplines: Theoreticians, observers, and experimentalists. New findings were presented and open issues discussed.

One of the pioneers in the field of extrasolar planets, Geoffrey Marcy of the University of Berkeley, California, reported one hundred planets that have been detected in a total of 1330 stars within an extended search program. This fraction of about seven percent surely represents only a lower limit since neither small, earth-sized planets nor planets with orbiting periods longer than about ten years are detectable at present. According to Marcy's estimates, every fifth solar like star might be surrounded by planets.

These satellites are not observable directly since they are outshined by their central star. Almost all of these invisible companions can only be detected indirectly through their gravitational effect on the star. In this way, the orbits of the planets and their minimum mass can be determined.

Peter Bodenheimer of Lick Observatory, who is dealing with star and planet formation for decades, recalled the origins of the present-day theory of planet formation. In the 18th century, Immanuel Kant and Pierre Simon de Laplace already had the correct basic idea: Planets are forming within rotating disks of gas and dust. While at the center of the disk the matter condensed to form a star, it clumped together in the outskirts to form planets. Laplace pictured the primeval sun to be surrounded by whirls of gas from which the planets formed. Today, many observational data are available that now have to be fitted together into a consistent picture. But this still will require considerable efforts.

One focus of the discussions had been the formation of giant planets comparable to the "gas giants" Jupiter and Saturn. All planets found so far are of masses ranging between about 1/20 and 17 Jupiter masses. Gas giants therefore belong to the normal "equipment" of a

Fig. V.6.1: About 50 astronomers from all over the world had come to Ringberg in order to participate in the workshop on planet formation.

Fig. V.6.2: Astrophysicists Doug Lin, Ed Thommes, and Hubert Klahr on the day before the conference, studying the growth of ice crystals as an analogy to the early stages of planet formation.

Fig. V.6.3: Two pioneers of theory and observation: Peter Bodenheimer and Geoffrey Marcy. (Zinnecker).

planetary system. But their formation history still raises considerable questions.

According to current notion, planets form within a protoplanetary disk of gas and dust. The solid particles there grow by colliding and sticking together. This way, they get heavier and heavier and gravitationally sink towards the center plane of the disk, forming a comparatively thin layer there. Since the dust density increases by this process the particles now collide more often and evolve into so-called planetesimals several kilometers in diameter. These bodies are then able to merge gravitationally to form planets. When such a rocky planet has reached about ten Earth masses it starts to accrete gas from its environs, surrounding itself with an atmosphere.

At present, only the first phase, the growing of dust particles to the size of stones, can be explained throughout. How in a second phase these chunks become planetesimals, which in turn grow to form planets in a third stage is not nearly clear yet. At these scales the problem of violent collisions between the bodies arises. In such collisions, they do not stick together but rather destroy each other.

A fundamental, difficult aspect concerns timescales. As Edward Thommes from the University of Toronto pointed out in his talk, planets have to form within a relatively short period of time. In view of these problems, Alan Boss of the Carnegie Institution in Washington had put the original Kant-Laplace model on the agenda again in the mid 1990s. According to it, planets form when individual parts within the disk become instable and condense gravitationally. A solid planetary core could form if dust sinks down to the center of a condensing clump of gas. In this way, a gas planet could form within a few thousand years – at least in theory. But it is unclear whether the necessary conditions can occur at all in a protoplanetary disk since it would have to be conside-

Fig. V.6.4: Heavy snowfall has lent Ringberg Castle a picturesque charm.

rably heavier and denser than observations so far suggest. And apart from that, these local gas condensations are very instable at first and can easily be disrupted within the rotating disk.

Hubert Klahr of MPIA recently developed a model that forges links between both competing models. According to it, “magnetic hurricanes” could develop within a disk, remotely comparable with high-pressure areas in the terrestrial atmosphere. Dust would stream into these whirls, accumulating there. This way, the “protoplanetary hurricanes” could act as boosters of planet formation (see Chapter II.2).

The processes in a protoplanetary disk are so varied and occur on scales so extended that they cannot nearly be described completely by simulations alone. Astronomical observations and recently also laboratory experiments are needed in order to provide facts that are constraining the theoretically possible scenarios. In this area considerable progress has been made.

According to Thomas Henning, director at MPIA, and his co-worker Kees Dullemond, many details of the protoplanetary disk can be derived from the observed infrared energy distribution. So, e.g., it is possible to determine the extension of the disk or to detect gaps that may have been cleared by a large planet. Infrared spectra like those provided recently by the SPITZER Space Telescope allow to detect the signatures of water-, carbon-monoxide-, and carbon-dioxide ice frozen out on silicate particles.

In addition to computer simulations and telescopic observations, laboratory experiments reconstructing the development of dust particles in protoplanetary disks are of increasing significance. This way, Jürgen Blum of the TU Braunschweig investigates the conditions necessary for small dust particles to coagulate and grow to form larger aggregates, as well as the properties of these aggregates. Great progress was made recently with the help of zero-gravity experiments carried out aboard a Space Shuttle or flown as payload in a ballistic rocket. These experiments showed tiny particles to stick together after slow collisions and to grow into larger particles.

Despite a considerable increase in the understanding of planet formation astronomers are eager to observe extrasolar planets directly. Wolfgang Brandner reported that a few young, bright Jupiter-like planets might be detected within the next few years using ground-based interferometers, e.g. at the ESO Very Large Telescope or at the Keck Observatory on Hawaii. However, in trying to achieve this objective astronomers are pushing the bounds of feasibility. The best chances will probably be offered by the successor to the HUBBLE Space Telescope, the James Webb Space Telescope (JWST). Its launch is planned for the middle of 2011. It should allow direct observation of gas giants in the infrared spectral region. Astronomers at MPIA are participating in the VLTI as well as in the JWST.

The study of protoplanetary disks, however, will enter a new phase even sooner – namely with the Atacama Large Millimeter Array (ALMA). This array built by E and the USA is currently being erected on the Chajnantor Mountain (5000 m) in the Chilean Andes. First measurements are planned for 2007; the entire array with 64 radio telescope will be put into operation in 2012.

(Hubert Klahr, Wolfgang Brandner)

V.7 First MPIA Student Workshop on the Rügen Island

From June 3rd to 6th, 2004, the first MPIA student workshop took place in Losentitz on Rügen. Goal of this event was to improve the communication between the students: first, by presenting their own work to their fellow students, and second, by strengthening the social contacts between them during common leisure activities, such as pleasant evenings together or hiking and swimming.

We were staying at a nice and friendly vacation complex not far from the Baltic in Losentitz and even on the day of our arrival immediately took advantage of the sunny afternoon to go for a swim. The day culminated in an amusing barbecue, and now we were ready for the two working days to come (Friday and Saturday).

In the mornings of both days, three talks each were held where the lecturers had 30 to 45 minutes to present the subject of their doctoral thesis and answer questions. Since students from all fields of research at MPIA were participating in this workshop many different fields of astronomy were touched. Most of us found this very informative and were happy to “see beyond our noses”. Due to the informal character of the event it was also possible to ask repeatedly for details.

The lively discussions were continued in the afternoons during trips across the island. On Friday, we visited the Ostseebad Binz and climbed the Königsstuhl, a local mountain apparently not unique to Heidelberg. The Königsstuhl on Rügen is a natural platform on top of a 118 m chalk cliff. According to legend, this cliff played a deciding role in electing the king: who succeeded in climbing the cliff from the seaward side was crowned king on a chair of stone. We did not try that, though.... On Saturday, our tour of the island took us to Kap Arkona, the northernmost tip of Rügen.

Fortunately, some of the students turned out to be experienced avid cooks who very quickly conjured up a delicious supper for rumbling stomachs. Revived, we now attended the evening talks that went on till late at night. Even then the audience never lost interest and many a lecturer was surprised when he or she realized that the talk intended to take 15 minutes went on for more than an hour.

In the end the students all agreed: Our first student workshop was a great success – and should be continued!

(Nadine Häring, Alessandro Berton, Siegfried Falter, Boris Häußler, Bernhard Keil, Stephan Kellner, Jens Rodmann, Marc Schartmann, Oliver Schütz, Konrad Tristram, Stefan Umbreit)

Fig. V.7: The young MPIA team before climbing the Königsstuhl.

V.8 Honoring Junior Scientists

In 2004, six young scientists at MPIA were honored for their excellent scientific work. At the annual general meeting of the Max Planck Society, Daniel-Rolf Harbeck and Sadegh Khochfar were awarded the renowned Otto Hahn Medal for the year 2003. In December of the same year, the Ernst Patzer Prize for Supporting Junior Scientists at MPIA was awarded for the first time. It went to Oliver Krause, to Nadine Häring and jointly to Daniel Apai and Ilaria Pascucci

Fig. V.8.1: MPG vice-president Kurt Mehlhorn presents the Otto Hahn Medal to Daniel-Rolf Harbeck (above) and Sadegh Khochfar (below).

Otto Hahn Medal

Since 1978, the Max Planck Society each year awards the Otto Hahn Medal to up to 40 young scientists for their excellent work. It is coupled with a certain sum and the opportunity for a one-year international research visit. Prize and research visit are intended to motivate particularly talented young scientists to aim at a future university and research career. The medal is awarded always during the general meeting in the following year.

Daniel-Rolf Harbeck was awarded the Otto Hahn Medal for proving that chemical self-enrichment also occurs in globular clusters. For about 50 years, globular clusters were considered plain stellar systems. According to this school of thought, they were "made in one casting", rendering their stars chemically homogeneous. Known variations of element abundances in massive members of these clusters were attributed to internal nuclear processes.

Using new observational data, Harbeck was able to show, however, that chemical inhomogeneities also occur in low-mass stars in which no internal enrichment is possible. From this he concluded that in globular clusters, too, the star formation phase went on for a longer period of time. This period must have lasted long enough for the first supernovae to explode within the cluster, enriching the interstellar gas with heavy elements even before all other stars had formed. He was also able to detect similar chemical inhomogeneities in so-called spherical dwarf galaxies which had been classified as equally plain systems as globular clusters. According to these new findings, there are no such plainly built stellar systems at all.

Sadegh Khochfar was awarded the Otto Hahn Medal for his work on the formation history of elliptical galaxies within the cosmological context. For some time, cosmologists assumed massive elliptical galaxies to have formed by mergers of two spiral galaxies. This relatively new notion was studied and tested in detail with the help of computer simulations. However, the products of the simulated mergers often did not match the properties observed in elliptical galaxies. Khochfar has developed detailed models which are able to predict which merging progenitors will produce the most massive elliptical galaxies. Accordingly, these are not spirals but again elliptical galaxies.

Fig. V.8.2: The winners of the Ernst Patzer Prize: Oliver Krause, Nadine Häring, Daniel Apai, and Ilaria Pascucci

Ernst Patzer Prize

The Ernst Patzer Prize for Supporting Junior Scientists is funded by the Scientific Ernst Patzer Foundation established by the widow of the philosopher and art lover Ernst Patzer. The goal of the foundation is to sponsor and support science and research mainly in the field of astronomy. The award of sponsorship goes to young scientists at MPIA in Heidelberg whose publications during their time as PhD students or post-docs at MPIA got the best referee reports. A selection board set up for this purpose – consisting of two MPIA scientists and one external scientist – examines the proposals submitted. Oliver Krause was awarded a sponsorship of 2000 Euro, the three other prizewinners 1000 Euro each.

Oliver Krause was awarded the prize for his work on cold dust in the direction of the supernova remnant Cas A (see Chapter II.3). This work was judged unanimously the most outstanding paper of a MPIA junior scientist in the period of time considered. Using well selected observational data, Oliver Krause disproved in his paper the claim made by other authors that supernova Cas A had produced large quantities of dust. Thereby he also called into question a recently proposed hypothesis according to which supernovae had been the principal sources of heavy elements and dust in the early universe. Krause's work excels particularly by recognizing an important astrophysical problem, scrutinizing it systematically and critically, and finally solving it.

Nadine Häring was honored for her work on the connection between the masses of central black holes in galaxies and the surrounding stellar bulges. It was considered the best publication at MPIA based on a diploma thesis. Using new data of the HUBBLE Space Telescope, Nadine Häring showed the relation between the masses of stellar bulges and central black holes in galaxies to be significantly closer and more unequivocal than assumed so far. By applying this relation to faint and distant galaxies it will be possible to determine more easily and accurately the masses of central black holes in galaxies of the early universe.

Daniel Apai and *Ilaria Pascuccci* were awarded the Ernst Patzer Prize for their work on the observation of the star TW Hydrae using a new method called polarimetric differential imaging (see Annual Report 2003, p. 25). For this purpose, they used the NACO camera (built at MPIA) at the VLT. In their work, Daniel Apai and Ilaria Pascucci demonstrated the potential of this novel observing method that allows to study the properties of circumstellar disks with unprecedented spatial resolution. Applying this method to the circumstellar disk of the young star nearest to the sun, TW Hydrae, they found that the hole in the central region of the disk has to be smaller than model calculations of other authors had suggested. This hole possibly is connected with the formation of planets. The work impressed mainly by the detailed and critical presentation of the analysis and interpretation of the novel data. It will encourage other scientists to apply this observing method to other objects and scientific problems.

V.9 The Transit of Venus Above the Schwetzingen Castle Gardens

On June 8th, 2004, people in Europe as well as in large parts of Asia and Africa were able to watch a rare celestial spectacle: a transit of Venus in front of the Sun. It was the first time since 1882 that such an event recurred. While professional astronomers hardly noticed the event, the spectacle attracted major public attention. Several institutions in Heidelberg, including MPIA, had invited the public to visit the Schwetzingen castle gardens. Several thousand visitors, including 16 school classes, streamed into the picturesque park watching the event in a carnival atmosphere and under sunny skies.

In order to witness the entire transit one had to arrive quite early, though. At 7.20 the black looking disk of Venus contacted the outer limb of the Sun; at 7.39 it had fully entered the solar disk. Then it wandered across the face of the Sun, contacted the opposite limb at 13.04 and exited the solar disk at 13.23.

There were many opportunities for the visitors to observe the transit. Employees of MPIA and many other private individuals had brought their telescopes. Projection screens were mounted, and in the orangery of the castle, live images from observatories all over the world were projected from the internet onto a large screen. Colored posters informed about the historical and astronomical background of the event. The TV had come too: The ZDF reported live from the castle gardens in its morning and noon magazines.

In the orangery of the castle, the Mannheimer Landesmuseum für Arbeit und Technik had exhibited historical instruments and documents of the time of the astronomer and Jesuit father Christian Mayers. Actually, the location had been chosen by the organizers not without reason. On June 6th, 1761, Mayer, together with

Fig. V.9.1: Thousands of visitors met in a historical setting to observe the transit of the Venus.

prince elector Carl Theodor had observed the then transit of the Venus at this very place. Subsequently, the astronomer had been instructed to erect an observatory. This observatory, in the beginning built on the roof of the castle, marked the beginning of astronomical research in the Electorate Palatinate and eventually led to the foundation of the Landessternwarte on the Königstuhl Mountain and its neighbor institute, the MPIA.

The successful event again showed the public ability to get enthusiastic about astronomy. Obviously it does not always have to be black holes! A black dot in front of the solar disk will do too...

(Organizers: Administration of the Schwetzingen Castle Gardens, MPIA, Landessternwarte Heidelberg, the editorial staff of "Sterne und Weltraum", "Spektrum der Wissenschaft", and "Astronomie heute", the Landesmuseum für Arbeit und Technik as well as the Heidelberger Explo)

Fig. V.9.3: Posters in the orangery informed about the historical and astronomical background.

Fig. V.9.2: Children and young persons in particular enjoyed the celestial happening.

V.10 Memories of the Institute and of Germany. An Interview with Steven Beckwith

Steven Beckwith was director of MPIA from 1991 to 1998. After that he went to Baltimore where he became director of the renowned Space Telescope Science Institute (STScI). But Beckwith always kept in contact with MPIA, for one thing, as an External Scientific Member and for another thing, through joint scientific projects, such as GEMS. We asked Beckwith about his professional and private experience made in Germany, about his own plans and about the future of the HUBBLE Space Telescope.

Why did the position as director of MPIA appealed to you back then?

SB: In 1990, when I was considering the choice, the MPIA seemed to be well endowed with resources, especially in having an observatory in southern Spain and a lot of flexibility to use its funding for science. Yet it struck me that there were many more things that it could be doing. Thus, I saw a great potential to do new science by making some strategic decisions about the best way to spend the resources.

At that time, my field of infrared astronomy was evolving rapidly, and the technology needed to make competitive instruments was becoming increasingly expensive. It was difficult for me, as a professor at Cornell, to get the support needed to build the next generation of competitive instruments for astronomy. The MPIA budget was clearly adequate to build these instruments, and therefore to do some front rank science – to me that was the real attraction.

Did your job turn out as you expected it to do?

SB: For the most part, the things I found fulfilled my expectations, and the Max Plank Society gave me superlative support for my work. Without that support, it would have been impossible to achieve very much. Of course, it was difficult to foresee the cultural challenges of moving to another country, especially as a Director. I know I made many mistakes when I first came on board, simply because I was not sensitive to the way in which people worked and the best way in which to get things accomplished. But the Institute's staff was ultimately forgiving of my mistakes, and I was persistent in working toward my goals. The position worked out quite well. I was very pleased with my decision to move to Heidelberg and to work with the staff at MPIA.

What did you find especially positive at MPIA?

SB: The infrastructure that Professor Elsässer had built up was excellent for producing scientific instruments. The machine shop was state of the art, and we even enhanced its capabilities. The workers were skilled. We were able to do almost anything we wanted in-house, make decisions quickly, and be flexible in response to changes in science. There were a number of very experienced and good scientists who had forward looking projects that I was able to support, and in some cases enhance, and I felt many people had the desire to see the Institute perform at an even higher level that it had in the past. There was potential for improvement and potential for change, and that gave me an opening to try some new ideas.

What did you rather dislike?

SB: The computing infrastructure needed a lot of investment and support. We lacked a number of critical components to make it really competitive for scientific research. Foremost among those were connectivity to the internet, but we also needed more modern CPUs and software that most astronomers used. Once again, the Max Plank Society was exceptionally good about helping us improve the systems. We bought many Sun Microsystems computers, connected them to the internet, and invested heavily in equipment for individual astronomers. Ultimately, we built one of the best systems for research in astronomy in the world. This was another area where the Max Plank Society was tremendously helpful. They were very open to my requests for more investment. Although it did cost them money, they recognized that my vision would not be carried out unless I was able to get their support and I was tremendously grateful for it.

I also thought that we had not made all the right strategic decisions in our investments in instrumentation for Calar Alto. Calar Alto had good telescopes, yet it was not the best site for astronomy in the world. The weather was often cloudy, and the rapid changes in temperature meant that the large telescopes took time to adjust after a front passed through. Thus the seeing, which is intrinsically quite good at Calar Alto, was often very bad following the passage of a front. The instrumentation duplicated classical instruments similar to those of other observatories on better sites, giving us no advantage. I shifted the emphasis to building state-of-the-art instrumentation much faster than other observatories. We lowered our disadvantage in weather with an advantage in new technology getting to the telescope quickly, and, of course, the MPIA was the perfect place to be able to do that.

What were your goals when you became director of MPIA?

SB: The primary goal was to do front-rank science. That was the reason I was there. In looking back on that time, I think there were a number of projects underway that I was expected to take over or lead, some of which I thought were pretty good, such as the CONICA project, and some that I felt were unlikely to produce useful science. It took me a few years to sort out the precise mix of things that we needed to do, and of course to take care of the people who were involved in those projects. Eventually, we worked it out.

Did you achieve these goals?

Overall, I think MPIA reached every goal I had hoped for when I came to the Institute; however, a number of these goals were not realized until after I had left. The nature of modern research in astronomy is such that projects often take many years to complete. Some of the projects that I helped put in place before I left, such as the MIDI project for the VLT, the widefield camera that Klaus Meisenheimer built for the 2.2 meter telescope in Chile and the LBT are ones that I value as among the best accomplishments of the MPIA during the period I was Director. These projects are just producing their fruit now. It is a great pleasure to go back and to see the excitement generated Christoph Leinert with MIDI and Klaus Meisenheimer and his colleagues on the widefield camera. The GEMS project (Galaxy Evolution from Morphology and Spectral energy distributions) was started by Hans-Walter Rix taking advantage of the results produced by that camera. GEMS exemplifies the goals I had for the MPIA, and I was delighted to see how well it has worked out for Hans-Walter and the rest of the staff.

What are the most significant differences in leading the MPIA and the STScI?

SB: The most striking difference is that the MPIA is a self-contained institute whose primary goal is to produce scientific research, mostly by the staff and the directors. The STScI is a service institute whose primary goal is to produce science by supporting a large community of astronomers, very few of whom are at the Institute itself. That means that the MPIA has much more flexibility than the STScI. At the MPIA we were able to make decisions on our own and move very rapidly to implement them. There was less need to check each of our individual decisions with a broader community before moving ahead.

Leading the STScI combines management and politics, and it is the political part of the job that is the most difficult. At the STScI, we often must choose between options all of which will make many people unhappy, and we have little control of the subsequent consequences. This situation was less true at the MPIA, and it meant that we had a much different attitude when we approached decisions than we do here in Baltimore.

Did you keep in contact with the colleagues at MPIA? Are there common projects?

SB: Yes. I remain in close contact with my colleagues at the MPIA, and I make an effort to go back to Germany at least twice a year for visits to keep these contacts vital. I have an appointment as an Auswärtiges Mitglied at the Institute, and I exploit that as much as my job in Baltimore allows. It gives me tremendous pleasure to return to Heidelberg and spend time talking to the people I knew there, both former colleagues and the many new scientists who have come since Hans-Walter Rix and Thomas Henning became the co-directors. It is an exciting and vital place for science right now.

The principal collaborative project we have is the GEMS consortium. I am a member of that team. It takes advantage of work done with the 2.2 meter telescope widefield camera to make HUBBLE images of a $^1/_2$ degree field studied by COMBO-17. This project has been one of the most productive I have been involved in. It is a wonderful way to keep scientific contact. We alternate meetings between Heidelberg and Baltimore, and occasionally other places, and I hope very much that this project continues for several years.

Two personal questions. Did your family find it difficult to settle down in Germany?

SB: We did have some problems, some of which we could anticipate, and others of which we could not. Our children were young when we moved to Heidelberg, four- and five-years-old, respectively. We immediately put them in the German kindergarten. Our expectation was that the kids would pick up the German language quickly and that they would become integrated into the society as well. But after having both children in German schools for two years, we found that they did not assimilate very well. My daughter did much better than my son, having attended first grade at the Dilsberg Grundschule. My son refused to learn German and isolated himself very much in the classroom. The teachers recommended that we send him to an English speaking school, and it was only practical to send both our children to the same place – so that was a difficulty that we did not anticipate.

My wife had studied German for many years in school so she spoke German fluently. She attended university in Würzburg, and understood the culture well. However, she had problems getting a permanent work visa. In fact, even after we had been there seven years, she was unable to get a permanent employment status. She was employed almost all of the time, first at IBM and later at SAP, but there were times when the German government forced those companies to advertise her job searching for qualified German nationals to do the work she did. This was very difficult for us psychologically. She was normally not notified of these advertisements and only saw them when they appeared in the paper. In the end, we felt that it would be very difficult for us to remain happy in Germany under that kind of pressure. She was a second-class citizen compared to me.

Are Germans more unfriendly or less helpful towards foreigners than Americans are?

SB: I cannot say that Germans are either more or less friendly to foreigners than Americans are, since I only have experience as a foreigner in one country. I think it is

Fig. V.10: Steven Beckwith at the MPIA

difficult for anyone to move to another country. There is no reason to expect the cultures to change to accommodate people from the outside. The work rules in Germany were certainly a challenge for us. Many women from America now expect to have full opportunities for employment equal to men, something that was not true in the past. In this regard, Germany is still behind. There are not enough facilities to provide childcare for families with two working parents. The rules for store hours and government offices make it very difficult for families with children to cope with the daily difficulties of life. Certainly German society is set up for a family, where one spouse, presumably the man, goes to work, and the other spouse, presumably the woman, stays home and takes care of the children. I think this is the most difficult thing for someone from the United States to encounter. On the other hand, I know full well, from many foreign colleagues who come here, that they also encounter difficulties in America simply because the culture is quite different then their own. They may not find food to their liking, have a difficult time with the driving rules, language and many other things. The American bureaucracy is famously difficult for foreigners, especially after 9-11. Coming to another country puts great strains on families and on individuals, and it will not always be easy for them to integrate into the society.

You will soon resign as the director of the STScI. Do you already have another job prospect?

SB: I will step down as the Director in September, but I will remain on the staff of the institute as an astronomer. I plan to take the next year after I step down to concentrate on a writing project. After that, we will see.

One last question about the HST. How do you judge the chance for a last service mission (either robotic or with the Shuttle)?

SB:I am personally very optimistic that Hubble will be serviced, and I am hopeful that that will be done with the space shuttle. The space shuttle presents the highest chance of mission success and overall the lowest cost to Nasa. Sean O'Keefe, who made the original decision to cancel the servicing mission, has left the agency and the administrator designate, Mike Griffin, has expressed privately his admiration for Hubble and his favorable view of the use of the shuttle for Hubble servicing. My hope is that with Griffin coming on board we will have a chance to re-examine the value of a Hubble servicing and that he will conclude that it is worth the use of one space flight.

(The questions were asked by Thomas Bührke)

Staff

Heidelberg

Directors: Henning (GF), Rix

Scientists: Andersen, D. (until 5. 10.), Barden, Bell, Böhnhardt (until 31. 3.), Brandner, Butler (since 1. 6.), Cannon (since 1. 9.), Dannerbauer (since 1. 6.), Debieu, Dullemont (since 1. 10.), Feldt, Fendt (since 1. 11.), Fried, Gässler, Graser, Herbst, Hetznecker, Hippelein, Hippler, Hofferbert, Huisken, Kiss (until 31. 8.), Klaas, Klahr, Kleinheinrich, Kniazev (until 30. 9.), Köhler, Kornet (since 1. 7.), Krasnokutski, Krause (until 24. 3.), Kürster (since 1. 4.), Kuhlmann (since 1. 12.), Launhardt, Leinert, Lemke, Lenzen, Ligori, Marien, Mathar (until 31. 1.), Meisenheimer, Mundt, Przygodda (since 1. 3.) Pitz, Röser, Rouillé, (until 30. 6.), Schinnerer (since 1. 8.), Schreiber (since 1. 6.), Setiawan, Staude, Steinacker, Stickel, Toth (until 31. 1.), Vavrek (until 31. 3.), Walter (since 1. 8.), Weiß (until 29. 2.), Wolf R., Wolf S., Xu (until 29. 2.)

Ph. D. Students: Andersen, M. (until 30. 6.), Apai (until 30. 6.), Berton, Bertschik (until 29. 2.), Birkmann, Borch (until 29. 2.), Büchler De Matos Costa (until 30. 9.), Chen (since 1. 9.), Debieu (since 1. 2.), Dib, Dziourkevitch (since 1. 11.), Dumitrache (23. 2. –23. 3.), D'Souza (since 1. 10.), Egner, Falter, Györyova (since 1. 4.), Hanke (since 1. 10.), Häring, Häußler, Hempel (until 31. 10.), Johansen (since 1. 8.), Keil, Kellner, Kovacs, Krmpotic, Linz (since 1. 5.), Pascucci (until 30. 6.), Peter (since 1. 1.), Puga, Quanz (since 1. 5.), Ratzka, Riechers (since 1. 6.), Rodler (since 1. 11.), Rodmann, Schartmann, Schegerer (since 1. 6.), Schütz, Semenov, Smolcic (since 7. 10.), Stegmaier (since 15. 11.), Stumpf (since 15. 10.), Sukhorukov (15. 4.–31. 7.), Tristram (since 1. 2.), Umbreit, Voigt (1. 11.–31. 12.), Walcher (until 31. 10.)

Diploma Students and Student Assistants: D'Souza (until 30. 9.), Geißler (since 1. 10.), Mertin (until 15. 9.), Rockenfeller (since 1. 7.), Schmidt (since 1.12.), Stumpf (until 31. 8.), Weise (since 1.11.)

Diploma Students/Master Students (FH): Boxermann (1. 3. – 30. 9.), Herberich (1. 3.– 31. 8.), Würtele (until 30. 6.)

Science Project Management: Bizenberger, Grözinger, Hinrichs (until 31. 5.), Laun, Leibold (since 1. 7.), Naranjo, Neumann, Quetz, Schmelmer

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

Elektronics: Alter, Becker, Ehret, Grimm, Klein, Mall, Mohr, Ramos, Ridinger, Salm, Unser (until 31. 3.), Wagner, Westermann, Wrhel

Precision Workshop: Böhm, Heitz, Meister, Meixner, Morr, Pihale, Sauer

Drawing Office: Baumeister, Ebert, Münch, Rohloff, Rosenberger (since 1. 8.)

Photo Shop: Anders-Öczcan

Graphic Artwork: Meißner-Dorn, Weckauf

Library: Dueck, Fehr (15. 2.–30. 11.)

Administration: Apfel, Gieser, Heißler, Hölscher, Kellermann, Papousado, Schleich, Voss, Zähringer

Director's Office and Administrative Support: Bohm, Janssen-Bennynck, Koltes-Al-Zoubi, Seifert

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

Trainees: Baungärtner, Euler (since 1. 9.), Gärtner (since 1. 9.), Maurer, Müllerthann, Resnikschek; Rosenberger, Sauer, Schewtschenko (since 1. 9.), Schmitt (since 1. 9.), Stadler

Freelance Science Writer: Dr. Th. Bührke

Postdoctoral Stipend Holders: Afonso (since 1. 6.), Alvarez, Apai (1. 7.–31. 8.), Bailer-Jones (until 30. 9.), Bouwman (1.9.), Butler (until 23. 4.), Chesneau (until 31. 10.), De Bonis (since 1. 2.), Farinato (since 15.2.), Goldmann (since 1. 8.), Gouliermis (since 1.5.), Goto (since 1. 4.), Heymans (since 22.9.), Hujeirat, Khanzadyan, Knudsen (since 1. 10.), Martinez-Delgado, Masciadri, Moro-Martin (1. 9.–30. 11.), Mosoni (since 1. 9.), Pascucci (1. 7. until 31. 8.), Penarubbia, Prieto, Soci, Staicu (1. 1.–31. 10.), Trujillo, Wang, Zucker

Guests: Abraham, Ungarn (March), Araya, Mexiko (August), Beckwith, USA (November/December), Bacmann, Frankreich (May), Bjorkman, USA (July), Blanton, USA (June), Bryden, USA (March/April), Carretero, Spanien (November), Diethard, Deutschland (August), Deil, Deutschland (July/August), Eisenstein, USA (August/September), Erwin, USA (June), Endl, USA (August), Franco, Mexico (June – August), Fulara, Polen (November/December), Hartung, Chile (July), Heavens, Scotland (December), Hofner, USA (July/August), Hogg, USA (August/September), Jonsson, USA (October/November), Kiss, Ungarn (October), Koposov, Russland (June-September), Ligori, Italien (November/December), Lodato, England (April), Maghakyan, Armenien (October/November), Maier, Deutschland (June), Marco, Chile (April/

May), Men'shchivov, Canada (May), Mosoni, Ungarn (September-November), Movsisyan, Armenien (October/ November), Pavluchenkov, Russland (February-May), Pentericci, Italien (February-April) Pizagno, USA (June/July), Rebolo, Spanien (August), Rodler, Deutschland (August), Schreyer, Deutschland (March), Shields, UK (August), Smith, USA (July/August, October), Somerville, USA (May), Stolte, USA (July), Toth, Ungarn (August/September), Trager, USA (October), Tylor, UK (July), Veres, Ungarn (September-October), Vibe, Russland (August-October), Weldrake, Australien (December), Willacy, USA (September), Williams, USA (August), Wyder, USA (June), Yasyunin, Russland (November/December), Yee, Canada (September)
Due to regular international meetings at the MPIA further guests stood at the institute for shorter periods, who are not listed here.

Interns: Hempelmann (1. 3. until 31. 9.), Holzschuh (19. 7. until 30. 9.), Kordell (since 1. 9.), Maier (19. 7. until 30. 9.), Schwarz Henriques (26. 7. until 25. 9.), Wagenblaß (since 1. 9.), Wiehl (1. 3. until 30. 9.), Zechmeister (1. 9. until 30. 9.)

Calar Alto, Almeria/Spanien

Local Directors: Gredel

Astronomy, Coordination: Thiele, Frahm

Astronomy, Night Assistants: Aceituno, Aguirre, Alises, Cardiel, Guijarro, Hoyo, Pedraz, Sánchez (since 1. 10.)

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, Barbero (since 1. 2.), Barón, Carreño, Corral, Domínguez, Gómez, Góngora, Klee, Rosario López, Márquez, Martínez, Romero, Sánchez, Tapia

Administration, Secretariate: Hernández, M., Hernández, M.J., López, M.I., Wagner M. (since 15. 2.)

Working Groups

Department »Planet and Star Formation«
Direktor: Thomas Henning

Space Astronomy in the Infrared
Dietrich Lemke, Stephan Birkmann, Helmut Dannerbauer, Ulrich Grözinger, Ralph Hofferbert, Armin Huber, Csaba Kiss, Ulrich Klaas, Oliver Krause, Ernest Krmpotic, Sven Kuhlmann, Stefan Mertin, Jürgen Schreiber, Jutta Stegmaier, Manfred Stickel, Viktor Toth, Roland Vavrek

Star Formation
Christoph Leinert, Cristina Afonso, Carlos Alvarez, Daniel Apai, Jeroen Bowman, David Butler, Xuepeng Chen, Cornelis Dullemond, Markus Feldt, Bertrand Goldmann, Miwa Goto, Bernhard Keil, Tigran Khanzadyan, Rainer Köhler, Kacper Kornet, Ralf Launhardt, Rainer Lenzen, Hendrik Linz, Laszlo Mosoni, Ilaria Pascucci, Diethard Peter, Elena Puga, Sascha Quanz, Thorsten Ratzka, Florian Rodler, Alexander Schegerer, Oliver Schütz, Dmitri Semenov, Nikolai Voshchinnikov, Hongchi Wang, Sebastian Wolf

Brown Dwarfs, Extrasolar Planets
Reinhard Mundt, Coryn Bailer-Jones, Kerstin Geißler, Wolfgang Brandner, Elena Masciadri, Boris Rockenfeller, Jens Rodmann, Johny Setiawan, Micaela Stumpf

Theory
Natalia Dziourkevitch, Anders Johansen, Hubertus Klahr, Bernhard Keil, Jürgen Steinacker, Stefan Umbreit

Laboratory Astrophysics
Friedrich Huisken, Olivier Debieu, Florian Dumitrace, Serge Krasnokutski, Gael Rouillé, Oleksandr Sukhorukov, Angela Staicu, Felix Voigt,

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

Adaptive Optics
Wolfgang Brandner, Carlos Alvarez, Joana Büchler, Alessandro Berton, David Butler, Fulvio De Bonis, Markus Feldt, Dimitrios Gouliermis, Stefan Hippler, Stefan Kellner, Elena Masciadri, Robert Weiß

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

Structure and Dynamics of Galaxies
Hans-Walter Rix, Eva Schinnerer, David Andersen, Ignacio Trujillo, Vernesa Smolcic, Richard D'Souza, Nadine Häring, Carl Jakob Walcher

Stellar Populations and Star Formation
Fabian Walter, Thomas Herbst, John Cannon, Alexei Kniazev, Kirsten Kraiberg Knudsen, David Martinez Delgado, Dan Zucker, Sami Dib, Dominik Riechers

Evolution of Galaxies and Cosmology
Eric Bell, Hans-Walter Rix, Helmut Hetznecker, Catherine Heymans, Zuzana Györyva, Martina Kleinheinrich, Marc Barden, Sadegh Khochfar, Angela Hempel, Andrea Borch, Siegfried Falterer

Active Galactic Nuclei
Klaus Meisenheimer, Almudena Prieto, Laura Pentericci, Nadine Häring, Marc Schartmann, Konrad Tristram

Sloan Digital Sky Survey
Eric Bell, Daniel Zucker, Alexei Kniazev, Laura Pentericci

Deep Surveys
Klaus Meisenheimer, Hermann-Josef Röser, Hans Hippelein, Zoltan Kovacs, Siegfried Falterer, Boris Häußler

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

Collaboration with Industrial Firms

ABB (ehem. Hartmann + Braun), Alzenau
ADR, Paris
Agilent Technologies, Böblingen
Almet-AMB, Mannheim
Amphenol-Tuchel Electronics, Heilbronn
Angst+Pfister, Mörfelden
APE Elektronik, Kuppenheim
Arthur Henninger, Karlsruhe
asknet AG
Auer Paul GmbH, Mannheim
bacuplast GmbH
Baier Digitaldruck, Heidelberg
Barr, Westford, USA
Barth, Leimen
Bectronic GmbH, Derschen
Beep, Almería
Best Power Technology, Erlangen
Beta Layout, Arbergen
Binder Magnete, Villingen-Schwenningen
Black Box Communications, S.A., Madrid
Blaessinger, Stuttgart
Bohnenstiel, Heidelberg
Böllhoff GmbH, Winnenden
Börsig, Neckarsulm
Bubenzer Bremsen, Kirchen-Wehrbach
Bürklin, München
C&K Components, Neuried b. München
C.A.P. CNC+Coating Technik, Zell. a. H.
CAB, Karlsruhe
Cadillac-Plastic, Viernheim
CAMCenter GmbH
Carl Roth, Karlsruhe
Caspar Gleidlager GmbH
Cherry Mikroschalter, Auerbach
Christiani, Konstanz
Coating-Plast, Schriesheim
Com Pro, Stuttgart
Compumess Electronik, Unterschleissheim
Comtronic GmbH, Heiligkreuzsteinach
Conrad Electronic, Hirschau
Cryophysics GmbH, Darmstadt
Dannewitz, Linsengericht
DELL-Computer GmbH
Delta-V, Wuppertal
Deltron Components GmbH, Neuried b. München
Demag Cranes & Components S.A., Coslada (Madrid)
Deti, Meckesheim
DMG-Service, Pfronten
DPV Elektronik, Eppingen
Dürkes & Obermayer, Heidelberg
Dyna Systems NCH, Mörfelden-Walldorf
E2V, Chelmsford
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
Europa-Lehrmittel, Verlag
EWF, Eppingen
Faber Industrietechnik GmbH, Mannheim
Farben Specht, Bammental
Fairchild Imaging, Milpitas/ USA
Farnell in One, Deisenhofen
Farnell Electronic Services, Möglingen
FCT Electronic, München
Fels Spedition, Heidelberg
Fisba, St. Gallen
Fischer Elektronik, Lüdenscheid
FPS-Werkzeugmaschinen GmbH, Otterfing
Frank GmbH
Franke, Aalen
Fresemann Andreas
Fritz Faulhaber, Schönaich
Future Electronics Deutschland, Unterföhring
Ganter, Walldorf
Geier Metall-u. Stahlhandel, Mannheim
GENOMA Normteile, Hameln
Gerwah Päzision GmbH
GLT, Pforzheim
Goodfellow
Gould Nicolet Meßtechnik, Dietzenbach
Grandpair, Heidelberg
Grulms-Pneumatik, Grünstadt
Grupo Hispatec Soluciones Globales S.L., Almería
GRW, Würzburg
Gummi Körner, Eppelheim
Gummi-Plast Schild, Gernsheim
Gutekunst, Pfalzgrafenweiler
Halm+Kolb, Stuttgart
H.Bieri Engineering GmbH, Winterthur
Heidenhain Dr. Johannes GmbH, Traunreut
Heräus, Hanau
Hilger und Kern, Mannheim
Hilma-Römheld GmbH, Hilchenbach
Helukabel, Hemmingen
Hema, Mannheim
Herz, Leister Geräte, Neuwied
Hewlett-Packard Direkt, Böblingen
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
Infosoft Siglo XXI S.L.L., Almería
Infrared Laboratories, Tucson, USA
Inkos, Reute/Breisgau
INVENT GmbH
iSystem, Dachau
Jacobi Eloxal, Altlussheim
Jarmyn, Limburg
Jngenieurbüro Steinbach, Jena
Joisten+Kettenbaum, Bergisch Gladbach
Hahn u. Kolb GmbH
Kaufmann, Crailsheim
Kerb-Konus-Vertriebs-GmbH, Amberg
Kniel, Karlsruhe
Knürr, München
Krüss Optronic, Hamburg
Kurt Norr & Co
KVT CANESPA, Langenhagen
Lambda Electronics, Achern
Laser Components
Layher, Güglingen
Leybold Vacuum, Köln
Lemo Electronik, München
Lineartechnik Korb, Korb
Lödige Aufzugstechnik GmbH, Paderborn
Lopez Baena S.A., Almería
LPKF CAD/CAM Systeme, Garbsen
LWS-Technik GmbH & Co.
Macrotron, München
Mädler, Stuttgart
Mankiewicz, Hamburg
Mannesmann Dematic AG, Wetter
Matsuo Electronics Europe, Eschborn
Matsushita Automation, Holzkirchen
Maxim Ges. f. elektronische integrierte Bausteine, Planegg
Melles Griot, Bensheim
Menges electronic, Dortmund
Mentor, Erkrath
Metrofunkkabel-Union, Berlin
Misco Ibérica Computer Supplies, S.A., Madrid
Mitsubishi-Electric, Weiterstadt
Möller-Wedel, Wedel
Moll, Bleche und Verarbeitung, Hirschberg
MSC Vertriebs-GmbH, Stutensee
MTI, Baden-Baden
Munz, Lohmar
Mönninghoff, Bochum
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
Olympus, Hamburg
Optima Research, Stansted, GB
Otto Faber, Mannheim
Otto Ganter, Furtwangen
Orglmeister
OWIS GmbH, Staufen
Parametric Technology, Muenchen
Parcom, CH-Flurlingen
pbe Electronic, Elmshorn
Pfeiffer Adolf GmbH, Mannheim
Pfeiffer Vacuum, Asslar
Pfister Büro
Phonix Contact GmbH & Co, Blomberg
Physik Instrumente, Waldbronn
Phytec Meßtechnik, Mainz
Phytron, Gröbenzell
Plastipol, Runkel
Pleiger, Witten
POG, Gera
PROUT Services+Handware GmbH
PSI Tronix, Tulare, California, USA
Pühl A. GmbH
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
Roland Häfele Leiterplattentechnik, Schriesheim
Roth Carl GmbH, Karlsruhe
RS Components, Mörfelden-Walldorf
RSP-GmbH, Mannheim
Rudolf, Heidelberg
Rütgers, Mannheim
Rufenach Vertriebs-GmbH, Heidelberg
Rutronik, Ispringen
Sauter-Cumulus GmbH
Sartorius, Ratingen
Sasco, Putzbrunn
Satec, Sevilla
Scantec, Planegg
Schaffner Elektronik, Karlsruhe
Schlossmacher Ingenieurbüro
Schrauben-Jäger AG
Schulz Bürozentrum GmbH
Schuricht, Fellbach-Schmiden
Schweizer Elektroisolierungsstoffe, Mannheim
SCT Servo Control Technology, Taunusstein
SE Spezial-Electronic, Bückeburg
Seifert mtm Systems, Ennepetal
Siemens IC-Center, Mannheim
SolidLine AG
Spaeter, Viernheim
Sphinx Computer, Lauderbach
Spindler & Hoyer, Göttingen
Spoerle Electronic, Dreieich
Stahlschlüssel Wegst GmbH
Steinbach M. Ingenieurbüro
Stirling Cryogenics, NL-5692 EB Son
Straschu Leiterplatten, Oldenburg
SUCO-Scheuffele, Bietigheim-Bissingen
Synatron, Hallbergmoos
Tautz GmbH
Tandler, Brauen
Technik Direkt, Würzburg
TELDIX GmbH
THK, Düsseldorf
Thorlabs, Gruenberg
TMS Test- und Meßsysteme, Herxheim/Hayna
Tower Electronic Components, Schriesheim
TRIVIT AG
TS-Optoelectronic, München
TWK-Elektronik, Karlsruhe
Vacuumschmelze, Hanau
VBE Baustoff+Eisen, Heidelberg
Vereinigte Baustoff-und Eisen GmbH
Vero Electronics, Bremen
VISION Engineering, Emmering
W. & W. Schenk, Maulbronn
Wietholt Heinrich GmbH
Wikotec, Bramsche

Wilhelm Gassert, Schriesheim
WS CAD Electronik, Berk Kirchen
Witter GmbH, Heidelberg
WIKA, Klingenberg
Zeiss Carl, Optronics GmbH
Zemax, San Diego, USA

Teaching Activities

Summer Term 2004

Henning, Th.: Physics of Star Formation (Seminar)

Meisenheimer, K.: High Resolution Observation of Active Galactic Nuclei (Lecture)

Winter Term 2004/2005

Fried, J. (with B. Fuchs): Galaxien (Lecture)

Henning, Th.: Protostellare Scheiben (Lecture)

Henning, Th.: Physik der Sternentstehung (Seminar)

Leinert Ch., Röser, H.-J.: Einführung in die Astronomie und Astrophysik (Lecture)

Lemke, D. (with M. Bartelmann, H.-P. Gail and J. Heidt): Introduction to Astronomy and Astrophysics III (Seminar)

Meisenheimer, K. (with J. G. Kirk and S. Wagner): Radio Galaxies and Quasars (Seminar)

Rix, H.-W. (with B. Fuchs, A. Just, R. Spurzem): Structure, Kinematics and Dynamics of Stellar Systems (Seminar)

Summer Term 2004

Leinert, Ch., Lemke, D., Mundt, R., Röser, H.-J., (with M. Bartelmann): Introduction to Astronomy and Astrophysics III (Lecture)

Rix H.-W.(with B. Fuchs, A. Just and R. Spurzem): Stellar dynamis (Seminar)

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 as 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

Conference organized at the Institute

Project Management Course, February (Lemke)

GEMS Workshop, 3.-5. March (Bell)

SISCO Workshop, 8.-9. March (Bell, Meisenheimer)

Board of Trustees' Colloquium, 9. March

MPIA Internal Symposium, 20.-21. April (Rix, Roddmann)

PRIMA science meeting, May (Launhardt, Setiawan)

First MPIA Student Workshop, Rügen, 3.-6. June (Nadine Häring)

Second Tübingen/Heidelberg Workshop on Astophysical Fluid Dynamics, 28./29. June

PRIMA DDL technical meeting, June (Launhardt, Setiawan)

Workshop »Laboratory Astrophysics«, 2. July (Steinacker)

2nd Heidelberg/Tübingen Workshop on Astrophysical Fluid Dynamics, 28./29. July. (Klahr, Umbreit, Kley/Tübingen)

Ringberg-Workshop »CHEOPS Phase-A Study Results«, 14.-17. September (Feldt, Henning, Hippler)

Inaugural Meeting of the Science Council of the European Interferometry Initiative, 24. September (Graser, Henning)

Workshop »Chemistry in Disks«, September (Henning)

Workshop »The Central Parsec of Galaxies«, 6-8. October (Haering, Prieto, Camenzind/LSW)

Workshop »Chemistry of Protoplanetary Disks: Algorithms and Results«, 11-13. October (Häring, Klahr, Semenov, Wolf)

VLTI/MIDI Data Reduction, Analysis and Science School, Leiden, 11.-15. October (mit NOVA und ESO)

Symposium »Die Planeten der Sonne und der fernen Sterne«, 26. October (Henning, Staude, Klaus-Tschira-Stiftung)

Fachbeirats-Kolloquium, 15. November (Brandner)

Board of Trustees' Colloquium, 17. November

Ringberg Workshop »Structure and Evolution of the Milky Way and its Surroundings«, Schloss Ringberg, 5.-9. December (Klahr, Rix)

Ringberg Workshop »Planet Formation: Theory Meets Observation«, Schloss Ringberg, 19.-22. December (Brandner, Kellner, Klahr, Johansen, Umbreit)

Second Workshop »Science Case for the mid-infrared imaging interferometer APRES-MIDI«, December (Wolf)

Other Conferences Organized

Coryn Bayler-Jones: GAIA Classification Meeting, University of Cambridge, 15.-16. April, GAIA Classification Meeting, Observatoire de Paris, 8 October; GAIA German Coordination meeting, November; GAIA classification meeting, National and Kapodistrian University of Athens, 25.-26. November; Conference »The three dimensional universe with GAIA«, Observatoire de Paris, 4.-7. October

Tomas Henning: 2nd. TPF/DARWIN International Conference »Dust Disks and The Formation, Evolution and Detection of Habitable Planets«, San Diego, 27. July

Tom Herbst: LBT Interferometry Meeting, Tucson, January

Friedrich Huisken: 24th International Symposium on Rarified Gas Dynamics, Special Molecular Beams Session, Bari, 10-16. July (mit V. Aquilanti)

Rainer Köhler: VLTI / MIDI School for Data Reduction, Analysis and Science at Lorentz Center, Leiden, Netherlands

Ch. Leinert, O. Chesneau, R. Köhler: MIDI data reduction school, Leiden, 1-15. October

Dietrich Lemke: SPIE Conference »Astronomical Structures and Mechanisms«, Glasgow, 21-25. June (Co-Chairman)

Sebastian Wolf: First Workshop »Science Case for the mid-infrared imaging interferometer APRES-MIDI«, Observatoire de la Côte Azur, February (Co-Organizer)

Partecipation in Conferences, Scientific and Public Talks

Scientific Talks and Poster Contributions

Daniel Apai: 2nd. TPF/DARWIN International Conference »Dust Disks and The Formation, Evolution and Detection of Habitable Planets«, San Diego, 27. July (talk)

Marco Barden: Ringberg workshop »Secular Evolution of Disk Galaxies«, Schloss Ringebrg, 17.-21. May (talk)

Coryn Bayler-Jones: GAIA photometry working group meeting, Torino, 21. Januar; GAIA science team meeting, Torino, 22.-23. Januar; GAIA science team meeting, ESTEC, Netherlands, 2.-3. March; Jahrestagung der Gesellschaft für Klassifikation, Dortmund, March (talk); MPIA Internes Symposium, April (talk); GAIA classification meeting, University of Cambridge, 15.-16. April; IAU Coll. 196, »Transits of Venus: New views of the solar system and Galaxy«, Preston, England, 7.-11. June (invited talk); GAIA photometry working group meeting, Copenhagen, 28.-29. June (talk) ; GAIA science team meeting, Copenhagen, 30. June – 1. Juli; »Cool Stars 13«, Hamburg, July (talk, 2 Posters); Technische Universität Berlin, 29. July (invited talk); »The three dimensional universe with GAIA«, Observatoire de Paris, 4.-7. October (invited talk, Poster); GAIA classification meeting, Observatoire de Paris, 8. Oktober; GAIA classification meeting, National and Capodistrian University of Athens, 25.-26. November; GAIA German Coordination meeting, November; GAIA science team meeting, Barcelona, 16.-17. December (talk)

Eric Bell: AAS Conference, Atlanta, January (talk, Press Conference); SDSS Workshop Las Cruces, New Mexico, 15.-18. March (talk); HST May Symposium, Baltimore, 3.-6. May (invited talk); AAS Conference, Denver, 31. May – 3. June (talk, Press Conference); The Environment of Galaxies, Kreta, 9.-13. August (talk); GEMS Workshop, Potsdam, 13.-15. September (talks); SISCO Workshop Groningen, 23.-24. September (talk); Massive Galaxies Workshop, 27.-29. September (talk); SDSS Meeting, Pittsburgh, 30. September – 2. October (talk); Ringberg Symposium »Galaxy Mergers« 1.-5. November (talk); Bad Honnef, Schwerpunkte Program Assessment, 8. November (poster); Colloquium in Göttingen (Poster) Alessandro Berton: SPIE Congress, Glasgow, 21.–25. June (zwei Poster); Michelson Summer School, Pasadena, 20.–23. July; CHEOPS Ringberg-Tagung, 14.–17. September (zwei Vorträge); IFS »Detection simulation«, XVI Canary Islands Winter School, Tenerife, 21. November – 3. December; CHEOPS Workshop at ESO, Garching, 15.–16. December

Alessandro Berton: SPIE Congress, Glasgow, 21.-25. June (2 Posters); Michelson Summer School, Pasadena, 20.-23. Juli; CHEOPS Ringberg-Tagung, 14.-17. September (two talks); IFS »Detection simulation«, XVI Canary Islands Winter School, Tenerife, 21. November – 3. December; CHEOPS Workshop at ESO, Garching, 15.-16. December

Wolfgang Brandner: Astronomical Polarimetry, Waikoloa, HI, USA, 15.-19. March (Poster) MPIA Internal Colloquium, 20.-21. April (talk); Calar Alto Colloquium, Granada, 27. April (talk); IMF at 50, Festkolloquium für Ed Salpeter, Spineto, Italien, 16.-20. May (talk); NAHUAL – High Resolution IR Spectrograph for GTC, La Gomera, Spain, 10.-12. June (talk); AG Frühjahrstagung »Cool Stars, Stellar Systems & The Sun«, Hamburg, 5.-9. July (Poster); CHEOPS Ringberg Workshop, 12.-15. September (talk); Planetenbildung, Münster, 6.-8. October (talk); MPIA Board of Trustees' Colloquium, 17. November (talk); Ringberg Workshop on Planet Formation, 19.-22. December (talk)

Stephan Birkmann: SPIE Conference »Optical, Infrared, and Millimeter Space Telescopes«, Glasgow, 21.-25. June (Poster); Sommerschule »Birth, Life and Death of Stars«, Alpbach, August

Joana Büchler Costa: 3. SPIE-Conference: »Astronomical Telescopes and Instrumentation«, Glasgow, 21.-25. June (talk, Poster)

David Butler: Ringberg Workshop »Structure and Evolution of the Milky Way and its Surroundings«, Schloss Ringberg, 5.-9. December (Poster)

Helmut Dannerbauer: ESO ALMA Community Day, Garching 24. September; »The Dusty and Molecular Universe – A prelude to HERSCHEL and ALMA«, Paris, 27.-29. October (Poster)

Sami Dib: Universitäts-Sternwarte München. 23. February (talk); MPIA's internal symposium, Heidelberg, 20.-21. April (talk); 2nd Heidelberg-Tubingen workshop on Astrophysical Fluid Dynamics, Heidelberg, 28.-29. June, (talk); Conference »Cosmic ray dynamics: From turbulent to Galactic-scale magnetic fields«, Copenhagen, 2.-4. September (talk); AG Splinter meeting: »Astrophysical Turbulence«, Prague, 20.-25. September (talk)

Cornelis Dullemond:Workshop on Planet Formation, Münster, October (talk); Workshop on Spectral Energy Distributions of Galaxies, Heidelberg, October (Poster); Workshop on Central Parsec of Galaxies, Heidelberg, October (talk); First Spitzer Space Telescope Conference, November (talk); Ringberg Workshop on Planet Formation, December (talk)

Sebastian Egner: Workshop »PSF reconstruction for Adaptive Optics«, Victoria, Canada, 1CH 12. May (talk); SPIE Conference »Advancements in Adaptive Optics«, Glasgow, 21.-25. June (Poster)

Siegfried Falter: 1. IAU Colloquium no. 195, »Outskirts of galaxy clusters: Intense life in the suburbs«, Turin, 12.-16. March (Poster); 7th Birmingham Extragalactic Workshop, »Constructing galaxy clusters« , Birmingham, 28.-29. June (talk); Astrophysik-Seminar, Bamberg, 14. July (talk)

Markus Feldt: CHEOPS General Meeting, Amsterdam, 4.-5. April; »CHEOPS« Ringberg-Workshop, 12.-15. September (talk); JRA1/Opticon Meeting, Garching, 1.-2. March (talk); »Exploring the Cosmic Frontier – Astrophysical Instruments for the 21st Century«, Berlin, 18.-21. May (talk); SPIE Europe International Symposium – Astronomical Telescopes«, Glasgow, 21.-25. June (talk)

Wolfgang Gässler: SPIE Meeting »Astronomical Telescopes and Instrumentation«, Glasgow, 21.-25. June (Zwei Vorträge, Poster); Workshop »Exploring the Cosmic Frontier, Astrophysical Instruments for the 21st Century«, Berlin, Harnack-Haus, 18.-21. May (Poster)

Dimitrios Gouliermis: International Conference »The Initial Mass Function 50 years later«, Abbazia di Spineto, Siena, 16.-20. Mai, (Poster); »The First NEON Archive Observing School Summer School«, ESO, Garching, 14.-24. Juli, (talk); Seminar on »Retrieval and reduction of HST/WFPC2 data from the HST Archive«, Athen, 17.-20. December

Roland Gredel: Opticon/Medium Sized Telescopes Working Group, Teneriffa, 22.-24. Januar; NEON Summer School, ESO Garching, 14.-17. July (talk); Opticon/Medium Sized Telescopes Working Group, Paris, 12.-13. August; JENAM Granada, 13.-15. September (Calar Alto Teleskopmodelle, drei Poster); Opticon/Telescope Directors Forum, OHP Frankreich, 17.-18. November

Nadine Häring: Lorentz Center Workshop: The Nuclei of Galaxies, Leiden, 25.-30. Juli, (talk); Workshop »The Central Parsec of Galaxies«, Heidelberg, 6.-8. October (talk)

Thomas Henning:Universität Göttingen, May (invited talk); Internationales Symposium »Exploring the Cosmic Frontier: Astrophysical Instruments for the 21st Century«, Berlin, May (invited talk); Banff Meeting »Cores, Disks, Jets and Outflows in Low and High Mass Star Forming Environments: Observations, Theory and Simulations«, Canada, July (Poster); ESA Workshop »Cosmic Vision 2015-2025, the Scientific Themes of Tomorrow«, Paris, September (invited talk); Symposium »Die Planeten der Sonne und der fernen Sterne«, Heidelberg, October (invited talk); Conference »The Dusty and Molecular Universe. A Prelude to HERSCHEL and ALMA«, Paris, October (invited talk); Universität Wien, December (invited talk); Ringberg Workshop »Planet Formation: Theory meets Observation«, Schloss Ringberg, December (invited talk)

Tom Herbst: LBT Interferometry Meeting, Tucson January (talk); Kuratoriums-Kolloquium, 9. March (talk);UK National Astronomy Meeting, Milton Keynes, 30. March (invited talk); MPIA Internal Symposium, 21. April (talk); SPIE Conference 22.-24. June (talk, invited talk); 2nd TPF/Darwin International Conference, San Diego, 27. July (invited talk); FrInGe Meeting, Heidelberg, 2. November (talk); Fachbeirats-Kolloquium, 15. November (talk)

Stefan Hippler: Workshop »Adaptive Optical Phase Forming – Future Development Objectives«, Dresden, 1. March (invited talk); CHEOPS Workshop, Amsterdam, 5/6. April (Eigener talk); Treffen zur Vorbereitung eines Sonderfo rschungsbereichs »Adaptive Optik«, Dresden, 28. June (talk); Ringberg-Workshop »CHEOPS«, 14.-17. September (talks); CHEOPS Phase-A Review, ESO, Garching, 16. December (talk)

Ralph Hofferbert: SPIE-Conference »Astronomical Telescopes and Instrumentation«,Glasgow, 21.-25. June (talk)

Friedrich Huisken: 14th Symposium on Atomic, Cluster, and Surface Physics, La Thuile, Aosta, 1.-6. February (invited talk); 24th International Symposium on Rarified Gas Dynamics, Bari, 10.-16. July (invited talk); International Conference on Advanced Laser Technologies, Rom und Frascati, 10.-15. September (invited talk); Universität Jena, 27. April: Vorstellung an der Fakultät für Physik (invited talk); Institut für Festkörperphysik, Universität Jena, 18. June (invited talk); 4th Lyon Workshop on Nano-Optics, Lyon, 20.-21. September (talk)

Anders Johansen: Münster Workshop für Planetenentstehung (talk); The Origin of Planetary Systems network mid-term review, Frejus (talk); Workshop on »Planet Formation: Theory meets Observations« (Poster)

Bernhard Keil: First MPIA Student Workshop, Rügen, 3.-6. June (talk); 2nd Tübingen/Heidelberg Workshop on Astophysical Fluid Dynamics, 28.-29. June; HLRS Parallel Programming Workshop, Stuttgart, 10.-11. Oktober; Summer School on Mathematical Modelling and Computational Challenges in Plasma Physics and Applications, Cargese (Corsica), 25.-30. Oktober

Stephan Kellner: SPIE Advancements in Adaptive Optics, Glasgow, 21.-25. June (talk); Ringberg Workshop »Planet formation and detection – therory meets observation«, 19.-22. December (talk); RTN meeting, Lund (talk)

Ulrich Klaas: HERSCHEL Calibration Workshop, Leiden, December (talk)

Hubert Klahr: Planet Formation Workshop, Santa Barbara, USA, March (talk); NCAC, Warschau, April (invited talk); Ringberg Workshop on Cirkumstellar Disks, April (invited talk); Workshop on Planet Disk interaction, Stockholm, May (talk); 2nd Tübingen-Heidelberg Workshop on Astophysical Fluid Dynamics (28.-29. June) (talk); Astronomisches Kolloquium, Heidelberg, July (talk); BAR-Meeting, MPIK, Heidelberg, September (talk); Workshop Chemistry in Disks, Heidelberg, October (talk); Workshop Planetenbildung, Münster, October (talk); Universität Braunschweig, November (invited talk); EU-Network School on Numerical Methods in Planet Formation, Frejus, November (Vorlesung); Ringberg Workshop on Planet Formation: Theory meets Observation, December (invited talk)

Kirsten K. Knudsen: BoA Meeting, Bonn, 29. November; Submm Astrophysics Workshop, Kopenhagen, 20.-21. December (talk)

Rainer Köhler: 3. SPIE-Conference: »Astronomical Telescopes and Instrumentation 2004«, Glasgow, 21.-25. June (Poster); Michelson Summer School, Pasadena; 2nd. TPF/Darwin International Conference, San Diego (Poster)

Kacper Kornet: Ringberg Worskhop »Planet Formation: Theory meets Observation«, 19.-22. December (talk)

Martin Kürster: Workshop Planetenbildung: Das Sonnensystem und extrasolare Planeten, 6.-8. October 2004 in Müns-ter (zwei Vorträge)

Ralf Launhardt: Moriond Conference »The Young Local Universe«, La Thuile (Italien), March (invited talk); Conference »Exploring the Cosmic Frontier – Astrophysical Instruments for the 21st Century«, Berlin, May (Poster); CEA Saclay, June (invited talk); Conference »Cores, Disks, Jets and Outflows in Low and High Mass Star Forming Environments«, Banff, Canada, July (zwei Poster); »The Second TPF/Darwin International Conference«, San Diego, CA, July (zwei Poster); Caltech, Pasadena, July (invited talk); Center for Astrophysics, Cambridge, October (invited talk); Conference »Astrometry in the Age of the Next Generation of Large Telescopes«, Flagstaff, AZ, October (talk); LAOG, Grenoble, December (invited talk)

Christoph Leinert: SPIE Conference »New Frontiers in Stellar Interferometry«, Glasgow, 21.-25. June (invited talk); Astronomisches Kolloquium, Heidelberg (talk); MIDI Data Reduction School, Leiden, 1.-15. October (lectures)

Dietrich Lemke: International Cryogenic Engineering Conference Nr. 20, Peking, May (invited talk); SPIE Conference»Astronomical Telescopes and Instrumentatio n«,Glasgow, 21.-25. June (talk, Posters); Sommerschule »Birth, Life and Death of Starts«, Alpbach, August (invited talk); Raumfahrt-Kolloquium »Forschung im Weltraum«, Aachen, November (invited talk)

Sebastiano Ligori: SPIE Conference »New Frontiers in Stellar Interferometry«, Glasgow, 21.-25. June (2 Posters), ALMA Day, Garching, 24. September

Hendrik Linz: Joint Meeting of the Czech Astronomical Society and 78. Jahrestagung der Astronomischen Gesellschaft, Prag, September (talk)

Elena Masciadri: SPIE-Tagung »Astronomical Telescopes and Instrumentations«, Glasgow, 21.-25. June (ein talk, 2 Posters); Conference on »Low-mass Stars and Brown Dwarfs: IMF, Accretion and Activity«, Volterra, 17.-19. October (talk); International Workshop at IA-UNAM (Mexico) 11.-12. February (talk); CHEOPS-Workshop, Ringberg, September (talk)

Klaus Meisenheimer: Physikalisches Kolloquium der Universität Freiburg, 12. July (talk); SISCO mid-term meeting, Groningen, 22.-24. September (talk); Workshop »The Central Parsec of Galaxies«, 6.-8. October (talk); Zwei Vorlesungen über Multiband Surveys, Neapel, 1.-9. September; Kuratoriums-Kolloquium am MPIA, 17. November (talk)

Reinhard Mundt: Workshop »The sun, cool stars and stellar systems 13«, Hamburg, 5.-9. July (talk)

Ilaria Pascucci: 2nd. TPF/Darwin International Conference »Dust Disks and The Formation, Evolution and Detection of Habitable Planets«, San Diego, 27. July (talk)

Jorge Penarrubia: Ringberg Workshop »The Structure and Evolution of the Milky Way and Its Surroundings«, Schloss Ringberg, 5.-9. December (invited talk)

Sascha Quanz: 37th Liege Colloquium »Science Case for Next Generation Optical/Infrared Interferometric Facility – the post VLTI era«, Lüttich, 23.-25. August; VLTI/MIDI Data Reduction, Analysis and Science School, Leiden, Oktober; XVI- Canary Islands Winterschool of Astrophysics: »Exoplanets«, Instituto de Astrofísica de Canarias, Tenerife, 22. November – 3. December

Hans-Walter Rix: Jerusalem Winter School at The Hebrew University, Jerusalem, Israel, 29. December – 10. January (drei Vorträge); Universität Basel, 13. January (invited talk) ; Space Telescope Science Institute, Baltimore, 3.-5. February (invited talk); SDSS Meeting, NMSU, New Mexico, 15.-18. March; Tagung »Growing Black Holes«, Garching, 21. June (talk); Tagung »PLUMIAN 300 – Quest for a Concordance Cosmology«, Cambridge, UK, 5.-8. July (talk); Aspen Summer Workshop, Aspen, Colrado, 9.-17. July (talk); FIRES Workshop, Sterrewacht Leiden, 15.-17. September (talk); Opticon Meeting Leiden, 21. September; Astronomisches Rechen-Institut, Heidelberg, 28. September (Institutskolloquium); JWST-Meeting »Cosmology with NIRSPEC«, Ottobrunn, 5. October (talk); Conference SED 2004 at MPI für Nuclear physics, Heidelberg, 6. October (talk); Ohio University, Ohio, 25.-28. October (talk)

Jens Roddmann: 2nd TPF/Darwin International Conference, San Diego, 27. July (talk); Fourth IRAM Millimeter Interferometry School, Grenoble, 22.-26. November (Poster)

Ralf-Rainer Rohloff: SPIE conference, Glasgow, 21.-25. June (talk)

Marc Schartmann: Workshop »The structure and composition of Active Galactic Nuclei: Optical interferometry and adaptive optics of NGC 1068«, Lorentz Center, Leiden, 12.-14. January (talk); Workshop »Introduction to Computational Fluid Dynamics«, HLRS Stuttgart, 29. March – 2. April; 2nd Tübingen/Heidelberg Workshop on Astrophysical Fluid Dynamics, Heidelberg, 28.-29. June; Jenam 2004, »The many scales of the universe«, Granada, 13.-15. September (Poster); SED Workshop »The spectral energy distributions of gas rich galaxies: confronting models with data«, MPIK Heidelberg, 4.-8. October (Poster); Workshop »The central pc of galaxies«, Heidelberg, 6.-8. October (talk)

Eva Schinnerer:Workshop »'The Evolution of Starbursts«, Bad Honnef, August, (talk); Cambridge, UK, September (talk); Eso Alma community day, September (talk); Conference »The Dusty and Molecular Universe: A Prelude to Herschel and Alma«, Paris, October (talk)

Dimitri Semenov: Chemistry Workshop On The Disk Chemistry – Algorithms and Results, Heidelberg, October (talk)

Johny Setiawan:MPIA internal symposium, April (talk); Workshop on Cool Stars, Hamburg, 5.-9. July (talk, Poster); Symposium of the Indonesian Physical Society, Pekanbaru, 24.-25. August (talk); Cheops workshop, Ringberg 12.-15. September; Workshop Planetenbildung, Münster, 6.-9. September (talk); Ringberg Workshop »Planet Formation: Theory meets Observation«, 19.-22. December (talk)

Roberto Soci: Spie Conference »Advancements in Adaptive Optics«, Glasgow, 21.-25. June (talk)

A. Staicu: 14th Symposium on Atomic, Cluster, and Surface Physics, La Thuile, Aosta, 1.-6. February (Poster); 68. Frühjahrstagung der Deutschen Physikalischen Gesellschaft, München, 22.-26. March (talk)

Jürgen Steinacker: Seminaire de l'Observatoire de Bordeaux, 1. April (talk); Bochum Science Seminar, 13. April (talk); Astronomisches Kolloquium Bonn, 11. June (talk); Eso, München, 22. June (Kolloqiumstalk); 2nd Heidelberg/Tübingen Workshop on Astrophysical Fluid Dynamics, Heidelberg, 28. June (talk); Conference »Cool Stars, Stellar Systems and the Sun 13«, Hamburg, 8. July (talk); Banff Meeting »Cores, Disks, Jets & Outflows in Low & High Mass Star Forming Environments: Observations, Theory and Simulations«, Kanada, 12. July (talk); AG Splinter meeting »The Formation of Massive Stars«, Prag, 21. September, (talk); Workshop »The Spectral Energy Distribution of Gas Rich Galaxies: Confronting Models with Data«, 4. October (talk); Workshop »Planet-Formation: The Solar System and Extra-Solar Planets, Münster, 7. October (talk); 1. Internal MPIA Symposium, Heidelberg, 20. April (talk); C3 Professorship Application ITA Heidelberg 25. October (talk); European Research-Training Network »Planets: Numerical Methods for the Simulations of Planet Formation«, Frejus, 29. November (Vorlesung)

Manfred Stickel: Conference »The Dusty and Molecular Universe – A prelude to Herschel and Alma«, Paris, Oktober

Ignacio Trujillo: Conference »Massive Galaxies Over Cosmic Time«, STScI, Baltimore, 27.-29. September (talk); 1st Arizona/Heidelberg Symposium: »The High Redshift Frontier«, Tucson, 30. November – 3. December (invited talk)

Stefan Umbreit:Astronomy of the American Astronomical Society, Cannes, 19.-23. April (talk); Annual Meeting of the AAS/Division of Dynamical Astronomy, May (talk); AG-Tagung Prag, September (Poster); Conference »Low-Mass Stars and Brown Dwarfs, Volterra, 17.-19. October (talk); Astronomical Institute of the University Bonn, 10. December (talk)

Karl Wagner: Spie Conference »Astronomical Telescopes and Instrumentation«, Glasgow, 21.-25. June

Fabian Walter: Seminaire de l'Observatoire de Bordeaux, 1. April (talk); Bochum Science Seminar, 13. April (talk); Astronomisches Kolloquium, Bonn, 11. June (talk); Eso Colloqium, Garching, 22. June (talk); Workshop »'The Evolution of Starbursts«, Bad Honnef, August, (talk); Cambridge, UK, September (talk); Eso Alma community day, September (talk); Paris, October (talk); C3 Professorship Application ITA Heidelberg, 25. October (talk)

Sebastian Wolf: Conference »Astronomical Polarimetry – Current Status and Future Directions«, Hawaii, 15.-19. March (talk); Conference »Modelling the Structure, Chemistry and Appearance of Protoplanetary Disks Schloss Ringberg, 13.-17. April (talk); 37th Liege Colloquium »Science Case for Next Generation Optical/Infrared Interferometric Facility – the post VLTI era«, Lüttich, 23.-25. August (talk); Workshop »Planetenentstehung«, Münster, 6.-8. October (talk); Workshop »Chemistry of Protoplanetary Disks: Algorithms and Results«, Heidelberg, 11.-13. October (talk); Conference »The Dusty and Molecular Universe – A prelude to Herschel and Alma, Paris, 27.-29. October (talk und Poster)

»Science Case for Next Generation Optical/Infrared Interferometric Facility – the post VLTI era«, Lüttich, 23.-25. August (talk); Workshop »Planetenentstehung«, Münster, 6.-8. October (talk); Workshop »Chemistry of Protoplanetary Disks: Algorithms and Results«, Heidelberg, 11.-13. October (talk); Conference »The Dusty and Molecular Universe – A prelude to Herschel and Alma, Paris, 27.-29. October (talk und Poster)

Public talks

Markus Feldt: Meeting series »Physik am Samstagmorgen« of the MPI for Nuclear physics, Heidelberg, 13. March (talk)

Roland Gredel:Deutsche Schule Marbella, 10. June (talk); University Almeria, 11. October (talk); University Almeria, 8. November (talk)

Nadine Häring: Meeting series »Physik am Samstagmorgen« of the MPI for Nuclear physics, HD, 13. March (talk)

Klaus Meisenheimer: talk in the Planetarium Mannheim (14. December)

Dietrich Lemke: Planetarium Wolfsburg, January (talk); Meeting series »Physik am Samstagmorgen« of the MPI for Nuclear physics, Heidelberg, 13.3. (talk); Astronomical Colloquium University Helsinki, April (talk); Planetarium Stuttgart, November (talk)

Axel M. Quetz: Meeting series »Physik am Samstagmorgen« of the MPI für Nuclear physics, Heidelberg, 13.3. (talk); Max-Rill-Schule, Reichersbeuern, 22.10.2004: »Entstehung von Planetensystemen«

Hans-Walter Rix: TÜV Annual meeting, Hamburg, 27. May (talk)

Jens Roddmann: »Languages of Science – Sprachen der Wissenschaft«, Berlin, 14/15 May (talk)

Jakob Staude: Annual meeting of the MPG, Stuttgart, June (School talk); Science Academy, Heidelberg, 6. September (talk); Symposium »Die Planeten der Sonne und der fernen Sterne«, Heidelberg, 26. October (invited talk)

Service in Comitees

Coryn Bayler-Jones: Member of GAIA Science Team; Leader of the GAIA Classification Working Group; Core member of the GAIA Photometry Working Group; Member of the Scientific Organizing Committee of Commission 45 (Stellar Classification) of the International Astronomical Union

Marco Barden: deputy member of the Calar Alto TAC

Wolfgang Brandner: Mitglied in: Calar Alto Time Allocation Committee, Calar-Alto-Instrumentierungskomitee, Spitzer Space Telescope Cycle 1 Proposal Review Panel, MPIA Vertreter der Mitarbeiter in der CPT-Sektion der MPG; Studenten-Auswahlkomitee des MPIA, PhD Committee for Herve Bouy

Josef Fried:Member of the Calar-Alto-Instrumenting committee

Roland Gredel:Calar Alto Programme Committee; Junta de Andalucia, Working Group for a law on light pollution; LBT operations advisory committee

Thomas Henning: member of the ESO Scientific and Technical Committee; member of the ESO Strategic Planning Group; member of the VLTI Implementation Committee; member of the ESO-VLT-Instrument Science Team for VISIR; member of the ESA Astronomy Working Group; member of the SOFIA Science Council; member of the European ALMA Board; chairman of the German Interferometry Centre FrInGe; President of the Science Council of the European Interferometry Initiative; chairman of the LBT-Beteiligungsgesellschaft; member of the Board of Directors of the LBT Corporation; member of the Executive Committee CAHA; member of the finding committee C3 »Theoretische Astrophysik«, Universität Heidelberg; Mitglied im DLR-Gutachterausschuss »Extraterrestrische Grundlagenforschung«; vice chairman of the Scientific Advisory Council of the Kiepenheuer Institute for Solar Physics in Freiburg; Co-I of the infrared instruments FIFI-LS (SOFIA), PACS (HERSCHEL), Miri (JWST), Cheops (VLT), Prima-DDL (VLTI); member of the Astronomische Gesellschaft and of the Deutsche Physikalische Gesellschaft; member of the Deutsche Akademie der Naturforscher Leopoldina

Tom Herbst: LBT Science Advisory Committee (chair); LBT Board (attendance as SAC Chair); ESA-DARWIN Terrestrial Exo-planet Science Advisory Team (TE-SAT); ESA-DARWIN GENIE Advisory Team; MPIA WBK; MPIA PhD Advisory Committee; MPIA Computer Committee

Ulrich Klaas: Co-Investigator in the Isophot Consortium; Co-Investigator in the HERSCHEL-PACS Consortium; member of the ISO Active Archive Phase Coordination Committee; member of the HERSCHEL Calibration Steering Group; member of the Miri EC Calibration Working Group; member of the Library Committee

Martin Kürster: Member of the IAU Working Group »Extrasolar Planets«

Klaus Meisenheimer: member of the Calar Alto Instrumentation Committee

Christoph Leinert: Eso OPC Panel member

Dietrich Lemke: Principal Investigator of the ISO-ISOPHOT Consortiums; Co-Investigator of the HERSCHEL-PACS Consortium; Co-Principal Investigator of the JWST-Miri Consortium

Hans-Walter Rix: Chairman of the Scientific Advisory Board and member of the Board of Trustees of the Astrophysikalisches Institut Potsdam; member of the Scientific Advisory Board of the Astronomisches Rechen-Institut Heidelberg; member of the Eso Visiting Committee; member of the Board of the Large Binocular Telescope Corporation and of the Board of the Large Binocular Telescope Beteiligungsgesellschaft; member of the Board of OPTICON; member of the VLTI Steering Committee; member of the SIRTF Time Allocation Committee and of the SIRTF Proposal Review Panel; member of the JWST/NIRSPEC Science Team; member of the SNWG Commission in the Max Planck Society; member of the BMBF Expert Committee »Astrophysics and Astro-particle Physics«; member of the DFG Emmy-Noether Panel

Jens Roddmann: Member of the Computer Committee

Hermann-Josef Röser:Secretary of the Calar Alto Time Allocation Committee; Allocation of MPG time at Eso/MPG 2.2 m telescope (with Rainer Lenzen)

Eva Schinnerer: member of the Ernst Patzer Awards Committee

Jakob Staude: member of the Jury of the national contest »Jugend forscht«

Further Activities at the Institute

Klaus Meisenheimer, Ulrich Bastian (ARI) and Michael Biermann (LSW), with the help of Stephan Birkmann, Monika Maintz, Holger Mandel und Nadine Häring, organized for the first time the BOGy Workshop »Berufs-Orientierung an Gymnasen«, which took place on February16-20.

Sebastian Wolf initated the Programme »Mini-research«, which offers to younger students the opportunity to collect early experiences in astrophysical research within our working groups. Projects which have been started within the programme »Mini-research« can eventually be continued as diploma theses.

Reinhard Mundt and Hans-Walter Rix initiated the »International Max Planck Research School for Astronomy & Cosmic Physics at the University of Heidelberg«

On the 8. of June, the editorial staff of »Sterne und Weltraum«, with the help of Stefan Birkmann, Sebastian Egner, Nadine Häring, Boris Häussler, Bernhard Keil, Stephan Kellner, Ernest Krmpotic, Jens Rodmann, Marc Schartmann and Oliver Schütz organized a public observation ot the Venus transit in front of the Sun in the Schwetzingen Castle Gardens. Numerous school classes and the general public (all together about 1500 people) saw the spectacular event at a historical site.

In the course of the year, a total of 450 visitors in 16 groups were guded through the Institute. (Axel M. Quetz, Stephan Kellner and others)

At Calar Alto about. 2000 visitors, about 75 % of which were spanish school classe and about 10 % members of public spanish organizations, were guided through the observatory.

Jakob Staude, assisted by Axel M. Quetz, edited the 43. Annual volume of the magazine »Sterne und Weltraum«.

Publications

In Journals with Referee System:

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