Max Planck Institute for Astronomy

Heidelberg-Königstuhl

Annual Report 2006

MAX-PLANCK-GESELLSCHAFT

Cover Picture:

This color image of the face-on spiral galaxy NGC 6946, was taken at the Large Binocular Telescope on 18 September 2006. The galaxy lies at a distance of about 16 million light years. The composite was made from images taken through near-ultraviolet, blue, and green filters, using one primary mirror and the blue optimized Large Binocular Camera.

The total exposure time was 560 seconds in U (near ultraviolet), and 400 seconds each in B (blue) and V (green), comprised of a stack of 20-second exposures, taken so as not to saturate the brighter stars. The U, B, V images are displayed in the 3-color composite as blue, green and red respectively.

Credits: Vincenzo Testa, Cristian De Santis, LBT

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Max Planck Institute for Astronmy

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Preface

In this Annual Report we provide an overview of the scientific 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.

The year 2006 has been yet another exciting year of new astrophysical discoveries and numerous positive developments at the MPIA. It has brought a rich scientific harvest on topics ranging from the merging history of galaxies to the early stages of planet formation.

2006 has also seen the continued arrival of a new generation of junior staff scientists: by now a total of eight new junior research groups are established at the MPIA. In part as a consequence of this rapid growth, the Institute has embarked on a thorough renovation and the first major expansion of its building, with a new top floor completed in August 2006.

The MPIA has also seen a number of other "firsts" in 2006, foremost the first scientific data from the LBT.

Finally, the year 2006 brought good steady progress on crucial upcoming facilities, the LBT, 2nd generation VLTI instruments and JWST instrumentation. These developments are sure to lay the foundation for future astronomical discovery.

In addition to brief presentations of current scientific results, we report in more depth on selected research fields at the Institute. We will continue these extended reports over the 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 staff members and friends of the Institute get a word in, in order to draw a vivid picture of the working atmosphere at the Institute and of its development in the course of time.

We hope that this Annual Review will give the reader new insight into the astronomical research carried out at our Institute.

Thomas Henning, Hans-Walter Rix

Heidelberg, July 2007

I. General

I.1 Scientific Goals

The goal of the Max Planck Institute for Astronomy (Fig. I.1) is to explore and understand the nature and evolution of planets, stars, galaxies and the Universe as a whole. Since its establishment in 1967, the MPIA has pursued a broad spectrum of astrophysical research by leading the development and operation of telescopes and their instrumentation; by designing, executing and analysing high-impact observing programmes and surveys; and by connecting to the physics using powerful theoretical models. The MPIA focusses its observational capabilities on the optical and infrared spectral regions, taking a leading role in both ground-based and space-borne instrumentation. Combining these strengths with state-of-the-art multiwavelength observations, the MPIA is able to stay at the forefront of this rapidly-developing field.

The research at the Institute is organized within two scientific departments: **Galaxies and Cosmology** (director: Hans-Walter Rix) and **Planet and Star Formation** (director: Thomas Henning). In addition to the long-term staff in these departments, there are seven independent Junior Research Groups (four Emmy Noether groups supported by the German Science Foundation DFG, and three groups supported by the Max Planck Society). There are 57 post-docs and 46 PhD students currently working at the institute. There are strong ties between the Institute

Fig. I.1: The Max Planck Institute for Astronomy on the Königstuhl Mountain in Heidelberg; the Institute's Elsässer-Laboratory is in the foreground.

and the University of Heidelberg and its Center for Astronomy (ZAH), both in teaching and research. Recent initiatives include the International Max Planck Research School (IMPRS) for Astronomy and Cosmic Physics and a successful proposal of the University of Heidelberg within its activities for the Excellence Initiative.

The main research fields of the two departments are complementary in both a scientific and practical sense. Obviously, star formation is a critical aspect of the formation and evolution of galaxies. Yet, also the instrumentation and capabilities required by both departments share strong commonalities; e.g., requirements for high spatial resolution, powerful survey capabilities, and the importance of access to the infrared spectral region.

Galaxies and Cosmology

We know that the Universe was rather "simple" and nearly homogeneous right after the Big Bang, yet now boasts rich "hierarchical" structure over a wide range of physical scales: from the filamentary distribution of galaxies on large scales (the "cosmic web") to galaxies themselves, down to clusters of stars, stars and their planets.

The formation of this structure on scales of galaxies and larger can be understood if, and only if, it is assumed to be driven by gravitational instability arising from a dominant, but yet to be identified, dark matter component.

The galaxies we observe in the present-day universe are a central level in this hierarchical order, consisting of billions of stars, of gas and dust, all embedded in halos of dark matter. As Edwin Hubble already realized 70 years ago, these "island universes" 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 rate of new star formation varies similarly; the physical sizes of different galaxies still vary by a factor of 100. While some galaxies apparently do not have a black hole at their centers, in other galaxies this central black hole has the mass of more than one billion suns. In contrast to the broad range of parameters, observations have shown, particularly in the last 15 years, that only a tiny fraction of the possible combinations of the characteristic galactic quantities (stellar masses and 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 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 random mass fluctuations existing after the Big Bang is the fundamental question of galaxy formation and a central issue of cosmology.

In principle, there can be three broad lines of explanation for the limited variety of galaxies:

1. Observed galaxies represent the only stable configurations.
2. The galactic parameters that have been realized directly result from the limited set of cosmological initial conditions.
3. The overall process of galaxy formation results in a limited set of outcomes because it is self-regulating due to different feedback processes. When and where any of these three mechanisms plays a role is the subject of current research.

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 to predict the properties of the small-sized central black hole from the overall size of a galaxy?
- Which processes determine the structure and morphology of galaxies and when do these 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?
- How did the Milky Way, our Rosetta Stone of galaxy evolution, form?

The approaches 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 through the observation of distant (high-redshift) objects; the comparison of observations with physical models. The observational capabilities for the field require survey telescopes, large telescopes for sheer photon collecting of faint sources, and interferometric techniques to achieve high spatial resolution. Comprehensive studies of galaxy evolution require observations from the X-rays to the radio wavelengths.

The most important facilities for survey work at MPIA are: the Sloan Digital Sky Survey (SDSS and Segue) for the Milky Way and Local Group, to be followed by the PanStarrs 1 survey in 2008; the 2.2 m telescope on La Silla, the Caha 3.5 m telescope with its Omega 2000 camera for galaxy evolution surveys; the VLT and soon the LBT to follow-up this survey work; the Irac and Mips instruments on the Spitzer Space Telescope, and (starting in 2008) the Pacs Instrument of the Herschel mission to study star formation and the Interstellar medium, complemented by the VLA, IRAM, APEX and soon ALMA at radio and sub-mm wavelengths.

Planet and Star Formation

The formation of stars is a fundamental process in the universe, shaping the structure of entire galaxies and determining their chemical state. The formation of individual stars can be best studied in nearby molecular clouds. The study of star formation in other galaxies allows us to understand this process under physical conditions which can be very different from those in the Milky Way. Our studies of star formation in the Magellanic Clouds allow an investigation of the effect of metallicity on the star formation process, which is certainly an important factor in understanding star formation in the early universe.

Stars are born in the dense and cold cores of molecular clouds, which become gravitationally unstable and, in general, fragment to form binaries and multiple stellar systems. The role of magnetic fields or turbulence in controlling the onset of star formation remains one of the open key questions which have to be answered. This question is immediately related to the shape of the initial (sub)stellar mass function in different environments. Dynamical interactions in multiple systems may be a crucial factor for the formation of Brown Dwarfs. Massive star formation takes place in clusters, leading to complex star-forming regions. The rapid evolution of massive protostars and the associated energetic phenomena provide an enormous challenge in identifying the formation path of massive stars.

The earliest phases of star formation are obscured by enormous amounts of dust and gas and can only be detected by sensitive far-infrared and (sub)millimetre observations. At later evolutionary stages, the objects “glow” at near- and mid-infrared wavelengths and finally become visible at optical wavelengths. Our observing programs cover a wide range of wavelengths with a special emphasis on infrared and (sub)millimetre observations.

The formation of planets and planetary systems is a natural by-product of low-mass star formation. Because of angular momentum conservation, accretion of matter onto the central protostar happens predominantly through a circumstellar disk. Disks around T Tauri stars are the natural birthplaces of planetary systems, resembling the solar nebula 4.5 Gyr ago. During the active accretion phase, bipolar molecular outflows and ionized jets are produced, which in turn play an important role in the evolution of star-disk systems. We are presently starting to use protoplanetary disks as laboratories for understanding the formation of our own solar systems and the diversity of other planetary systems detected so far.

The research of the planet and star formation department is focused on the understanding of the earliest phases of stars, both in the low- and high-mass stellar regime. Observations with space observatories such as ISO and SPITZER, as well as ground-based infrared and (sub)millimetre telescopes allow the detection and characterization of massive protostars and their subsequent evolution. The vigorous use of submillimeter facilities is preparing the department for the Atacama Large Millimeter Array (ALMA), which will soon commence operation.

The investigation of Brown Dwarfs, which were first detected in 1995, is another important research topic. How do Brown Dwarfs form? Are young substellar objects also surrounded by disks? What is the binarity fraction and the exact mass of the objects? What is the composition of their atmospheres? These are among the burning questions which are attacked by MPIA scientists.

With the detection of the first extra-solar planets, the study of planet formation in protoplanetary disks entered a new phase of explosive growth. The department is well-positioned to play an important role in these studies, with a combination of infrared and millimetre observations, numerical (magneto) hydrodynamical simulations, and radiative transfer studies. Imaging with the HUBBLE Space Telescope and the wealth of data from the SPITZER telescope provide new insights into the earliest stages of planet formation. Improved spatial resolution from our adaptive optics program, infrared interferometry with large telescopes and long baselines, and the use of millimetre interferometers provide insights into disk structure and evolution on spatial scales relevant to planet formation.

We have started new observing programs to search for extra-solar planets through direct imaging, the transit technique, and astrometry. With the Spectral Differential Imaging facility at the VLT, we are providing a new mode for high-contrast imaging with the adaptive optics instrument NACO. This system presently outperforms any other similar device in the world and is paving the way for the development of ESO’s PLANET FINDER instrument.

The theoretical programme of the PSF department focuses on complex numerical simulations of protoplanetary disk evolution, including the interplay between radiation, dynamics, chemistry, and grain evolution. The study of the formation of Brown Dwarfs constitutes another topic for theoretical studies. Multi-dimensional radiative transfer codes, both for molecular lines and the dust continuum, have been developed in the department. The theoretical studies are also well integrated with the various observational key projects.

The understanding of many of the microphysical processes and the composition of dust and gas requires dedicated laboratory studies. Such a laboratory astrophysics unit is part of our department, and is located at the Institute for Solid-State Physics of the University of Jena. This group investigates the spectroscopic properties of nanoparticles as well as molecules in the gas phase.

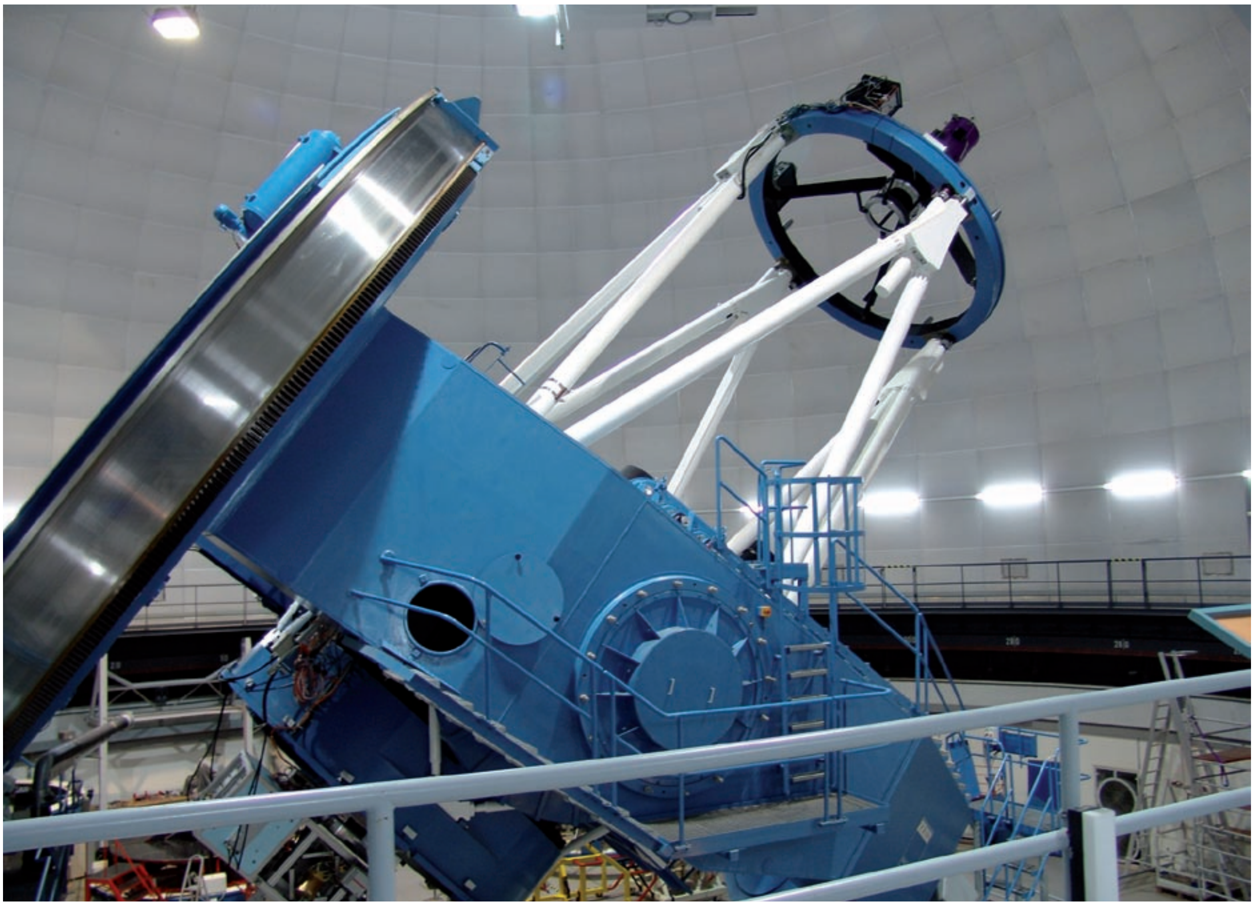
I.2 Observatories, Telescopes, and Instruments

The MPIA is a key driver and partner in the construction and operation of two large ground-based observatories: During the 1970s and 1980s the construction of the Calar Alto Observatory, the largest observatory on the European continent, had been the central focus of the MPIA, and the 2.2, and 3.5 m telescopes are still scheduled for competitive observing programs. Since 2005 the observatory is jointly operated by the Max Planck Society (represented by the MPIA) and the Consejo Superior de Investigaciones Científicas (CSIC) (represented by the IAA) as Centro Astronomico Hispano-Alemán, an organization of Spanish law. Since 1997 the MPIA has been the coordinating institute for the German participation in the Large Binocular Telescope (LBT), which is under construction on Mt. Graham near Tucson, Arizona. By the end of 2006, the first prime focus camera had been commissioned and images of outstanding quality have been obtained. The MPIA also has a 2.2 m telescope on La Silla, Chile, operated by the European Southern Observatory (Eso), with 25 % of the time available to MPG researchers.

The MPIA has a prominent and successful tradition of developing and building instruments for ground-based and space-based astronomical observations. In many instances, ground- and space-based observations are complementary. Ground-based telescopes usually have larger mirrors and therefore a larger light-gathering power than space telescopes. By using cutting-edge techniques like adaptive optics and interferometry – where the MPIA has played a leading role in the development – they can also achieve higher angular resolution. Space telescopes, on the other hand, are the only way to carry out observations in wavelength regions where the atmosphere absorbs the radiation or generates a bright background, as it is the case, e.g., in wide regions of the infrared spectral regime.

Since the pioneer days of infrared astronomy in the 1970s, the MPIA has been a leading instrument developer for this field of astronomy. In particular, Isophot,

Fig. I.2: The 3.5 m telescope on Calar Alto.



one of four scientific instruments aboard the world's first Infrared Space Observatory Iso of the European Space Agency Esa, was built under the coordinating leadership of the Institute. From 1996 to 1998, Iso acquired excellent data, particularly in the previously inaccessible far-infrared range. The know-how gained with Iso has enabled the institutes prominent role in new space projects like the Herschel Space Telescope and the James Webb Space Telescope (JWST). At present, astronomers at the MPIA are also actively participating in legacy science programs with Spitzer Infrared Observatory.

The new generation of instruments for 8 m-class telescopes and space missions are too large and expensive to be built by a single group, such as the MPIA. At present, the Institute is therefore participating in, or leading a number of international collaborations for, building new large telescopes and scientific instruments, thereby gaining access to the world's most important observatories. An example in the southern hemisphere is the Eso Very Large Telescope (VLT) in Chile with its four 8 m telescopes that can be linked to form a powerful interferometer.

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

In the northern hemisphere, MPIA is participating in the Large Binocular Telescope (LBT) in Arizona. This extraordinary telescope is now equipped with two mirrors of 8.4 m diameter each, fixed on a common mount, making it the world's largest single telescope. In the fall of 2005, the LBT had "first light" with the first of the two primary mirrors. With commissioning of the first prime-focus camera in 2006, the LBT is now poised for science observations in 2007. In 2006, MPIA joined the international PanStarrs1 (PS1) collaboration on Haleakala/Maui, which grants full data access rights to MPIA. These 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, cf. Chapter IV.10).

Ground-based Astronomy – Instrumentation

Over the last decade, MPIA has made great efforts in developing adaptive optics systems to achieve diffraction-limited imaging (in the near-IR) from the ground. The construction of the Alfa adaptive optics system at the 3.5 m telescope on Calar Alto was completed in 2001.

Currently, this work is continued with the development of a multiconjugate adaptive optics system. First light for the novel wavefront sensor Pyramir developed in the adaptive-optics laboratory at the Institute was achieved in 2006. Experience gained in this work is already being incorporated into the development of new instruments for the VLT and LBT.

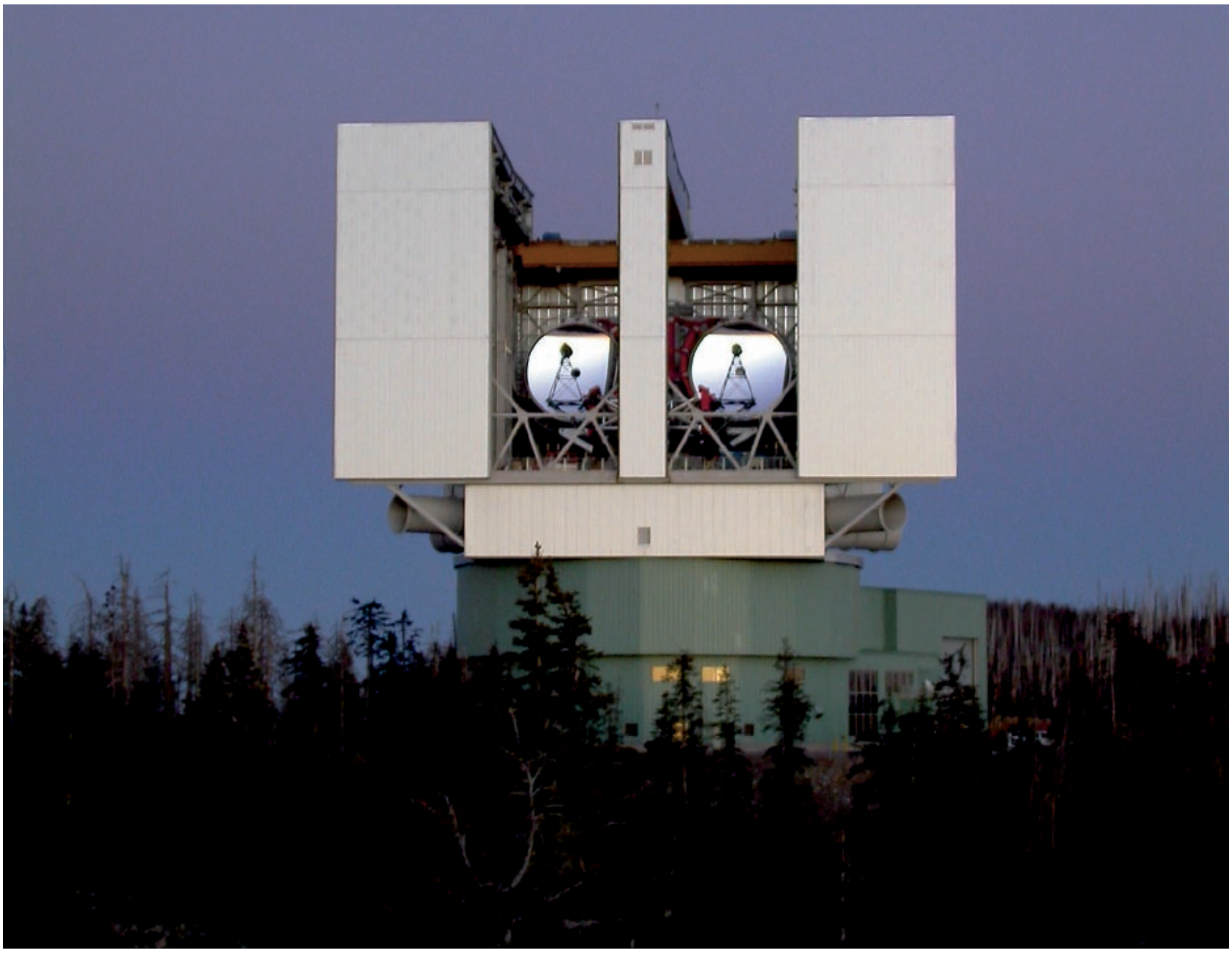
Instrument contributions of the Institute in the Eso Very Large Telescope on Cerro Paranal (Fig. I.3) are of major importance both at the MPIA and Eso. Presently, MPIA is building the Planet Finder Sphere, in collaboration with the Laboratoire d'Astrophysique de l'Observatoire de Grenoble (Laog) and other European Institutes. In 2001, the Conica high resolution infrared camera – forming the Naco system together with the Naos adaptive optics system – was successfully put into operation.

The construction of a common Laser Guide Star Facility (LGSF) for the VLT is in its crucial stage, to be used at the Naco and Sinfoni instruments at the VLT, both of which are equipped with their own adaptive optics system. 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. The first successful operation of the Parsec laser took place in January 2006 (see chapter IV.2).

The work on Alfa, Conica and Parsec has been in close collaboration with the MPE in Garching, combining the expertise of two leading groups.

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. This instrument allowed very successful interferometric observations in the mid-infrared with a resolution of only a few hundredths of an arcsecond. At present, the MPIA is a leader in the development of second-generation VLT/VLTI instruments. The institute is co-leading in Sphere (Eso's Planet Finder, see Chapter IV.4), aimed at searching and characterizing extrasolar planets with extreme adaptive optics. At the same time, the MPIA, together with institutes in Geneva and Leiden, is developing the "differential delay lines"

Fig. I.4: The Large Binocular Telescope (LBT), with its two 8.4 m mirrors located on Mt. Graham in Arizona. (Image: LBTO)



for the PRIMA system, that enable ultra-precise astrometry. Other projects – in collaboration with several other institutes – are the 2nd generation VLT instruments for the extension of the VLT Interferometer, a project called MATISSE, and GRAVITY (the former MIDI24 / APRÉS-MIDI), to combine 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 that 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 makes the LBT the world's most powerful single telescope. Furthermore, the unique design of the double mirror will allow observations with the telescope acting as a Fizeau interferometer. In this mode, the spatial resolution of the LBT will correspond to that of a single mirror 22.8 m in diameter.

Under the leadership of the Landessternwarte Heidelberg, the German partners are building the LUCIFER near-infrared spectrograph for the LBT (Chapter IV.6). The MPIA is providing the total detector package and developing the overall design of the cryogenic system. While the integration and tests of the instrument are carried out

Fig. I.5: The European HERSCHEL Infrared Observatory, to be launched in 2008.

in the laboratories of MPIA, the planning and building of the LBT interferometer, which will be equipped with an adaptive optics system, is in full swing. MPIA leads the development of LINC (the beam combining, diffraction-limited camera (Chapter IV.5), which ultimately will allow interferometric imaging 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, led by the MPIA. LINC is currently the largest ground-based instrumental development of the institute.

The MPIA is participating actively in instrumentation studies for the future European Extremely Large Telescope (E-ELT). The E-ELT has been established as a project at the European Southern Observatory and has in December 2006 entered Phase B, where the spending of some 57 Million Euro has been approved by the ESO council to further this project. MPIA is participating in pre-conceptual design studies of various instruments for the E-ELT, and has provided comprehensive input for instruments originally planned for the 100 m OWL (Overwhelmingly Large Telescope), the near-infrared Imager (ONIRICA) and the sub-mm instrument T-OWL.

Space-based Instrumentation

The MPIA continues to lead the ISOPHOT archive effort in the ISO project of the European Space Agency ESA. Meanwhile, numerous papers have been published that are based on ISO measurements and the ISOPHOT instrument built under the coordinating leadership of the Institute. The MPIA runs the ISOPHOT data center. The ISO database is planned to be part of a globally accessible "virtual observatory" for all wavelength ranges.

The experience gained with the development of the ISOPHOT instrument on ISO was decisive for the MPIA's crucial and prominent role in the construction of the PACS infrared camera and spectrometer (Chapter IV.11). This instrument will operate aboard the European HERSCHEL Infrared Observatory. HERSCHEL's 3.5 m mirror will be the largest one ever used in space, providing unprecedented observations of very cold, distant and poorly known objects. The satellite and its cryogenic instruments are currently undergoing extensive ground tests. The launch is scheduled for 2008. (Fig. I.5)

The MPIA is the lead institute in Germany for the development of instrumentation for the successor to the HUBBLE Space Telescope, the James Webb Space Telescope (JWST) (Fig. I.6). 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

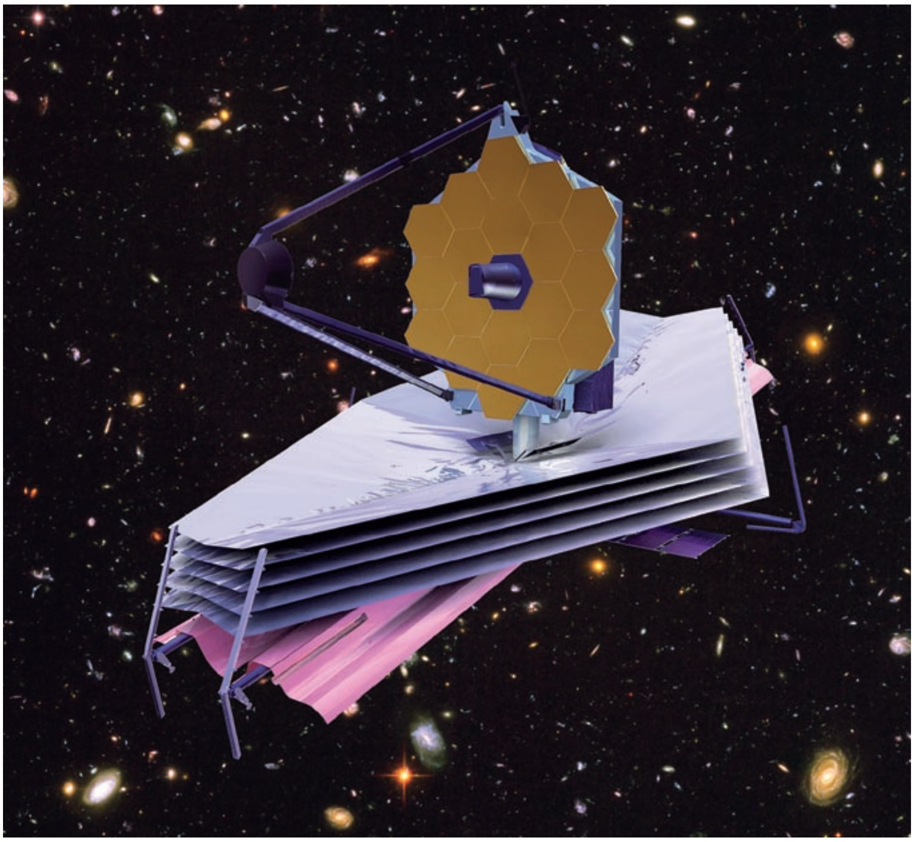


Fig. I.6: Foreseen design of JWST, the successor of the HUBBLE Space Telescope to be launched in 2013, with the large primary mirror and the characteristic sun shield.

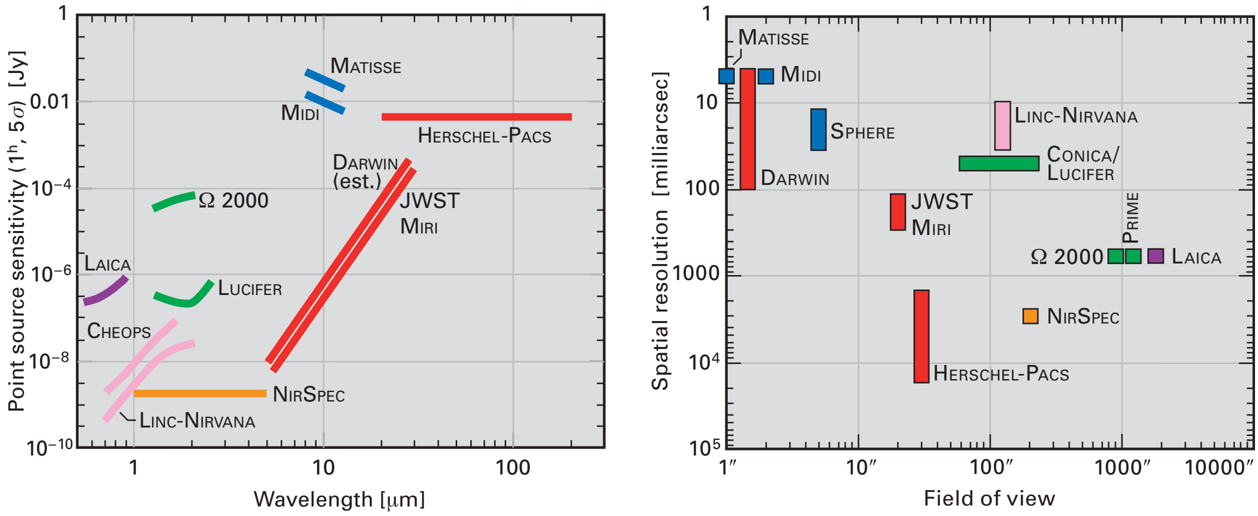


Fig. I.7: The Institute's major instruments. *Left:* sensitivity as a function of wavelength. *Right:* spatial resolution as a function of the field of view.

focal-plane instruments called Miri (Chapter IV.12). 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.

The MPIA will also provide crucial parts of the second focal-plane instrument of the JWST, a near-infrared multi-object spectrograph called NirSpec (Chapter IV.12), by delivering the cryo-mechanics. This contribution will provide the astronomers at MPIA with further excellent opportunities for high-resolution and highly sensitive infrared observations. For the development of the precision-optical hearts of Miri and NirSpec, the MPIA is also closely cooperating with Carl Zeiss Optronics, Oberkochen.

The MPIA has been representing Germany since 1998 within the Darwin Science Advisory Team. Darwin is a space interferometer to be launched by the European Space Agency Esa not before 2015. In the plan it will comprise up to eight telescopes orbiting the Sun at the Lagrangian point L2, at 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 carrying out preparatory technology studies.

The MPIA also contributes 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. With this the satellite will measure positions, magnitudes, and radial velocities of one billion stars, in addition to 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 needs not be provided with an input catalogue, but will measure systematically all accessible objects. An automatic object classification will thus be of major importance for data analysis. At present, concepts for coping with this demanding task are being developed at the MPIA (supported by a grant from DLR).

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 (*left*), and spatial resolution as a function of the size of the field of view (*right*).

I.3 National and International Cooperations

Its location in Heidelberg embeds the MPIA into an exceptionally active astronomical environment. Cooperation with the department Kosmophysik of the MPI für Kernphysik and with the institutes of the Center for Astronomy Heidelberg (ZAH), established on January 1st 2005, is manifold: the ZAH consists of the Landessternwarte, the Astronomische Rechen-Institut, and the Institut für Theoretische Astrophysik der Universität. At present, this is particularly true for the long-standing DFG-Sonderforschungsbereich No. 439, "Galaxies in the Young Universe", in which all Heidelberg institutes named above are participating. There is also a close cooperation within the "International Max Planck Research School" (IMPRS) for Astronomy and Cosmic Physics (see I.4). In addition, MPIA supports the University of Heidelberg in its activities for the Excellence Initiative.

Nationally, cooperation with the MPI für extraterrestrische Physik in Garching and the MPI für Radioastronomie in Bonn as well as with numerous German institutes is extensive. An overview is given in Fig. I.8.

The establishment of the German Center for Interferometry (Frontiers of Interferometry in Germany, or FrInGe), 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 and to accomodate the interests of the German astronomical community in the European Interferometric Initiative. Another specific goal is the preparation of the next generation of interferometric instruments. This includes the preparation of second generation VLTI-instruments such as Matisse – an imaging interferometer consisting of four telescopes – and Gravity. 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, is 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 Astrophysikalische Institut Potsdam, the Astrophysikalische Institut der Universität Jena, the Kiepenheuer-Insitut für Sonnenphysik in Freiburg, the MPI für extraterrestrische Physik in Garching, the MPI für Radioastronomie in Bonn, the Universität Hamburg, and the I. Physikalische Institut der Universität zu Köln.

MPIA is participating in a number of EU-networks and worldwide collaborations, in part as project leads. These include:

Fig. I.8: Location of German collaborative partner institutes of MPIA

Opticon: A network of all operators of major telescopes in Europe, financed by the European Union. Its one main goal is to optimize use of the scientific-technical infrastructure in order to increase scientific results and reduce costs. Opticons other main goal is to coordinate technology development for the next generation of ground-based telescopes.

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 Caha Program Committee get free access as well as scientific and technical support in the realization of their observations. For this service, Caha is compensated financially from Opticon. MPIA participates in the training schools of Neon (Network of European Observatories in the North), which provide training in ground-based observations at 2 m-class telescopes as well as archive research. Neon is supported by Opticon as well as by a Marie Curie grant, and holds 1 – 2 schools per year for some 20 students per School from the European Community.

The Matisse study at MPIA mentioned above is supported by Opticon and the European Interferometry

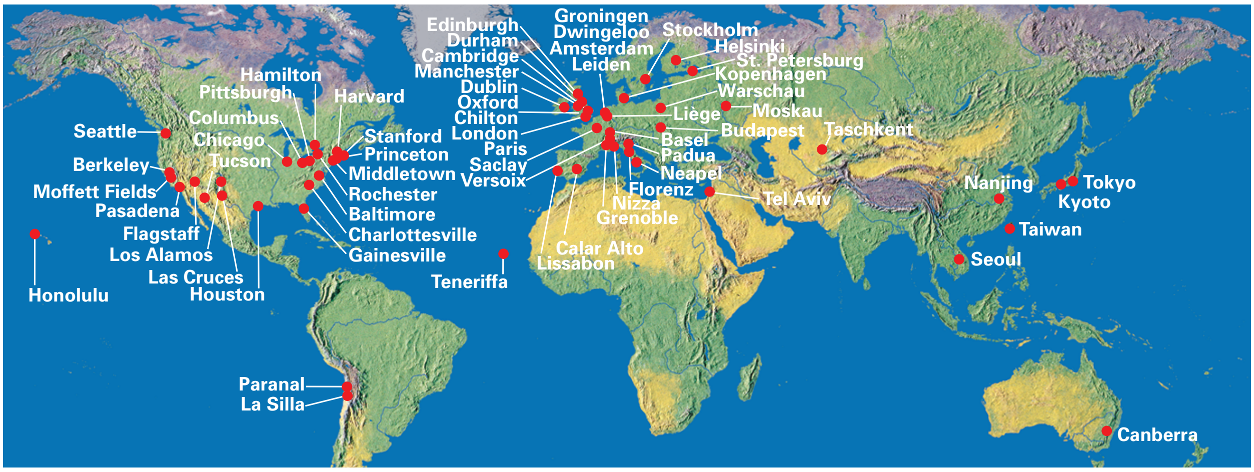


Fig. I.9: Distribution of the international partner institutes of MPIA.

Initiative (EII), as is the software work on image reconstruction for Linc-Nirvana (Chapter IV.5).

Opticon is also supporting a so-called Joint Research Activity (JRA) of MPIA with the Osservatorio Astrofisico di Arceti and the University of Durham and other partners. 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 involving the adaptive-optics image field correction for the extremely large next-generation telescopes.

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

Sisco (Spectroscopic and Imaging Surveys for Cosmology): This EU network is dedicated to the study of galaxy evolution with the help of sky surveys. The Institute has made pivotal contributions to this network through Cadis, Combo-17, and Gems surveys. Additional 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.

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 Programs: 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. The MPIA is participating in approved programs, the first of which is to study the star-formation in the most nearby galaxies (Sings) and the earliest stages of star formation in the Milky Way. Within the Feps (Formation and Evolution of Planetary Systems) legacy program, together with Steward Observatory and other institutes, MPIA is responsible for the data reduction of the spectroscopic data and actively partecipates in the Feps science. Within Sings, the MPIA is leading the effort on radio data and dwarf galaxies.

Gif (German-Israeli Foundation): Within this collaboration, a program to study gravitational lenses is carried out. The partner of the MPIA is the University of Tel Aviv. Through a separate grant, a wide field camera for the Wise Observatory is being built to search for planet transits.

Intas: An FP6-funded collaboration with Armenia, Russia, and the UK, which allows visitor exchange between these countries and with Armenia in particular.

The Sloan Digital Sky Survey (SDSS) has revolutionized wide-field surveying at optical wavelengths. It is the most extensive imaging and spectroscopy 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, Japanese, and German institutes. MPIA was the first, of now 12, European partner institutes in SDSS, and the only one to participate since the inception of surveying. 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. In 2005, the "original" SDSS was completed, but an extension, focusing for example on Milky Way structure was approved.

Arena (Antarctic Research European Network for Astrophysics): This network comprises 21 partners from research and technology from seven European countries and Australia. The goal of this cooperation is the long-term development of the Antarctic (particularly of the site Dome C) for observations in the optical and infrared regime.

Furthermore, the MPIA started an official collaboration in the field of star and planet formation with the Purple Mountain Observatory in China.

I.4 Teaching and Public Outreach

Students are coming from all over the world to the Institute to carry out the research for their diploma or doctoral thesis. A majority of these students are formally enrolled at the University of Heidelberg for their studies. In turn, a number of scientists at the MPIA have adjunct faculty status at the University.

Students of earlier semesters can get a first taste of scientific work at the MPIA. The Institute offers advanced practical courses or enables the students to participate in "mini research projects". These last about two months and cover a wide range of questions, including the analysis of observational data or numerical simulations as well as work on instrumentation. These practical courses offer the students an early, practically orientated insight into astrophysical research, particularly in view of a later diploma or doctoral thesis.

The International Max Planck Research School (IMPRS) for Astronomy and Cosmic Physics, which was established in July, 2004 by the Max Planck Society and the University of Heidelberg, made a successful start (Chapter V.3) on 2005. The school offers 40 PhD students from all over the world a three year education under excellent conditions in experimental and theoretical research in the field of astronomy and cosmic physics. It is sponsored by the five astronomical research institutes in Heidelberg.

The Institute's mission also includes the educating and informing of the general public about results of astronomical research. 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 that 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 that is very popular among teachers of physics and mathematics in Baden-Württemberg is held regularly in autumn at MPIA.

A special highlight in the year under report has been the "Lange Nacht der Museen", when in the whole region a large number of institutions opened their doors to the public until after midnight. Due to the isolated location of the Königstuhl and to the many alternatives offered downtown, we participated to this initiative without expecting much attention. Instead, the rush of people on the Institute was overwhelming, as described in Chapter V.6. In addition, our new initiative for the general public, a series of eight "Public Lectures on Sunday Morning", was immediately sold out.

As in the years before, the one week long practical course which was offered to interested schoolboys and -girls (BOGY), was immediately booked out. Applicants came from all-over the country.

Again in 2006, the MPIA participated in the *Girls' Day*, a nationwide campaign intended to encourage schoolgirls to learn about professions that are still mainly male-dominated. At various stations about 60 schoolgirls got a general idea of the work at an astronomical institute (Chapter V.6).

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

Great interest was shown in the *School project*, which was initiated in 2005 in cooperation with the Academy of Advanced Training of Teachers of the Land Baden-Württemberg, Donaueschingen, and with the support of the Klaus Tschira Foundation. For selected articles published in SuW, detailed didactic materials are developed each month and made freely available in the internet. About four times a year training courses for teachers based on these materials are held at the Academy. 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.

II. Highlights

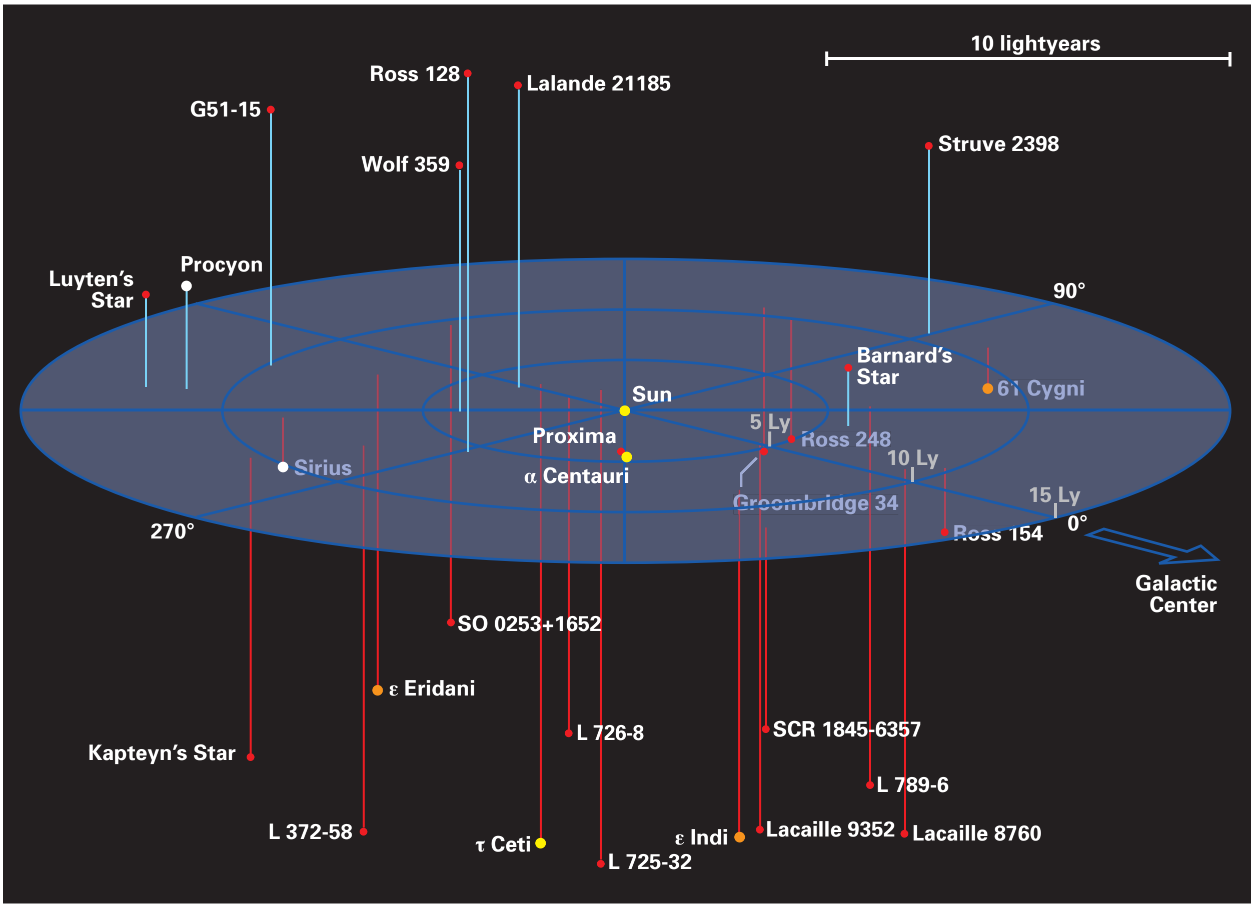
II.1 Second Nearest Brown Dwarf Discovered

Astronomers of MPIA have discovered the second nearest Brown Dwarf known so far. It orbits around a low-mass star of spectral class M8.5 at a distance of 12.7 light years from the sun. Its observation was made possible by the NACO SDI camera, which was constructed at the MPIA and is mounted on one of the four telescope units of the Very Large Telescope. The Brown Dwarf named SCR 1845-6357B has special significance because its orbit should be precisely measurable within the next few years. This will provide the opportunity to very precisely determine the mass of the object and to verify the models presently available for Brown Dwarfs.

Since the first Brown Dwarf was discovered in 1995, several hundred of these celestial bodies have been found, but none of them in the near surroundings of the sun, i.e. within a radius of about 15 light years. However, Brown Dwarfs that are very near the sun are of particularly great importance to astronomers because they can be analyzed in great detail. For this reason, new instruments have been used in the past few years to systematically search for Brown Dwarfs accompanying low-mass stars. The chances of discovering these objects are especially good because there is a relatively low contrast in brightness between the star and the Brown Dwarf.

At the MPIA, a camera was specifically built to perform the task of recording cool objects of low luminosity in the near surroundings of a star. This instrument, called NACO SDI (NACO Simultaneous Differential Imager), works according to the following principle: the camera contains adaptive optics that eliminate the blur caused by turbulence in the atmosphere of the Earth. The SDI additional optics disperse the light of a single star into four identical images at neighboring wavelengths within and outside the infrared methane bands characteristic

Fig. II.1.1: The stars in the sun's vicinity. The recently discovered object SCR 1845-6357B is 12.7 light years away.



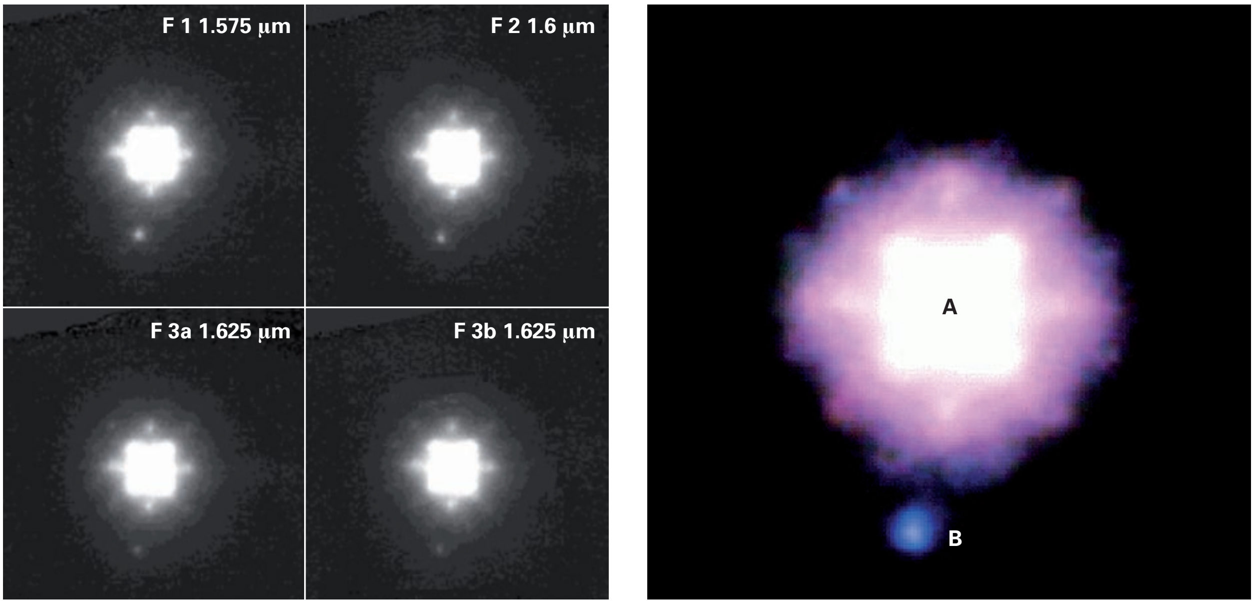


Fig. II.1.2: Images of SCR 1845-6357 taken at three different wavelengths. The Brown Dwarf at a distance of 1.17 arcseconds is clearly visible to the left below the main star. The three images at wavelengths of 1.575, 1.6 and 1.625 micrometers were superimposed, resulting in the false color image shown at right.

of low-mass objects. The main star and its bright halo almost entirely disappear on differential images of these four shots, and the low-mass, cool companion becomes clearly visible.

As early as in the test phase of NACO SDI, an important discovery was made when the object ε Indi B, 12 light years away, was separated into two T dwarfs. The two components ε Indi Ba and Bb are the nearest known Brown Dwarfs. More success followed. For instance, AB Dor C was the faintest companion to be discovered at an angular distance of only 0.16 arcseconds from its main star, and for G1 86B, the only known White Dwarf in an exoplanetary system, the orbiting motion could be proven. Not least, the camera also obtained very detailed images of the surface of Titan, Saturn's largest moon.

The low-mass star SCR 1845-6357 of spectral type M8.5 was discovered only recently and placed 24th in the list of the stars nearest to the sun (Fig. II.1.1). Astronomers from the institute observed it in May 2005 using NACO SDI when they discovered a companion at an angular distance of 1.17 arcseconds which is 35 times less luminous than the main star at a wavelength of 1.575 µm. With the precisely measured distance of 12.7 light years, the distance between the two objects works out to be 4.5 Astronomical Units.

The companion is characterized by strong methane absorption at wavelengths greater than 1.6 µm, which was determined by taking four images at neighboring wavelength ranges (Fig. II.1.2). In particular, the strength of the methane bands was measured using narrow-band images taken at a wavelength of 1.575 and 1.625 micrometers, and compared to model spectra of L and T dwarfs. This resulted in the spectral type T5.5 ± 1 (Fig. II.1.3). Spectra recorded later confirmed this spectral type.

According to recent models, Brown Dwarfs of this type have a temperature of approx. 850 K. Their absolute brightness in the H band around 1.65 µm was determined as 15.23 mag. The likelihood of the object being a T dwarf simply located near SCR 1845-6357 rather than a fixed companion is rather remote. Moreover, recent observations have shown that SCR 1845-6357 A and B have the same proper motion, indicating that they indeed are a physical pair bound to each other by gravitation.

Including ε Indi Ba and Bb, SCR 1845-6357B, G1 229B and G1 570D, five T dwarfs are now known to be within a 20 light years radius of the sun, all of which are located in double systems. Within the same volume, only two T dwarfs without a companion were found in the 2MASS all sky survey. Although these numbers are small and rather insignificant statistically, they at least indicate that there are more T dwarfs in double systems than single stars.

This could provide clues concerning the origin of Brown Dwarfs. In particular, if confirmed by future research, it will be difficult to explain using the so-called ejection theory. This theory is based on the assumption that Brown Dwarfs originate as part of a multiple system. However, in this case they could not grow to full stellar size because they would be ejected out of the system during their earliest evolution, while they are still accreting matter from their surroundings.

While the dwarf's distance from SCR 1845-6357 could be determined with an accuracy of 0.5 per cent, its age remains uncertain. Any value between 100 million

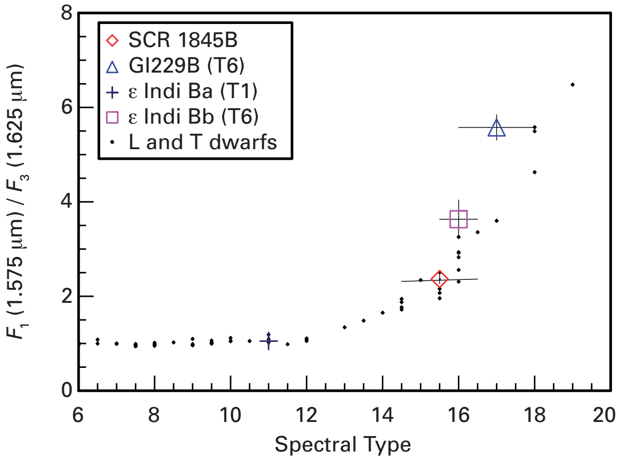


Fig. II.1.3: Methane spectral indices for SCR 1845-6357B and for the T dwarfs G1 229B and ε Ba and Bb.

and 10 billion years is possible. Therefore, the mass of the Brown Dwarfs can only be estimated very imprecisely. For dwarfs of spectral type T5.5 within this age group, models indicate values between 9 and 65 times Jupiter's mass. Thus, the object clearly is a Brown Dwarf.

In the next few years, astronomers from the institute will try to determine the orbit of SCR 1845-6357A and B around each other using NACO SDI. From this information, the total mass of both bodies can be determined. An additional measurement of the relative radial speed of SCR 1845-6357A and B will then reveal the mass ratio, and thus the value of the individual masses. The Brown Dwarf would then be an ideal source of mass-luminosity calibration for T dwarfs.

Wolfgang Brandner.
Other institutes involved:
European Southern Observatory (ESO);
Steward Observatory, Tucson;
Keck Observatory, Hawaii

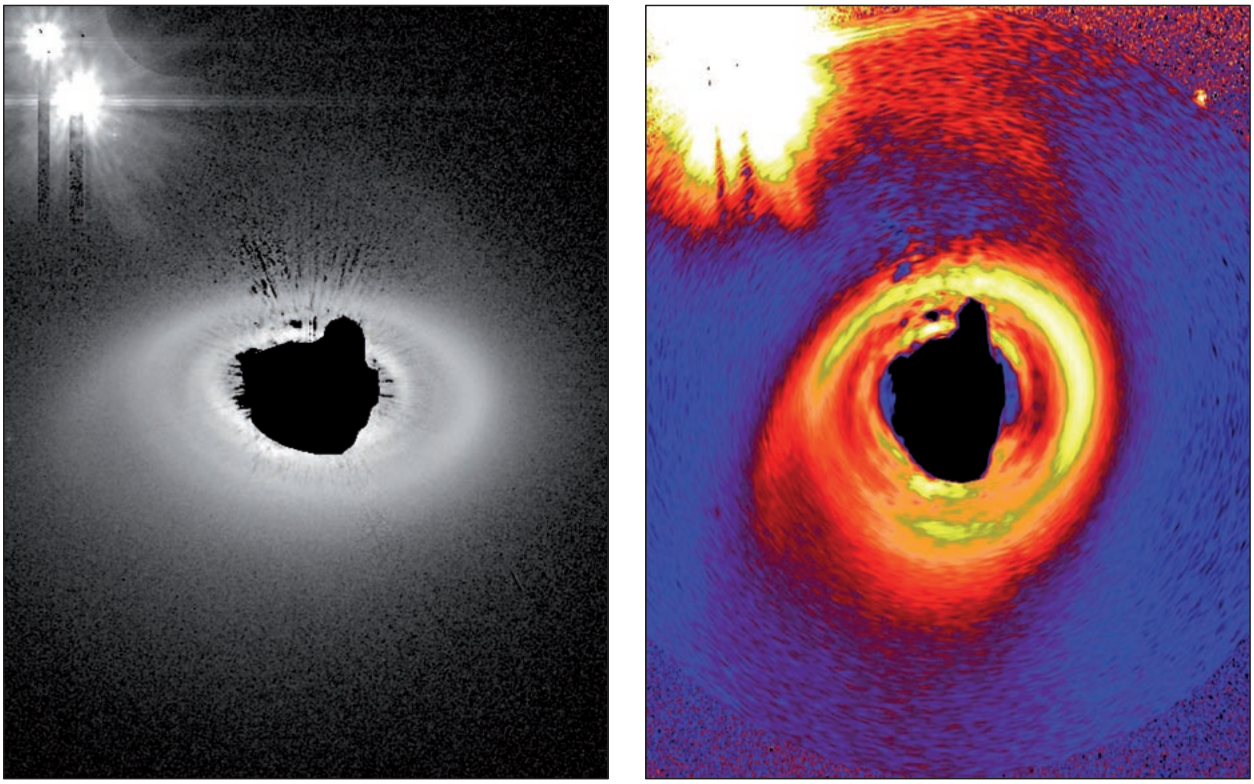
II.2 The Inner Edge of a Circumstellar Disk

Circumstellar disks around young stars are potential birthplaces of planets and therefore have been an active focus of recent astrophysical research. As part of a collaboration with colleagues from the National Astronomical Observatory of Japan, astronomers from the MPIA have investigated the internal structure of such a circumstellar disk around the young Herbig-Ae star HD 141569A located at a distance of approximately 350 light years away from the Earth. Using the 8-meter telescope SUBARU on Mauna Kea (Hawaii), an infrared spectrum of the CO($J = 2 - 1$) line could be recorded. The result: no CO gas was detected within a radius of 11 astronomical units around the star. The five-million year old star has probably already consumed the gas from the inner part of the disk. This left almost no time for any possible gas planets to form.

The Herbig-Ae star HD 141569A is part of a triple system, with two lower-mass companions (spectral types M2 V and M4 V) are located at a distance of 7.55 and 8.9 arcseconds (corresponding to 815 and 960 astronomical units (AU)), respectively. The age of this system has been determined fairly precisely as being 5 ± 3 million years, and the mass of HD 141569A is estimated to be approximately two solar masses. According to model predictions, the star is currently developing from a Herbig-Ae into a main sequence star. It is surrounded by a dust disk.

HD 141569A was discovered in 1986 on images taken by the IRAS infrared satellite. At that time, the existence of circumstellar dust around this star had been inferred from its observed infrared excess. Images taken by the HUBBLE Space Telescope later showed a dust disk of unusual structure (Fig. II.2.1): the inner range of the disk is largely dust-free at a distance of up to 175 AU from the star. Outside this gap, a dense, spiral-shaped dust arm stretches out to a distance of 215 AU. Between 215 AU and 300 AU, there is a relatively thin distribution of dust whereas a second spiral arm extends between 300 and 400 AU. This unusual spiral structure may be due to interaction with the other two components of the triple system.

Fig. II.2.1: The dust disk of HD 141569A, picture taken by the Advanced Camera for Surveys (ACS) on board of the HUBBLE Space Telescope. To the right, the image of the disk, which is inclined towards the line of sight, was tilted by 39 degrees in the computer, to give the viewer a vertical view of the disk. The false color image increases the contrast of the scattered light (photo: NASA/ESA).



High-resolution Observations of the CO Gas

While these observations concentrated on the dust, little was known about the gas content. CO gas, a common tracer for the total molecular gas content of a system, had been detected in the outer parts of the disk, leading to an estimated gas content of approximately 300 Earth masses (most of which presumably in the form of molecular hydrogen). However, it had not been possible to spatially resolve the inner range up to a distance of approx. 30 AU from the star. The gas content in this area is of key importance for the formation of gas planets.

One possibility for observing this inner part of the disk around HD 141569A is the near infrared, where vibrations of the CO molecule lead to line emission at wavelengths

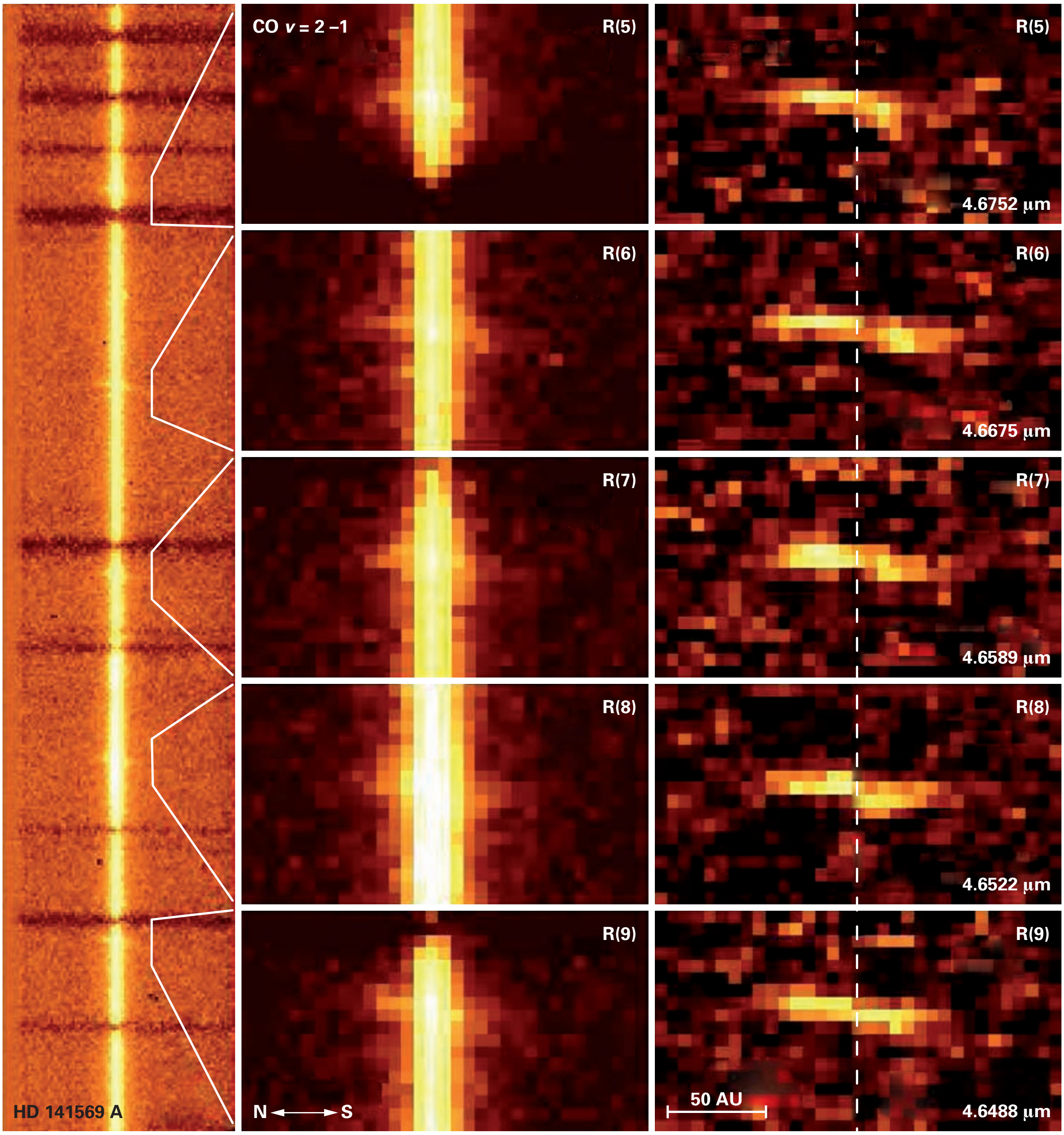


Fig. II.2.2: Spectrum of HD 141569A at a wavelength of 4.6 µm. The slit ran from south to north along the main axis of the dust disk (north is to the left). *Left:* section from the spectrum. *Middle:* magnified view of the sections containing the individual CO lines. *Right:* as in the middle, however, after subtraction of the stellar continuum, whose position is marked by the dashed line. The Doppler shift of the lines caused by the rotation of the gas disk is obvious, with the northern part moving away from us.

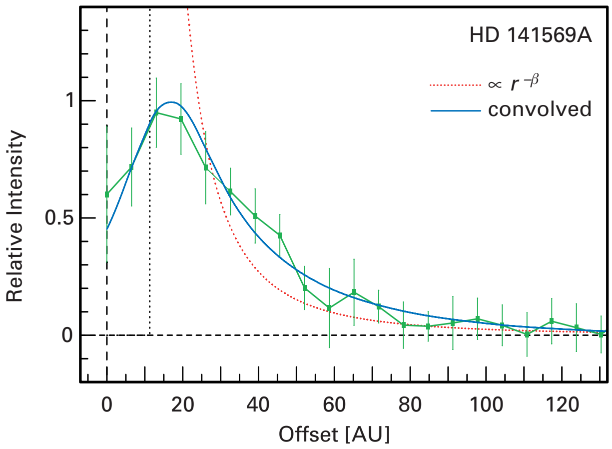
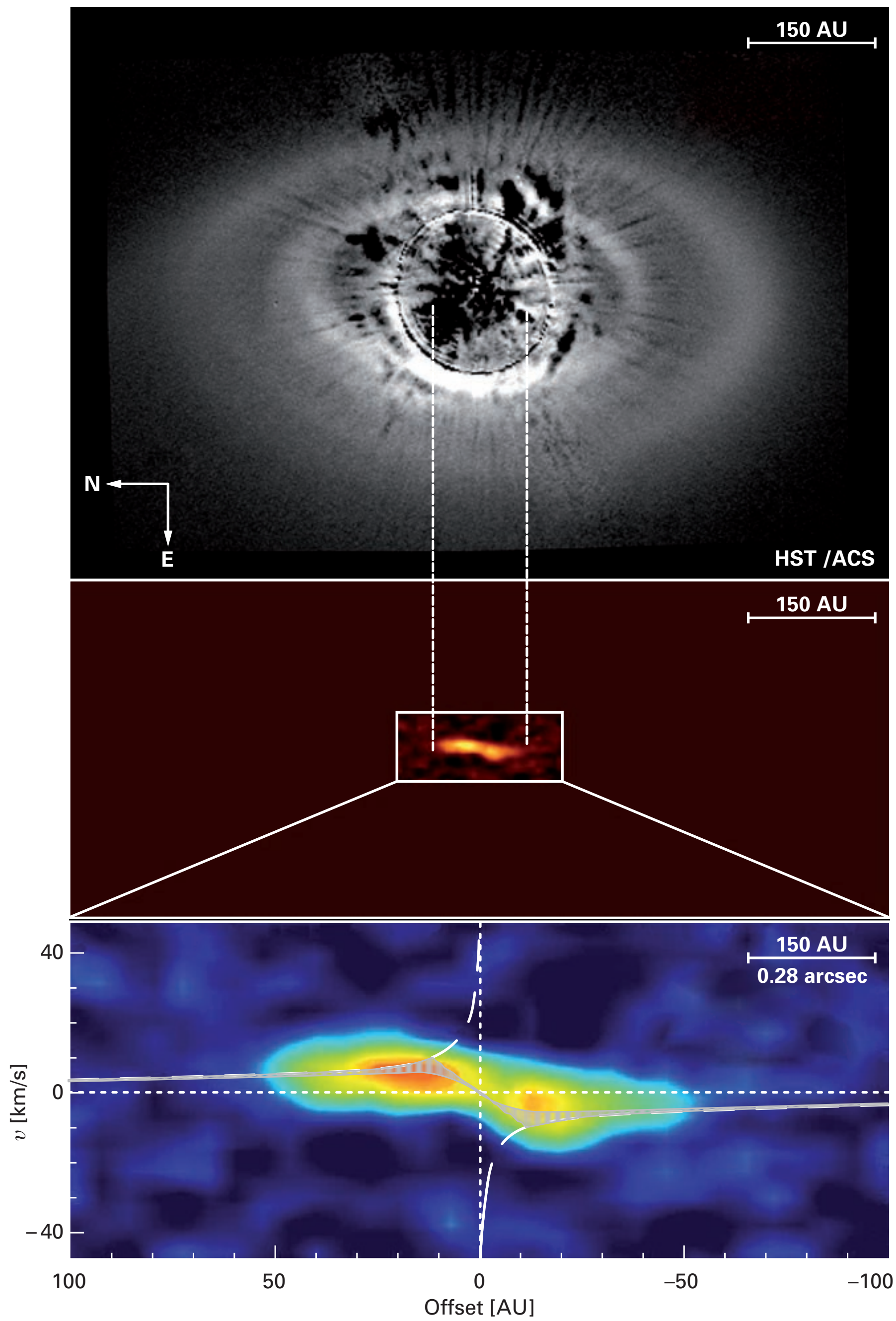


Fig. II.2.3: Radial intensity profile of the CO lines. The dotted line shows a "power law" function, of the form $y = x^{\beta}$, with the value $\beta = -2.6$. Hardly any CO gas is present within 11 AU.

Fig. II.2.4: *Top:* The image of HD 141569A taken by the HUBBLE space telescope. The image covers the inner 100 AU of the disk. *Middle:* The velocity of the gas (ordinate) is shown as a function of the distance from the central star (abscissa). *Bottom:* Magnified view of the middle image. The two curves indicate the path of the Kepler rotation with a central mass of two solar masses.



above approximately 4.6 μm. The observations were made in May 2005 with the 8-meter telescope Subaru on Mauna Kea (Hawaii). A long-slit infrared spectrograph with adaptive optics and a spatial resolution of 0.24 arcseconds (FWHM) was used for this purpose.

The CO lines were detectable up to a distance of 50 AU from the star (Fig. II.2.2). When the stellar continuum was subtracted, the Doppler shift of the CO lines caused by the rotation of the gas disk was clearly visible. The northern part of the disk is moving away from us, the clockwise motion coinciding with the curvature of the dust spiral arms.

The measured data show how the gas moves around the star following Kepler's Law in the outer ranges of the disk. Closer to the star, however, a further increase in velocity is no longer detectable (Fig. II.2.4, bottom). Therefore, the measured data proves that there is hardly any CO gas near the star. When radially adding up the CO emission, the profile shown in Fig.II.2.3 is obtained. The CO emission steadily increases with decreasing distance from the star, reaching its maximum at 15 AU and further decreasing rapidly towards the inside. The resulting cutoff radius is 11 ± 2 AU: no CO gas could be detected closer to the star. In our solar system, the inner edge of the hole would approximately correspond to the orbit of Saturn. Fig.II.2.4 summarizes the results.

Origin of the Hole in the Center of the Disk

How can the hole in the center of the gas disk be explained? If the magnetic field of the central star was responsible for the hole, it would have a radius of approx. 0.01 AU and thus would hardly be larger than the actual star. If the hole was caused by the fact that stellar radiation causes the dust to be sublimated (transferred from solid state directly to a gaseous state), we would expect a hole with a radius of approximately 0.1 AU. Other processes must be responsible for the disappearance of the gas at greater distances.

It is striking that the outer edge of the hole approximately coincides with the so-called gravitational radius. There, the sonic speed of the ionized medium is identical to the system's escape velocity. The gravitational radius thus defines the innermost part of a disk where stellar radiation could expel ionized gas from the system. As this approximately coincides with the observed outer edge of the hole, it appears likely that the dissolution of the inner circumstellar disk is controlled by two different processes: photoevaporation, i.e. evaporation by high-energy radiation in the extreme UV range, and accretion of disk material onto the star.

In the early stage of development of the circumstellar disk, photoevaporation and accretion do not cause the inner disk to dissolve. The viscosity of the dense disk is still high, therefore, matter from the outer regions continuously replenishes the gas disappearing from the inner region. The thinner the disk, the lower the viscosity becomes, the gas can no longer reach the inner part of the disk, and the supply dwindles. Now photoevaporation prevails, and a hole is created within the gravitational radius.

This process defines temporal limits for the formation of gas planets. Current models predict that the formation of a Jupiter-like planet would take 1 to 10 million years. This is barely compatible with the average life of circumstellar disks. However, the observations of HD 141569A, which is believed to be 5 million years old, show that the gas disappears after a relatively short period of time in the area in which the gas planets are presumably formed. Therefore, Jupiter-like planets must battle against the rapid disappearance of their raw material resources during their formation phase. This process would inevitably lead to a diversification of planetary systems: if the disk dissolves relatively slowly, a gas giant may form, and otherwise it cannot.

With HD 141569A it is conceivable that a gas planet has already formed which has collected the gas in the inner part of the disk. However, there are no indications of the existence of such a planet. Future instruments will enable the search for such a possible companion. Suitable instruments will have extreme adaptive optics, such as the Sphere planet finder instrument at the Very Large Telescope (VLT) in which the MPIA holds a stake. The James Webb Space Telescope will also offer good chances of finding a dark companion.

Miwa Goto, Cornelis Dullemond,
Thomas Henning, Hendrik Linz.
Other institute involved:
Subaru Telescope, Hilo;
Thüringer Landessternwarte Tautenburg;
National Astronomical Observatory of Japan, Tokyo

II.3 The Interplay Between Planets and Circumstellar Disks

The growth of a planet, which starts with a grain of dust, spans more than 13 orders of magnitude in size. It is impossible at present, and will be in the near future, to simulate this kind of development "in one piece" at the computer. Therefore, theoreticians concentrate on different phases. One interesting aspect of their work is the gravitational interaction between the emerging planet and the circumstellar disk it is still embedded in. In a recent study performed in cooperation with a colleague from the University of Tübingen, MPIA researchers investigated for the first time this problem three-dimensionally by including the thermodynamics of the gas involved, and obtained some surprising results. For example, a Jupiter-like planet is not surrounded by a thin accretion disk, as had previously been assumed, but rather by a hot gas bubble. The way in which this phenomenon influences planet growth has to be determined by further studies. However, its influence on the migration behavior of the planet is obviously fairly insignificant. The effects on the observability of the planet at the moment of its birth are considerably more important.

The development of a massive gas planet in the circumstellar disk is governed by a complex interplay of different processes, For example, the planet changes the structure of the disk, and conversely, the gas and dust making up the disk influence the planet. Computer simulations done in the past few years have shown that a massive planet can produce interference such as spiral arms and ring-shaped gaps in the disk caused by its gravitation. This is due to the fact that the particles within the planetary orbit move faster around the star than the planet itself. Therefore, it slows down the particles through its gravitational force. In other words, the particles lose their angular momentum and move further inward. By contrast, the particles outside the planetary orbit are slower than the planet, gaining additional angular momentum from it. This makes them faster, so that they move further outside. By this process a ring-shaped gap is opened in the disk to the left and right of the planetary orbit.

Furthermore, the angular momentum of the particles in the disk and the planet may mutually influence each other. The matter inside the orbit provides the planet with angular momentum. For this reason, the planet should move outward. However, the disk matter located outside its orbit reduces its angular momentum, which should cause it to move inward. These two effects are not equally strong. In all cases investigated, the planet loses some of its angular momentum and moves inward. This migration is an explanation of the existence of extrasolar massive planets revolving around their central star in a very near orbit. These bodies are also referred to as "Hot Jupiters".

Computer simulations done in the past few years have shown that a planet that is formed at a distance of five astronomical units from the sun, corresponding to the current orbit of Jupiter, will have swept the gap in the disk free after several thousand years. At the same time, it will move inward. After only few tens of thousands of years, its distance from the star will be half of its previous value, whereas its mass will have doubled because it absorbs matter from its surroundings during migration. The migration will only stop when the disk has completely dissolved. It is currently under investigation whether or not other effects, such as magnetic fields or tidal forces, influence deceleration.

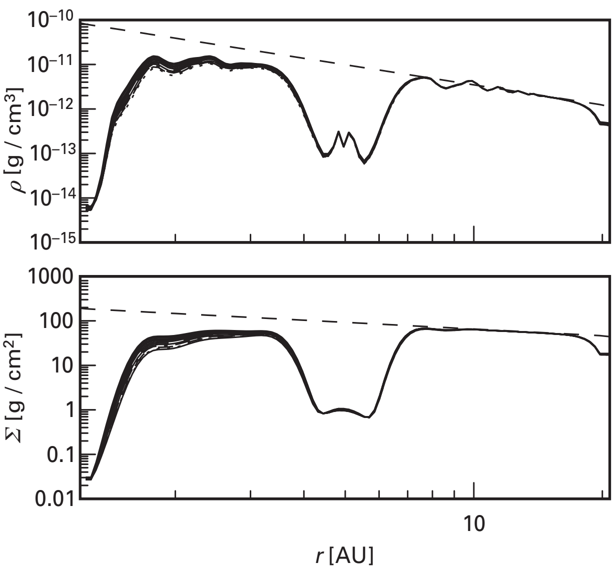
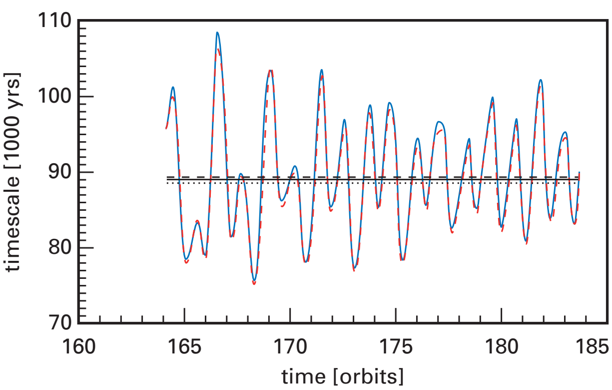
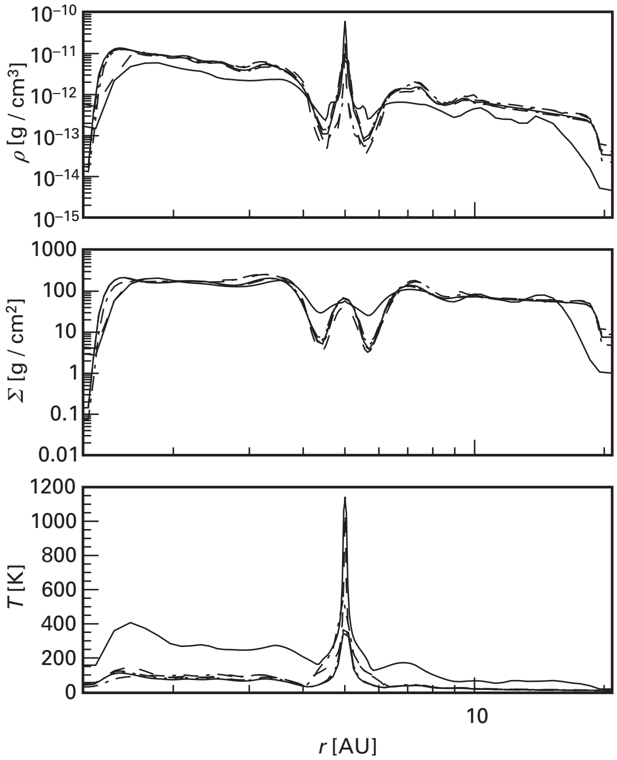


Fig. II.3.1: *Left:* model 1, radial density distribution ρ in the central plane of the disk (above) and surface density Σ after 184 revolutions (below). *Right:* development of the rate of migration. The straight line at approx. 90 000 years indicates the time-averaged duration of migration.



The complexity of this interplay requires that all computer simulations adopt simplified models. For example, calculations including magnetic fields and turbulence (magnetohydrodynamics) could be extended from two to three dimensions only a few years ago. However, all previous numerical calculations have treated the disk as being locally isothermal. Initial attempts to compute the dissipation of energy by the viscosity of the disk matter had to be limited to two dimensions.



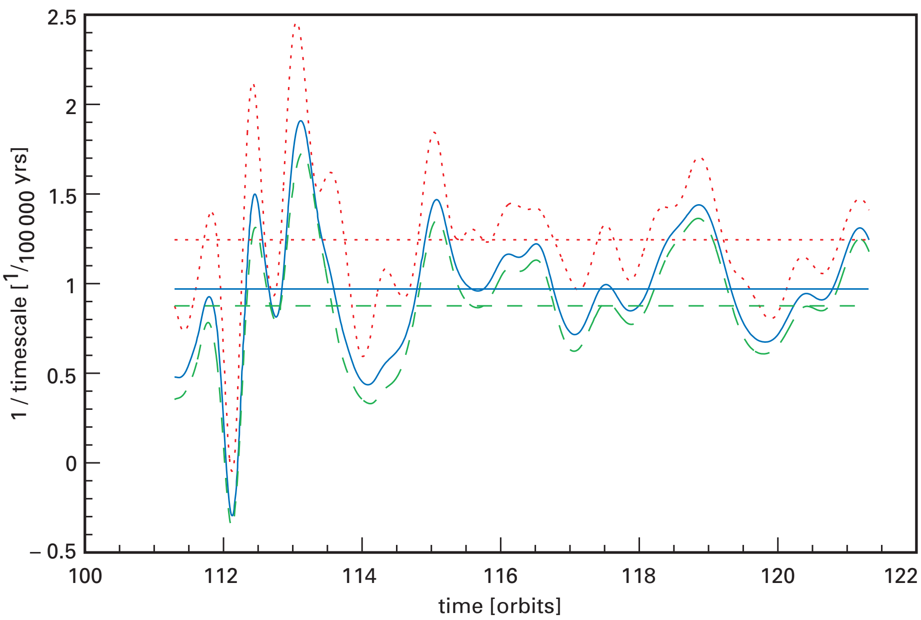
Formation of Gaps, Migration and Accretion

In the recent study conducted by the MPIA in cooperation with the University of Tübingen, the calculations were extended to three dimensions by accounting for thermodynamics. The aim was to investigate the influences of physical parameters, such as radiation transport and matter accretion, on the young planet. This method has to account for the fact that the temperature distribution within the actual disk depends on the mass contained in it because the mass affects the variation of the optical depth.

In their simulations, the two theoreticians assumed a standard scenario and then changed the individual parameters. In all cases, they investigated an initially circumstellar disk extending between a distance of 1.25 and 20 AU from the star. Within this disk, the temperature initially decreases in inverse proportion to the distance, whereas it is assumed to remain constant in the vertical direction. The initial density decreases as $r^{-1.5}$ starting from the star, with the density at the equatorial plane at 5 AU being 10^{-11} g/cm^3. At this distance, a planet with a Jupiter mass is located at the beginning of the simulation. In the course of the simulation, a temperature profile is quickly obtained that is characterized by an equilibrium between cooling by radiation and heating through accretion and hydrodynamic processes.

In the simulation runs, the volume within which the planet accretes matter was also subjected to variation. A measure of this process is the Roche volume. It indicates the area within which the matter is gravitationally bound to the planet. Any mass outside this area is forced onto an orbit around the central star.

Fig. II.3.2: *(left)* Model 4: Radial density distribution at the central plane of the disk after one hundred revolutions, surface density and temperature; *(below)* development of the rate of migration.



Four different models were calculated in order to compare the influence of thermodynamics on the results of the simulation:

1. Isothermal conditions with matter accretion, whereby the accreted matter is removed from the simulation together with the internal energy with each revolution.
2. As in model 1, but taking the planet's radiation into account.
3. As in model 2, plus accounting for the thermal energy of the accreted matter that collects in the Roche volume. When the simulation is started, there is already a gap in the disk around the planet.
4. As in model 2, plus accounting for the thermal energy of the accreted matter, but the model starts without a gap.

Only the essential results of model 1 and model 4 will be discussed below, including a comparison of the differences between the two.

The first model is the least realistic, however, it can still provide insight into the basic processes with fairly short computing times. Fig. II.3.1 demonstrates how a stable gap has opened around the planetary orbit after 184 revolutions. The planet's rate of accretion remains almost constant at 1.5×10^{-4} Jupiter masses per revolution. The gravitational influence of the disk on the planet's migration varies by a factor of two, however, the averaged migration time scale of 90 000 years coincides fairly well with the results of other simulations and analytical estimates.

Fig. II.3.2 shows the comparison with model 4. Here, an equilibrium with a gap is reached after approx. hundred revolutions. However, the rate of accretion of 6×10^{-4} Jupiter masses per revolution is four times as high as in the first model. It is known from other simulations that after about one thousand revolutions enough dust has been removed from the gap to prevent accretion. The simulation for this complex model could not be continued for such a long period, therefore, it was not possible to determine the total mass accreted. Fig. II.3.2 demonstrates that the increased rate of accretion compared to model 1 has considerable effects on the planet's migration within a short time frame. In extreme cases, the planet may even temporarily distance itself from the star. Nevertheless, the time scale averaged for more than one hundred revolutions once again reaches almost 100 000 years. Fig. II.3.3 shows the density distribution after 121 revolutions. The ring-shaped gap as well as spiral-shaped structures are visible.

A significant result of of this investigation is that accounting for radiation transport has little effect on the mean time scale characterizing the planet's migration. This important quantity thus seems to have been largely clarified from the theoretical point of view.

However, an important change can be seen in Fig. II.3.2. The density and temperature rise considerably around the planet (at 5 AU). This can be easily explained by physical phenomena. Although the gas is removed from the model as soon as it enters the Roche volume in this calculation, its energy is retained locally. The potential and kinetic energy released by accretion is added locally (in each lattice cell) to the internal energy. This results in convection above the planet's poles in the optically dense disk. This flow is very slow and cannot emerge from the disk like a fountain. Instead, it leads to the formation of a hot bubble in the surroundings of the planet (Fig. II.3.4) where maximum temperatures of 1500 K are reached (Fig. II.3.2). Thus, the planet is by far the hottest area within the disk. If this is really the case, the planet should be observable with high-resolution telescopes.

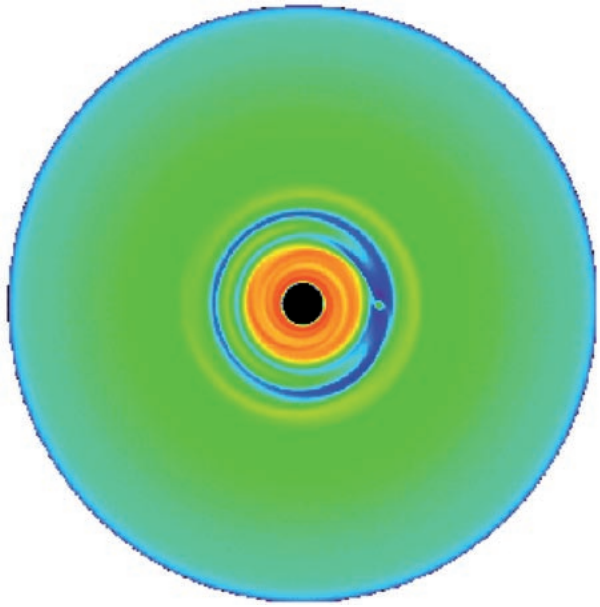


Fig. II.3.3: Model 4, density distribution in the central plane of the disk after 121 revolutions. The gap *(dark)* as well as spiral-shaped structures can be seen.

The issue of observability has already been addressed by MPIA astronomers in detail at an earlier stage of the simulations. They arrived at the conclusion that the large international millimeter array Alma and the planned VLTI instrument Matisse will offer good opportunities to observe hot protoplanets in the mean infrared (annual reports 2004, Section III.2 and 2005, Section III.2). Fig. II.3.5 shows how such a planet could possibly be observed using Alma in the sub-millimeter range due to the radiation it emits. At shorter wavelengths (Fig. II.3.6), the light of the central object is dominant, which is primarily scattered towards the observer along the spiral structures around the planet. In principle, the latter phenomenon could be observed with Matisse.

At the same time, the pressure of the hot gas bubble prevents the emergence of a Kepler disk around the planet. An almost spherical shell is formed instead that fills its entire Roche volume. Accretion now takes place even

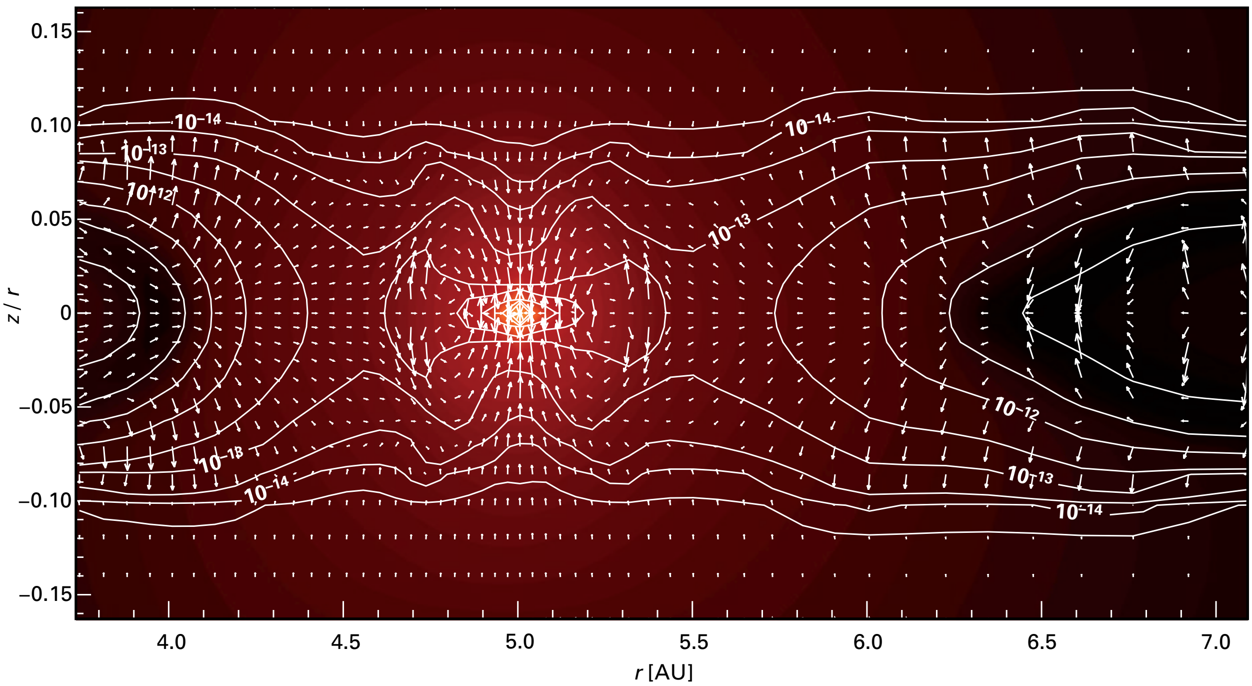
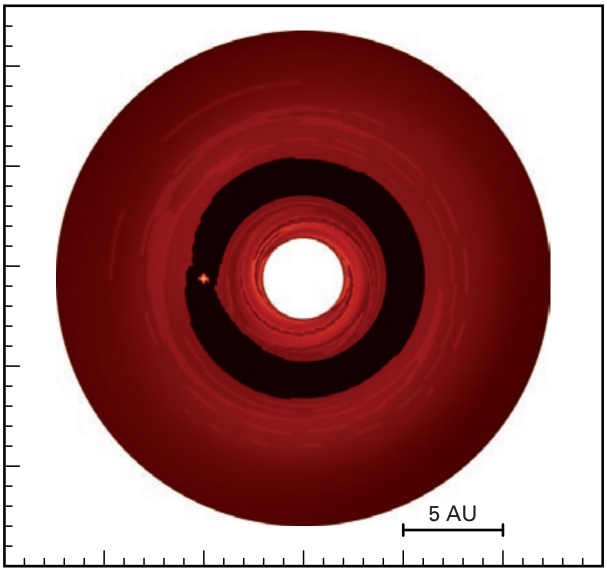


Fig. II.3.4: Temperature and velocity distribution in the disk after 141 revolutions. The temperature varies between 30 and 1500 K. The flow onto the planet occurs via the poles, but not along the central plane.

via the poles and not at the equatorial plane. This would probably also mean that no moons can be formed in the surroundings of the planet, at least during this stage.

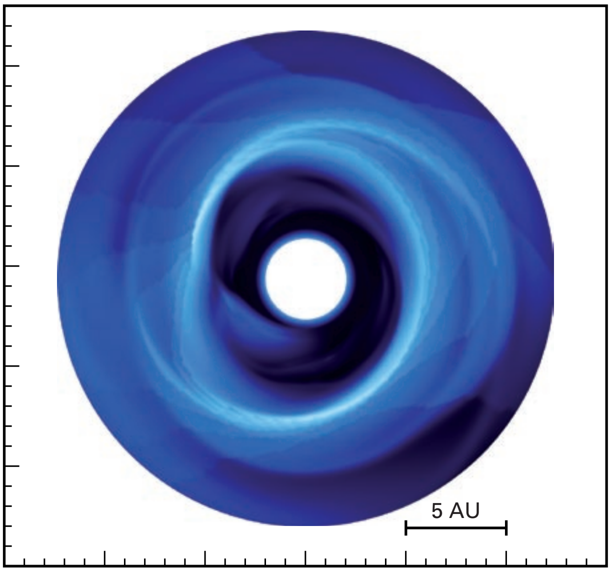
Fig. II.3.5: Thermal emission of dust and gas in the disk. The image shows the radiation emitted by the photosphere of the disk and by the gas shell around the planet. The luminosity of the planetary accretion, temperature rise caused by turbulence of the disk and irradiance by the central object were included for the purposes of this model. The planet is clearly visible in its gap, as are the signs of spiral density waves in the disk.



Future simulations will investigate whether this previously unknown phenomenon also occurs if the planet grows slowly instead of being placed into the simulation as a full-grown planet of the size of Jupiter.

Hubert Klahr, Sebastian Wolf.
Other institute involved:
Institute for Astronomy and Astrophysics of the University of Tübingen

Fig. II.3.6: The planet is hidden in its gap when observed in the scattered light of the central object. But in this case, the spiral wave pattern stimulated by the planet can be seen more clearly. This structure mainly scatters the light of the central object because it stands out from the disk.



II.4 Massive Star Formation

The formation of stars has been a focus of interest at the MPIA for many decades. Research mainly concentrated on low-mass, sun-like stars, rather than on the early evolutionary phases of massive stars. For one, massive stars are much rarer and they form much faster than low-mass stars – which is why it is quite unlikely to be able to observe their early stages. In addition, all regions with massive young stars are at a greater distance from our solar system, resulting in stringent requirements for the resolution and sensitivity of the instruments used for observation. However, today the new interferometers in the sub-millimeter and millimeter range enable the investigation of more distant star formation regions at high spatial resolution and sufficient sensitivity. An international team lead by MPIA managed to gain interesting insights into several massive star-forming regions, including the famous Orion KL region.

Massive stars are of great importance for the dynamics, physics and chemistry of the interstellar medium, although they are quite rare. During their formation stage, which lasts approximately 100 000 years, they generate intense particle winds and jets, and then they emit high-energy ionizing UV radiation in the course of the 4 to 40 million years of their life. And in the final stage, they enrich the interstellar medium with heavy elements through strong winds and supernova explosions.

Up to now, many questions concerning the formation of massive stars have remained unanswered. According to the simplest assumption, their formation process is but a higher-scale version of the processes occurring in low-mass stars. However, this assumption seems to be questionable for the following reason: stars with more than about eight solar masses radiate very large amounts of energy during their formation so that the radiation pressure on the surrounding material consisting of dust and gas inevitably decelerates its collapse. If the accretion rates for stars of all masses were identical, this radiation pressure would totally prevent massive star formation.

During the past few years, various suggestions were made for dealing with this hindrance. The formation pattern of low-mass stars could basically be retained if the accretion rates strongly increased with the mass of the star being formed. In this case, the radiation pressure would not be able to decelerate star growth. An alternative approach results from the observation that massive stars are always formed as part of compact clusters of hundreds or even thousands of low-mass stars.

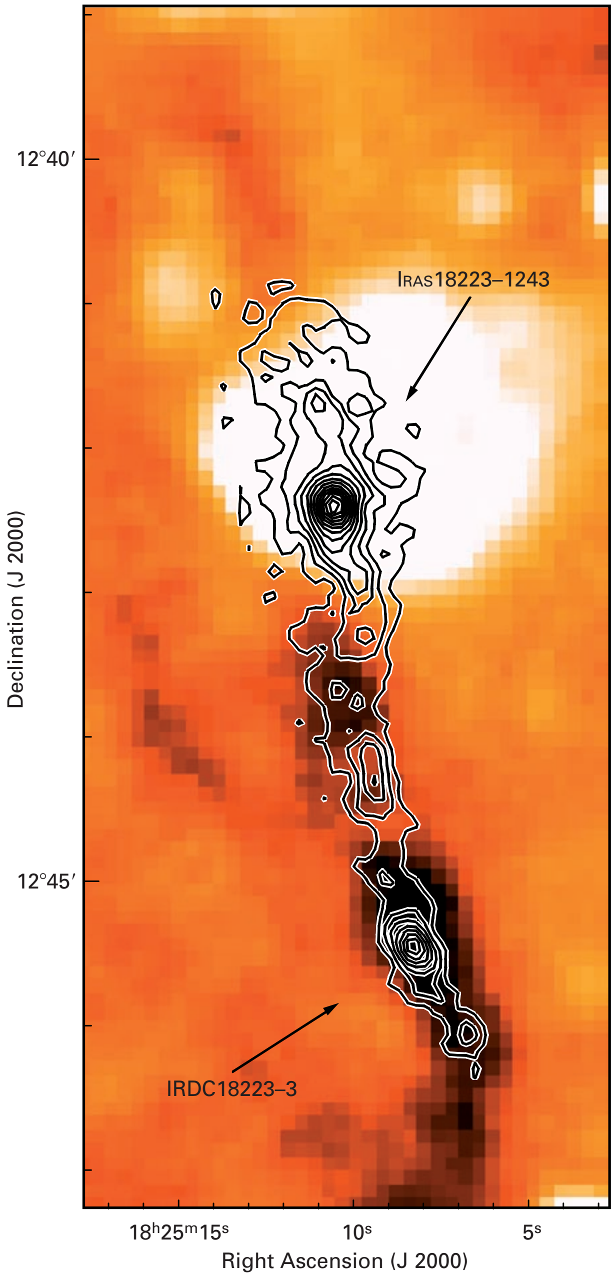


Fig. II.4.1: Image of the IRDC 18223-3 Dark Cloud taken by the SPITZER Space Telescope at a wavelength of 8 μm. The contours reflect the intensity at 1.2 mm as obtained by observations using a single telescope.

It is possible that the stars initially are so close together in such star clusters that mean- and low-mass stars collide and fuse into more massive stars. However, no stable disks could survive around the growing stars in

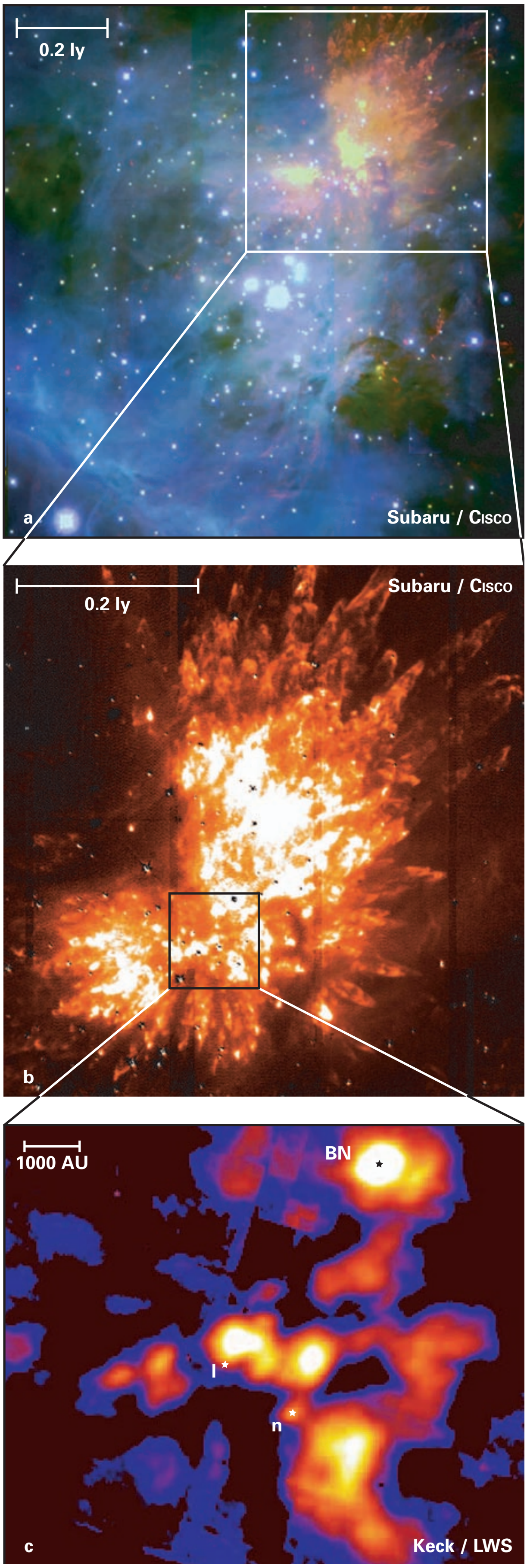


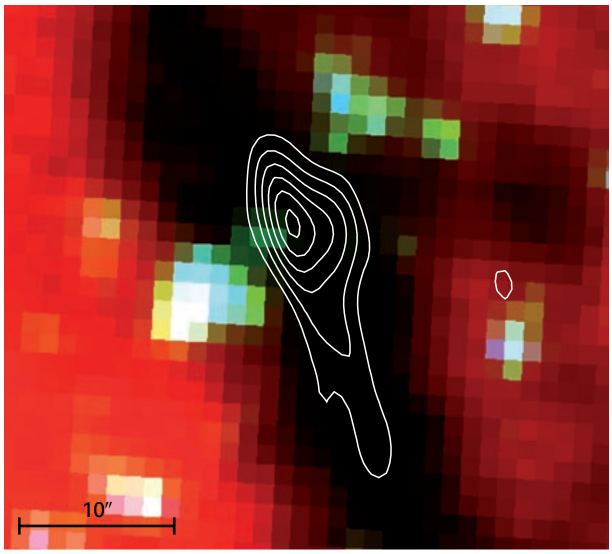
Fig. II.4.2: *a*) The BN/KL region of star formation within Orion Nebula is located near the Trapezium seen in the middle. *b*) The figure shows a small area in the infrared light of the H_2 emission. *c*) This sectional view shows the map of Orion KL in the sub-millimeter continuum obtained in the framework of the present study, which was taken by the SMA.

such a scenario. For this reason, one of the primary goals of this field of research is to search for accretion disks around young massive stars.

Early observations at a low spatial resolution yielded the first indications of bipolar molecular outflows from massive star formation regions. This was considered evidence of the existence of accretion disks. Although much has been learned about massive outflows during the past few years, many details remain unsolved. So far, there is no statistical basis of sufficiently high spatial resolution data to enable a better classification of the initial results.

For this reason, interferometers will be used from now on for observations of star formation regions. In the millimeter range, the instrument on the Plateau de Bure is available for this purpose, and the sub-millimeter array (SMA) on Hawaii also started operating recently. Using these high-resolution instruments, the emission lines of many chemical compositions can simultaneously be observed. These instruments provide details on important physical quantities such as density and temperature of the gas that enable conclusions concerning the kinematics and dynamics of the medium to be made. And finally, it is also interesting to study the complex chemical network in star-forming regions and search for development processes.

Fig. II.4.3: Superimposition of three Spitzer images taken at wavelengths of 3.6 (*blue*), 4.5 (*green*) and 8 μm (*red*). The contours show the emission at a wavelength of 3 mm.



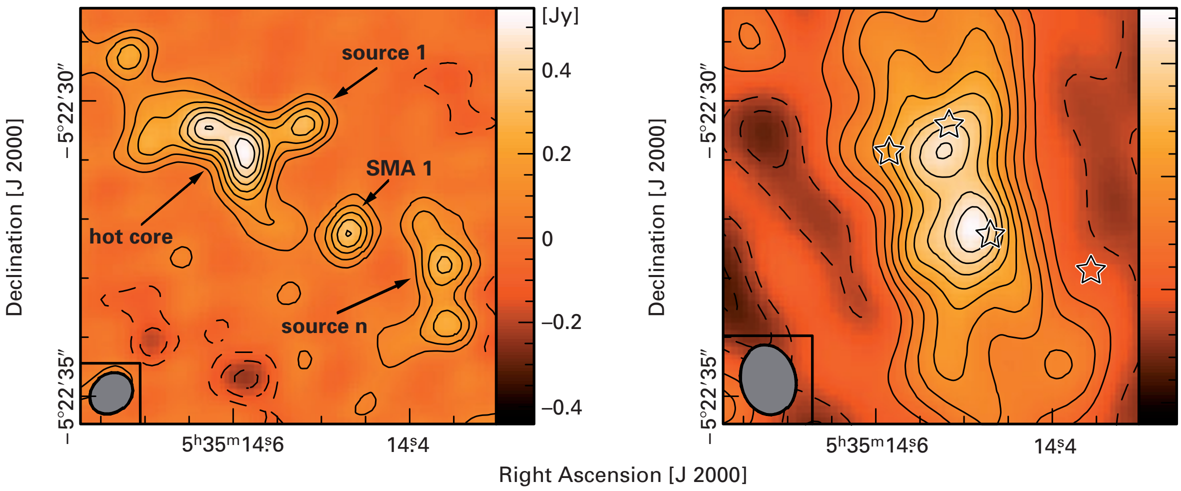


Fig. II.4.4: To the right, the new map of continuum emission at 440 µm compared to previous observations with the SMA at 850 µm. A fundamental difference lies in stronger emission around source 1 compared to the hot core at the higher wavelength. In the recent observations, the emission lines around 440 µm could be spatially separated between the continuum emission at source 1 and the hot core.

Extremely Young, Protostellar Objects in IRDC 18223-3…

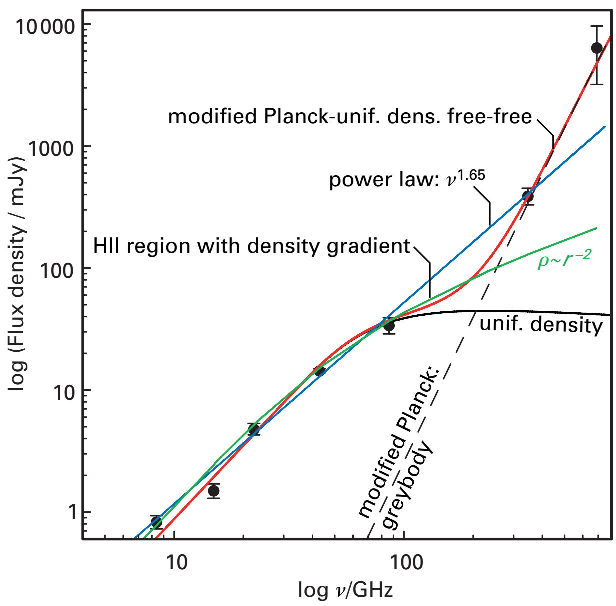
The formation of massive stars takes place in four different stages. First, a starless core is formed by gravitational contraction inside a cloud of dust, which then becomes a protostar of low to mean mass collecting matter from its surroundings (accretion). By this process, the massive protostar is formed in the third stage (with more than eight solar masses) which eventually presents itself as a main sequence star (fourth stage) that starts dissolving the parent cloud. The massive protostars that are still deeply embedded into their molecular cloud (mainly in stage three) form hot molecular cores around themselves which are presumably associated with compact HII regions. More recent observations have also suggested a distinction between hyper-compact (radius less than 0.01 pc) and ultra-compact HII regions (radius less than 0.1 pc).

These different stages are difficult to identify and to characterize because they take place in the highly obscured interior of dense dust clouds. In search of objects that are in the first stage of star formation, astronomers became aware of a region at a distance of approx. 3700 pc (12 000 light years) named IRDC 18223-3 (IRDC stands for Infrared Dark Cloud, refer to Fig. II.4.1). It is located south of an infrared source discovered by the IRAS satellite within a lengthy dust cloud and had attracted attention there for emissions at a wavelength of 1.2 mm. Observations of NH_3 indicated a temperature of 33 K, as can be expected of a very young star-forming region.

The astronomers observed IRDC 18223-3 using the Plateau-de-Bure interferometer at a wavelength of 3 mm, and the data was complemented by observations with the SPITZER Space Telescope between 3.6 and 8 µm. As demonstrated by Fig. II.4.3, no protostellar core was detected in the mean infrared, whereas an elongated agglomeration extending 28 000 AU from east to west became apparent in the millimeter range whose visual extinction amounts to a factor of up to 1000. The mass contained in this agglomeration amounts to approx. 184 solar masses. Most likely, IRDC 18223-3 is a massive gas condensation in a very early stage of development.

In Fig. II.4.3, bright green areas can be seen to the west and east of the millimeter source on the SPITZER image at a wavelength of 4.5 µm. They most likely show

Fig. II.4.5: Spectral energy distribution of source 1 which can be best described as free-free radiation plus dust emission.



emission lines of H_2 and CO, stimulated by a bipolar outflow. There may even be several outflows in this region, as suggested by other emission areas in this image.

Spectroscopy analyses of the emission line of N_2H^+ performed by the Plateau-de-Bure interferometer IRAM furthermore suggested that the velocity dispersion increases in the central area of the millimeter source. Whether this is due to turbulence, rotation, inflows or outflows could not yet be determined and requires further observation. However, the kinematics also leads to the conclusion that star formation is underway. A comparison of the mass determined at 3 mm to the virial mass also supports the notion of a contracting gas cloud.

In summary, several observations support the notion that the IRDC 18223-3 millimeter source is an extremely young protostellar object. This object probably still has a very low mass; however, it is located deep within a molecular cloud core from which it collects high mass quantities in order to develop into a massive star.

... and in Orion KL

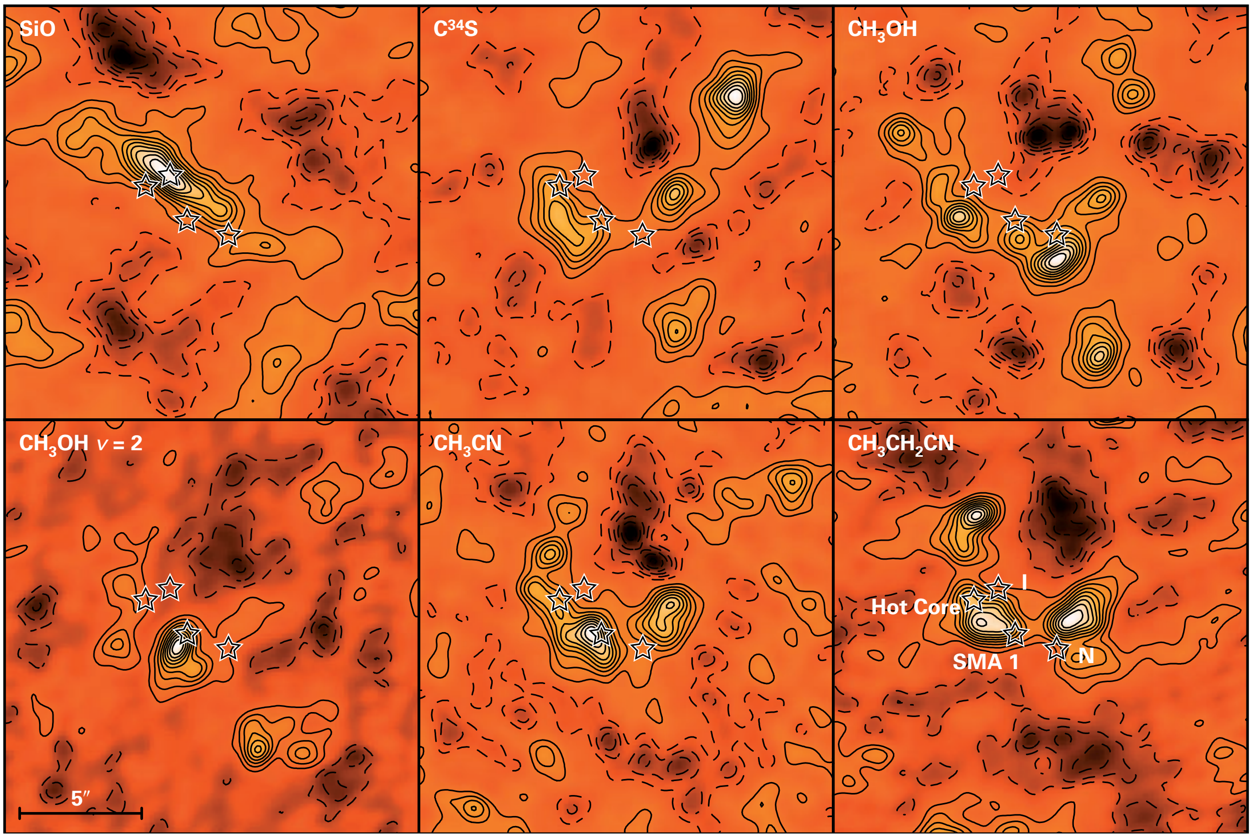
Orion KL in the Orion nebula stands at the very top of the list of known regions of massive star formation. Located at a distance of 450 pc (1500 light years), it is also the nearest region of massive star formation (Fig. II.4.2).

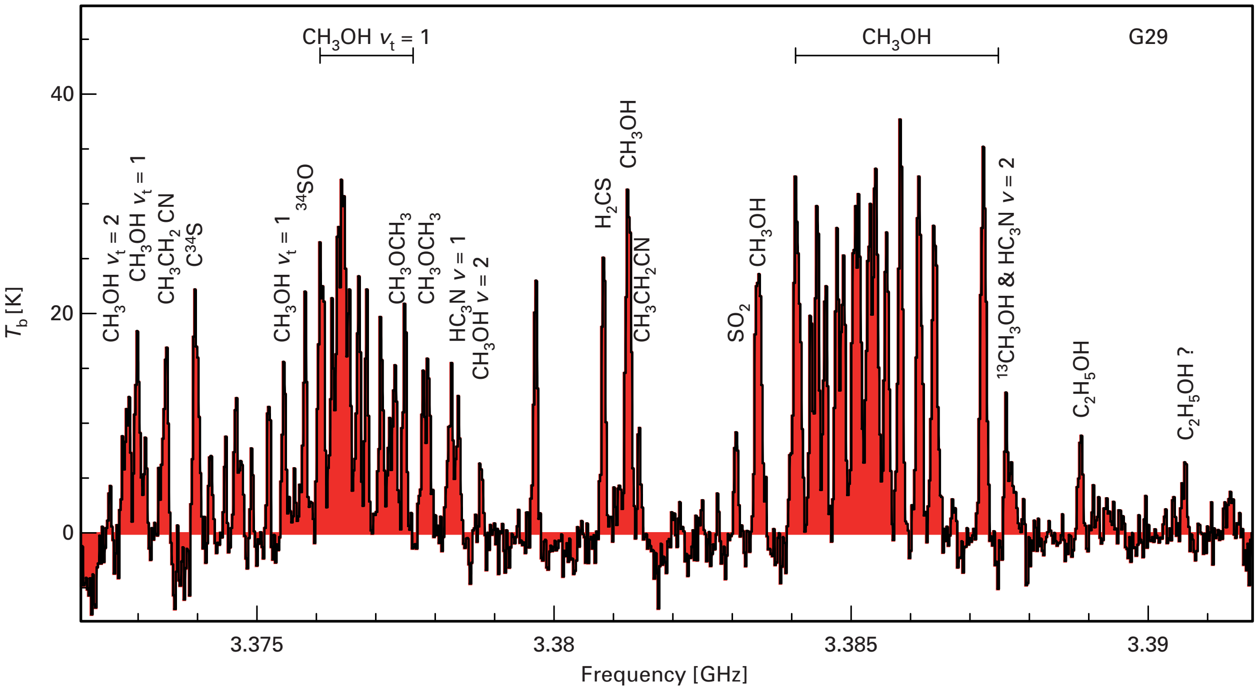
The Orion KL region has a "hot core" with temperatures of several hundred degrees Kelvin which is rich in sometimes very complex organic molecules. It can be detected in the millimeter and sub-millimeter range and consists of a number of agglomerations at a distance of approx. one arcsecond from radio source I. In addition, this region features a cluster of several infrared sources from which at least two outflows have been detected so far. The sources of these flows have not yet been clearly identified; possible candidates include object I mentioned above as well as an infrared source named n which was also detected at radio wavelengths where it is referred to as L.

This interesting region was studied for the first time with high resolution at a wavelength of 440 µm using the sub-millimeter array (SMA) in Hawaii (Fig. II.4.4). For this measurement, six telescopes with base lines between 16 and 68 m were connected by interferometry at this wavelength for the first time ever.

The spectral energy distribution of the source should now provide insights into its evolutionary stage. The flows at 345 and 690 GHz measured with the SMA were of particular importance here, as demonstrated by Fig. II.4.5. They enabled researchers to distinguish between several models for source I. The data can best be explained by the assumption that the radiation measured is

Fig. II.4.6: Emissions of some molecules in Orion KL.



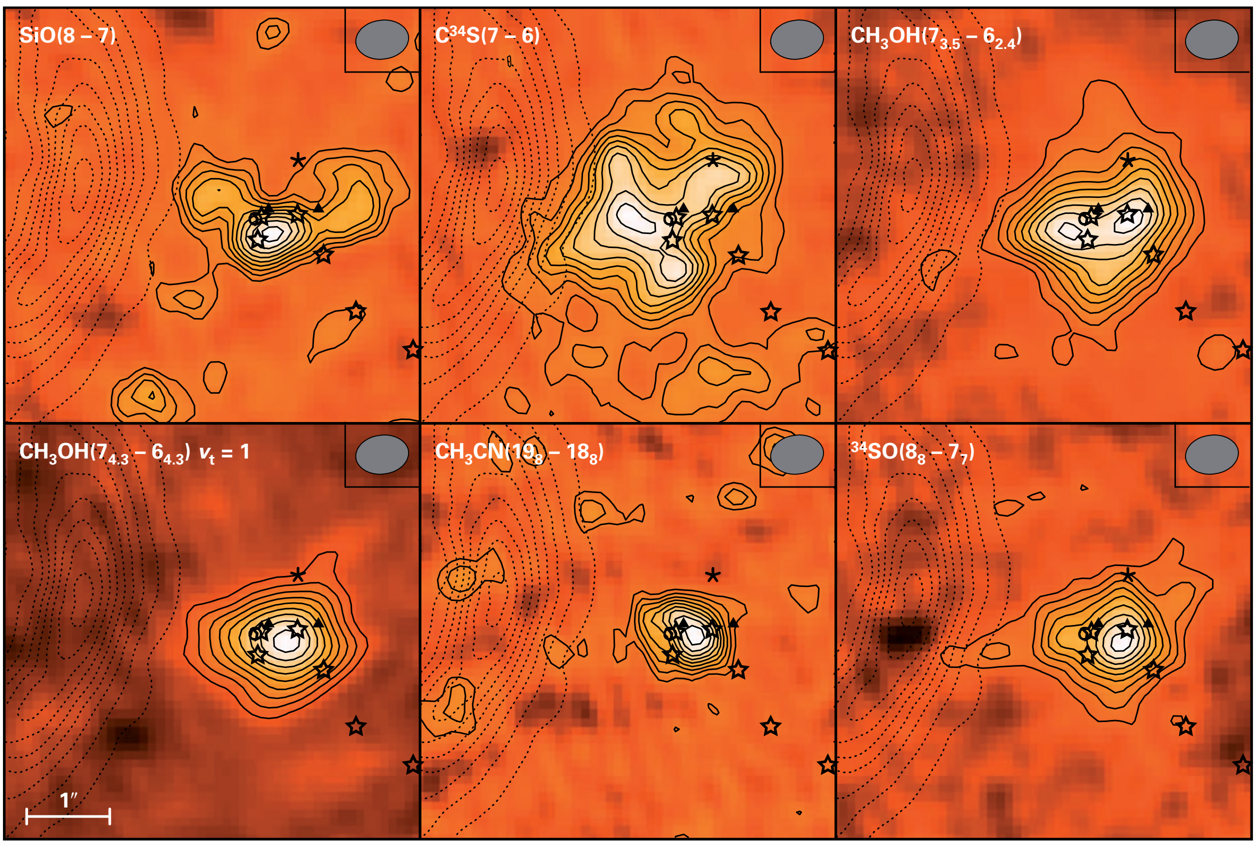


a mixture of free-free radiation of electrons and protons at low frequencies, and of thermal dust emission at high frequencies. This is typical of a protostellar core that is deeply embedded in a dust cloud.

The situation is different with another source discovered, SMA 1. It is not a continuation of the hot core,

Fig. II.4.7: Sectional view of the spectrum obtained of G29.96 with SMA.

Fig. II.4.8: Maps of the emissions of different molecules. One or even two bipolar outflows can be identified for SiO.



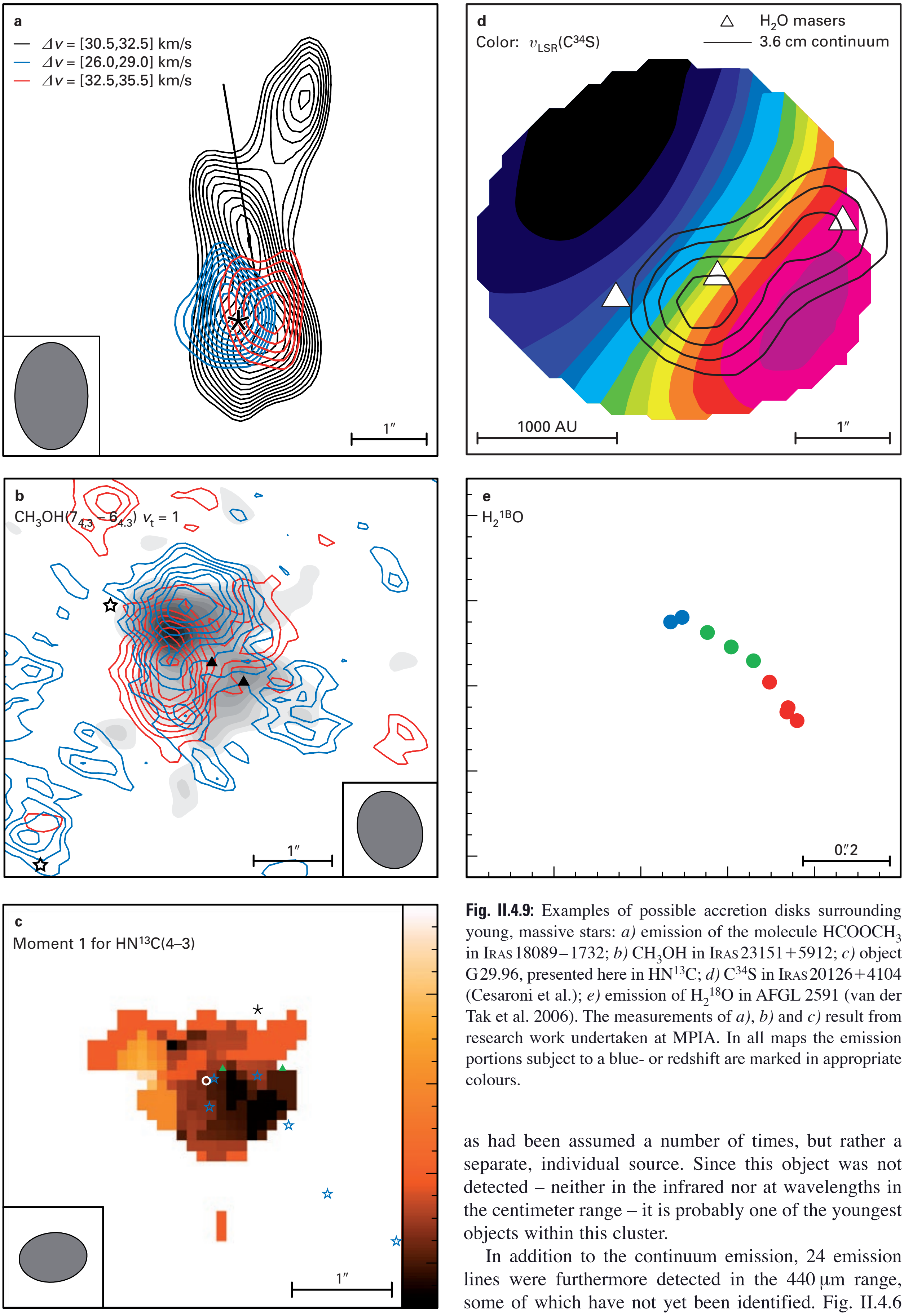


Fig. II.4.9: Examples of possible accretion disks surrounding young, massive stars: *a)* emission of the molecule $HCOOCH_3$ in IRAS 18089−1732; *b)* CH_3OH in IRAS 23151+5912; *c)* object G29.96, presented here in $HN^{13}C$; *d)* $C^{34}S$ in IRAS 20126+4104 (Cesaroni et al.); *e)* emission of $H_2{}^{18}O$ in AFGL 2591 (van der Tak et al. 2006). The measurements of *a), b)* and *c)* result from research work undertaken at MPIA. In all maps the emission portions subject to a blue- or redshift are marked in appropriate colours.

as had been assumed a number of times, but rather a separate, individual source. Since this object was not detected – neither in the infrared nor at wavelengths in the centimeter range – it is probably one of the youngest objects within this cluster.

In addition to the continuum emission, 24 emission lines were furthermore detected in the 440 µm range, some of which have not yet been identified. Fig. II.4.6

shows the emissions of some molecules in Orion KL. As a result, it was determined that high-excitation lines in the 440 μm range appear intensely at source I, indicating a high temperature. In particular, it was possible to infer the temperature more precisely in I, in SMA 1 and in the hot core from the emission of CH_3CN ($37_K - 36_K$). A value of 600 K was obtained with an uncertainty of 200 K. This temperature value is several hundred Kelvin higher than earlier estimates. This can be explained by the fact that the very high-frequency spectral lines observed originate from warmer gas than the low-frequency lines obtained by earlier observations.

Hot Molecular Cores and Accretion Disks

Hot cores of the type found in Orion KL have temperatures of more than 100 K and are considered early stages of massive star formation. These objects accrete matter from their surroundings, without having formed an ultra-compact HII region yet.

The observation of molecular emissions enables the investigation of the physical condition of such an object if telescopes with a very high spatial resolution are available. The known hot molecular core G29.96 at a distance of about 20 000 light years was observed with the SMA at a wavelength ranging at 850 μm with a resolution of 0.3″ in the continuum and 0.5″ in the emission lines. Through the observations of the continuum, the source could initially be subdivided into four individual objects.

At the same time, about 80 spectral lines of more than 18 types of molecules were identified (Fig. II.4.7). However, none of the molecule emissions showed the four continuum sources (Fig. II.4.8). This may be due to the fact that the molecule maps do not achieve the same very high spatial resolution as the continuum map. A physical explanation may also be that the molecular emissions originates from optically dense areas, thus characterizing the external ranges but not the embedded sources. The different types of molecules cover a temperature range of 40 to 750 K, i.e. it is possible to study quite different regions at the same time in this wavelength range. Furthermore, a bipolar outflow could be identified on the basis of the SiO emission, and maybe even two outflows.

One of the fundamental results of the present study was the possibility of observing different types of molecules with spatial separation. This means that physical models, and especially also models of the chemical network, can now be tested both for this region and in comparison with other regions of star formation. This task still needs to be done, yet it promises new findings concerning the processes taking place during massive star formation.

One of the most important motivations for high-resolution observations of molecular emissions is, as outlined above, to detect accretion disks around massive (proto)stars. A few objects showed signs of such disks in recent observations. Some examples are shown in Fig. II.4.9; e.g., Italian astronomers found a disk around the infrared source IRAS 20126 + 4104, where they were able to detect Keplerian rotation (Fig. II.4.9d) – however, the accreting protostar probably has only seven solar masses. The main problem is to distinguish the emission of the disk from that of other components, such as outflows and the surrounding cloud core that might fall in.

Furthermore, the chemistry in the surroundings of the protostar changes with the star's age. As a result, a single type of molecule is not suitable as an indicator for all disks. For the hot core G29.96, the structure could be best detected in the light of molecule $HN_{13}C$ whose velocity field is indicative of a disk.

These first experiments confirm the high potential of interferometry observation of the regions of massive star formation in the sub-millimeter and millimeter range. In particular, the high bandwidth of modern receivers facilitates the simultaneous observation of many molecules which serve as indicators of different spatial regions. This method has also brought us closer to one of the most important goals: a detailed investigation of accretion disks surrounding young, massive stars.

All of the projects described here are but first steps on a long road. The earliest stages of massive star formation, as with IRDC18223-3, belong to the development stages with the lowest research activity so far, and have only recently become accessible to observation in statistically significant numbers through the infrared satellites ISO, MSX and SPITZER. This field of research will experience a boom in the next few years. The investigation of massive accretion disks is considered the Holy Grail of researching massive star formation and pursued by a number of working groups. In addition, studying the chemistry of the hot molecular cores is an important basis of astro-chemistry. It is the foundation of future studies in astro-biology, or the search for complex molecules in space which are necessary for life as we know it. The fact that the investigation of massive star formation is increasingly gaining importance is also reflected by a large international conference on this issue to be held in September 2007 in Heidelberg, organized by the MPIA.

Henrik Beuther.
Other institutes involved:
Harvard-Smithsonian Center for Astrophysics, Cambridge, (USA); Academia Sinica Institute of Astronomy and Astrophysics, National Taiwan University, Taiwan; National Astronomical Observatory of Japan, Tokyo

II.5 Molecular Gas in Highly Redshifted Quasars

Probing the Fuel for Star Formation in the Early Universe

MPIA researchers succeeded in the first detection of the HCO^+ molecule in high redshift galaxies. The observations show that it is a good indicator of dense molecular gas in the star forming regions of these very distant galaxies. The detection of this molecule enables a first study of the dense phase of the molecular interstellar medium and its structure in galaxies in the young universe more than 10 billion years ago. This opens an entirely new approach to the study of the conditions of star formation in the early universe.

A central tool in studying the properties of star forming regions in galaxies is the observation of rotation transitions of molecular gas, normally CO. The comparatively dense molecular gas is the building material of star formation; therefore the amount of such gas determines the number of stars a galaxy is capable of forming at a certain point in time. In the course of the past 15 years, researchers have managed to observe this gas in ever more distant galaxies in order to study the formation and development of galaxies in the very young universe. As the line transitions in these distant galaxies appear redshifted, normally one does not observe the lines emitted by transitions to the ground state, as would be the case with nearby galaxies, but rather lines that reflect higher excitation conditions. These conditions can then be observed in the same wavelength windows as the fundamental rotation transition in nearby galaxies. In contrast to normal spiral galaxies like ours, it was found that the molecular gas is often highly excited in the very distant, highly redshifted galaxies, and thus radiates much more strongly in the higher transitions than in the lower ones.

The question of whether or not these galaxies contain a low-excitation component in addition to the high-excitation one, as would be the case in the Milky Way system, for example, is one of the key issues of these studies. Such a component cannot be detected by the observation of high rotation transitions, but could nevertheless dominate radiation in the fundamental transition. For this reason, it has been argued that only observations of the low-luminosity fundamental transition provide a measure of the entire molecular mass available for star formation. This question is of great importance for the birth and development of galaxies.

For the first time, an international group of astronomers lead by the MPIA has succeeded in detecting this fundamental transition, which is a very difficult task in the case of highly red-shifted quasars (up to $z = 4.69$, or 1.3 billion years after the Big Bang), using the two largest free-moving radio telescopes. The analysis of the emission lines indicates that there are no significant additional gas reservoirs in these quasars next to the highly-excited molecular gas component. In a second project, researchers now managed to detect HCO^+ as an ionized molecule in highly red-shifted galaxies for the first time. The luminosity of HCO^+ is ten times lower than that of CO, and it is only the third molecule detected in the early universe. In the nearby universe, this molecule is known to be a direct indicator of star formation.

To date, molecular gas has been detected in the form of CO in more than 30 galaxies with redshifts greater than $z = 2$. Molecular gas is normally detected either in the form of a disk around the center of a galaxy, or – in the event of a merger – in the area of the central regions and the area of the overlapping region where the gases of the two galaxies mix. It is the matter stars are made of. The most distant object in which CO was detected is a quasar located at $z = 6.42$. We see it at the point of time in which the universe was only 870 million years old. For this reason, such CO observations offer the possibility of studying the formation and development of stars and galaxies even in such an early epoch of the universe.

Almost all similar studies of the young universe only investigated high rotation transitions [CO ($J \rightarrow J-1$), ($J \geq 3$)]. This is due to the fact that firstly, these higher transitions have been shifted to the CO wavelength ranges typical of observations, and secondly, the molecular gas is highly excited at $z > 2$ in practically all systems studied so far, so that it radiates more brightly at the higher transitions than at the lower ones. This differs from normal spiral galaxies such as the Milky Way system with a much lower molecular gas excitation, which emits a great portion of the radiation at the lower transitions, especially from the fundamental excitation level to the basic level: CO ($J = 1 \rightarrow 0$).

For this reason, one fundamental question in this context is whether or not an additional, low-excitation component is present in the highly excited galaxies at $z > 2$. This component would be very difficult to detect in the high transitions normally observed, but it could dominate the emission at the basic state. For this reason, such a component could contain a significant portion of the total mass of the molecular hydrogen (H_2) existing in a galaxy, which is detected indirectly via CO, the second most common molecule in the universe. With a share of more than 99.9 %, H_2 is the most frequent molecule in the interstellar medium, however it does not have any rotation transitions because of its symmetry, and for this reason cannot be detected in the distant universe. The observation of CO ($J = 1 \rightarrow 0$) in highly red-shifted galaxies is also important as it enables a direct comparison of the distant and nearby starburst

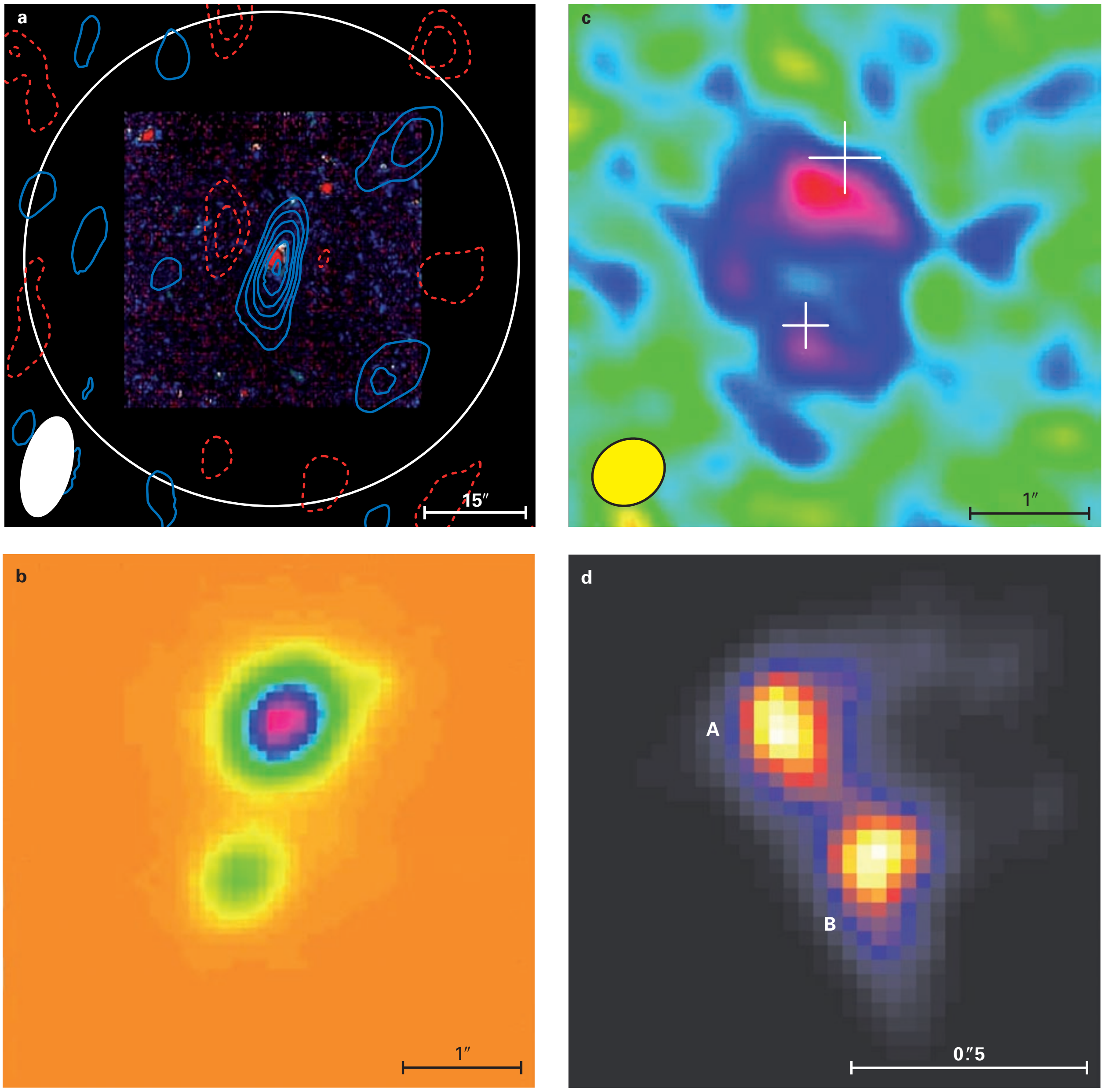


Fig. II.5.1: *a)* The quasar BR 1202-0725 (imaged in the light of the rotational emission line CO $J = 5 \rightarrow 4$, picture taken with the NMA (contours), superimposed to an optical image); *b)* the quasar PSS J2322+1944 (image in the optical range taken at the Keck observatory); *c)* same object, the molecular Einstein ring, taken by the VLA in CO ($J = 2 \rightarrow 1$) and *d)* the quasar APM 08279+5255 (X-ray image taken by CHANDRA).

galaxies because the nearby systems are mainly studied in the CO ($J = 1 \rightarrow 0$) transition.

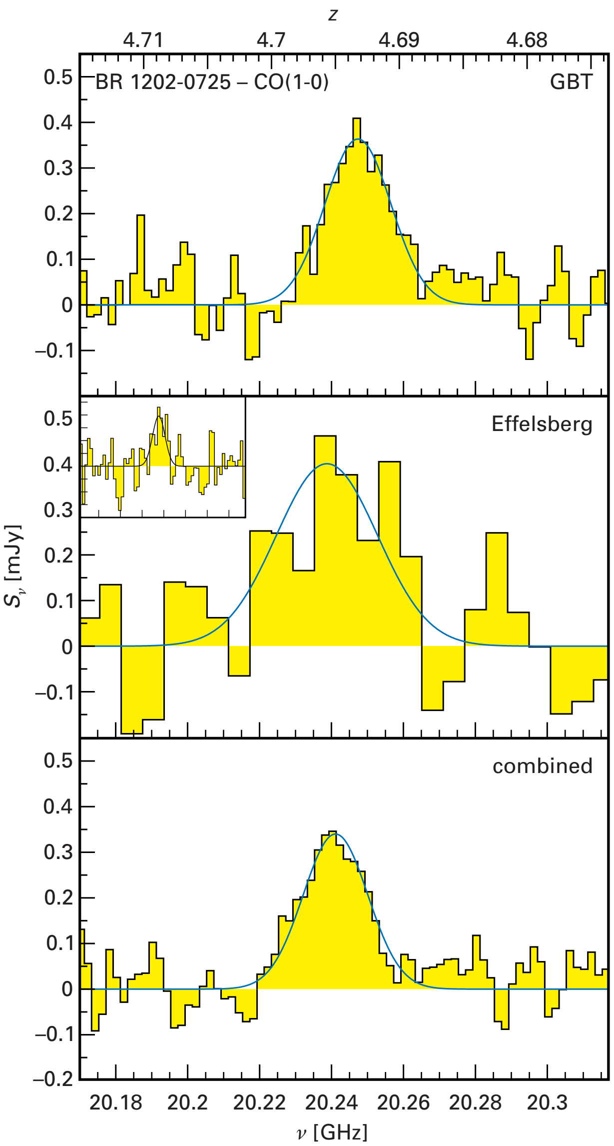
Because of its generally low intensity, line radiation of the CO ($J = 1 \rightarrow 0$) transition is even more difficult to detect than that of the transitions at a higher level. Moreover, this transition in the most distant systems is red-shifted up to the typical radio observation ranges at $z > 4$; therefore, it can only be observed using classical radio telescopes. The first telescope capable of detecting CO ($J = 1 \rightarrow 0$) at this distance was the Very Large Array, however it does not provide any detailed information concerning the line profile due to its limited bandwidth and spectral resolution. The ongoing technical upgrades of the two large 100 m radio telescopes, the NRAO Green Bank Telescope (GBT) and the telescope operated by the MPI for Radioastronomy in Effelsberg, now for the first time enable the observation of CO ($J = 1 \rightarrow 0$) in distant quasars with a high sensitivity, bandwidth and spectral resolution.

CO Gas in Three Distant Quasars

In order to study the excitation of CO in several transitions and to be able to separate a component with a possibly low excitation from a highly excited one, the astronomers chose three quasars that had already been detected at high CO transitions. BR 1202-0725 ($z = 4.69$), PSS J2322+1944 ($z = 4.12$) and APM 08279+5255 ($z = 3.91$) (Fig. II.5.1). These represent one-fifth of all quasars observed at $z > 2$ in CO. We see these three objects at the point of time in which the universe was between 1.3 and 1.6 million years old.

As the intensities are at the limit of what can be detected using current radio technology, very long integration times are necessary. For this reason, a total of 130 hours of observation time were available on both telescopes. The spectra of the two instruments were combined in order to improve the signal-to-noise ratio. In all three cases, the CO ($J = 1 \rightarrow 0$) line was clearly detectable (Fig. II.5.2). Thus, molecular gas in the form of CO

Fig. II.5.2: The spectral line CO ($J = 1 \rightarrow 0$) of the quasar BR 1202-0725 (redshift of 4.69), taken with the radio telescopes in Green Bank (*top*) and Effelsberg (*middle*). A combination of the two spectra is shown at the bottom.



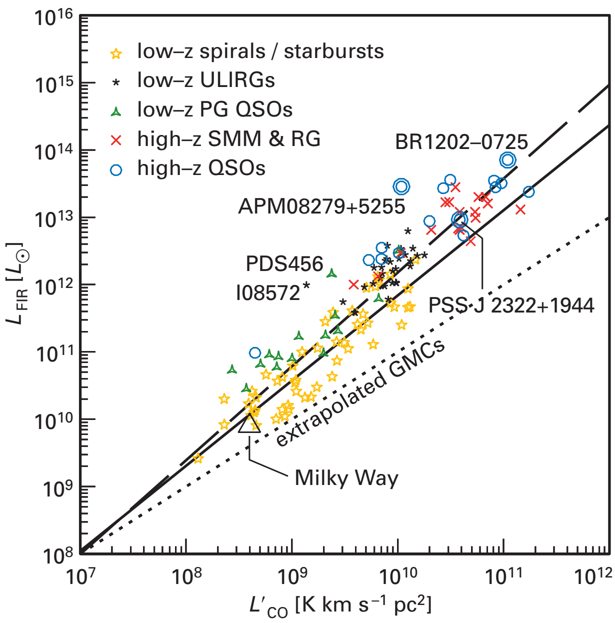


Fig. II.5.3: Correlation between the total luminosity in the far-infrared (FIR) and the CO line luminosity for various types of galaxies at low and high redshifts. This illustrates how well these observations of tracers of star-formation rate track each other.

was detected for the first time at high redshifts using the GBT and the Effelsberg telescope.

In particular, the lines were measured with a spectral resolution that had never been reached previously. Thus, it was possible to study the line profiles in detail and to very precisely determine the luminosity of the lines. The overall mass of the H_2 gas in the three quasars investigated resulted from a conversion factor calibrated locally. For the measurements described here, total H_2 masses typically reach 4×10^{10} solar masses. This molecular gas is mostly converted into stars in the course of the development of these galaxies. The infrared luminosity of the three quasars investigated resulted in a star formation rate of several 1000 solar masses per year, i.e. its entire gas reservoir could be converted into stars in 10 to 100 million years. This is just a lower limit value because the gas is not fully converted into stars (with 100 % efficiency), and because the massive stars emit some of the matter through stellar winds and supernova explosions.

When the mass of the molecular gas had been determined, the question could be addressed as to whether the CO ($J = 1 \rightarrow 0$) line indicates a component with low excitation in addition to the highly excited gas component.

For this purpose, the astronomers modeled the properties of the molecular gas on the assumption of a large velocity gradient. The result was the same in all three cases: The flow densities measured with respect to the fundamental CO rotation transition are fully associated with the highly excited gas and do not provide an indication of an additional component with lower excitation. In the framework of the uncertainties associated with the observations and models, such a component could make up no more than about 20 % of the flow density observed without dominating the CO emission in any way. This observation differs fundamentally from normal spiral galaxies such as our Milky Way which contains large quantities of low-excitation molecular gas.

This result means that the total H_2 mass can also be well determined from the highly excited CO lines alone which are easier to measure. With this result, the molecular gas masses of all galaxies detected at high redshifts in the CO emission can be estimated more precisely. Thus, the properties of these early systems are easier to compare to those of nearby galaxies observed in CO ($J=1\rightarrow0$).

Based on the new study, the relation between the total luminosity produced by thermal dust emission in the far infrared and the CO line luminosity could be extended to the highly red-shifted objects (Fig. II.5.3). This diagram defines a relationship between the entire star formation rate and the total amount of molecular gas, thus describing the efficiency of H_2 transformation into stars by galaxies. The diagram contains Palomar-Green Quasars (PG-QSOs), (ultra)luminous infrared galaxies (ULIRGS) and local spiral and starburst galaxies, all at $0 < z < 0.3$. In addition, it includes all of the objects found at high redshifts, divided into quasars and other galaxies (mainly sub-millimeter and radio galaxies).

Interestingly, all of the different types of galaxies follow a relation within a certain mean variation which nevertheless deviates from a linear function in case of a high star formation rate and massive molecular gas reservoirs. This applies, in particular, to the comparison of nearby and distant galaxies as indicators of galaxy development. However, it also applies to the comparison of galaxies with and without an active nucleus. This is surprising because a quasar, for example, has an active nucleus (AGN) which stimulates infrared emission by the surrounding dust, whereas exclusively young stars that have only just been formed in star forming regions are probably responsible for this process in a ULIRG. This would mean that star formation dominates distant infrared emission even in quasars, whereas the active nucleus contributes little to this process.

HCO^+ in the Clover Leaf Quasar

As described above, CO is an excellent indicator of the total amount of molecular gas in a galaxy, and thus of the material stars can be made from. However, there are some other molecules that are better suited to investigate the dense component of the molecular gas only. This component most likely contains the core regions in which star formation actually takes place. Such high-density gas and dust clouds can be separated from the rather diffuse component of the molecular interstellar medium by observing molecules with a high dipole moment, such as HCN and HCO^+.

The radiation of rotation transitions of these molecules is normally weaker than that of CO by more than a factor of 10, and much more difficult to detect for this reason. In addition to CO, only HCN could so far be detected at high redshifts. At $z > 2$, emission of this molecule could be detected for only four quasars. A team headed by the MPIA has managed for the first time to detect a third molecule, ionized HCO^+, in the early universe.

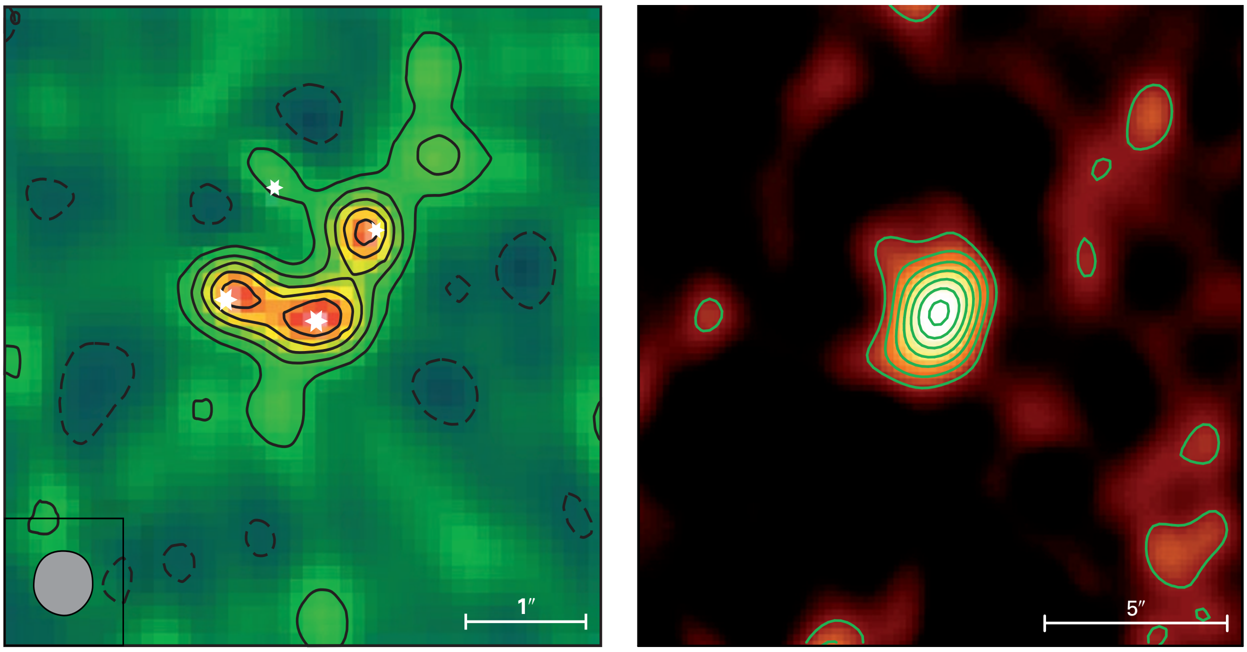
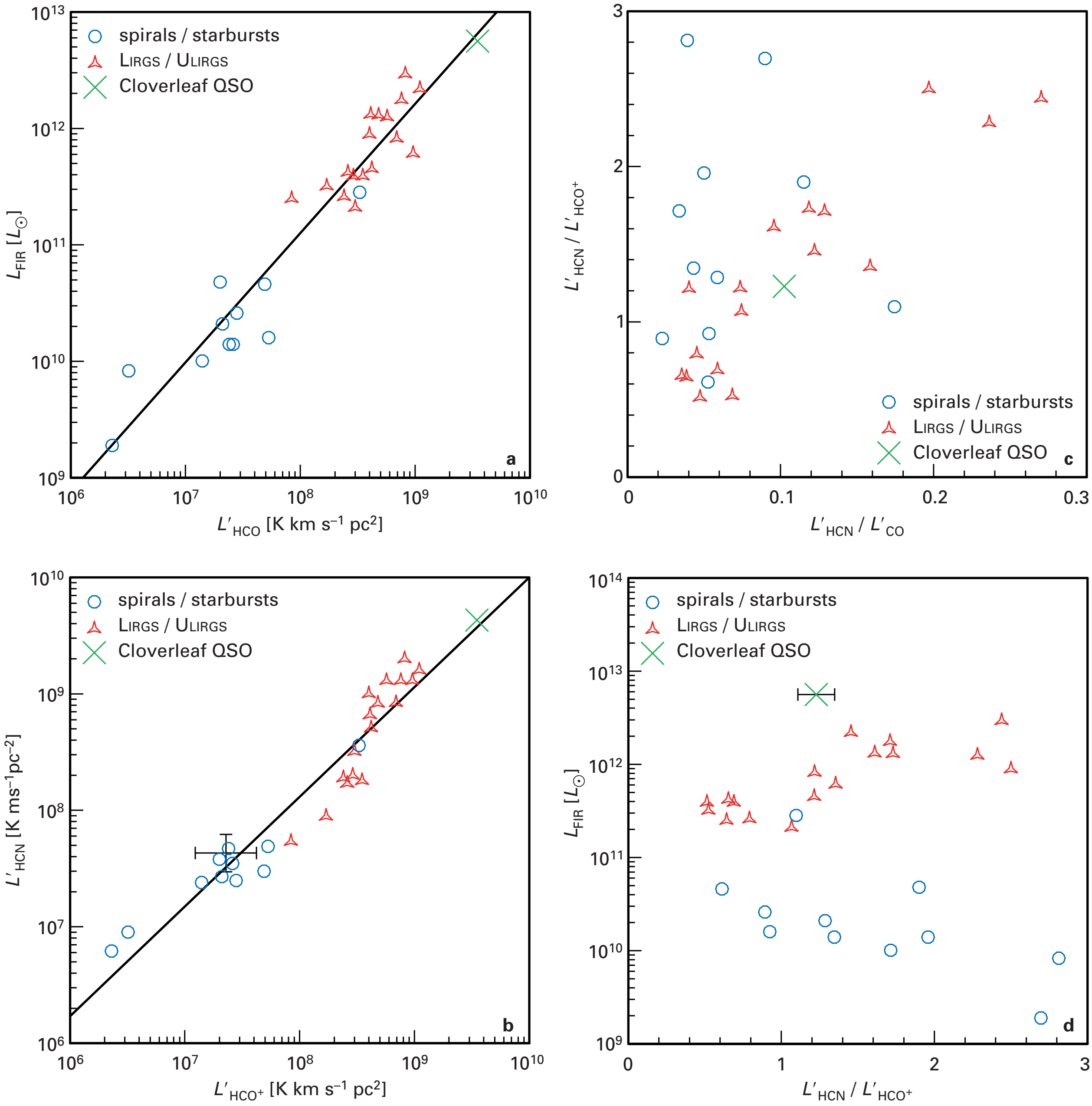


Fig. II.5.4: The clover leaf quasar. *Left:* the emission line of the high rotation transition CO ($J = 1 \rightarrow 6$), taken in 1994 with the IRAM interferometer; *right*: the emission of HCO^+ ($J = 1 \rightarrow 0$) detected for the first time in 2005/06 with the VLA.

The HCO^+ emission of transition $J = 1 \rightarrow 0$ found in the clover leaf quasar (Fig. II.5.4) is the molecular emission line with the lowest luminosity that was detected for this source. The source is a quasar appearing in four images due to the process of gravitational lensing, with its intensity being increased by a factor of 11. The emission line $HCO^+(J = 1 \rightarrow 0)$ was detected in a measuring time of 25.5 hours with the VLA. Together with the known intensities of the $HCN(J = 1 \rightarrow 0)$ line and various transitions of the CO molecule in the clover leaf quasar, the luminosity of this line contains important information concerning the chemical composition and physical properties of the molecular interstellar medium in the star forming regions of this galaxy. This leads to important conclusions concerning the conditions of star and galaxy formation in the early universe.

Figure II.5.5 shows the correlations between the far infrared and HCN luminosity as a function of the HCO^+ luminosity for nearby spiral and starburst galaxies and ULIRGS. These correlations are even closer than the relationship between CO and far infrared luminosity shown in Fig. II.5.3. They demonstrate that HCN and HCO^+ are similarly suitable indicators of active star formation as the far infrared luminosity. It is obvious that the distant clover leaf quasar is very much in line with the correlations of the local galaxies. It is striking that no

Fig. II.5.5: Correlations of the luminosities in the far infrared and in the HCN emission on the one hand an the luminosity in the HCO^+ emission on the other. The values corresponding on the clover leaf quasar are marked by a cross.



clear difference can be seen between the correlation of HCN with HCO^+ for current galaxies and for the clover leaf quasar in the young universe. Accordingly, there is no clear difference in the chemical composition of the molecular gas. Astronomers infer from the result that the HCN luminosity is approximately the same as that of HCO^+ and that both molecules have their origins in a comparable, optically dense area.

The observations confirm the hopes that HCO^+ is a good indicator of a dense molecular gas in the star forming regions of highly red-shifted galaxies. The detection of this molecule enables a first study of the dense phase of the molecular interstellar medium and its structure in galaxies in the young universe at $z > 2$ (more than 10 billion years ago).

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II.6 The Slow Evolution of Galaxies in Their Dark Matter Halos

According to the current standard cosmogony, galaxies have formed in extensive dark matter halos. This development can be traced comparatively well using computer simulations. However, the model calculations predict that the galaxies will grow faster than is actually observed. Theoreticians at the MPIA have investigated a new model that accounts for the internal structure of dark matter halos. These studies have shown that, for a given mass, the characteristic size of the observable, stellar part of galaxies increased by only 15 to 20 percent in the second half of cosmic development (since the redshift $z \approx 1$). This is now in line with the observed size growth of galaxies quantified recently by an MPIA team.

In the current standard model of cosmology, dark matter clouds (halos) are a decisive prerequisite for galaxy formation. In this scenario, extensive halos were formed in the early universe which were contracted under the influence of gravity and sometimes even fused together in the course of time. At the same time, the "normal" baryonic matter flowed into the centers of gravity of the halos where it condensed into the first disk galaxies. In return, some of these galaxies fused together, thus growing to their current size. The characteristic parameters of galaxies, such as their size, mass or luminosity, are thus closely linked to the development of dark matter halos.

One fundamental property of dark halos is the angular momentum they received after the Big Bang. This momentum was almost entirely maintained during contraction, with the result that the originally almost spherical structures were flattened into disks. The angular momentum of the baryonic matter was also preserved. The assumption that the specific angular momentums (referring to a unitary mass) of dark and baryonic matter are approximately of the same size leads to a prediction of today's size distribution of disk galaxies that mainly coincides with the observations.

Nevertheless, the physical processes accounted for in current models have not yet been totally understood. Thus, some disks of the protogalaxies lose their angular momentum in complex numerical simulations, and the resulting galaxies become too small and too compact. Cooling the baryonic gas and star formation also have a strong influence on the development of the fundamental galaxy parameters.

Modern sky surveys have recently offered an increasing number of possibilities of comparing the results of the computer models with reality. Thus in the course of the HST project GEMS (Galaxy Evolution from Morphology and Spectral Energy Distributions) in combination with data obtained from the COMBO-17 Calar Alto survey in the year 2005, astronomers at the MPIA found out that disk galaxies of a given size were about 1 mag brighter at a redshift of $z = 1$ (almost eight billion years ago) than they are today. The total mass of stars only increased by max. 10 % during the same period of time, however. This result is consistent with a slow increase of the mean mass/luminosity ratio as can be expected from an aging star population.

Comparable sky surveys have shown that the surface brightness of the galaxies has decreased by 2 to 3 mag arcsec^{-2}, or a factor of 10, since $z = 2.5$. The mean size at a fixed total stellar mass has not even increased by a factor of 2 during the same time period.

Discrepancies between Theory and Reality

Simple scaling models are not capable of explaining these results, because they predict a stronger development of the galaxy size than has been observed. These models are based on the assumption that the size of a galaxy grows in proportion to a spin parameter and the virial radius of the dark halo. On this condition, the galaxies should have grown by a factor of 1.7 since $z = 1$ and by a factor of 3.2 since $z = 3$.

This discrepancy between theory and reality is due to excessively simplified assumptions for this model which do not account for a number of effects. For example, the halos have a density profile that does not coincide with the simple virial case. More recent models of Navarro, Frenk and White include different density profiles. In addition, the baryonic matter located in the center of the halo modifies the halo's density profile, especially in its central range. And third of all, the disks of protogalaxies may become instable and form a bar or bulge (central spherical agglomeration).

Theoreticians at the MPIA have introduced a simplified form of these three effects into an extended scaling model which they examined for possible effects on the formation and development of the galaxies. Their model is based on the following assumptions: There is a disk galaxy in the center of each halo with an angular speed of less than 350 km/s (the angular speed of a halo being specified for a critical radius r_{200}). The density profiles correspond to that of the Navarro-Frenk-White model. A certain ratio between the halo mass and the galaxy's mass is assumed. Each disk galaxy has the same specific angular momentum as its halo, and a stability criterion was defined that specifies the decay of a disk into a bar or a bulge.

On these assumptions, the development of dark halos and the galaxies contained in them was simulated, and the results were then compared to observation data at several redshifts. The astronomers used the Gems image and the MPIA survey Combo-17 (cf. below) for that purpose.

Finally, a total of 5664 galaxies were available to the astronomers whose characteristic radius r_d was determined by adjusting a brightness profile. The uncertainty concerning r_d amounted to approx. 35 %, the brightness values could be defined with an accuracy of approx. 0.2 mag. This group of galaxies was complete down to a smallest mass of 10^{10} solar masses, therefore, the following analysis is limited to galaxies of this minimum size.

Testing the New Model

Fig. II.6.1 shows a comparison of the new model (left) with the results observed (right). The chart shows the frequency distribution of the apparent brightness values of the galaxies and their characteristic sizes r_d subject to the mass at different redshift ranges since $z = 1.05$. The images only show stable disk galaxies, i.e. without any bars or bulges. As a result of the stability criterion defined for this process, a bar or bulge mainly occurs in massive galaxies. The exclusion of these instable galaxies reduced the mean size variation considerably for the given mass. The proportionate share of instable galaxies varied between 5 % at $z = 0.1$ and 3 % at $z = 1$.

The new model reflects the data of the observation much better than the previous scaling model. The increase in the size-mass ratio and the mean size variation for a given mass are well in line with reality. In particular, the model predicts that the mean size of a given stellar mass has grown by 15 to 20 % until today since $z = 1$. This value was also obtained from the analysis of the Gems image. However, the model predicts too many galaxies whose masses are above 10^{11} solar masses. This is not surprising because it was assumed that each dark halo contains exactly one galaxy. However, this assumption is not realistic because very massive halos are more likely to contain elliptical galaxies. Therefore, these massive galaxies were not considered in the analysis further below.

As a second test of the models, the stellar surface density was determined as a quantity that is calculated from the mass and the galaxy's radius. Fig. II.6.2 shows the temporal development of this quantity from $z = 1$ until today. The measured values for galaxies with 10^{10} to 10^{11} solar masses (solid squares) hardly indicate any development at all, whereas the previous models (dashed and dotted curves) predict much too fast a development. The new model supplies the best match when disregarding the instable galaxies (blue dots). When including the instable galaxies (open circles), the development curve was once again too steep.

The good predictive value of the new, extended scaling model supported the idea of also applying this model to galaxies with higher redshifts. From other observations, a data collection of galaxies up to $z = 3$ was recently made

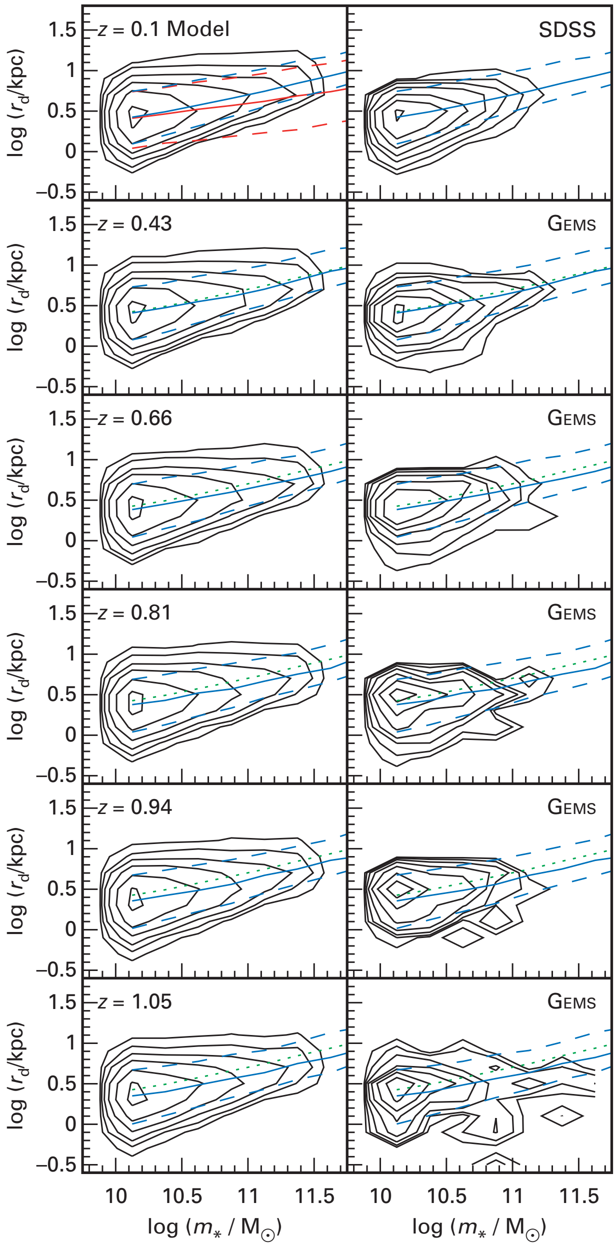

Fig. II.6.1: Development of the galaxy sizes (r_d) as a function of the mass since z=1.05. *Left*, the results of the model; *right*, the results observed for comparison. For the local environment ($z = 0.1$), data of the Sloan Digital Sky Survey (SDSS) was used, for the more distant galaxies, the Gems image with redshift values from Combo-17 was available.

available, although its quality did not equal the one used up to $z = 1$. This collection of values for mean galaxy sizes from $z = 0$ to $z = 3$ was based on the Gems image as well as the SDSS and Fires surveys.

Fig. II.6.3 once again shows the comparison of the models with the data from the observation. The simple scaling model once again predicts a temporal development that is much too steep, whereas the new, extended model is well in line with the observations. It predicts that galaxies of a given stellar mass should have 60 %

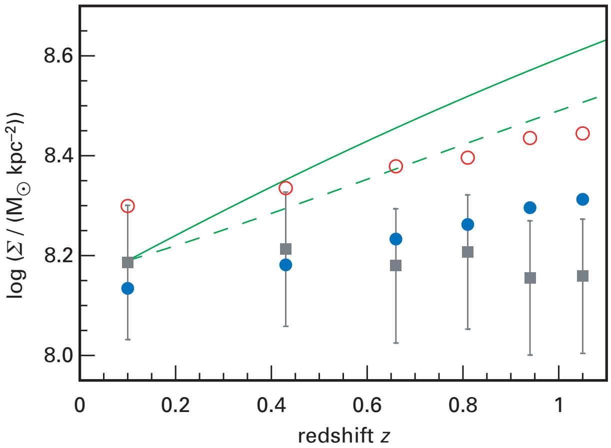

Fig. II.6.2: Temporal development of the stellar surface density of galaxies with 10^{10} to 10^{11} solar masses (*solid squares*). The earlier models (*dashed and dotted curves*) predict much too fast a development. The new model supplies the best match when disregarding the instable galaxies (*blue dots*). When including the instable galaxies (*open circles*), the development curve was once again too steep.

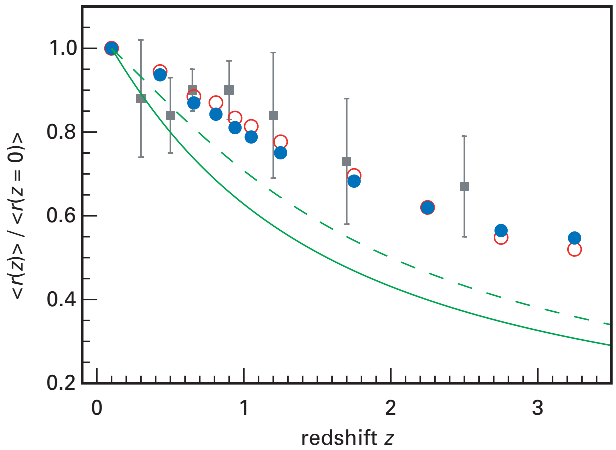

Fig. II.6.3: Temporal development of the mean galaxy size since $z = 2.5$ (symbols as in Fig. II.6.2). The new model once again reflects the data from the observation fairly well.

of their current size at around $z = 2.5$. This is a slightly stronger development than indicated by the measured values, however, it still is within the inaccuracy range of the observations.

Although the new model is not capable of accounting for all the physical processes that play a role in the development of galaxies, it much better reflects reality than the old scaling model. This is mainly due to the fact that the size of a galaxy does not simply grow in proportion to the virial radius of the dark halo. In turn, this conclusion results from the temporal development of the density structure of the halo according to the following description: In the course of time, halos collect matter from their surroundings. Computer simulations have shown that this process takes place in two stages. First, the halo's concentration in its central area is growing. In a second stage, the halo still collects matter, however, this matter is evenly distributed across the whole range. The virial radius continues to grow, but the relationship between the outer range and the central range remains almost the same, and concentration decreases. However, a less concentrated halo results in the formation of a bigger galaxy than a halo with a strong rise in concentration, according to the models. This trend, which is opposed to the development of the virial radius, results in a weaker development of the size-mass ratio of the galaxies.

The new scaling model ignores some physical processes important for galaxy development, which will be accounted for in the next step. These include, in particular, cooling of gas, star formation, repercussions of star formation on the interstellar medium and interaction of galaxies.

The observation data used for this new study were obtained from the GEMS image and the MPIA survey COMBO-17. GEMS is the largest color image obtained from the HUBBLE space telescope so far. Astronomers at the MPIA were in charge of taking it and it serves to study the morphological properties of roughly 10 000 galaxies. The field of the sky was selected so that the redshifts of these galaxies could be obtained from the COMBO-17 survey. In the course of this sky survey, images of a large area of the sky were taken through 17 filters and the brightness of the galaxies was measured in the corresponding number of color arrays. This method can be used for the classification of galaxies and for exactly determining their redshifts up to a red brightness of 24 mag with only a few per cent uncertainty. The decisive precondition of the project was the large image field of the wide field camera (Wide Field Imager, WFI) that was developed under the leadership of the MPIA in cooperation with ESO. It operates at the 2.2 meter MPG/ESO telescope on La Silla and has an image field sized 32′ to 33′, roughly corresponding to the surface of the full moon. A total of 25 000 galaxies have been covered, therefore, COMBO-17 is one of the most comprehensive and most far-reaching sky surveys worldwide.

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II.7 The Black Hole in the Center of Centaurus A

The nearby elliptical galaxy Centaurus A (NGC 5128) is in many ways an ideal target to study active galactic nuclei. At a distance of 11 million light years, it is the nearest large elliptical galaxy, the nearest radio galaxy with two jets and it is the product of two galaxies that have fused only recently by cosmological standards. Its proximity to us offers the opportunity of investigating the near environment of its super-massive central black hole using high-resolution observation methods. This was achieved by an international team headed by the MPIA using the NACO and SINFONI instruments at the ESO Very Large Telescope. The adaptive optics of these instruments supplied unique data with an unprecedented spatial resolution. Thus, it was possible to decrypt the kinematics of the gas disk and to determine the mass of the black hole. The new value is an impressive demonstration of the fact that – in contrast to previous observations – Cen A is in line with the known relations between the masses of the black holes and the surrounding bulges as well as their velocity dispersions.

Numerous studies conducted in the past few years have arrived at the conclusion that there is most likely a black hole in the center of every elliptical or spiral galaxy. The masses of these objects vary between approx. 10^6 and 10^{10} solar masses. Interestingly, there is a close correlation between the masses of the black holes and the total masses of the surrounding bulges and their velocity dispersions – a fact that is surprising because the gravitation of the central black hole does not reach far enough to influence the dynamics of the bulge.

The radius of influence of a black hole grows in proportion to its mass and decreases in inverse proportion to the velocity dispersion of the stars in the bulge. Within this radius, the gravitation of the black hole is dominant; outside, that of the bulge prevails. The radii of influence are typically in the range of 30 to 300 light years, whereas bulges are approximately two magnitudes of size larger.

Since most of a bulge does not "feel" the gravitation of the central black hole, the correlation between the masses of the black holes and the surrounding bulges mentioned above must have a profound cause based on the history of development of the galaxies. Not all of the details are known, but computer simulations have shown that the fusion and growth of galaxies play an important role. In such a process, a lot of matter gets into the center of the emerging galaxy where it is taken up by the black hole, which in turn also grows. On the other hand, huge clouds of dust are swirled by the process of fusion, agglomerate and become enormous star forming regions. The Antennae galaxy is a famous example of a pair of colliding galaxies. How does Cen A fit into this scenario?

Cen A is an elliptical radio galaxy with two jets emerging from its center which mainly become visible in radio and X-ray images (Fig. II.7.1) The galaxy was presumably formed by the fusion of two galaxies some hundred million years ago. This was already assumed by Walter Bade and Rudolph Minkowski in the mid-1950s. This hypothesis is also supported by the large-scale, shell-like structures observed on optical images. Especially striking about Cen A are the elongated dust clouds which attenuate the visible light by up to 14 mag, thus making it more difficult to observe the central region (Fig. II.7.2). Nevertheless, an ionized gas disk could be detected in the near infrared which surrounds the central black hole. And the velocity dispersion of the central bulge could be determined to be 138 km/s.

Thus, the reference relation between the mass of a black hole and the velocity dispersion in the bulge predicts a mass of approx. 3×10^7 solar masses for the black hole. In the year 2001, astronomers arrived at a value of 2×10^8 solar masses, far above the relation. However, the mass of the black hole can be reliably determined only if the area within the radius of influence can be spatially resolved. For Cen A, the dispersion provided above results in a radius of influence of approx. 16 light years, corresponding to an angle of $0.''3$. This resolution has not been reached by previous observations.

Astronomers at the MPIA made use of the powerful features of two instruments at the Very Large Telescope (VLT) of the European Southern Observatory (ESO). With NACO, they achieved direct images in the *K* band (around 2.2 μm) and long-slit spectroscopy in the *H* band (around 1.6 μm). The observing conditions were excellent: the diffraction limit of $0.''057$ was reached in the *K* band (and observations were not far from it in the *H* band at $0.''11$). Furthermore, Cen A was studied using the imaging spectrometer SINFONI at the VLT. In the two wavelength ranges covered, i.e. 1.43 to 1.87 μm and 1.93 to 2.47 μm, many emission lines of ions and molecules were found in various excitation stages. These observations were also made very close to the diffraction limit. The aim of these efforts was to determine the kinematics of the disk and the mass of the black hole for the first time with sufficient resolution.

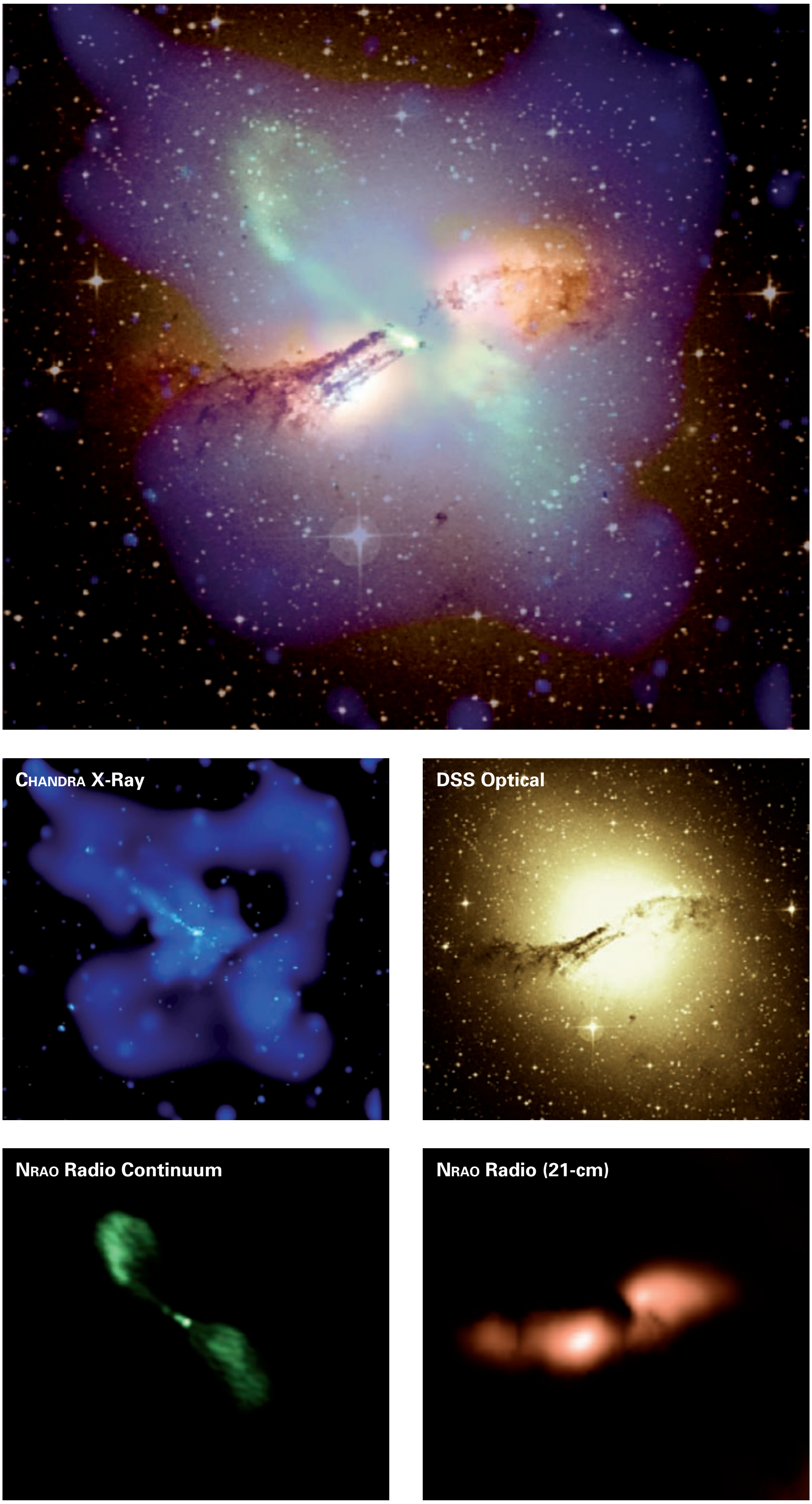

Chandra X-Ray
DSS Optical
NRAO Radio Continuum
NRAO Radio (21-cm)

Fig. II.7.1: *Top:* A multi-wavelenth view of Cen A with superimposed X-ray, radio and optical images. The individual images at the bottom: X-ray (NASA/CXC/M. Karovska et al.), optical (Digitized Sky Survey U.K. Schmidt Image/STScI), radio continuum (NRAO/VLA/J. Condon et al.), radio 21cm (NRAO/VLA/J. van Gorkom/Schminovich et al.).

Weighing the Black Hole with Data from the NACO Camera

A strong iron emission line [FeII] at a wavelength of 1.66 μm was best suited to analyze the NACO long-slit spectrographs (Fig. II.7.3). Furthermore, the spectrum was chosen in which the slit was on the large axis of the inclined disk at a positional angle of 32.5 degrees. This has the advantage that the surface brightness is determined along the split independent of the disk's angle of inclination. The surface brightness is an important parameter for the disk models.

To develop the model, the contribution of the central star component towards the entire gravitation potential was initially determined from pictures from the archive. The value of 8×10^7 solar masses is much higher than the estimated gas quantity of approx. 1000 solar masses in the disk, so the gravitation of the disk matter could be ignored in the models.

The rotation curve measured corresponds to that of a flat, rotating disk. Especially noteworthy is a very high velocity dispersion of 300 km/s in the very center. The origin of this phenomenon is unknown; a very high spa-

Fig. II.7.2: An optical image of Cen A, taken with FORS 2 at the VLT. The dense dust filaments are especially visible here. (Photo: ESO)

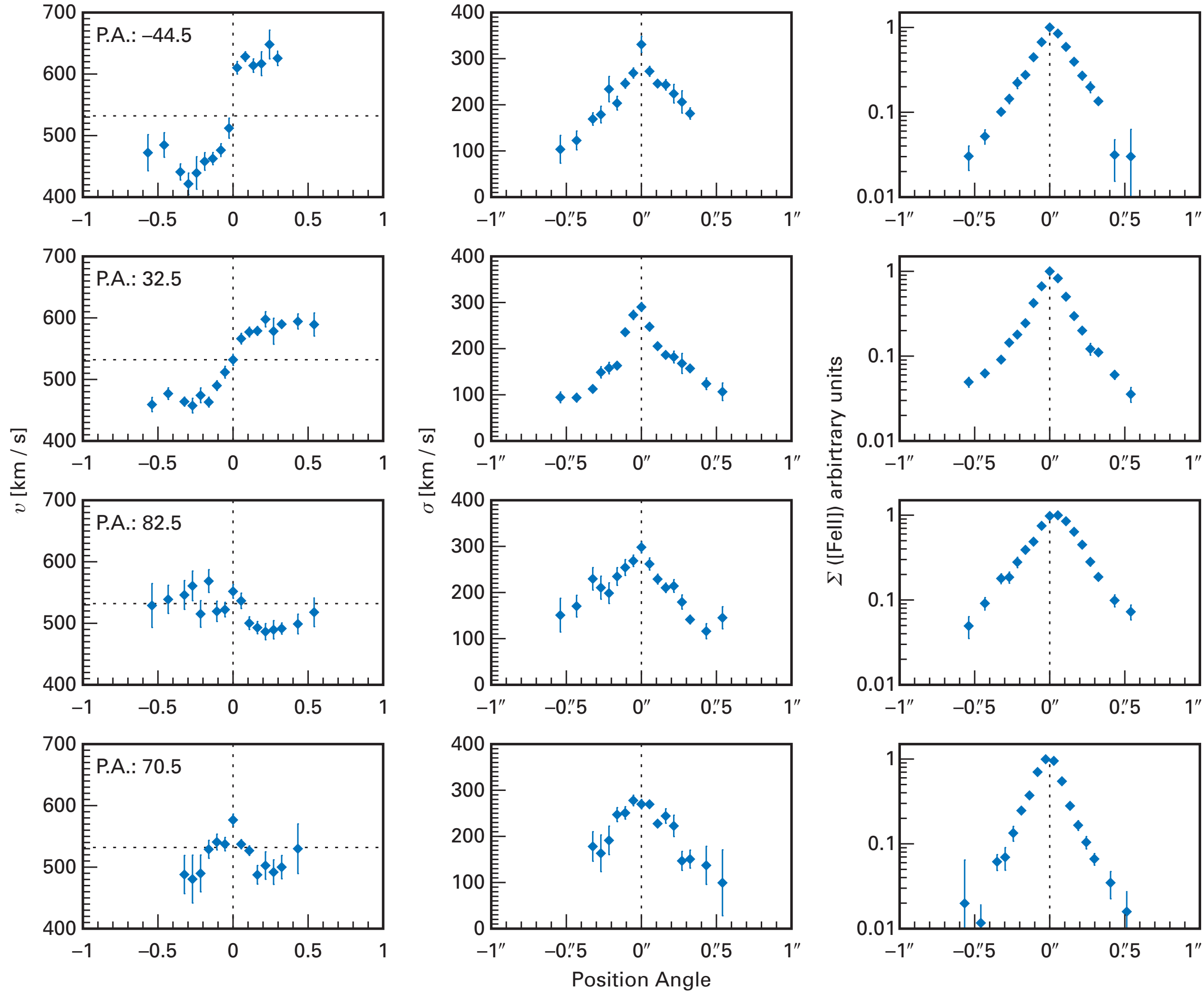


Fig. II.7.3: NACO data from the central area of Cen A. Rotation curves (*left*), velocity dispersion (*center*) and surface brightness (*right*) at four position angles.

tially unresolved velocity component would be viable. In order to determine the mass of the central black hole, three models were set up, and the optimum match was searched for using the measured data.

Model 1: A thin, cold disk where the velocity dispersion observed is entirely due to the circulation of the gas around the center. This model is certainly not realistic because it does not account for the physics of the gas, in particular its temperature rise. It supplies a lower limit for estimating the mass. Several parameters were included in the model which were adjusted by a fit, such as the inclination of the disk against the line of sight, the surface brightness and the mass of the black hole, which amounted to 4×10^7 solar masses according to this model.

Model 2: A thin hot disk where the cause of the velocity dispersion is interpreted as isotropic gas pressure. This model supplies a value of 6.1×10^7 solar masses for the mass of the black hole.

Model 3: A large number of gas clouds distributed spherically and symmetrically around the center and circulating around it. This model is not very realistic, but it supplies an upper limit for the mass of the black hole of 1×10^8 solar masses.

Model 2 probably supplies the best physical value. This value is much lower than the previously applicable value and amounts to only twice the value predicted by the mass relation of the black hole and the bulge.

SINFONI Supplies More Details from the Central Region

Another excellent possibility for studying the details of the central region of Cen A is offered by the imaging near infrared spectrometer SINFONI at the VLT. The integrated spectrum shows a number of emission lines of different excitation stages, including the highly excited emission [Si VI] at 1.96 µm and the low-excitation emission of molecular hydrogen H_2 at a wavelength of 2.12 µm.

Fig. II.7.4. shows an example of the results obtained for these two lines. Obviously, the emissions originate from different spatial areas. The velocity field inferred from the [Si VI] emission consists of two components rotation and translation. The translatory motion is clearly influenced by the jet going from the center into two opposite directions. However, as shown by the Doppler shift of the lines, the gas flow leads into the center. This may be due to material that is initially carried away to the outside by the jet, but then returns to the central disk.

The spatial structure of the H_2 emission shows an entirely different behavior. It displays all the characteristics of a rotating gas disk and for this reason is most suitable for inferring the mass of the black hole from the disk kinematics. The total mass of the disk in the range covered by SINFONI amounts to approx. 2×10^6 solar masses, and can thus be neglected compared to the mass of the black hole.

As in the [FeII] emission, an unusually high velocity dispersion of 300 km/s appears in the central region. Without investigating its details, it was assumed to contribute to the pressure of the disk gas in the models.

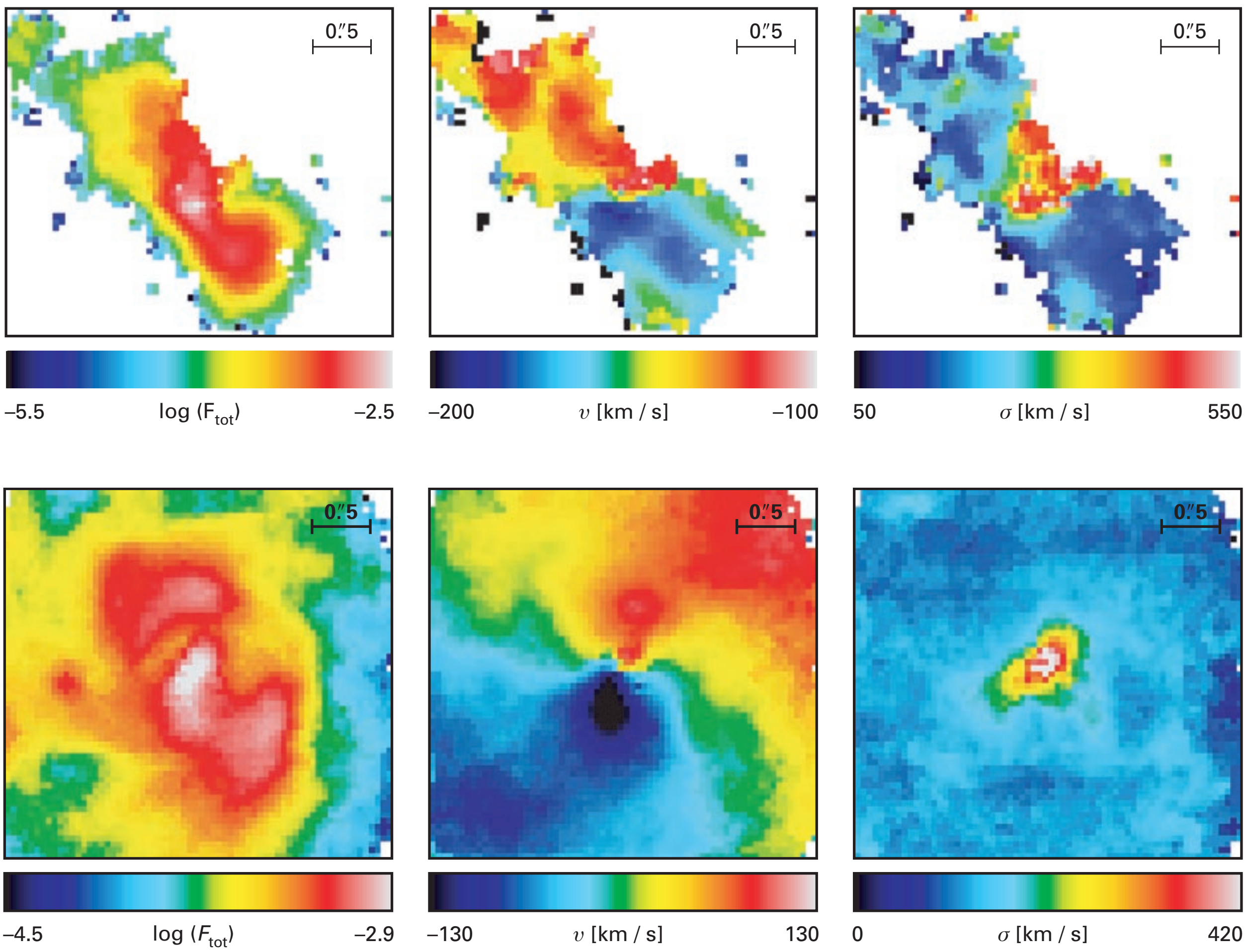
Fig. II.7.4: SINSFONI data from the central region of Cen A. *Top:* Flow, velocity and velocity dispersion, inferred from the emission line of [Si VI] at 1.96 µm. *Bottom:* the same quantities, inferred from the H_2 emission line of molecular hydrogen at 2.12 µm.

The assumption of a simple disk model as for the NACO data did not properly reflect the observational data. A better match was obtained by a turned disk. Fig. II.7.5 shows a top and side view of the best model.

When adjusting the measured data, a special dependency on the mean angle of inclination was determined. In the best model, the disk had a mean inclination of 27 degrees, the mass of the black hole was 7×10^7 solar masses. A precise analysis of the data additionally revealed a small asymmetry near the center. There, the velocity of the blue-shifted line is 30 km/s higher than the red-shifted one on the opposite side of the center. In addition, the blue-shifted area is brighter than the corresponding red-shifted one. This may be due to a gas flow in the disk, leading to a higher gas density. If such an asymmetry is accounted for by the model, the model and the measured data are in even better alignment (Fig. II.7.6).

Cen A is not an Anomaly after All

Thus, two new measured values are available for the black hole in the center of Cen A, 6.1×10^7 solar masses (NACO) and 7×10^7 solar masses (SINFONI). Both values are in coincidence within a tolerance of 10 to 15 %.



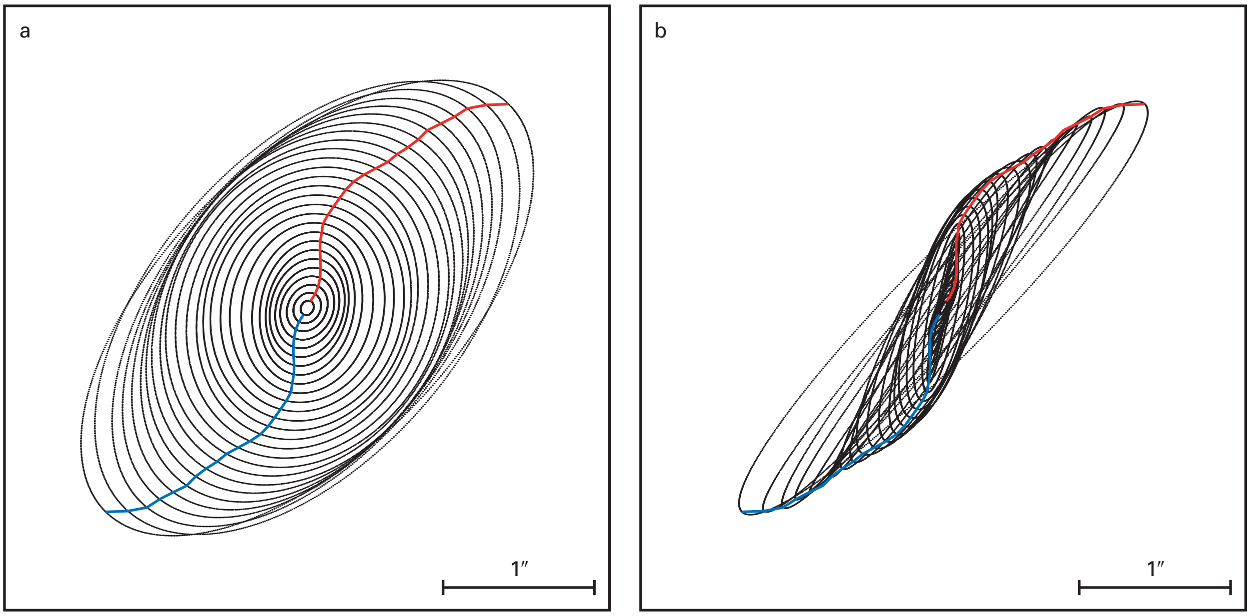


Fig. II.7.5: Top and side view of the warped disk model. The nodal line has been depicted.

However, the discrepancy between the values also has a physical reason. The observations made with SINFONI demonstrate that kinematics of the higher excitation gases have a component that results from the influence of the jet. Therefore, they are not too well-suited for determining the mass of the black hole from the kinematics of the disk. This would rather be the case with the [Fe II] line observed with NACO. The resolution of the NACO and SINFONI data shown here is approximately four times

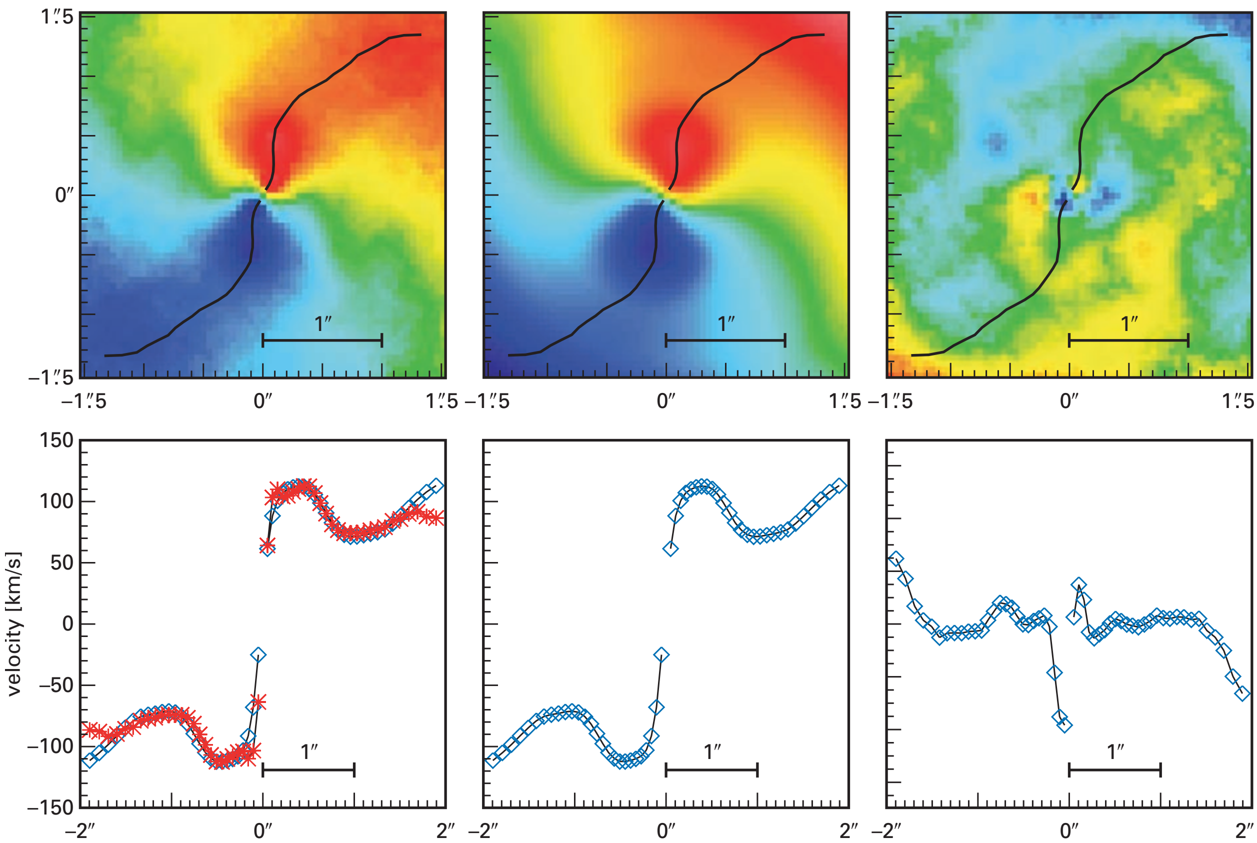
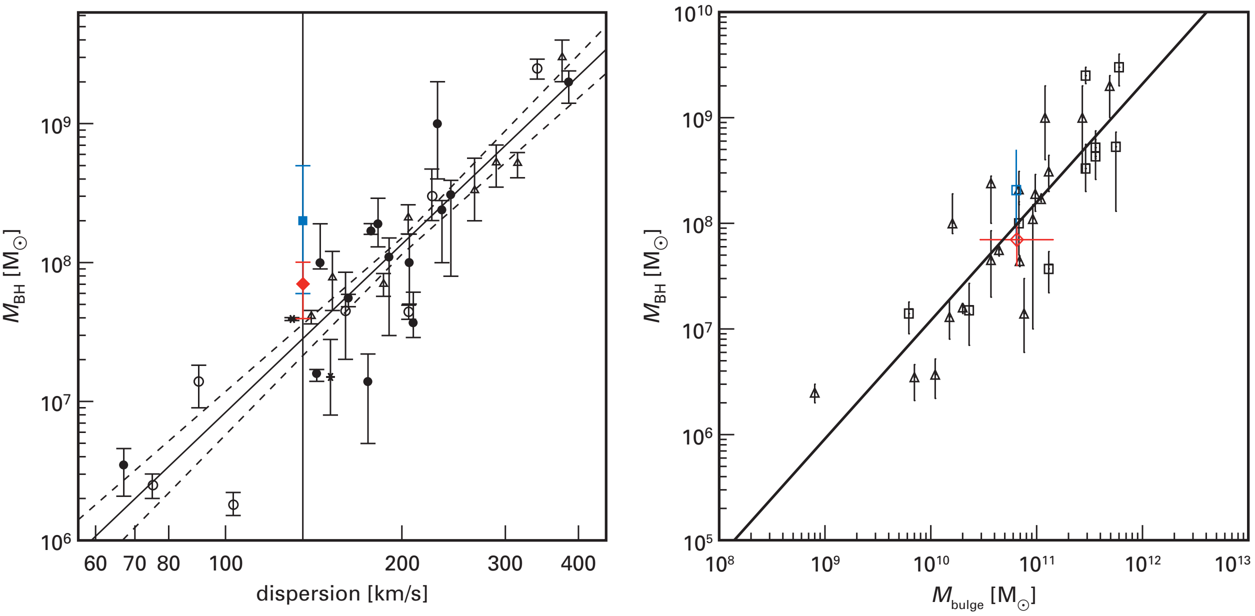


Fig. II.7.6: Comparison of the measured data (*left*) and the model (*center*). The top image shows the velocity map and the nodal line of the turned disk, and the bottom image the velocity curves along the nodal line. The two images to the right show the differences between the model and the data.



higher than that of the images previously taken by the Hubble Space Telescope. The resolution of those images was not sufficient to obtain a spatial resolution of the sphere of influence of the black hole and the influence of the jets. This resolution could now be obtained for the first time. The new data impressively demonstrate that Cen A does actually match the relations of the black hole and the bulge, contrary to prior assumptions. (Fig. II.7.7)

During these observations, several young star clusters were also discovered near the center. They will be studied more precisely in the near future in order to follow up the question as to the principle of bulge growth.

Fig. II.7.7: Relations between the masses of the black holes and the surrounding bulges (*left*) as well as their velocity dispersions (*right*). The new values for Cen A are shown in red.

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II.8 The Jet of Quasar 3C 273

Many radio galaxies and quasars exhibit an interesting phenomenon. Two gas jets are ejected from their central regions reaching up to several million light years into space. Hardly any of the jets has so far been studied as meticulously as that of quasar 3C 273 at a distance of 2.5 billion light years. Together with U.S. colleagues, astronomers of the MPIA have now undertaken new observations using the Chandra X-ray observatory. The results confirm a theory established at the MPIA several years ago, namely, that the jet exclusively emits synchrotron radiation generated by two particle populations of different energies. An additional investigation of the infrared radiation emitted by the jet, conducted by other U.S. colleagues using the Spitzer space telescope, arrived at the same result.

Astronomers at the MPIA have studied intensively extragalactic jets since about 1980, in particular the jet of 3C 273. They have contributed substantially to the understanding of the phenomenon. The jet of 3C 273 can be observed in visible light between 11 and 22 arcseconds away from the quasar. This corresponds to a distance projected on the sky of 98 000 and 196 000 lightyears. (These values hold for a Hubble constant H_0 = 70 km/s/Mpc and a flat universe with dark energy). On deep images the jet appears as a sequence of bright knots embedded in a diffuse medium.

The jet is produced in the center of the quasar where a black hole of almost one billion solar masses is located according to recognized theories. This black hole is surrounded by a gas disk from which matter swirls into the black hole. Due to an unknown process – most likely magnetic fields – gas is also accelerated vertically with respect to the disk, where it is bundled into jets that spread into the intergalactic medium.

In any case, electrons flow inside the jets generating the synchrotron radiation. It is not yet clear whether their antiparticles (positrons) also keep the jet electrically neutral, or whether this is only done by the protons. Since the radiation observed forms a pure continuum without any absorption or emission lines, the flow velocity of the gas is not directly measurable. Based on numerous findings, however, it is today considered a fact that the material inside the jet moves at nearly the speed of light.

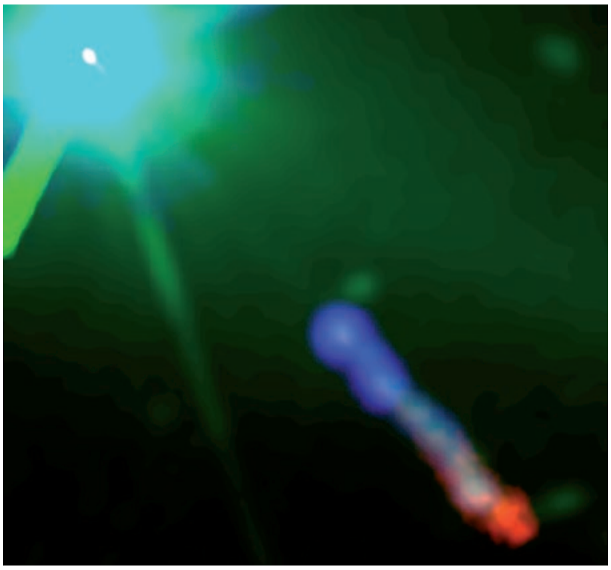
However, the way in which the parts are continuously accelerated to the high relativistic energies necessary to generate synchrotron radiation within the jet (comparable to those in terrestrial particle accelerators such as Desy, Cern and Fermilab) remains a mystery. The particles quickly lose energy due to the emission of radiation. Some of them are only able to move several hundred light years. They are definitely not capable of bridging the entire length of the jet of 3C 273 and have to be constantly re-accelerated during their rapid journey.

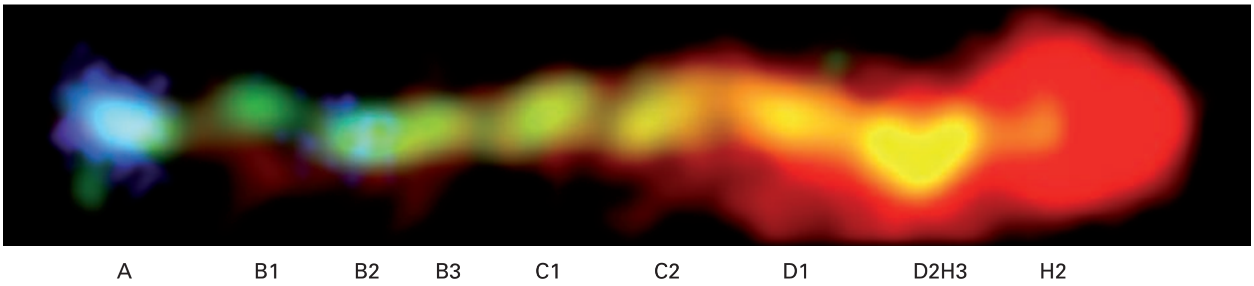
The emission of the 3C 273 jet consists of synchrotron radiation from the optical to the radio range (synchrotron radiation occurs when electrically charged particles move in strong magnetic fields). This is confirmed by polarization measurements conducted for the first time in the 1990s by astronomers of the MPIA. The similarity of optical and radio polarization suggests that a single particle population generates both optical and radio emission.

By contrast, the X-rays measured by Rosat and later on by Chandra do not appear to be of the same origin. Based mainly on Chandra observations, astronomers of the MPIA had presumed some years ago that there is a second, high-energy particle population which emanates this high-energy radiation. These observations could also explain the systematic differences observed between the spectral response in the optical/ultraviolet range and simple synchrotron spectra.

Inverse Compton emission, an alternative mechanism of X-ray emission, was also discussed. It features a single particle population where the relativistic particles with the lowest energy collide with the photons of cosmic background radiation in the jet, thus transmitting so much energy to the photons that they enter the X-ray

Fig. II.8.1: False color image of the 3C-273 jet. It depicts a superposition of the images with Chandra (blue, photon energy 0.5 8 keV), Hubble (green, 620 nm) and the VLA (red, 3.6 cm). The quasar can be seen in the upper left part.





Dominant Band:	X-ray	X-ray	X-ray	radio / optical	radio
	2 zones inverse Compton (IC) model				
Zone:	spine	spine	spine	sheat	hotspot shock
Process:	IC	IC	IC	synchr.	synchr.
	2 zones synchroton model				
Zone:	sheat	sheat	sheat	spine	hotspot shock
Process:	synchr.	synchr.	synchr.	synchr.	synchr.

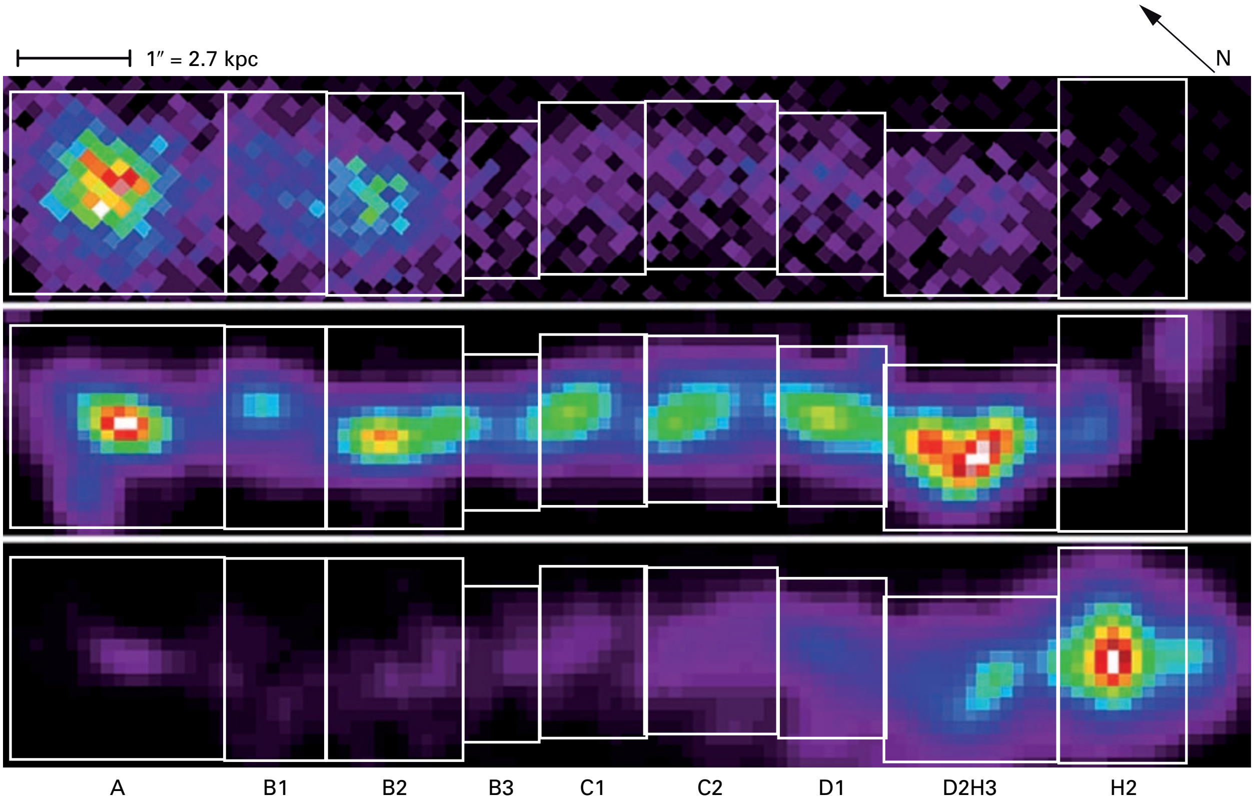


Fig. II.8.2: *Above* – The same image of the jet as in Fig. II.8.1, with the names of the emission nodes, the dominant type of radiation and details of the two emission models discussed above. *Below* – The 3C-273 jet, taken with Chandra (*top*, in X-ray light), Hubble (*middle*, at 620 nm) and the VLA (*bottom*, at 3.6 cm).

range. To bring this model into alignment with the observations, the entire jet material needs to have highly relativistic velocities. These had only been detected at much smaller distances from the central black hole until now.

Observations Using Chandra

New observations using the Chandra, Hubble and Spitzer space telescopes, together with older data from Hubble and the radio telescopes of the Very Large Array (VLA) in New Mexico should now bring clarity to this issue.

The Chandra observations were based on a total exposure time of 45 hours, and other data from the Chandra archive could be used in addition. Together with more archive pictures taken by Hubble and the VLA, it was

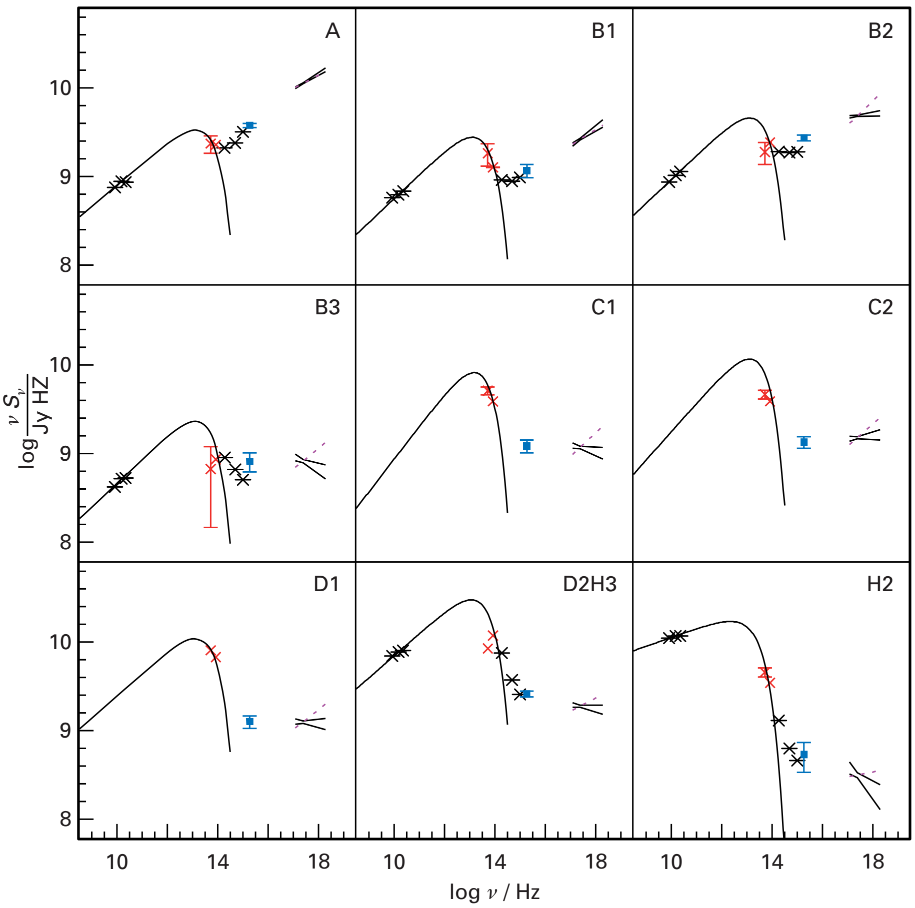


Fig. II.8.3: Spectral energy distribution of the nine nodes from the radio to the X-ray range. The dashed straight lines indicate the spectral response as predicted by the Inverse Compton Model for a single particle component, with an identical slope in the X-ray and the radio range (dotted magenta straight line). The red × marks are the measuring points of SPITZER at wavelengths of 3.55 µm and 5.73 µm, corresponding to frequencies of 5.2 and 8.5×10^{13} Hz, respectively. The blue squares reflect the new HUBBLE data at 150 nm (2×10^{15} Hz). The continuous lines are examples of the curves of the two spectral components.

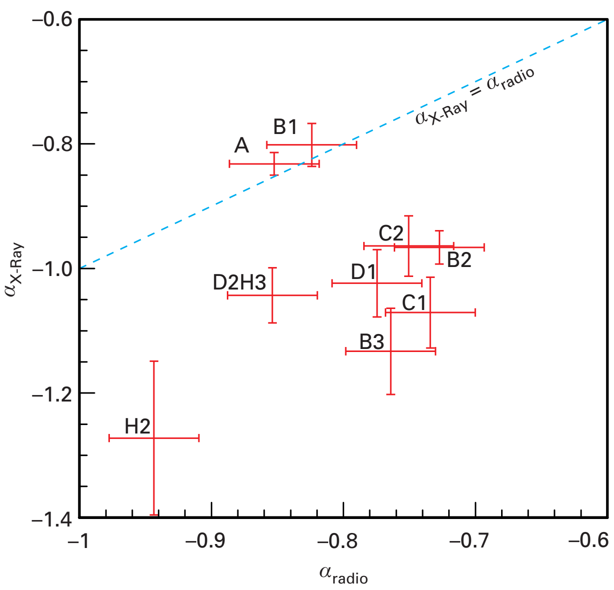
possible to perform a spectral analysis for nine regions of the jet. A superposition of the pictures taken by these three telescopes is shown in Fig. II.8.1. The individual images are depicted in Fig. II.8.2.

It was possible to determine the spectral energy distribution of the nine nodes between the radio and the X-ray range from this data (Fig. II.8.3). The dashed straight lines in magenta indicate the spectral response as predicted by the Inverse Compton Model for a single particle component the spectral response in the X-ray range was supposed to reflect that in the radio range (dotted magenta straight line). Matches were only found for nodes A and B1. The X-ray spectral indices of all other nodes beyond B1 were too small. This becomes even more obvious in Fig. II.8.4, where the spectral indices have been plotted for the radio and X-ray range.

The data clearly contradict the Inverse Compton Model for a single particle component yet does it also enable a distinction to be made between an Inverse Compton Model and a synchrotron model if they both include two different particle components?

Fig. II.8.5 is a schematic representation of the potential location of the particle populations within the jet. There is good reason to believe that the flow velocity is higher along the spine than at the sheath. This transverse velocity gradient would affect the Inverse Compton Emission. In this case, the highly relativistic inner part would be responsible for the X-ray emission, whereas the synchrotron emission would be produced with lower energy at the sheath. The radiation processes would be difficult to predict in such a case. However, an estimate shows that the flow velocity of the jet material should be extremely

Fig. II.8.4: The spectral indices for the radio and X-ray ranges in the nine jet nodes.



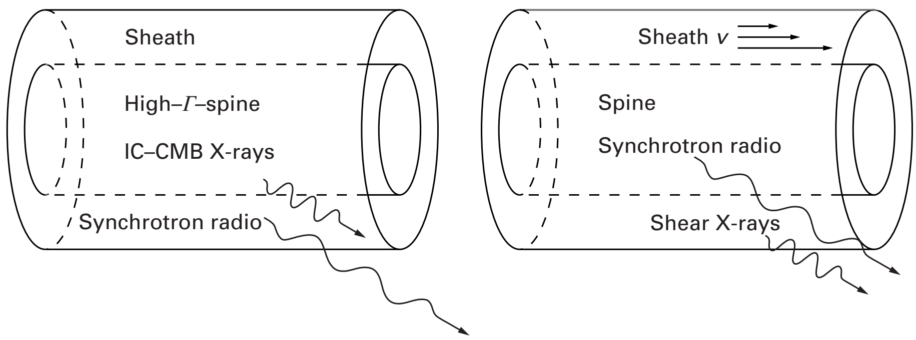


Fig. II.8.5: Two-component models for the Inverse Compton Emission of cosmic background radiation (*left*) and for synchrotron emission (*right*).

relativistic in the central region. Estimates regarding the Lorentz factor known from the special theory of relativity lie between 50 and 100, values that do not appear to be plausible for such jets. In addition, the Inverse Compton Model requires very special assumptions in order to explain why the spectrum is characterized by a "softer" response in the X-ray range than in the radio range.

The pure synchrotron model is capable of providing a simpler explanation of the data observed based on the assumption of a transverse velocity gradient. In this case, lower-energy particles in the central region generate the radio synchrotron radiation, whereas magnetic effects in the velocity gradients of the sheath produce energy-rich particles emitting X-ray synchrotron radiation.

Observations Using Hubble and Spitzer

The wavelength range covered in the UV was extended to 150 nm using Hubble. This made it possible to examine whether the spectral deviations in the optical range were actually generated by the same component as the X-ray radiation. Another possibility for deciphering the processes in the 3C 273 jet was offered by observations using the Spitzer infrared telescope at four wavelengths between 3.6 and 8 μm. These were obtained and evaluated under the leadership of astronomers at Yale University. The distances of approx. 1″ between the emission nodes are slightly smaller than the telescope's resolution. However, intensity fits of the luminosity distribution along the jet's spine enabled photometry of the jet's nodes.

The Spitzer data filled a critical gap in the spectral energy distribution, as shown in Fig. II.8.3. The measured points at a wavelength of 3.55 and 5.73 μm (corresponding to frequencies of 5.2 and 8.5×10^{13} Hz, respectively) are in a range in which the distribution curve is strongly bent. Again, the deviant behavior of nodes A and B1 compared to that of C1, C2 and D1 is quite obvious. These two inner nodes are characterized by intense radiation in the X-ray range, while the others are mainly found in the mean infrared.

It can also be very clearly recognized here that the spectral energy density increases from the radio range to the infrared range in A and B1, experiencing a cutoff at approx. 5×10^{13} Hz. The high-energy component curve is then plotted steadily from the optical up to the X-ray range at 10^{17} to 10^{18} Hz. Even the outer nodes are characterized by a cutoff, however, their energy density does not increase towards the X-ray range.

More recent data in the various spectral ranges indicate that radio radiation, infrared and optical light as well as X-ray radiation are not generated independently. Rather, the entire radiation emitted by the jet originates from ultra-energetic particles in the form of synchrotron radiation. As suggested by the MPIA scientists involved some years ago, a certain portion of the emission in the infrared, optical and ultra-violet range is generated by the same particle population as the X-ray radiation, and at least half in nodes A, B1 and B2.

The high optical polarization in these nodes was originally interpreted as a generation of radio and optical synchrotron radiation by the same particle component. However, the new data suggests that the optical polarization also reflects that of the X-ray component which most likely also constitutes synchrotron radiation.

The Inverse Compton Model of cosmic background radiation has not been clearly contradicted by this study, however, the physical conditions that need to be present to explain the data appear to be rather unlikely. In any case, there must be two particle populations in order to explain the spectral energy distributions, in particular, as regards the outer nodes. Polarimetry with a high spatial resolution using the Hubble telescope could eliminate these last doubts.

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NASA/GSFC, Greenbelt; ISAS/JAXA, Kanagawa

III. Selected Research Areas

III.1 Young Extrasolar Planets

One of the most exciting fields in astronomy today is the exploration of planetary systems beyond our own Solar System. A new era started with the first discoveries of extrasolar planets about a decade ago. The MPIA is involved in several programs devoted to forefront instrumental development as well as the search and study of extrasolar planets.

The first extrasolar planets found were indeed orbiting stars which are very different from our Sun, known as pulsars. The discovery of the first extrasolar planet around a solar-type star in 1995 by the Geneva group was certainly one of the greatest discoveries of the last century. Following this success, more than 200 extrasolar planets have now been discovered around solar-like stars. Unexpectedly, many of the planets discovered are giant planets located very close to their host stars. They orbit their central stars within a couple of days. Also planets on very eccentric orbits and in locked resonances have been discovered. Most planetary systems found so far are indeed very different from our Solar System. At this time there is still no clear-cut explanation how such planetary systems have formed. Disk evolution, planet migration and interactions between the planets certainly play a role in explaining the diversity of planetary systems. Recently, the radial velocity technique has led to the detection of smaller, Neptune-mass planets and the transit method allowed astronomers to determine the density of giant planets. Microlensing events provided evidence of planets with masses close to the mass of the Earth.

Most of the stars that host planet are solar-type stars. Very few objects with masses, atmospheres and evolutionary stages different from those of the Sun have been searched for the presence of planets. In particular, there is still no convincing evidence for planetary companions around young stars, which are actually very important to understand how planets form. Future discoveries of young planets will certainly provide important constraints on the theories of planet formation.

Fig. III.1.1: The ESPRI logo (Exoplanet Search with PRIMA)

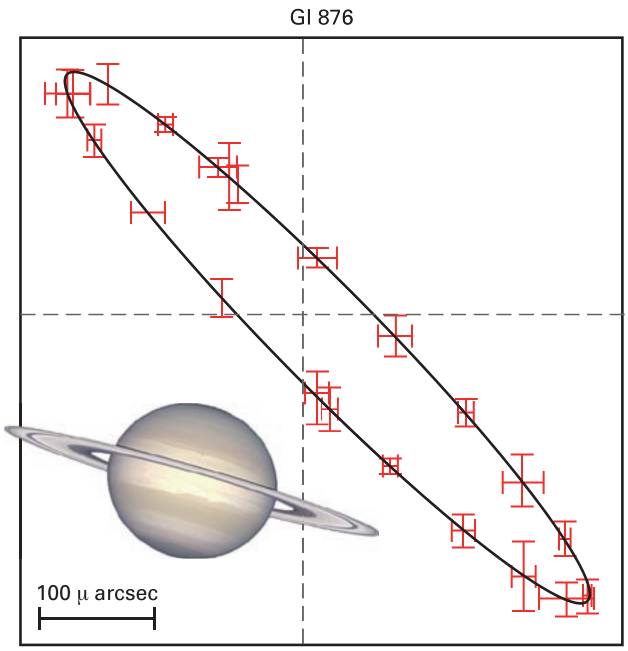


Fig. III.1.2: 30 measurements of the star Gl 876 over three years of 10 μ arcsec per measurement.

Planet Search Programs at the MPIA

The majority of the extrasolar planets have been discovered by the radial velocity technique. Currently, there are many dedicated planet search programs and instrumentation projects which search for extrasolar planets using all the various available techniques, ranging from transit detections to direct imaging.

Our Institute is participating in a number of large planet search projects, both by providing instrumentation and performing science projects. With the adaptive optics system NACO at the VLT and its new differential imaging device, we performed a very comprehensive imaging survey for substellar companions. This tech-

Fig. III.1.3: The SPHERE logo.

nique provided the largest contrast ratio attained thus far by ground-based observations. Just recently, we participated in getting the first spectrum of a giant planet with the SPITZER space telescope. With this instrument we also investigated the relation between the presence of planetary systems and asteroid and Kuiper belts, uncovering the whole structure of planetary systems.

One of the promising methods to detect extrasolar planets is high-precision astrometry (10 micro-arcsec). The MPIA is part of an international consortium that builds and delivers the Differential Delay Lines and the astrometric data reduction software for PRIMA (Phased Referenced Imaging and Microarcsec Astrometry) at the VLTI (Very Large Telescope Interferometer). The astrometric facility PRIMA will use two Auxiliary Telescopes (AT) at the ESO Paranal observatory. In return for this effort, the consortium has been awarded guaranteed time observations to conduct a large and systematic astrometric planet search program with PRIMA (ESPRI: Exoplanet Search with PRIMA). The MPIA is the leading partner for the preparatory observations for ESPRI.

The most spectacular technique to find extrasolar planets is certainly the direct imaging method. The MPIA is involved in the direct imaging planet instrumentation project, which is called SPHERE (Spectroscopic and Polarimetric High-contrast Exoplanet REsearch). This is one of the second generation instruments for the VLT which comprises an extreme adaptive optics system (XAO), a differential polarimeter working in the visual, an integral field spectrograph and a versatile NIR (differential) imager and spectrometer. Designed solely for the benefit of high-contrast science, SPHERE will be able to detect a Jupiter-mass planet of age 10 Myr down to separations of $0\farcs2$ around an $M_\odot$ star at 40 pc, and a planet of 10 Jupiter masses down to $0\farcs1$ around a 1 Gyr old $M_\odot$ star at 10 pc. The MPIA is the Co-PI institute in the SPHERE consortium with a total share in the project of between 10 % and 15 %.

In addition to the astrometry and direct imaging projects, the MPIA is developing an instrument for the transit planet search with the 1 m Wise telescope in Israel (LAIWO project) and is leading a large exoplanet transit search survey (PAN-Planets). The PAN-Planets project is a search for transiting extrasolar Jupiter-like planets with the 1.8 m PS1 telescope and its wide field camera of 7 square degrees, at the Lure Observatory at Haleakala, Maui, Hawaii. The main goal of this survey is to find more than 100 very hot to hot Jupiters. This program will start in 2008.

Fig. III.1.4: The 2.2 m MPG/ESO telescope in La Silla observatory in the foreground. The New Technology Telescope and the 3.6 m telescope are seen in the background.

Search for Young Planets

Complementary to our ongoing instrumentation projects and surveys (Espri, Sphere and Pan-Planets), we are carrying out extensive stellar radial velocity monitoring of selected nearby young stars to search for sub-stellar (brown dwarf/planetary) companions. This radial velocity survey, called Seram (Search for Exoplanets with Radial-velocity At MPIA), was started in December 2003.

The Seram project uses Feros, an echelle spectrograph located at the 2.2 m MPG/Eso telescope at the Eso La Silla Observatory (Chile). The objective of this survey is to observe stellar radial velocities and their variation by using a "simultaneous calibration" method. This means that the calibration spectra are taken simultaneously while recording the stellar spectra. This method enables correcting for instrumental instability when measuring the radial velocities. The long-term radial velocity accuracy of Feros is better than 10 m/s, as measured in HD 10700 from December 2003 until January 2007, which has been used as our radial velocity standard star.

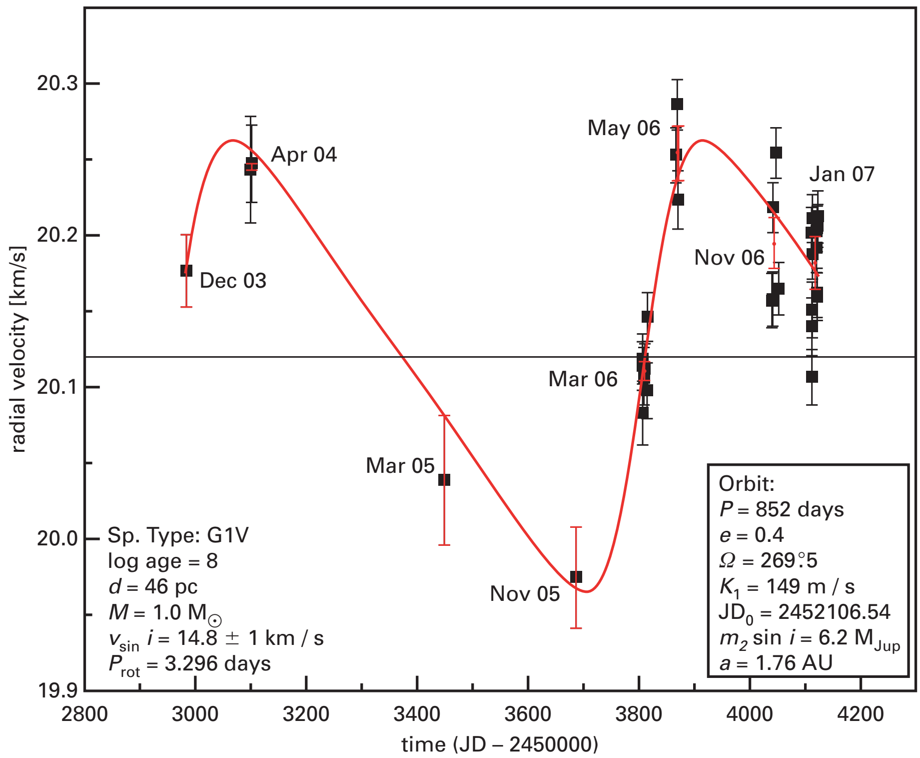
Unlike other large radial velocity planet search programs, which are concentrating on planet searches around stars similar to the Sun, the Seram project monitors radial velocity variations of stars which are different from solar-type stars. In particular, the majority of the targets are active, especially young stars (with ages of a few million to about 300 million years).

There are three possible sources for radial velocity variations in active stars. These are (i) stellar companions in binary or multiple stellar systems, (ii) surface inhomogeneities such as starspots (similar to sunspots) or stellar pulsations, and (iii) substellar companions (planets or brown dwarfs). These sources can be distinguished, for example, by the analysis of the spectral line profiles or characteristics of the variation in radial velocity (periodicity, amplitude).

Stellar companions produce variability of the observed radial velocities with amplitudes from several hundreds m/s up to km/s. Starspots and stellar pulsations induce variations of spectral line profiles, which are correlated with the radial velocity. This feature can be found in the variation of the shape of the spectral line profile. Finally, the presence of substellar companions can be concluded, if the observed radial velocity variation is neither due to stellar companions nor surface inhomogeneities. However, planets can also be found in binary or multiple stellar systems as well as around stars with starspots. This may require additional independent measurements like photometry, astrometry, etc.

The planet detection by the radial velocity method has some limitations. For example, it can be optimally applied only to cool, slowly rotating stars. The main weakness of this technique is that the real mass of the planet cannot be determined by this method. It only allows one

Fig. III.1.5: Radial velocity variation of HD 70573, measured with Feros from December 2003 until January 2007.



to measure the minimum mass of the planet due to the unknown inclination angle. Moreover, the radial velocity technique is only sensitive to planets orbiting close-in. Also, it cannot be used to measure the size of the planet. All of these problems can be solved by other detection methods, such as precise astrometry, direct imaging, transit searches, and microlensing.

A Planet Candidate Around the Nearby Young Star HD 70573

In the three year period of observations, the SERAM project has discovered a number of spectroscopic binaries or stars in multiple stellar systems, starspots and pulsations in active stars as well as several planet candidates around young stars.

The first great success came with the detection of a planetary-mass companion around the giant star HD 11977. This star is an intermediate-mass star of 1.9 $M_{\odot}$. There have been very few discoveries of planetary companions around intermediate-mass stars until now. This mass range covers the spectral type of A to early F in the main-sequence phase. Such stars are not accessible with the radial velocity method. However, after the star has evolved to the giant branch, precise radial velocity measurements can be performed.

The most recent result is the discovery of a planetary-mass companion around the young star HD 70573 (Fig. III.1.5). This star belongs to the Hercules-Lyra association, a group of stars comoving in space towards the constellation of Hercules. The star is located at a distance of about 150 light years from the sun. From our spectroscopic measurements of the Lithium equivalent widths, which can be used as an age indicator, we derived an age within the Pleiades age regime (78 – 125 Myrs). We were also able to determine stellar parameters such as the spectral type, stellar mass, effective temperature and stellar metallicity. We found that HD 70573 has a similar mass to the Sun but has only 66 % of the solar metallicity.

The radial velocity measurements of HD 70573 show a variation with a period of about 852 days and a semi-amplitude of 149 m/s. On a smaller time scale of several days, we also detected short-term variations which are probably due to stellar activity. By analysing the shape of the spectral lines we have been able to discern the nature of the radial velocity variation. In particular, we found that the observed radial velocity variation is not due to the stellar activity, but rather due to a sub-stellar companion. We derived the minimum mass of the companion, which is 6.1 times the mass of Jupiter. Thus, this mass falls in the planetary mass regime. Our computations yield an orbital solution with a semi-major axis of 1.76 astronomical units and an orbital eccentricity of 0.43.

Thus far, HD 70573 is the youngest star with an extrasolar planet, discovered with the radial velocity technique. The discovery of planets around young stars provides important constraints for theories of planet formation. An example is the migration process of planets, occurring in the gas-rich phases of protoplanetary disks. The detection of young planets will also allow us to study the relation between extrasolar planets and the structure of debris disks. Since HD 70573 is part of the young star sample of the SPITZER/FEPS legacy program, the detection of a planetary companion around this star is of great interest for the study of the relation between debris disks and planets. The planetary system around HD 70573 could resemble the young Solar system, but its architecture is quite different.

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III.2 The Birthplaces of Planets

The structure of protoplanetary disks, and its relation to the types of stars which are formed within them, is a central research topic at MPIA. Only by a broad approach and by a combination of theory and observations, real progress can be made in this area. To achieve this goal, we have built a large research group over the last few years which covers a wide range in observational and theoretical approaches to study these disks.

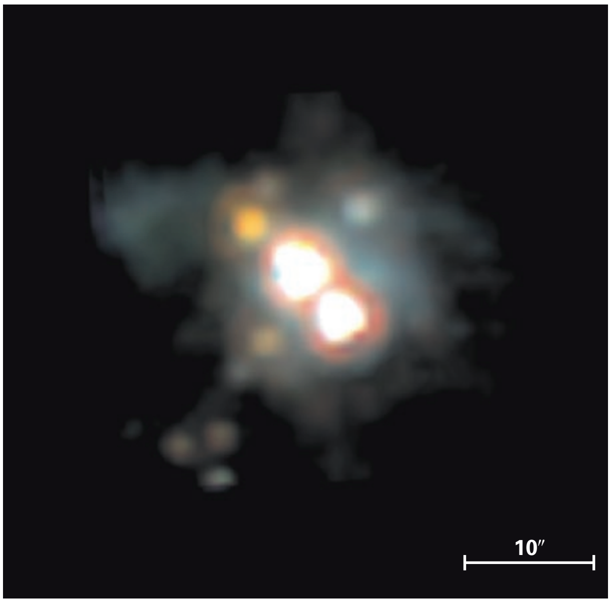
In the last decade, the question of how planets form has become one of the key questions of astronomy. One of the reasons for this is the discovery, since 1995, of over 200 extrasolar planets orbiting around other solar-type stars, proving that our solar system is not unique. Another reason for the increased interest in planet formation is the enormous advance in observations of protoplanetary disks, the planetary cradles surrounding many young stars. Beginning in the mid-nineties the Hubble Space Telescope has produced spectacular images of such disks, and telescopes such as the Very Large Telescope Interferometer (VLTI) in Chile, endowed with new infrared instruments such as the Mid-infrared interferometric instrument (Midi, built at the MPIA) have produced an infrared view of these disks with unprecedented spatial resolution. We can now directly observe and analyze the "habitable zone" in a protoplanetary disk around nearby young stars. With the InfraRed Spectrograph (IRS) on board the Spitzer Space Telescope, covering the wavelength range of 5 – 37 micrometers, infrared spectra have been obtained from objects as faint as Brown Dwarfs (with stellar mass $M_* \leq 0.08\ M_\odot$) to objects as bright as Herbig Ae stars (with stellar mass $M_* \approx 2\ M_\odot$). Finally, with submillimeter telescope arrays such as the Plateau de Bure Interferometer the thermal dust emission as well as various molecular lines from a number of young protoplanetary disks have been studied. These, and many other observations have produced evidence of the on-going process of aggregation of dust particles to bigger aggregates – the first small steps along the long road of planet formation in these disks. As a result, we now have a much better picture than a few years ago of how these "proto-solar systems" form, what their structure is, how they evolve and what ultimately leads to their demise.

The Planet and Star Formation (PSF) department at the MPIA is strongly active in the study of these protoplanetary disks. With a comprehensive approach, the PSF department aims at producing a view of the bigger-picture: the process from a collapsing protostellar cloud core through the formation and evolution of a disk, eventually to a full-fledged planetary system. This requires both extensive observational campaigns as well as theoretical modeling. The fact that both theory and observations are strongly represented in the PSF department of the MPIA is advantageous. Observations are routinely compared to theoretical models, allowing the observations to be better understood, as well as the theoretical models to be refined. In this article we give an overview of PSF research activities covering nearly the entire field of protoplanetary disks, and the study of how planets are formed in these disks.

Formation and Evolution of Disks

Protoplanetary disks are by-products of star formation. As a low or intermediate mass star is formed from a gravitationally collapsing rotating molecular cloud core, the conservation of angular momentum leads to the formation of a rotating disk around the star. Magneto-turbulent torques within this rotating disk subsequently allow most of this matter to accrete onto the star, leaving, after a few hundred-thousand years, a remnant disk which is generally called a protoplanetary disk. Such a

Fig. III.2.1: Spitzer Space Telescope color-composition image of the region around the FU Orionis type star+disk sources RNO 1B/1C taken with the Irac camera at 3.6, 4.5 and 8.0 µm. This image shows the co-existence of FU Orionis type star + disk sources with deeply embedded class 0/I sources, providing evidence that FU Orionis objects are extremely young star + disk systems.



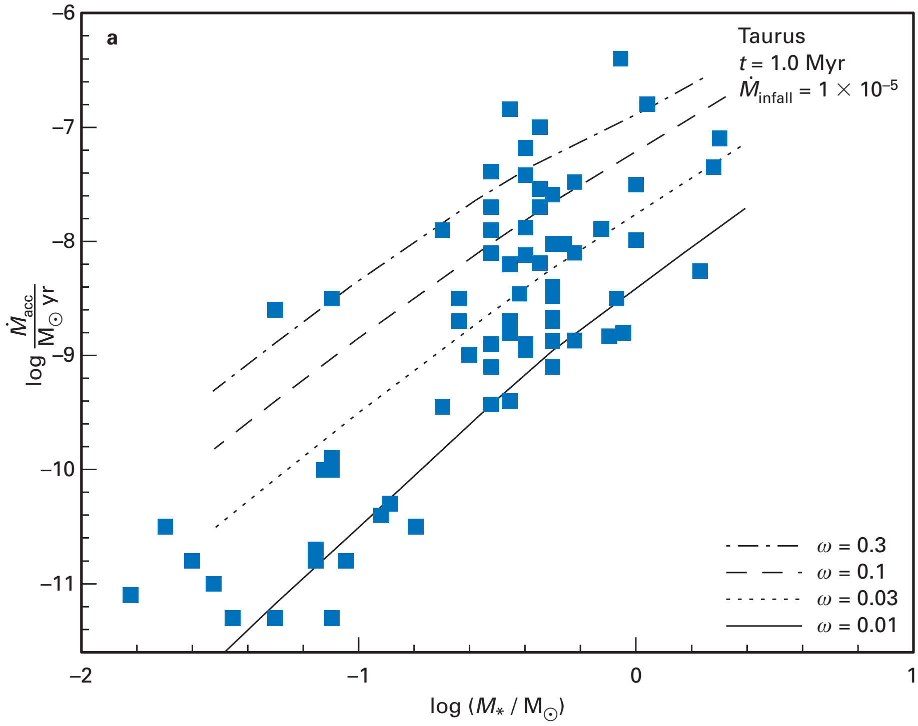
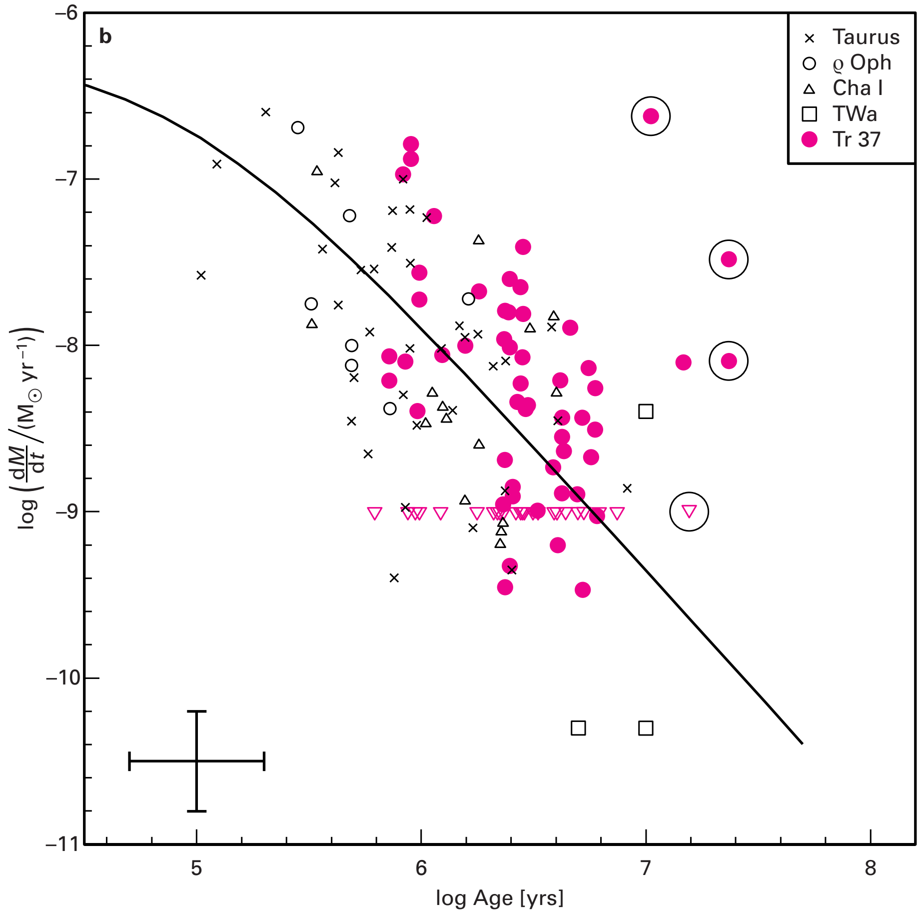


Fig. III.2.2: *a)* The measured accretion rates in solar masses per year as a function of stellar mass in units of solar masses for a sample of young stars in the Taurus molecular cloud complex. The lines are model predictions, created with our disk evolution models for various assumed rotation rates, ω, of the original cloud core from which these stars and disks were formed. *b)* The accretion rate as a function of age measured for a sample of stars in the Tr 37 cluster. *Solid line:* model prediction for one set of initial disk conditions.



disk typically lives a few million years, after which it rapidly disappears, presumably due to a combination of accretion, photoevaporation by stellar UV photons and the conversion of disk material into a planetary system. In the PSF department we study the formation, evolution and dissipation of disks, both from a theoretical and from an observational perspective.

The earliest evolutionary stages of protoplanetary disks are presumably represented by sources known as FU Orionis objects. These are presumably star + disk systems that experience very bright and long-lived outbursts in luminosity. The standard theory is that these outbursts are caused by instabilities that can occur in very massive young disks, meaning that these stars represent perhaps the youngest star + disk systems known. We have recently found evidence for their youth from an image of a very young protostellar cluster taken with the SPITZER Space Telescope (Fig. III.2.1).

As these disks evolve past the unstable initial stages, their masses and accretion rates go down. In the PSF department, we develop models of this disk evolution, from the very early formation stage through the protoplanetary phase (one to a few million years) to the disk's dispersal. These models make predictions for various observable properties of star + disk systems, such as the rate of accretion of disk material onto the stellar surface as a function of the observed stellar mass (at a given age) or as a function of age (for a given stellar mass), both of which can be compared to observed values for samples of young stars (Fig. III.2.2).

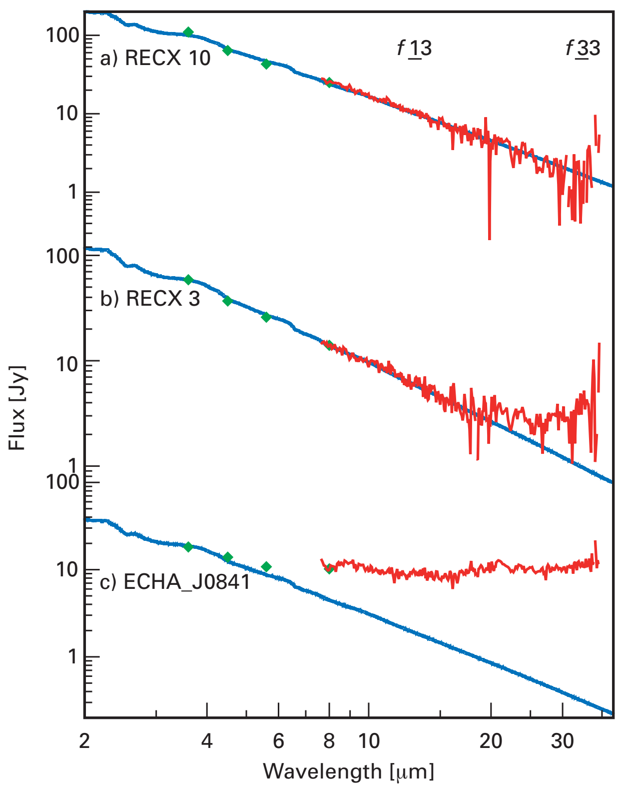
As can be seen in Fig. III.2.2a, observations show that the accretion rates of such stars have a large spread, but exhibit a rough general trend with stellar mass: $\dot{M} \sim M_*^2$. Stationary (non-evolving) disk models are not able to reproduce this quadratic trend, nor provide a satisfactory explanation for the spread.

However, time-dependent models of disk formation and evolution show that this trend can be naturally explained as a result of the very early formation history. The observed spread in accretion rate $\dot{M}$ for a given stellar mass is thereby naturally explained as a consequence of the initial rotation rate of the parent cloud from which the system was formed. Moreover, from basic considerations of angular momentum of clouds of different mass, the $\dot{M} \sim M_*^2$ trend is naturally reproduced with these models.

One can also include more disk properties in the analysis, such as the infrared photometry and spectroscopy of such sources. We have studied the accretion rates, stellar masses and the infrared spectral energy distributions of 160 stars in the 4 million year old rich cluster Tr 37. We found that many of the stars do not have a disk anymore, consistent with expectations for a cluster of this age. The accretion rates measured from the star+disk systems appear to be consistent with disk evolution models (Fig. III.2.2b). Interestingly, about 10 % of these objects show infrared spectral energy distributions that are indicative of these disks having a large inner hole. For these stars, all the matter inward of a few AU appears to have been removed by some process. One conjecture is that these are disks which are on the verge of being destroyed by photo-evaporation. In this scenario the UV luminosity of the star continuously burns away matter from the surface of the disk until, ultimately, the disk disappears altogether. Indeed, models of disk evolution predict such inner holes to be produced just prior to the full disk photo-destruction.

There are also other factors that can influence the presence and structure of disks. One such factor is the binarity of these stars. The companion star may, by its own gravity, affect or destroy any originally present disk. We obtained SPITZER Space Telescope spectra of the late-type members of the about 8 Myr-old η Chamaeleontis star cluster. As a result of the coeval nature of the cluster, differences in disk properties and dust composition cannot be caused by age, but rather by other stellar properties such as luminosity and mass or binarity, or different initial masses of the disks. As one can see in Fig. III.2.3, substantial differences

Fig. III.2.3: Spectra of circumstellar disks (and their stars) around single and binary stars in the η Chamaeleontis cluster. *Blue:* a model of the stellar photospheric spectrum. *Red:* the spectrum observed with SPITZER. The excess emission above the prediction of the photospheric model is disk emission. By measuring the ratio of the fluxes at the marked positions (13 and 33 microns), one can determine whether a disk is present and if so, whether it is a young disk or a disk with inner hole which is on the verge of dissipation.



between the SED of the systems exist. While in some of the systems disks have already dispersed, others still have a massive, actively acreting protoplanetary disk. We find that the presence of a circumstellar disk is anti-correlated with binarity, with all but one disk associated with single stars (Fig. III.2.4). An estimate of the characteristic mean timescale on which a disk is dissipated gives approximately 5 million years for the binaries and 9 million years for the single stars. The much shorter disk lifetime in close binary systems suggest that planet formation, particularly Jovian planet formation, in the core-accretion scenario could be severely inhibited in close binary systems. In the last Section we will focus more on the problem of planet formation in disks.

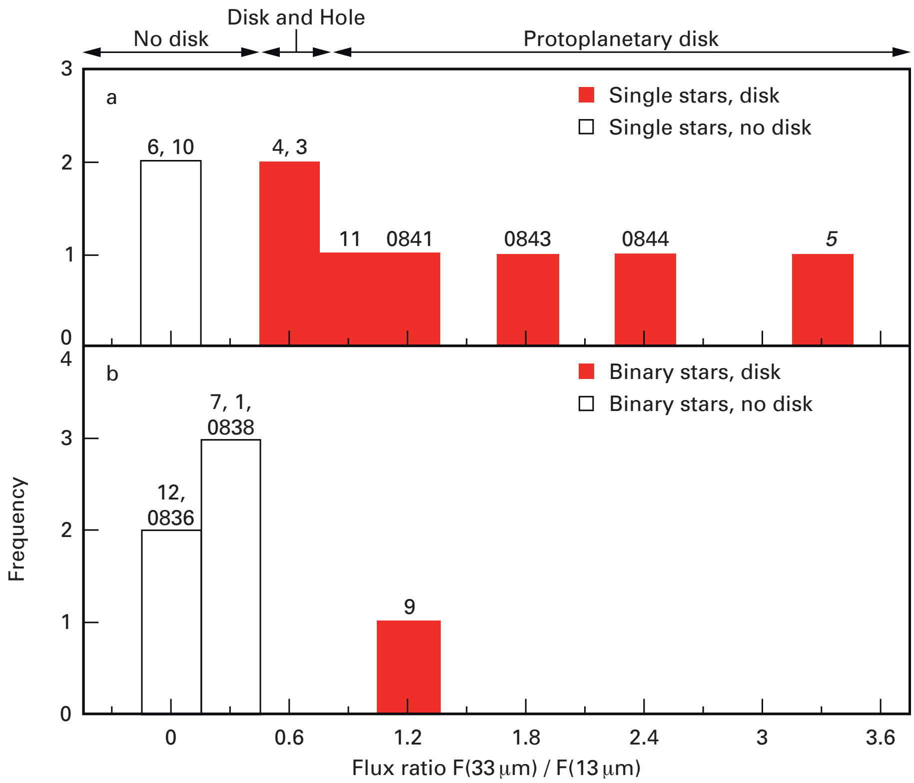
Three-dimensional Dynamic Models of Protoplanetary Disks

Protoplanetary disks have a rich and complicated structure. Spatially resolved images (see below, p. 69) show spiral and elliptical structures in the outer regions of these disks at scales of a few hundred astronomical units (AU), but also the inner regions of disks behave in a complicated way. We have a team of theoretical astrophysicists that work on various detailed numerical models of disk structure. As we reported in the Annual Reports of 2004 and 2005, we produce model predictions of how embedded planets in these disks affect their appearance as seen by future millimeter arrays (see also Section II.3 in this Annual Report), and we model the nature of turbulence in such disks. We now also perform detailed radiation-hydrodynamic models of the disk structure. Parallel to this, we also develop simpler 2-D axisymmetric hydrostatic models which – because they are far less computer-time consuming – lend themselves to easier direct comparison with observations. In this section we show two examples of our 3-D hydrodynamics models.

Turbulence in Protoplanetary Disks

Although we have studied turbulence already for several years in a shearing sheet approach (see annual report 2005), we are now extending this research to global models. Local simulations naturally suppress large scale modes of turbulence and the effects of radial variations in the disk. Now the ZEUS-MP package is used to simulate the magneto-rotational instability in the global frame. In a first study we have demonstrated that the radial pressure stratification introduces no significant changes with respect to the local analysis. Strong fluctuations in the vorticity distribution are found in the disk (Fig. III.2.5). Those fluctuations have shown to be the seeding points for planetesimal formation. We currently add the explicit treatment of dust in the global simulations and test the effects of globality on dust diffusion, concentration and planetesimal formation.

Fig. III.2.4: Frequency of disks with different structures around single and binary stars in the η Chamaeleontis cluster, as determined from their flux measured at 13 and 33 microns.



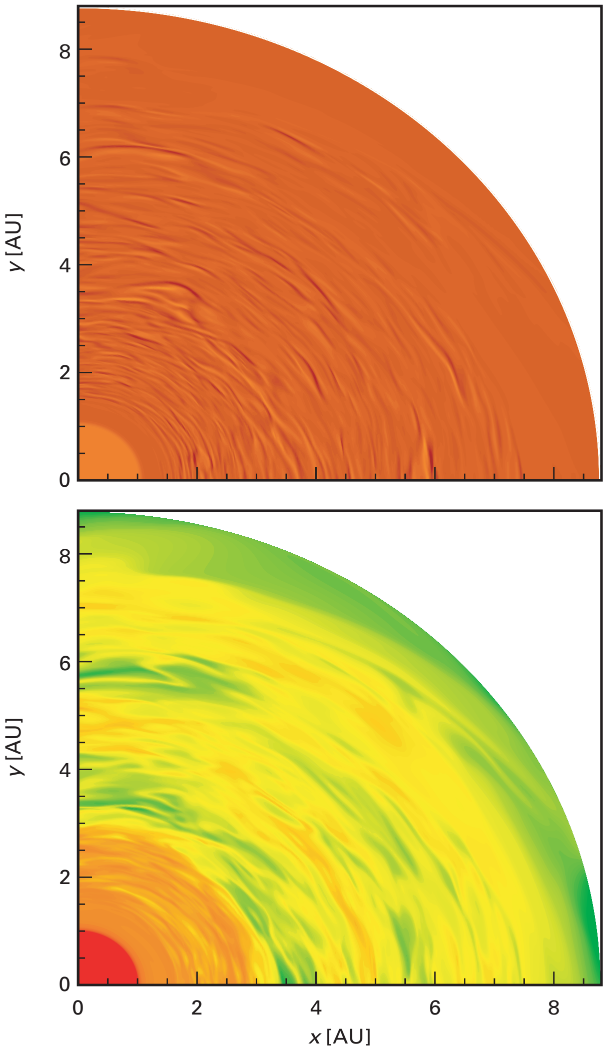


Fig. III.2.5: Vorticity and turbulence in global magneto-hydro simulations of protoplanetary accretion disks. The time shown is 400 orbits after the start of the simulation. *Above:* Mid-plane slices of vorticity: white is for cyclonic, red is for anti-cyclonic vorticity. *Below:* Logarithmic density at the midplane; red is maximum and green is minimum.

Inner Edge of Disks

In order to test the predictions for the so-called puffed up inner rim of disks around Herbig Ae stars, we now perform the first 3D Radiation hydrodynamic simulations of these rims, including irradiation from the central object via ray tracing and emission from the dust grains in the flux limited diffusion approach. These studies confirm the existence of a slight shadow casting inner rim for the first time in time dependent hydro-simulations, even though the shadow-casting rim is not as strongly puffed-up as was predicted by earlier models (Fig. III.2.6). The long term evolution is now studied. As expected, the formation of non axi-symmetric modes are observed in the density structure of the inner rim coupled with the formation of anti-cyclonic vortices. Yet, the optical apperance from a homogenous inner rim is not significantly altered.

Gas-phase Chemistry in Protoplanetary Disks: Theory and Observations

Although protoplanetary disks are most easily observed in the continuum emission originating from dust grains, the disk consists of 99 percent gas. It is therefore of obvious interest to find ways to directly probe the gas phase of the disk in order to test theories of disk structure and kinematics, but also of the gas-phase chemistry in these disks. Moreover, chemistry determines the degree of ionization in the disk, which is the most important parameter regulating the accretion rate in the disk. The gas of protoplanetary disks can be probed directly by measurement of molecular lines such as the CO ro-vibrational lines discussed above as well as (sub-)millimeter rotational lines of a wide range of molecules, from simple molecules such as CO to more complex molecules such as H_2CO. However, the information about the structure of the disk is well "hidden" in these emission line spectra and often cannot be easily interpreted. The modeling of chemistry in protoplanetary disks followed by molecular line radiative transfer simulations is a unique way to put tight constrains on physical conditions as well as kinematics and composition of disk matter. We developed a robust and state-of-the-art chemical model of an evolving protoplanetary disk that includes the chemo-dynamical interaction between various gas elements as well as dust grains (turbulent mixing). In essence, turbulent mixing acts as an efficient mechanism of desorption of frozen molecules back to the gas phase, and as a catalyst of rich surface chemistry leading to the formation of complex (organic) species. With this model it was possible to explain a puzzling observational fact – the presence of a large reservoir of very cold CO gas in the disk around DM Tau observed by Dartois et al.~(2003), see Fig. III.2.7. This is in contrast to the results of static (non-mixing) chemical models where all CO molecules completely freeze out in the dark, dense and cold disk midplane ($T < 20$ K) within only a tiny fraction of the disk lifetime of a few Myr.

Under the framework of the "Chemistry in Disks" (CID) collaboration between MPIA, Observatoire de Bordeaux, Jena, and Observatoire de Paris we observed two Sun-like stars (DM Tau, LkCa 15), and a more massive Herbig Ae star (MWC 480) with the Plateau de Bure radio interferometer. In all three disks around these stars we detected molecular emission from N_2H^+ and HCO^+ and derived for the first time the radial distribution of their column densities (the total amount of material in vertical direction). The observed quantities were compared to our model predictions (see Fig. III.2.8). It was found that the total amount of N_2H^+ in disks is much less than reported earlier and is only ≈ 0.03 of the HCO^+ abundance. We concluded that HCO^+ is the dominant observable ion tracing the degree of disk ionization, while C^+ is the most abundant yet unobservable charged species in disks.

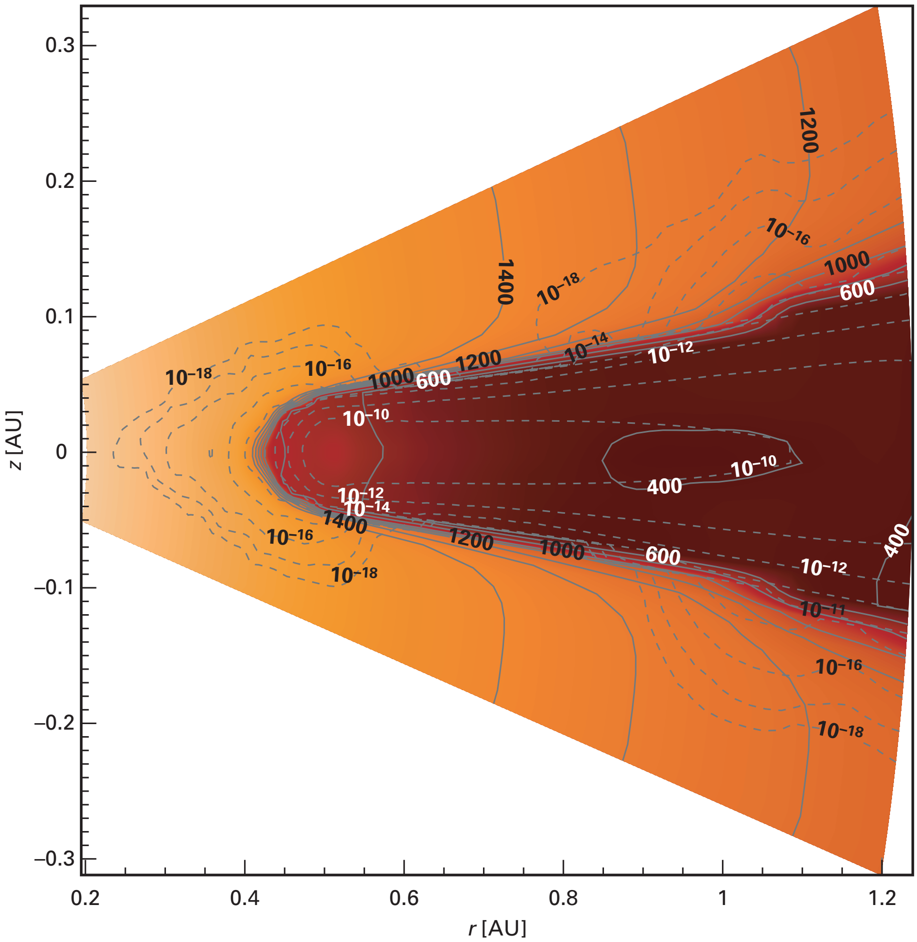
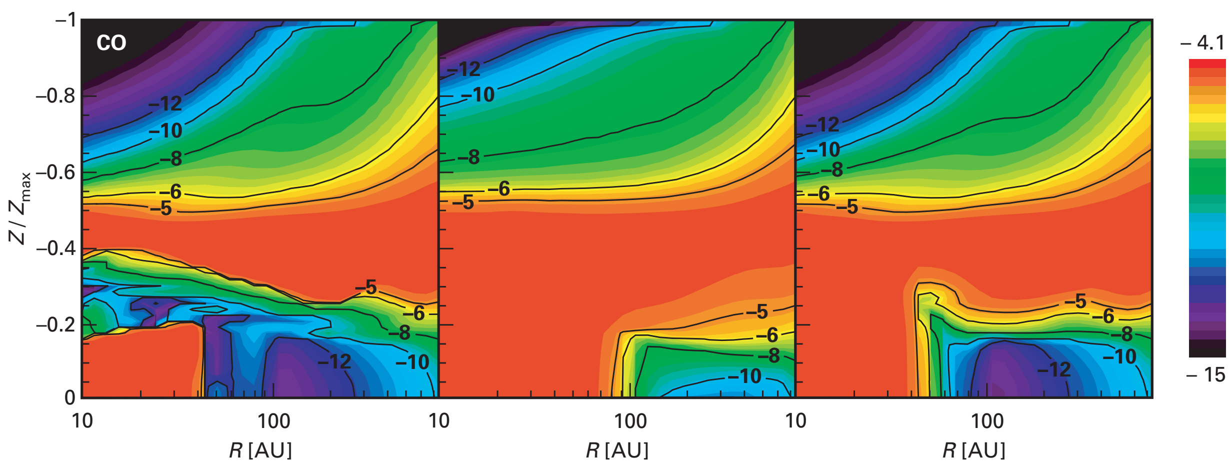


Fig. III.2.6: A vertical cross-section of the inner dust rim of a protoplanetary disk, as calculated with a radiation-hydrodynamics simulation. Colors denote temperature, as do solid contours; the dotted contours denote the density.

Fig. III.2.7: Chemical model of the protoplanetary disk around the star DM Tau. Color shows the abundance of gas-phase CO as a function of radial distance from the star (*x-axis*) and vertical height above the disk midplane (*y-axis*). Shown here are the results for three chemical models: (*left*) static (non-mixing) model, (*middle*) two-dimensional mixing model, (*right*) two-dimensional mixing model with 100 times reduced efficiency. Note that the amount of the CO gas in the cold disk midplane at $R > 100$ AU, $Z \approx 0$ is substantially enhanced in the mixing model only (*middle panel*).



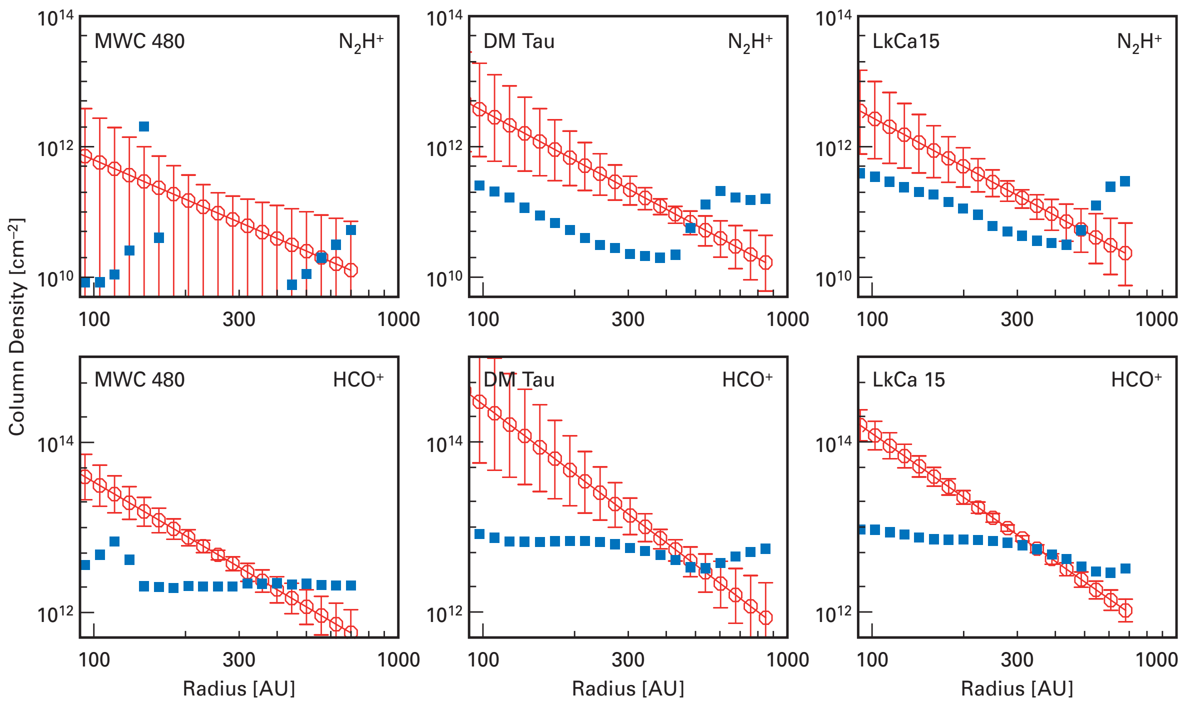


Fig. III.2.8: The observed (*open circles*) and modeled (*filled squares*) radial distribution of the HCO^+ (*bottom row*) and N_2H^+ (*top row*) ions in three protoplanetary disks: MWC 480, DM Tau, and LkCa 15.

In addition to observations of (sub-)millimeter wavelength gas lines, we also observe disks in rotational-vibrational infrared transitions, which trace hotter gas. This includes the work on spatially resolved CO rovibrational line detections described above, as well as attempts to detect signatures of molecular hydrogen in disks.

Analyzing the Dust Content of Disks with the Spitzer Space Telescope

The dust within protoplanetary disks constitutes, for a large part, the raw material of planetary systems. This dust originates from the interstellar medium as sub-micron size grains consisting mainly of amorphous silicates. Once they enter the disk these grains undergo various levels of processing. Thermal heating events transform these grains into crystals, and modify their chemical composition. Collisions between grains can lead to the formation of ever larger aggregates, which is considered the first phase of growth in the formation process of planets. Because the dust is much more efficient in radiating thermal energy than the gas, these transformations of the dust also affect the thermal structure of the disk themselves. Spectroscopic observations of the thermal infrared emission from the circumstellar matter have proven to be crucial in our understanding of these dust alteration processes. With the sensitivity of the Spitzer Space Telescope large samples of protoplanetary disks around solar-type stars can be observed. With our involvement in the Spitzer Legacy Program "Formation and Evolution of Planetary Systems" (Feps) and leading multiple open time programmes on Spitzer, we are at the fore-front of protoplanetary disk evolution research.

Spitzer Spectroscopy of Disks Around Solar-type Stars

One of our main efforts is concentrated on the study of protoplanetary disks around Herbig Ae and T Tauri star systems, the present-day analogs of the proto-solar nebula. An example of Spitzer spectroscopy can be seen in Fig. III.2.9. These spectra show multiple emission features from silicate dust species. In the top-right panel we show the multiple emission features of crystalline forsterite and silica observed in some disks.

The presence of crystalline silicates in these disks provides information about turbulent transport and large-scale circulation of material through the disk, because the location in the disk where these species are discovered is usually not the region where these crystals could have formed.

The observed infrared features also provide information about grain sizes: grains smaller than 1 µm display a strong pointy feature at 10 µm while larger grains display a flatter and weaker 10 µm feature. Such flattening is seen in the lower few sources in the left panel of Fig. III.2.9, which shows that grains in these disks have grown well beyond the size of dust grains in the interstellar medium.

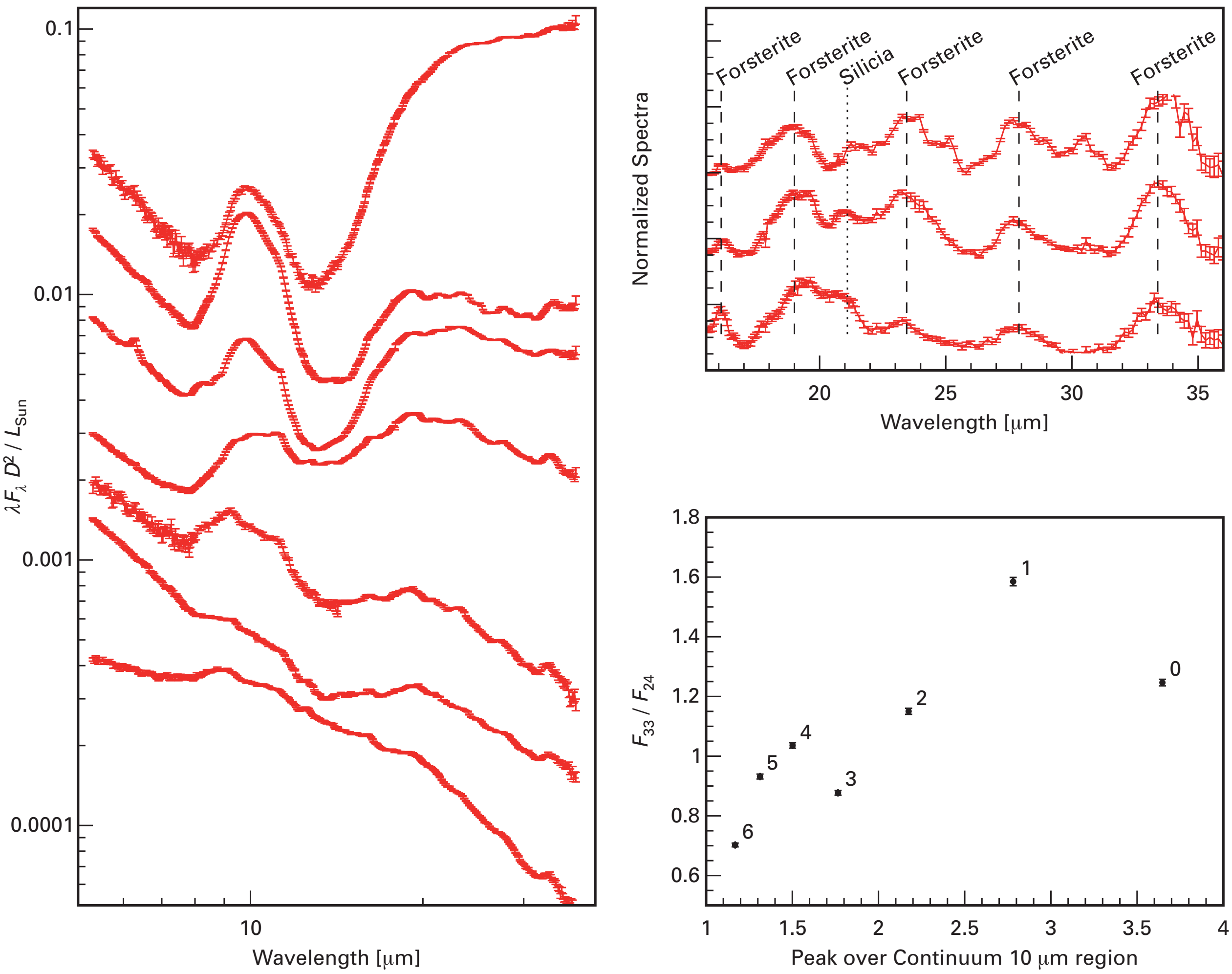


Fig. III.2.9: Example of SPITZER spectra of the disks around solar-type pre-main sequence stars. *Top right panel:* The crystalline silicate bands in the spectra of the T Tauri stars. *Lower right panel:* Correlation between the strength of the 10 μm silicate feature, measuring grain size, and the long wavelength slope of the spectral energy distribution, measuring disk flaring.

We can ask what effect coagulation could have on the disk structure itself. Strongly flaring disks, intercepting a substantial fraction of the radiation from the central star at large radii, show strong mid- to far-infrared emission peaking at around 100 μm. "Flattened" disks, on the other hand, intercept far less of the radiation from the central star, and show a power-law-like spectral energy distribution decreasing with wavelength. Coagulation models (see below, p. 71) predict that if the dust grains in the upper layers of a flared disk become sufficiently large, they will gravitationally settle towards the mid-plane of the disk, resulting in a flattened disk geometry.

In Fig. III.2.9 (lower-right panel) we explore the relation between the amorphous silicate grain sizes, as measured by the strength of the 10 μm silicate feature, and the disk geometric thickness, as measured by the ratio of the fluxes neasured at 33 μm and at 24 μm. With increasing grain size (decreasing 10 μm silicate band) the disk appears to become flatter (as traced by the slope of the SED towards longer wavelengths). Our results are in qualitative agreement with the model predictions, and provide direct spectroscopic evidence for the link between the typical size of the dust grains and the disk structure. These results suggest that in TTS systems it is coagulation and grain settling towards the mid-plane which determines the disk geometry.

The Processing of Dust: Also in Disks Around the Lowest Mass Stars

Brown Dwarfs are often considered to be "failed stars" because they are not massive enough to burn hydrogen. They occupy the realm between stars and planets. Yet, in the last few years a number of young Brown Dwarfs have been discovered to be surrounded by dusty circumstellar disks much like the protoplanetary disks typically surrounding T Tauri stars. Scientists in the PSF department have been involved in leading research in the discovery and analysis of these disks. The star BD Tau 4 was the first Brown Dwarf for which multi-wavelength photometry (in the mid-infrared and at millimeter wavelengths) was obtained and studied, partly by comparison to theoretical models of protoplanetary disks. The same

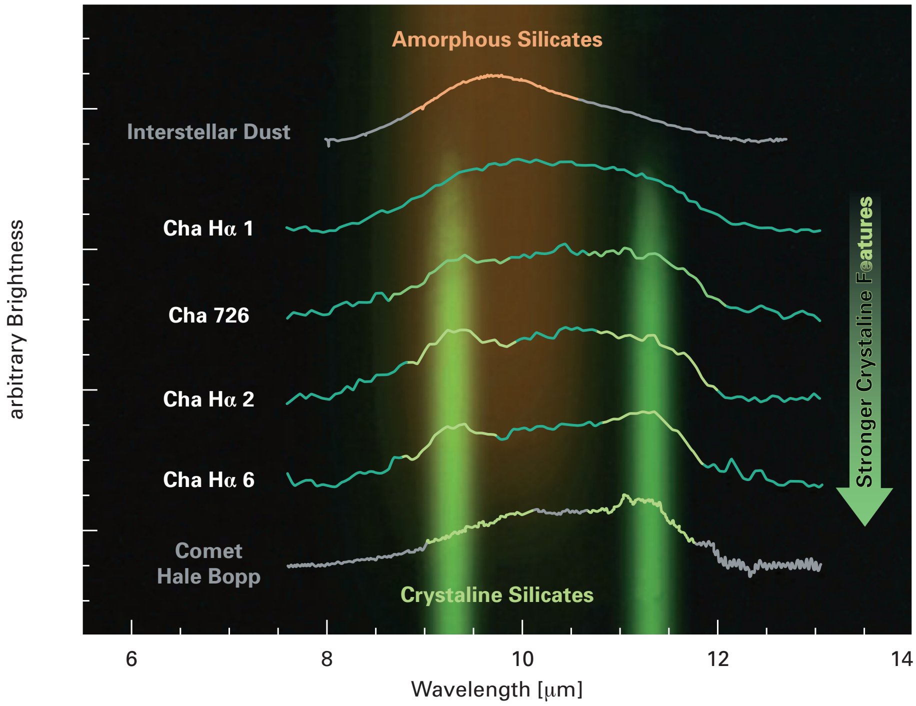
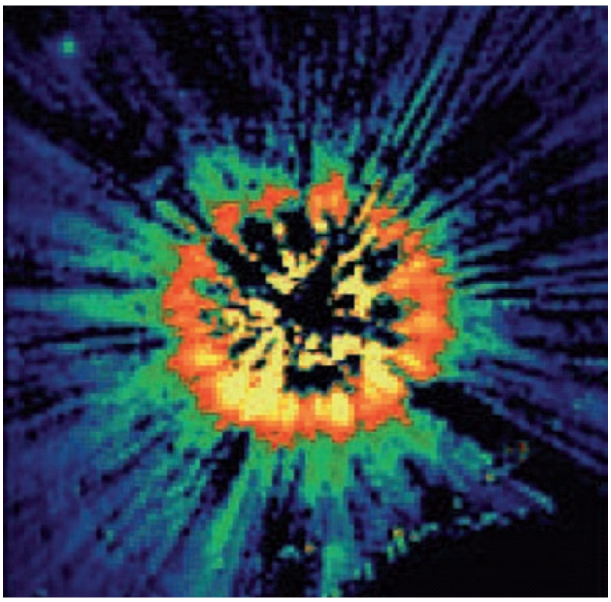
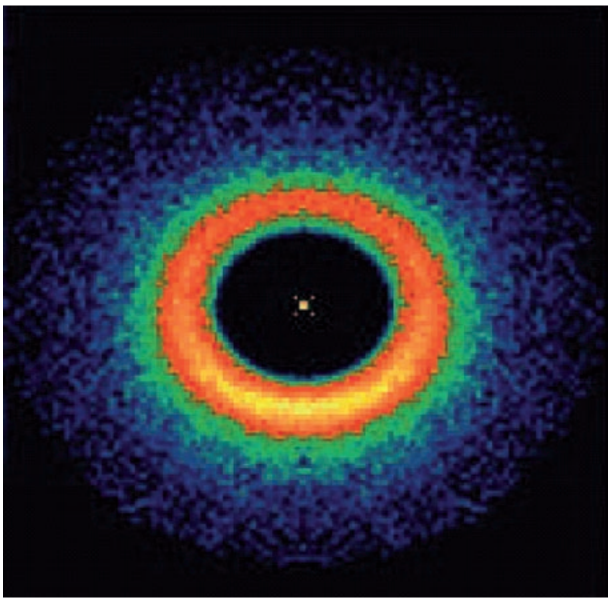


Fig. III.2.10: The first sample of Brown Dwarf stars for which *N*-band spectra with the SPITZER Space Telescope were obtained. These spectra show that similar processes related to the very early stages of planet formation take place around these "failed stars".

team of scientists obtained and published the first sample of *N*-band spectra of such disks with the SPITZER Space Telescope (Fig. III.2.10). We discovered that, very much like their more massive counterparts, the disks around Brown Dwarfs contain crystals in large abundances. This indicates that the same processes that modify and grow the dust in protoplanetary disks around T Tauri stars also operate in these very light-weight disks around very low mass stars. This leads to speculation that the process of planet formation, which is closely linked to this dust processing, may operate around Brown Dwarfs too. This would put Brown Dwarfs more in the league of low-mass stars than in the league of high-mass planets, thereby resolving a long-standing question about the nature of these objects.

Fig. III.2.11: Circumstellar debris systems imaged in scattered light with HST. *Left:* NICMOS image of the debris disk system HD 181327. *Right:* model image from a Monte Carlo radiative transfer computation. Both image and model from Schneider et al. (2006).





Spatially Resolved Observations of Disks

Although spectra of disks contain a lot of information, ultimately one needs spatially resolved data to really constrain the structure and composition of protoplanetary disks.

Direct Imaging of Disks at Optical and Infrared Wavelengths

We are involved in a comprehensive approach to use the HUBBLE Space Telescope for characterizing protoplanetary and debris disks and to search for faint companions around these objects. Recently, we discovered a 36 AU wide debris disk ring around the F5/F6 V star HD 181327 (Fig. III.2.11): This star belongs to the 12 Myr old beta Pictoris moving group. This new addition to the growing menagerie of circumstellar debris disks is, in many respects, similar to the HR 4796A star-disk system. The recent imaging of a broader ring abround the older solar analog, HD 107146 suggests that such structures are a common (if not prevalent) outcome of the planet formation process.

Analyzing T Tauri Star Disks with the VLT-MIDI Interferometer

Direct imaging with infrared and optical telescopes only allows us to spatially resolve the regions of protoplanetary disks outward of about 30 AU from the star, roughly corresponding to the Kuiper belt in our own solar system. The regions For very nearby sources such as TW Hydrae it is nearly possible to reach spatial scales of 5 AU, but these sources are rare. If we want to put these protoplanetary disks in relation to our own solar system, we are interested in the planet forming region (at roughly 0.5 – 30 AU distance from the host star). With the MIDI infrared interferometer instrument on the Very Large Telescope (VLT) it has recently become possible to perform observations at these extreme spatial resolutions. The drawback is that one does not obtain images, but "only" correlated and uncorrelated spectra (or in more common terms: spectra from the inner or outer regions of the disk respectively). The resolved spectrum probes the disk outward of roughly 2 AU from the star, while the unresolved spectrum probes the disk inward of 2 AU (for typical VLT baselines and a source at 140 pc). This method has been demonstrated for very bright stars, such as Herbig Ae stars. Recently, however, we have managed to apply the method to the much fainter, but for comparison to the solar system much more interesting, T Tauri stars. These measurements probe, for the first time in a spatially resolved manner, the "habitable zone" around young stars similar to the young sun.

TW Hydrae, is one of those "inner hole" sources described above believed to be a disk on the verge of destruction, and therefore at the end of its planet-formation phase. Any gas giant planets must have formed by this time, since the gas will likely be removed in the

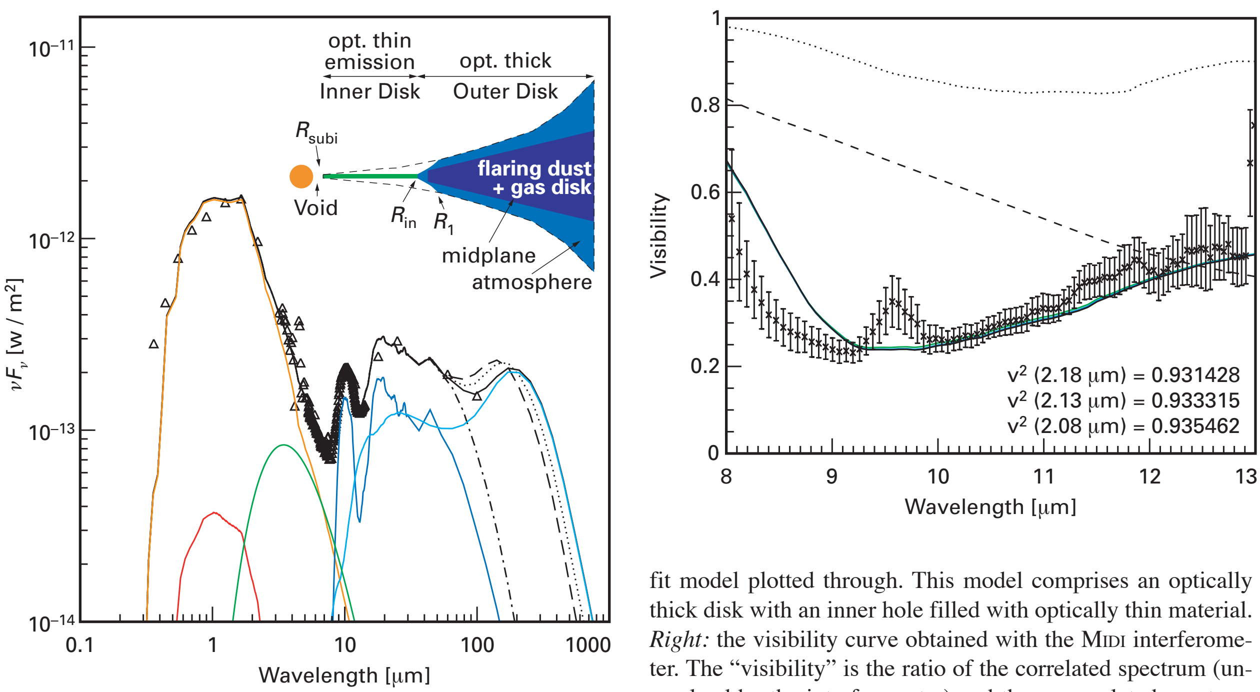


Fig. III.2.12: Analysis of the observations of the T Tauri star TW Hydrae. *Left:* the spectral energy distribution, with the best-fit model plotted through. This model comprises an optically thick disk with an inner hole filled with optically thin material. *Right:* the visibility curve obtained with the MIDI interferometer. The "visibility" is the ratio of the correlated spectrum (unresolved by the interferometer) and the uncorrelated spectrum (resolved by the interferometer). Model prediction is the solid line. Previously suggested and now ruled-out models are the other lines.

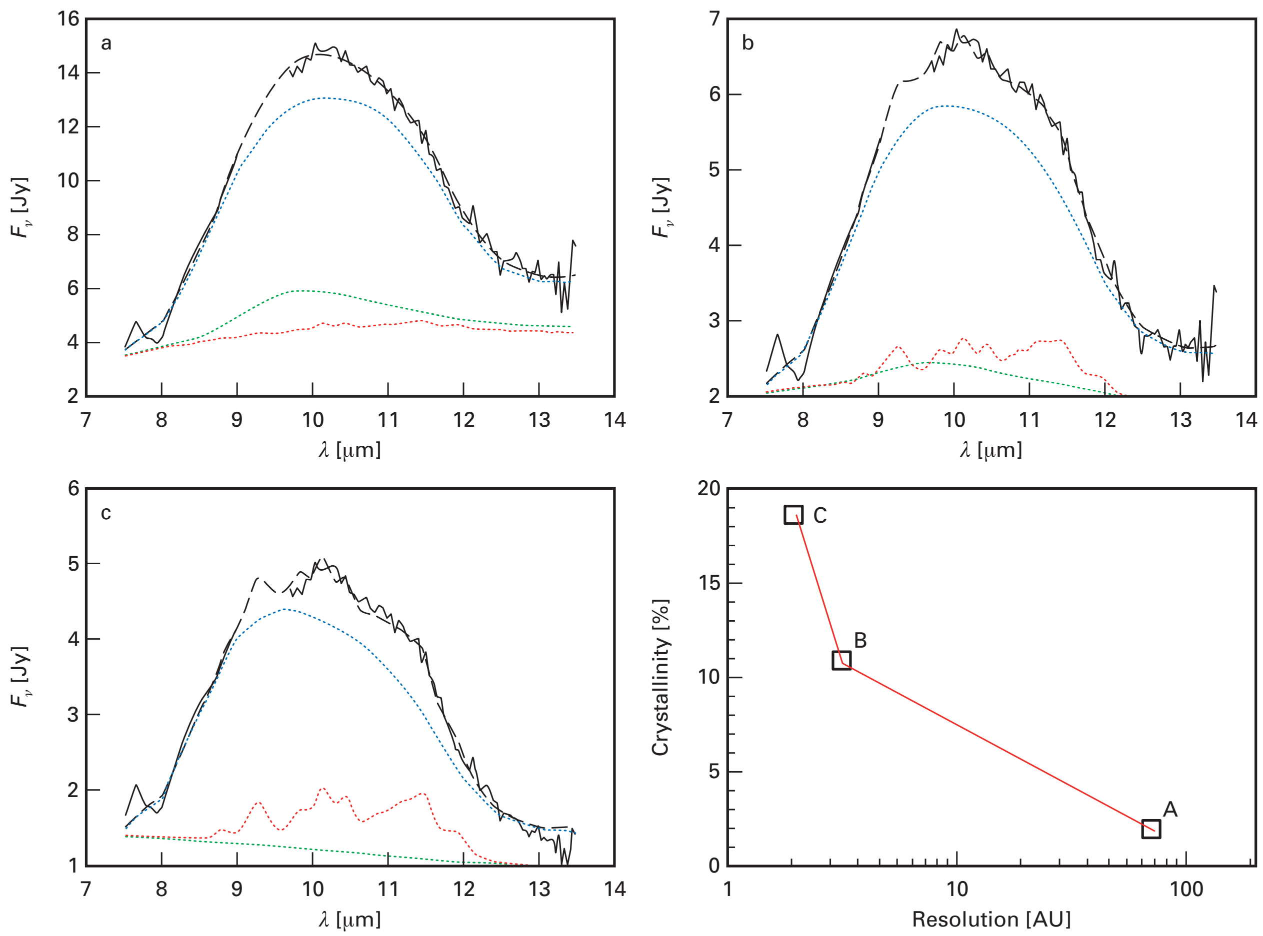
very near future. One of the problems is that these inner holes have until now only been inferred indirectly from the absense of near-infrared emission in the spectral energy distribution. With the MIDI instrument we have managed to directly resolve and confirm the presence of this hole by the combined analysis of the spectral energy distribution and the interferometry data with theoretical models (Figure III.2.12). We found that its size is four times smaller than was inferred by earlier papers from the spectral energy distribution alone.

Another source observed with MIDI, RY Tau, is a well-known, six million years old T Tauri star that belongs to the Taurus-Auriga molecular cloud at a distance of about 450 lightyears. The spectral energy distribution and the interferometry measurements with MIDI were analyzed by comparison to predictions from a hydrostatic disk model combined with Monte-Carlo radiative transfer calculations. It was shown that for the RY Tau system an additional tenuous envelope was needed to explain the near- and mid-infrared flux levels. The MIDI data also allowed us to analyze the dust composition in this disk. Figure III.2.13 shows the shape of the 10 μm silicate feature, the strongest solid-state feature in the infrared. These measurements show that the dust closer to the star is more processed, i.e. it contains more crystalline dust species and consists of larger grains than the outer regions of the disk. This has been observed before for the bright Herbig Ae stars, but is now also confirmed for T Tauri stars.

Resolving Disks at Millimeter Wavelengths

With large millimeter-wave telescope arrays the outer regions of disks can also be spatially resolved. In contrast to current mid-infrared interferometers, millimeter interferometers can reconstruct actual images. The advantage of observations at these wavelengths is that the disk is optically thin and the total disk mass can be derived. Moreover, the slope of the spectrum in these wavelength ranges allow the determination of grain sizes in the range of 0.1 to 1 millimeter. This probes

Fig. III.2.13: Three *N*-Band spectra of RY Tau obtained with MIDI: *a):* one full disk and two correlated flux spectra from the inner disk; *b):* correlated spectrum at a baseline of 48 meter; *c):* correlated spectrum at a baseline of 78 meter. Dotted lines are model components. *Red:* crystalline silicates, *green:* 0.1 μm sized amorphous silicates, *blue:* 1.5 μm sized amorphous silicates. *Lower right panel:* the abundance of crystals as a function of position in the disk, as derived from the results in the other panels.



the growth of grains to somewhat larger sizes than can be determined by infrared observations. We have been, and remain, involved in observational campaigns in this field with the aim of characterizing the dust in the outer regions of protoplanetary disks. Our activities were described in the Annual Report of 2004.

Modeling the Growth from Dust to Planets

With the strong efforts analyzing the structure of disks, both theoretically and observationally, the next question is: how do planetary systems form in them.

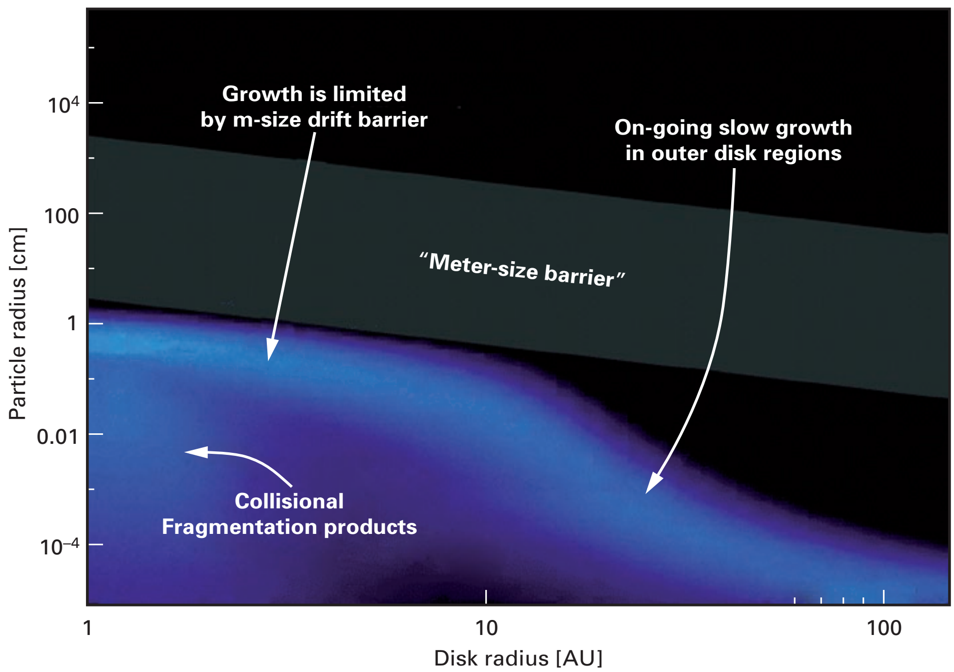
The Growth of Dust Aggregates in Disks

There is by now ample observational evidence that the small submicron-sized dust particles in protoplanetary disks aggregate to form larger agglomerates. Apart from being the very first step along the road of planet formation, this "dust growth" also affects the disk's structure and appearance. In the PSF department we aim to develop models of this growth process, and how it affects the disk's spectra and images. Until recently, typical models of dust aggregation in disks were simplified in that the calculations were done as separate sub-models at different distances from the star. Moreover, the process of aggregate fragmentation, which happens when aggregates collide at too high velocities, was only barely included. The models developed at the MPIA over the last two years involve a new and efficient multi-dimensional dust growth model in which the fragmentation of aggregates and the movement of dust in all directions is included. A snapshot of this model is shown in Fig. III.2.14, in which it is seen how the growth of particles is inhibited by the so-called "meter-size barrier": a regime of grain sizes in which rapid radial drift and collisional fragmentation hamper growth. Exploring ways to break through this meter-size barrier is one of the main questions that are addressed. Moreover, these models form the framework into which new physical input data from laboratory experiments and hydrodynamic simulations will be inserted (see above, p. 63). Initial results show that when compared to observations, these models can put strong constraints on the environment in which the dust growth process takes place.

Jumping the Meter-size Barrier by Gravity

One very promising possible way that the growth of solid bodies can break through the meter size barrier is with the help of gravity. When a large fraction of the solid bodies reach sizes of a few decimeter, the population of these "boulders" start to experience instabilities in the two-fluid gas/solid mixture, leading to strongly non-linear feedback-behavior. Simulations performed by our team show that under such conditions clumps of boulders form that are massive enough to remain bound by their

Fig. III.2.14: A diagram showing the size- and space-distribution of dust particles in a protoplanetary disk, computed with the dust evolution computer program developed at the MPIA. The blue hue denotes the amount of dust at that location in the disk (x-axis) and at that particle size (y-axis). Shown here is a snapshot taken at 5000 years after the start of the simulation.



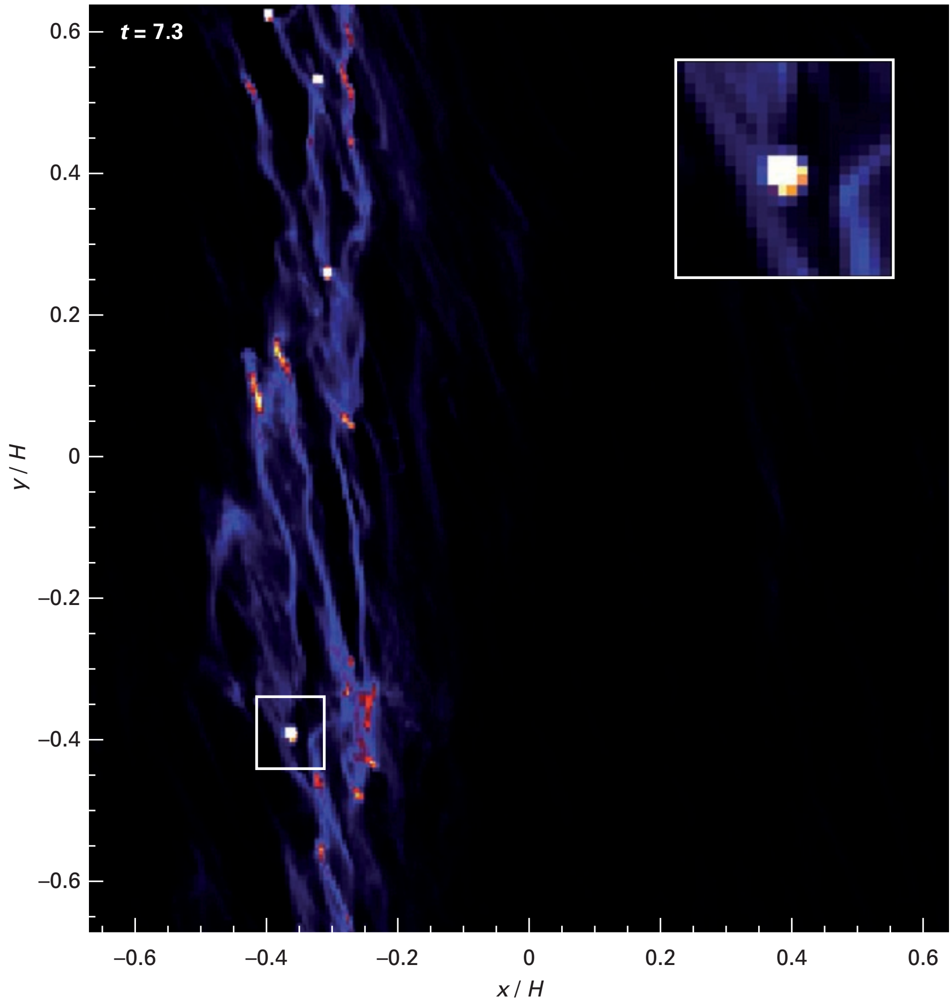


Fig. III.2.15: Formation of planetesimals by self-gravity. The plot shows the column density of dust boulders in a protoplanetary disk. A gravitationally bound clump with the mass of a few dwarf planets has condensed out of the turbulent flow.

own self-gravity, leading to the rapid formation of planetesimals of a mass of about 10^{-4} times the Earth's mass. Fig. III.2.15 shows a snapshot of one such simulation, where the the gravitationally bound object is shown as a zoom-in. These simulations were the first to combine 3-D hydrodynamics with particle motion (including feedback to the gas) and self-gravity.

The Formation of Planets

With the current findings about these disks and the early stages of planet formation, it is a natural question to ask what kind of planetary systems can form out of such disks. A fully detailed model of this process is, even with current computer facilities, still not feasible. However,

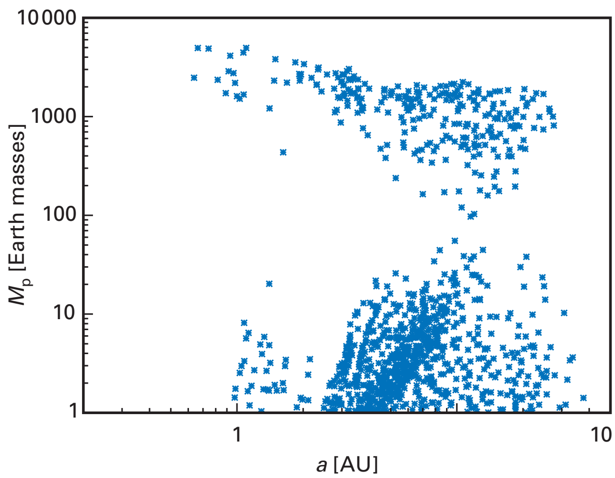


Fig. III.2.16: The predicted position a and mass M_p of planets resulting from our Monte-Carlo models for a star of 1 solar mass. Effects of planetary migration and growth of a planet after gap opening are included. These predictions can be directly compared to the a vs. M_p distribution of detected planets.

well-chosen simplifications and idealization can reduce the complexity dramatically. Models of this kind were developed in the PSF department. These models consist of two steps. The first step evolves gas and solid material from an early stage, when all solids are in the dust form, to the stage when most solids are in the form of a planetesimal swarm. In the second step we investigate the range of masses and orbits of giant planets which will form in protoplanetary disks characterised by different initial conditions. Using the models of evolved planetesimal swarms from step 1, a Monte Carlo procedure is applied in order to calculate the evolution of the mass of a seed planet due to accretion of gas and planetesimals, and its radial distance a from the star due to gravitational interactions with the disk. The procedure allows us to characterise the relationship between the final orbital radii and masses of planets that are in general possible to obtain and to check how the resulting a vs. M_p distribution changes when including different physical processes such as migration and gas accretion by the planet after gap opening. Fig. III.2.16 shows an example result of such an a vs. M_p diagram.

Conclusion

There are still many open questions regarding the structure and formation of protoplanetary disks and how and what planets are formed in them. Only by a combination of theory and observations, and with a broad view of the topic can one make real progress in this area. To achieve this goal, our research group covers a wide range in observational and theoretical approaches to study these disks. The strong interplay between theory and observations, and at the same time a fundamental approach to the problem at hand are an integral part of this.

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III.3 Mapping the Halo of Our Galaxy

The last decade has seen tremendous progress in our understanding of galaxy formation and evolution. Deep observations of galaxies at intermediate and high redshift, a number of them led by the MPIA, have unveiled the star formation history and evolution of galaxy morphologies on cosmic scales. These observations have helped to build and solidify our current model of galaxy formation – the ΛCDM paradigm.

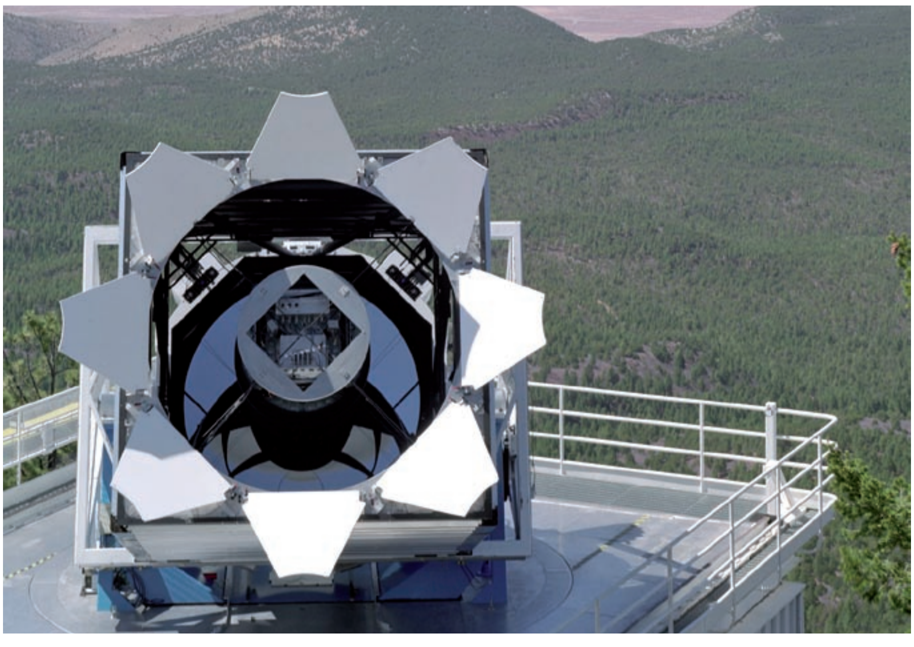
One of the key predictions of galaxy formation models in a universe with cold dark matter (with or without a cosmological constant) is that all massive galaxies, even disk-dominated galaxies such as the Milky Way, should frequently interact with and tidally disrupt dwarf galaxies in their local environment – often called galactic cannibalism. In this picture, the stellar halo around the Milky Way (a low-surface brightness, very extended, nearly spherical cloud of metal-poor stars surrounding the Milky Way, travelling on almost random orbits) would represent the remnants of ancient disruptions. In this way, the stellar halo of the Milky Way would carry with it a unique record of the assembly of the Milky Way.

Spectacular evidence of galactic cannibalism was uncovered in 1995, with the discovery of the Sagittarius dwarf galaxy, and the realisation that it was in the process of being tidally disrupted by the Milky Way. In subsequent years, great progress towards understanding the role of hierarchical build-ups of the Milky Way halo has been made; the latest results from MPIA researchers show that our halo may well consist *entirely* of disrupted satellite streams.

The Sloan Digital Sky Survey

A particularly powerful tool for understanding the properties of the diffuse stellar envelope of the Milky Way, as well as that of galaxies in the Local Group, has been the Sloan Digital Sky Survey (SDSS), in which the MPIA is a partner institution. SDSS is both an imaging and a spectroscopic survey utilizing its own dedicated 2.5 meter telescope (Fig. III.3.1), that has imaged approximately $^1/_4$ of the entire sky to unprecedented depths. The fully automated data reduction pipeline has identified over 200 million unique objects in the imaged sky area, and for over one million of these objects spectra have been obtained. To make all of this possible, the SDSS telescope is fitted with a wide-field imaging camera using a drift-scanning technique and a fibre-fed multi-object spectrograph. The MPIA has participated in both the original SDSS survey, as well as its subsequent extension, SDSS-II. Whereas the main motivation for the SDSS was to understand large scale structure and cosmology, one of the main science goals of SDSS-II (through the SEGUE project: SDSS Extension for Galactic Understanding and Exploration) is to study stars in our own Milky Way galaxy, and in nearby galaxies.

Fig. III.3.1: The 2.5 meter telescope of the Sloan Digital Sky Survey, located at the Apache Peak Observatory in New Mexico in the United States.



The key to the effectiveness of the SDSS in probing faint stellar populations in the Local Group is that one can use individually-detected stars to identify structures. Oftentimes, one would rely on detecting diffuse emission from the unresolved stellar population to find and characterise faint structures; this naturally is limited to probing surface brightnesses of typically 1 % of the sky surface brightness and higher (~ 26 magnitudes per square arcsecond). In the case of the study of faint stellar populations in the Local Group, the SDSS can individually detect many of the stars, leading to effective surface brightness limits three or more magnitudes fainter, $\sim 29-30$ magnitudes per square arcsecond. This extra depth has enabled a near-doubling of the number of Milky Way satellites, and has allowed detection and characterization of ghostly streams of stars torn off of dwarf galaxies and globular clusters. Together, these discoveries are starting to provide important clues as to how the stellar halo, and the Milky Way in general, was built up.

Most prominent among all star streams in the Milky Way halo is the Sagittarius stream. It consists of stars that have been torn off of the Sagittarius dwarf galaxy over the course of the last few billion years. In the SDSS data the Sagittarius stream can be traced all the way through the surveyed area, providing precise spatial information that can be used to constrain dynamical models of the system and the potential of the Galactic halo (through study of the precession of the orbit with time). Moreover, from the SDSS data it has become clear that the stream is split into two or more separate arms, a discovery that has so far defied a satisfactory explanation and may give important insight into the shape of our dark matter halo.

In 2002 another large stellar stream was first seen in SDSS data by astronomers from several SDSS member institutions, including the MPIA. This stellar stream was first detected as an overdensity of stars close to the plane of the Galactic disk, with subsequent SDSS spectroscopic data confirming it was distinct from the already known Sagittarius stream. Detections of this new stream in other directions suggest that it forms a giant ring of stars all the way around the Galactic disk, always at low Galactic latitudes. This suggests that if this Low-Latitude stream, like the Sagittarius stream, is the result of the tidal disruption of a dwarf galaxy, its progenitor should also be located close to the Galactic plane. Subsequently, an overdensity of stars was discovered in the direction of the constellation Canis Major (CMa). Because of the apparently large size of the system and because it is located close to the disk, it might be the progenitor of the Low-Latitude stream.

Not only in the halo of the Milky Way, but also in the halo of the Andromeda galaxy (M 31), the nearest large spiral galaxy, substructure was detected using SDSS and other surveys. A giant stellar stream was discovered using survey data from the Issac Newton Telescope, and a "ring" of debris around M 31, similar in character to the Low Latitude stream in the Milky Way, was discovered. In addition, using SDSS and other data, MPIA astronomers have discovered five new satellite galaxies around M 31 in the last three years, all among the faintest galaxies ever discovered.

In total, SDSS data have led to the discovery of more than 10 new dwarf galaxies in the Local Group, a few Milky Way globular clusters, and several stellar substructures such as tidal streams in the Milky Way and M 31 halo. These results clearly give weight to the idea that galaxy halos may be built up by the disruption of smaller systems, such as dwarf galaxies.

There are many open questions remaining regarding these new discoveries, two of which we will discuss in much more detail below.

- First of all, the nature of the Low Latitude stream is still unclear; is this structure torn off of the disk, or is the low-latitude stream the debris of a dwarf galaxy disruption? The existence and properties of a stream progenitor would provide key evidence for a dwarf galaxy interpretation. Although the CMa overdensity seems a prime candidate, its nature is still a matter of debate. Accordingly, astronomers at MPIA have studied in detail the properties of the Low Latitude stream and CMa in an effort to resolve this question.
- Secondly, do the properties of the Galactic stellar halo match the expectations from disruption of dwarf galaxies? Now that SDSS has provided us with a detailed view of the stellar halo, we might for the first time be able to compare the smoothness (or lumpiness) of the halo with model predictions.

Canis Major and the Low Latitude Stream

The Low Latitude stream and the CMa overdensity might be the remnants of an accreted and disrupted dwarf galaxy, similar in size as the Sagittarius dwarf galaxy. Together, these two cannibalized systems would be prime examples of on-going galaxy formation and assembly at present times. Unfortunately, the interpretation of the Low Latitude stream and the CMa overdensity is not straightforward, because of their location close to the plane of the disk. The disk itself shows a lot of substructure, for example spiral arms. Therefore it is a priori not clear whether any substructure in the distribution of stars at low Galactic latitudes is intrinsic to the disk itself or if it has some external cause. Alternatively, the CMa overdensity has also been interpreted as a projection effect of the warp of the Galactic disk and as an out-of-plane spiral arm. Also unclear is whether the young and old stellar populations seen in the direction of CMa are actually at the same distance, or, as has been suggested, if the young stars are located several kiloparsecs behind the old stars. Over the past years, researchers from the MPIA have studied the nature of the CMa overdensity and its possible connection with the Low Latitude stream following several approaches.

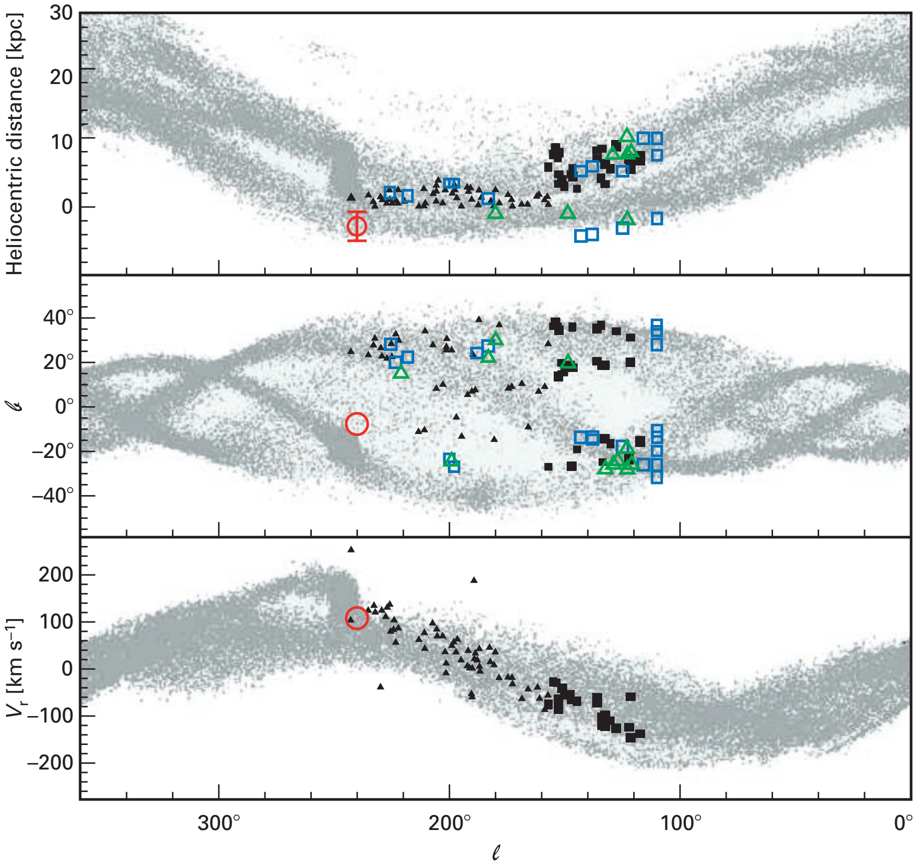


Fig. III.3.2: Model of the Low Latitude Stream in three projections: Galactic longitude versus heliocentric distance, Galactic latitude, and radial velocity. The light grey dots show the positions of particles in an N-body realization of the model. The approximate position of the center of the Canis Major overdensity is indicated with the large circle. Smaller black symbols show the observational constraints to which the model was fit.

Deep photometric follow-up observations were obtained to help constrain the stellar properties of the overdensity. These data revealed the presence of two distinct populations in the direction of Canis Major, one young (about 1 to 2 billion years old) and one relatively old (about 6 billion years). Furthermore, the data showed that the old stars must be located in a narrow distance range along the line-of-sight, centered at a distance of approximately 7.5 kpc. Several known dwarf galaxies in the Local Group also contain old stars and younger stars, but the same of course goes for the Milky Way. The narrow distance range within which the CMa stars are located can be explained both by the spiral arm and the accreted dwarf scenario, but seems harder to reconcile with the hypothesis that the overdensity is an effect of the warp of the disk.

Dynamical Models: Using the available observational constraints on the spatial structure and the kinematics of the Low Latitude stream, MPIA researchers constructed dynamical models of the Low-Latitude stream. The main aim was to see if models were feasible with the CMa overdensity as the progenitor of the stream. Indeed, a model was found that fits the observations of the stream very well, with a progenitor at roughly the same location as the CMa overdensity (Fig. III.3.2), but, intriguingly at a distance higher than that which we observed for the CMa overdensity.

A new wide-area survey with the MPG/ESO 2.2 m telescope of the CMa overdensity: In an effort to obtain a more global picture of the overdensity, and its relationship with the Low-Latitude stream, a large survey of the CMa region was undertaken using MPIA time on the MPG/ESO 2.2 m telescope with the Wide Field Imager camera. The survey does not cover a contiguous area, but consists of roughly 200 1° × 1° fields spread over a large region of sky, in order to probe the whole overdensity. Density profiles were constructed by counting the number of main sequence stars in a certain colour-magnitude box in all fields, see Fig. III.3.3. The overdensity turns out be much more stretched out in Galactic longitude (parallel to the disk plane) than previously thought. In the direction perpendicular to the disk the distribution of stars is much more constrained, but very close to the disk measurements are not possible because of the high dust extinction. There is a clear difference between the distributions of the old and young stars, with the young stars much more concentrated and the old stars more extended. Since the overdensity is so stretched out it seems unlikely that it is a gravitationally bound system. This means that if it once was a dwarf galaxy, it has been completely

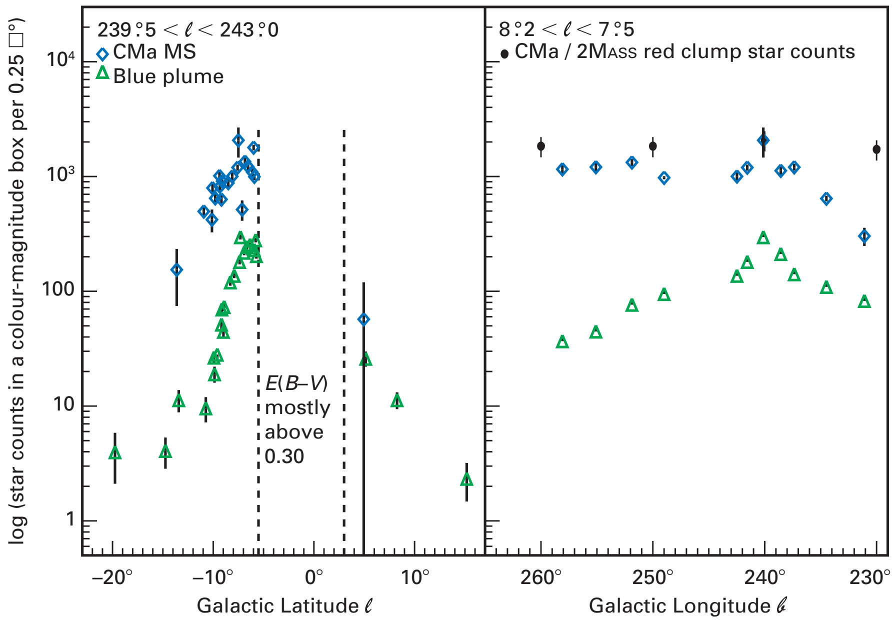


Fig. III.3.3: Stellar density profiles of the old (blue symbols) and young (green symbols) populations in the Canis Major overdensity, plotted versus Galactic latitude (*left*) and longitude (*right*). The density of stars increases rapidly towards the Galactic midplane, but the young stars are somewhat more strongly concentrated.

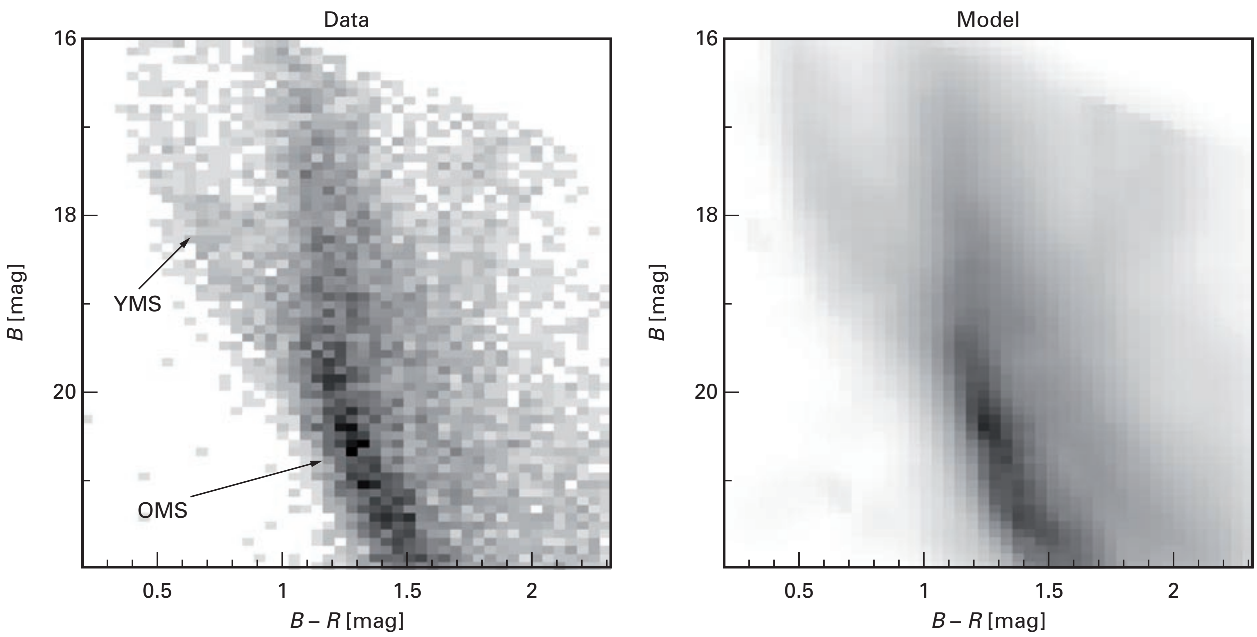


Fig. III.3.4: *Left:* Hess diagram of one of the fields used for the Hess diagram fitting analysis of the Canis Major overdensity. The main sequence of the old and young populations are labeled with OMS and YMS respectively. There is a lot of contamination from thin and thick disk stars in the fore-and background. *Right:* the corresponding best-fitting model Hess diagram. It is a combination of the Hess diagrams of model stellar populations and that of a control field to fit the fore-and background stars.

torn apart. The distance and line-of-sight spread of the overdensity was also constrained for the survey fields. Again a distance of 7.5 kpc was found and an upper limit for the full-width-half-maximum of the overdensity of about 4 kpc. A comparison of this distance and width with models of the warp of the disk shows clearly that an overdensity at this distance cannot be explained by such models.

An important question regarding the CMa overdensity concerns the relation between the old and young stars.

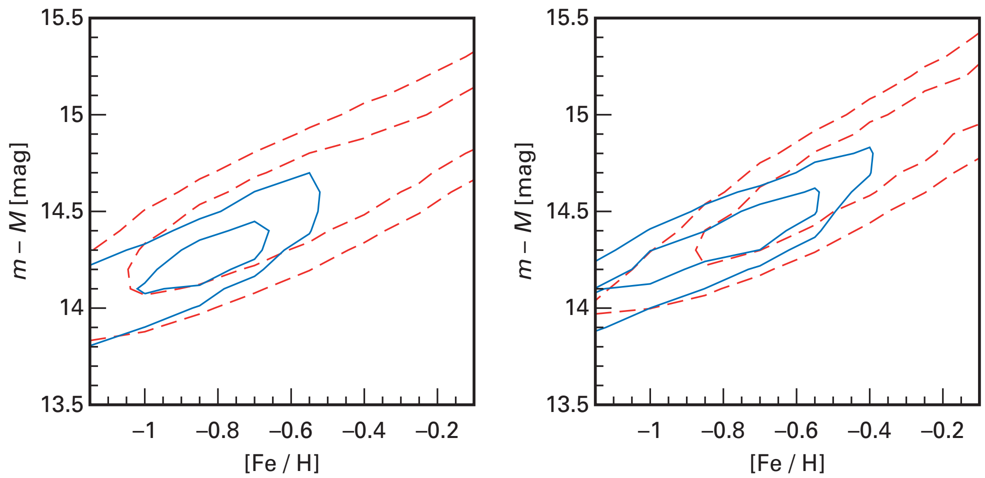
While the distance to the old stars is quite certain (about 7.5 kpc), the distance to the young stars is a matter of dispute. Knowing this distance is crucial to understand if they are actually related to the old stars or merely seen together in projection. Also this distance is important for understanding the possible relation of the young stars to intrinsic disk substructure, such as spiral arms. Using a small number of fields from the Wide Field Imager survey of the CMa region the relation between the two population has been studied in more detail.

To optimize the use of all information available in the photometry, sophisticated Hess diagram fitting techniques were used (a Hess diagram is a plot of the density of stars as a function of colour and magnitude). In this method, model Hess diagrams that are constructed from theoretical evolutionary tracks and accurate models of the observational uncertainties, are compared with the observations. The properties of a stellar population, such as distance, age, and metallicity influence the locations of the stars in the Hess diagram, so that these properties can be constrained by finding the best-fitting models. An example of an observed Hess diagram and its best-fitting model counterpart is shown in Fig. III.3.4. With this technique, for the first time robust measurements of the properties of the stellar populations in CMa could be made.

For the old stars, the distance was determined to be 7.5 kpc, with a fullwidth-half maximum spread along the line-of-sight of 3.5 kpc. This agrees very well with estimates that were obtained previously. The metallicity of these stars was found to be about [Fe/H] = – 1.0, and the ages vary between 3 and 6 billion years. For the young stars, ages of a few hundred million years up to 2 billion years are estimated. Unfortunately there is a degeneracy when measuring the distance and the metallicity of stars from a Hess diagram, such that a metal-rich and distant population look the same as a more metal-poor and nearer population. This is illustrated in Fig. III.3.5 where the goodness-of-fit contours are shown in the distance-metallicity plane for both the old and young stars. For the young stars, the contours are very elongated and do not constrain either parameter well. Two scenarios are equally consistent with the data. Either the young stars have a similar metallicity as the old stars and are at the same distance, or they are more metal-poor and farther away.

Bringing it together: What do these results tell us about the nature and origin of the CMa overdensity? Fig. III.3.6 shows a schematic view of the third quadrant of the Milky Way, with the location of the sun and the spiral arm structure indicated. The position of the old stars is indicated with a grey dot. If the young stars have a similar metallicity as the old stars, this is also the location of the young stars. Shown as a black dot is the location of the young stars if they are more metal-rich, [Fe/H] = – 0.3. The old stars are located between two spiral arms and are more metal-poor than thin disk stars, giving credence to the idea that these stars are coming from outside the Galaxy. For the young stars the picture is uncertain, because of the distance-metallicity degeneracy. If they share the same metallicity and distance with the old stars, their position between spiral arms and low metallicity would make them also likely to be "outsiders" in the Galaxy. But if they have a metallicity close to that of the Sun, their distance coincides with the outer Cygnus spiral arm. In this case both their position and metallicity would suggest that they are normal disk stars. This problem can only be solved with spectroscopic measurements of the metallicity of the young stars, and that is the next planned step in this research project.

Fig. III.3.5: Goodness-of-fit contours (1 and 2 sigma) for the old stars (solid lines) and young stars (dashed lines) as a function of distance modulus, m-M, and metallicity, [Fe/H], for two different Wide Field Imager survey fields near the center of the Canis Major overdensity. The metallicity and distance of the old stars are reasonably well constrained, but because of the degeneracy between distance and metallicity, the contours for the young stars are very elongated and not closed. The results are consistent with both populations having the same metallicity and being at the same distance, but also with the young stars being more metal-rich and farther away.



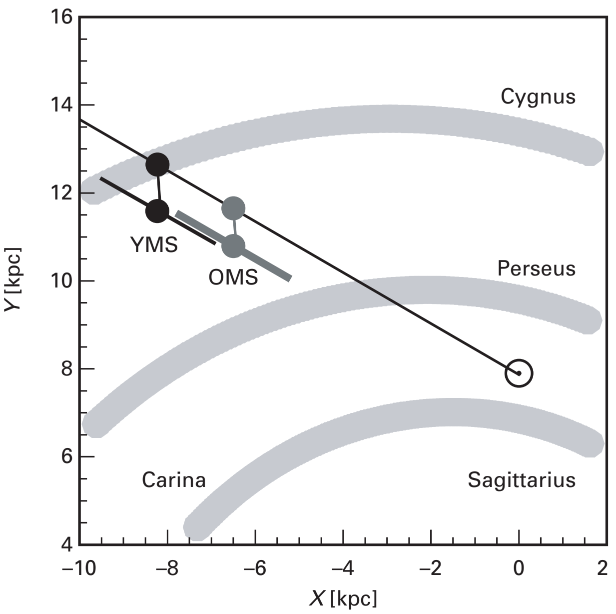


Fig. III.3.6: Schematic picture of the third quadrant of the Milky Way, seen face-on from above. The light grey bands trace the spiral arms. The position of the sun is indicated and the Galactic center is at (0,0) in these X,Y coordinates. Drawn as a solid line is the projection onto the Galactic plane of the line-of-sight towards the center of the Canis Major overdensity. The dark grey dot and line labeled with OMS show the position and distance spread of the old stars; this is also the position of the young stars if they have a similar metallicity. The distance of the young stars in case they have a metallicity of [Fe/H] = – 0.3 is shown by the black dot and line labeled with YMS.

The Structure of the Milky Way Stellar Halo

A second key question relates to the nature of the Milky Way halo itself. Given the discovery of so much substructure in the stellar halo of the Milky Way, it is a natural question to ask if i) such streams are a new, and minor addition to an already built-up smooth stellar halo, or if ii) these streams, and their older bretheren, *are* the stellar halo.

MPIA astronomers are using the SDSS to address this question. The stellar halo of the Milky Way has a number of distinctive characteristics which make it a key probe of galaxy formation processes. Milky Way halo stars have low metallicity, alpha element enhancement, a high degree support from random motions, and a roughly r^{-3} power law distribution in a roughly oblate halo. The low metallicities and alpha element enhancements suggest that the stars formed relatively early in the history of the Universe. Yet, there has been disagreement about where these stars formed: did they form in situ in the early phases of the collapse of the Milky Way; or, did the stars form outside the Milky Way in satellite galaxies only to be accreted by the Milky Way at a later date?

A key discriminant between these pictures is the structure of the stellar halo. In situ formation would predict relatively little substructure, as the formation epoch was many dynamical times ago. In contrast, current models of galaxy formation in a hierarchical context predict that the vast majority of stellar halo stars should be accreted from disrupted satellite galaxies. The accumulated debris from ancient accretion eposides rapidly disperses in real space, forming a relatively smooth stellar halo. The debris from accretions in the last few Gyr can remain in relatively distinct structures. Simulations predict quite a wide range in "lumpiness" of stellar halos, with a general expectation of a significant amount of recognisable halo substructure.

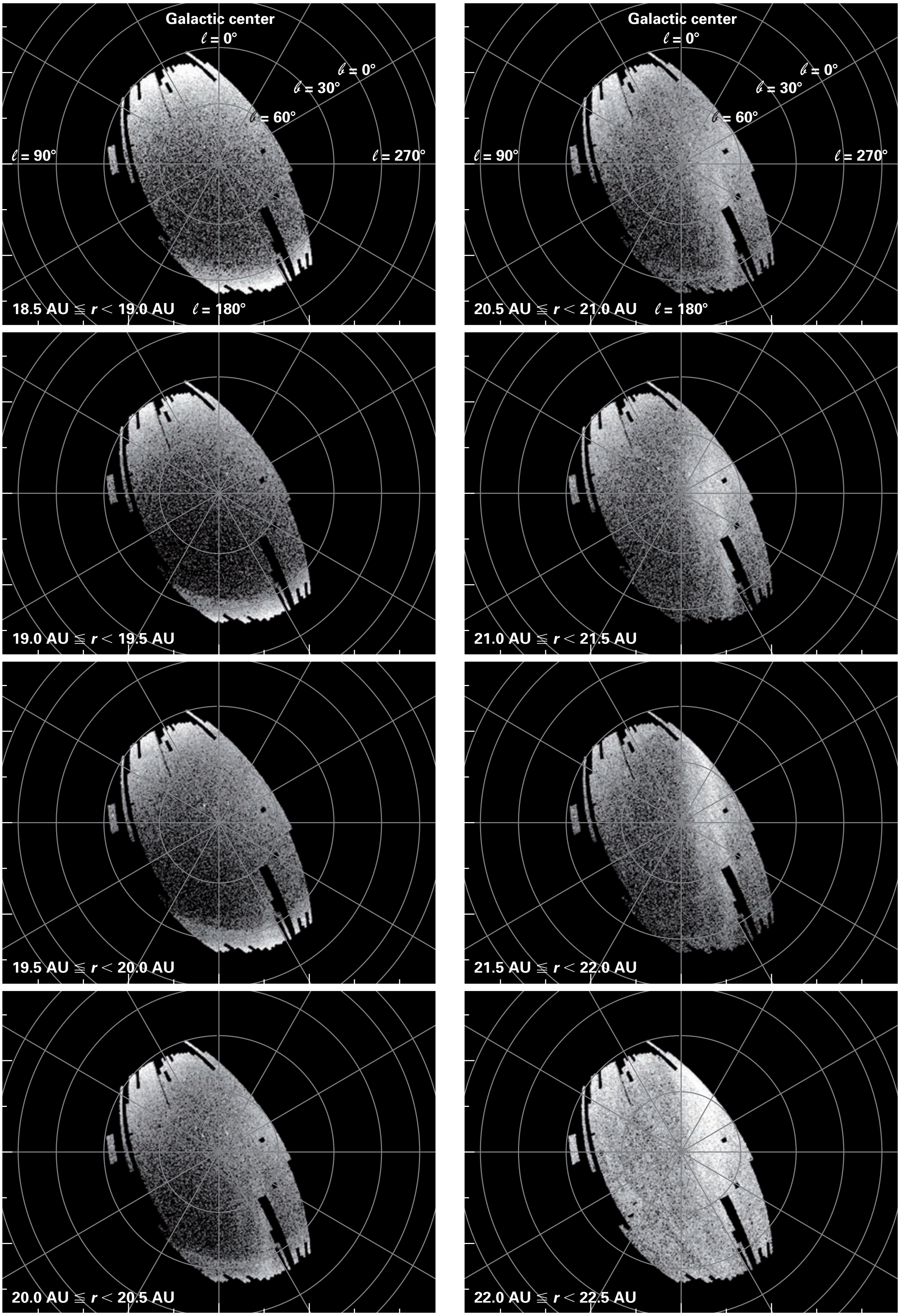
The structure of the stellar halo was explored using Main Sequence Turn-Off (MSTO) stars. MSTO stars in the stellar halo have a distinctive color, and a relatively narrow range in absolute magnitude (with a sigma of 0.9 magnitudes). Accordingly, MSTO stars can be used as standard candles, and different ranges in apparent magnitude correspond to different MSTO star heliocentric distances.

MSTO stars in the stellar halo: In Fig. III.3.7, the distribution of MSTO stars is shown on the North Galactic Cap in a Lambert equal area projection, split into eight slices in apparent magnitude. The bins are narrower than the distribution of MSTO absolute magnitudes; therefore, some degree of cross-talk between different apparent magnitude slices is expected. In all bins, there is a relatively smooth distribution of MSTO stars. In the brightest (nearest) bins, there is an overdensity of stars towards the Galactic Centre: this to first order reflects the high density of halo stars at smaller galactocentric radii. In the brighter bins towards the anticenter, one can see an overdensity of stars at low galactic latitudes: this is the low latitude stream. In the fainter bins, stretching across the sky, one can very easily see the Sagittarius stream. Yet, from these maps alone, it is difficult to tell if the streams are simply the "frosting" on the halo cake, or if streams and structures dominate the stellar mass of the Milky Way's halo.

In order to address this issue, smooth oblate (and triaxial) broken power-law models were fit to the data, to account for the "smooth" component seen in Fig. III.3.7. Best models were chosen to minimise the devi-

Fig. III.3.7 (Page 80): The stellar halo of the Milky Way as seen by SDSS. The grey scale denotes the logarithm of the number density of MSTO stars per square degree in eight different magnitude (therefore distance) slices; a Lambert azimuthal equal-area polar projection is used. "Hot pixels" are stellar overdensities from globular clusters and dwarf galaxies.

Fig. III.3.8 (Page 81): Residuals (data – model) smoothed using a sigma = 42′ Gaussian from the best oblate model in 8 different distance slices. Black denotes that the data density is only 40 % of the models' density; white denotes that the observed stellar density is 200 % or more of the model density expected in that magnitude and position bin.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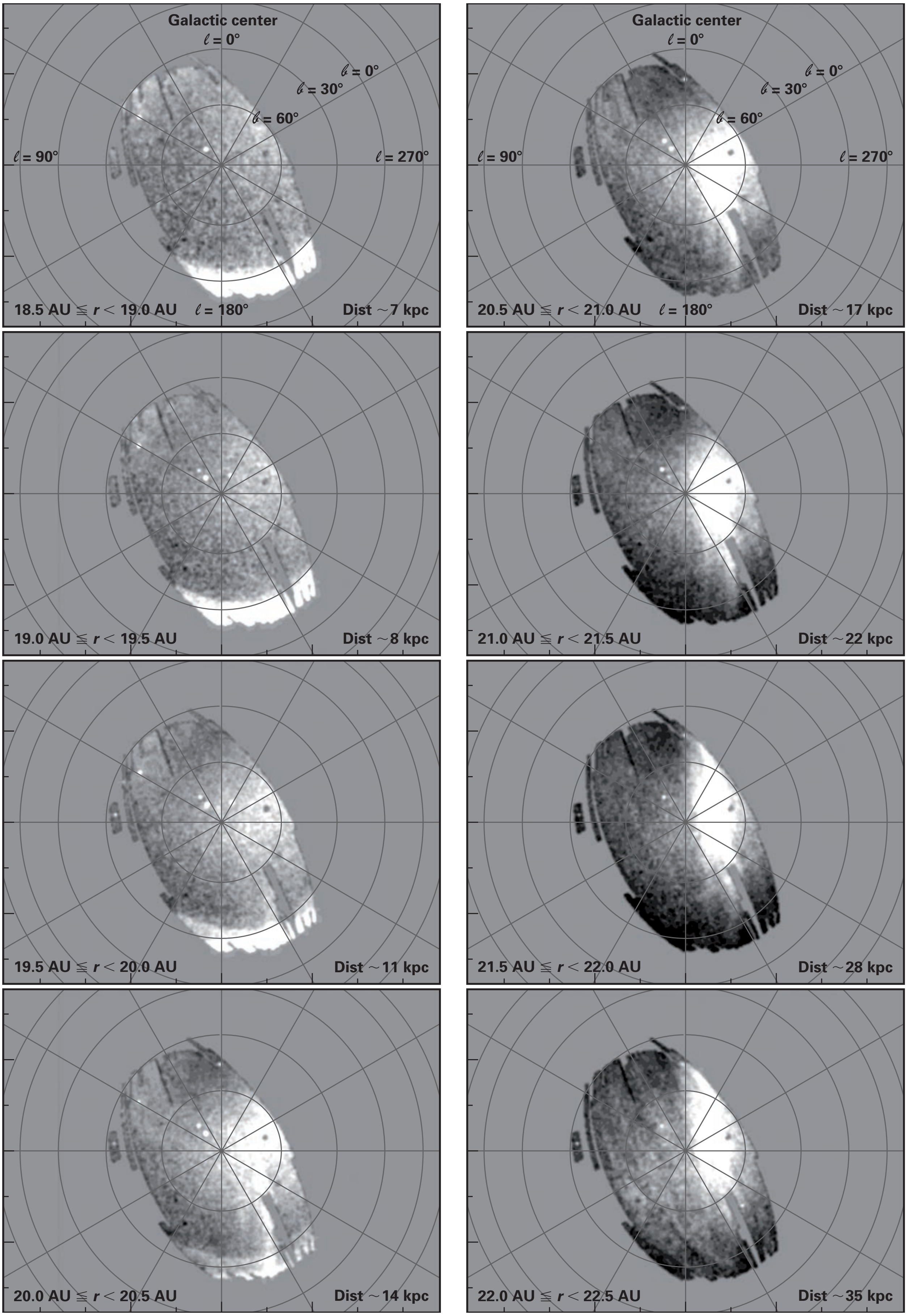
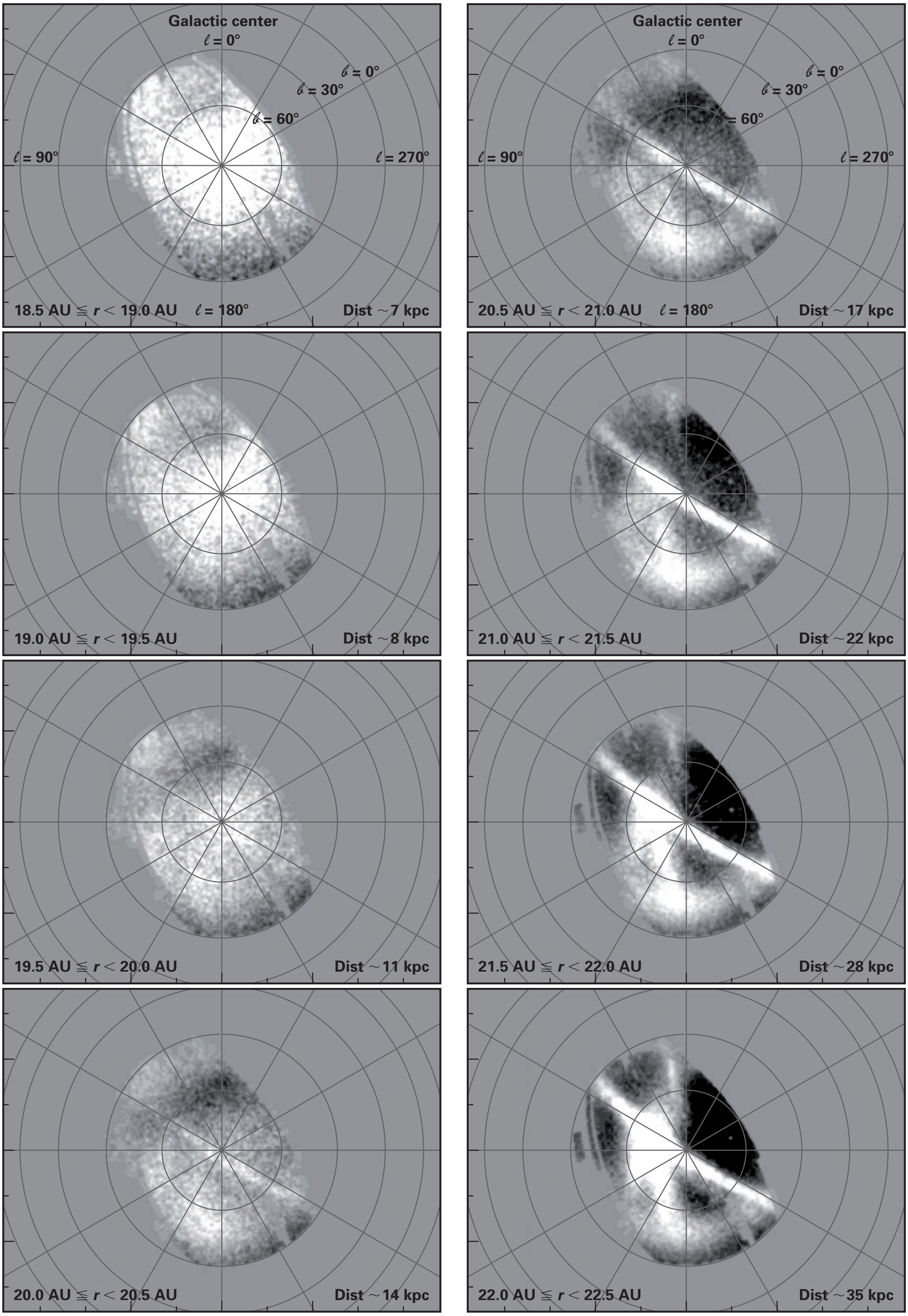
ℓ = 0°
b = 0°
b = 30°
b = 60°
ℓ = 90°
ℓ = 270°
18.5 AU ≦ r < 19.0 AU
ℓ = 180°
Galactic center
ℓ = 0°
b = 0°
b = 30°
b = 60°
ℓ = 90°
ℓ = 270°
20.5 AU ≦ r < 21.0 AU
ℓ = 180°
19.0 AU ≦ r < 19.5 AU
21.0 AU ≦ r < 21.5 AU
19.5 AU ≦ r < 20.0 AU
21.5 AU ≦ r < 22.0 AU
20.0 AU ≦ r < 20.5 AU
22.0 AU ≦ r < 22.5 AU


Galactic center
ℓ = 0°
b = 0°
b = 30°
b = 60°
ℓ = 90°
ℓ = 270°
18.5 AU ≦ r < 19.0 AU
ℓ = 180°
Dist ~7 kpc
Galactic center
ℓ = 0°
b = 0°
b = 30°
b = 60°
ℓ = 90°
ℓ = 270°
20.5 AU ≦ r < 21.0 AU
ℓ = 180°
Dist ~17 kpc
19.0 AU ≦ r < 19.5 AU
Dist ~8 kpc
21.0 AU ≦ r < 21.5 AU
Dist ~22 kpc
19.5 AU ≦ r < 20.0 AU
Dist ~11 kpc
21.5 AU ≦ r < 22.0 AU
Dist ~28 kpc
20.0 AU ≦ r < 20.5 AU
Dist ~14 kpc
22.0 AU ≦ r < 22.5 AU
Dist ~35 kpc



Galactic center
ℓ = 0°
b = 0°
b = 30°
b = 60°
ℓ = 90°
ℓ = 270°
18.5 AU ≦ r < 19.0 AU
ℓ = 180°
Dist ~7 kpc
20.5 AU ≦ r < 21.0 AU
Dist ~17 kpc
19.0 AU ≦ r < 19.5 AU
Dist ~8 kpc
21.0 AU ≦ r < 21.5 AU
Dist ~22 kpc
19.5 AU ≦ r < 20.0 AU
Dist ~11 kpc
21.5 AU ≦ r < 22.0 AU
Dist ~28 kpc
20.0 AU ≦ r < 20.5 AU
Dist ~14 kpc
22.0 AU ≦ r < 22.5 AU
Dist ~35 kpc

Fig. III.3.9: Residuals of the ΛCDM simulation. The format of this Figure is the same as Fig. III.3.8.

ation between the model and the data, in terms of the RMS of the data around the model, after having had taken out the expected contribution of Poisson noise in quadrature. The results are shown in Fig. III.3.8 and Fig. III.3.10.

A structured stellar halo: Visual inspection of Figs. III.3.8 and 10 shows that the stellar halo of the Milky Way is highly structured, with an RMS totalling some 40 % or more of the number of stars in the halo. While it is clear that much of the variance is in the largest structures (Sagittarius and Monoceros), 60 % of the total variance is in other structures (as determined by masking out Sagittarius and Monoceros before fitting; as shown by crosses in Fig. III.3.10).

Comparison with models: In the last years, theorists have constructed sophisticated models where the properties of disk galaxy stellar halos are predicted. In Figs. III.3.9 and III.3.10, results from the analysis of a state-of-the-art model from Kathryn Johnston, Sanjib Sharma (both Columbia University), and James Bullock (University of California, Irvine) are shown. The models are treated in exactly the same way as the data. The run of RMS with heliocentric distance is shown in Fig. III.3.10 for two models (solid and dashed lines); it is clear that the models describe reasonably well in quantitative terms the structure of the stellar halo of the Milky Way. The fitting residuals of one of the models are shown in Fig. III.3.9; many of the same qualitative features can be discerned as were seen in the SDSS data. There is a tendency for the model stellar streams to be rather more tightly confined than the real streams; this is likely due to model shortcomings (the Milky Way dark matter halo in the model is approximated with a smoothly-growing rigid halo, instead of a more realistic "live halo").

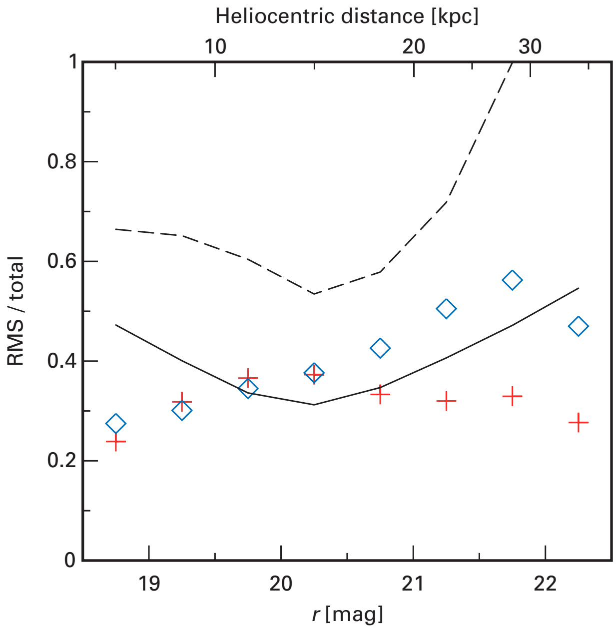


Fig. III.3.10: The RMS, as a fraction of the total number of stars, as a function of heliocentric distance. Diamonds denote the RMS of all halo stars (with galactic latitude greater than 35 degrees); crosses denote the RMS of halo stars taking out the areas of sky with contributions from Sagittarius and the Low-latitude stream. The solid line shows the residuals of the simulation shown in Fig. III.3.9. The dashed line shows the residuals of another simulation.

Outlook

The last decade has seen magnificent progress in our understanding of the faint stellar envelopes of the Milky Way, M 31, and a number of other galaxies. These stellar halos are all richly-structured, in excellent qualitative and quantitative agreement with state-of-the-art models of galactic halo formation. Study of individual streams yields more detailed constraints still. A particular mystery is the nature and origin low-latitude stream, and its possible progenitor the Canis Major overdensity, both of which are the subject of ongoing research at MPIA.

In this context, the involvement of the MPIA in the upcoming PanStarrs project is of particular interest. By the end of its 3.5-year survey, PanStarrs will have surveyed $^{3}/_{4}$ of the entire night sky in 5 passbands about 1.5 magnitudes deeper than the SDSS, and with factor of two better angular resolution. MPIA astronomers are leading the investigation of the structure and dynamics of the Local Group using these data. Owing to its depth, wide area coverage, and redder passbands, PanStarrs will be an ideal tool for the study of the low-latitude stream, the structure of the Milky Way's halo and thick disk, and study out to large radii of the halo of M 31 and other Local Group galaxies.

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University of California Irvine,
New York University, Basel,
and the SDSS collaboration

III.4 Deep Multi-Wavelengths Surveys

Deep images in many filters, spread across a wide range of the electromagnetic spectrum, can be combined to produce low-resolution "spectra" of all objects in the field detected above a given threshold. These spectra are used to classify the objects in terms of object class and – in case of extragalactic objects – also of redshift, i.e. distance. Such a data base can then be utilized for a variety of projects, two of which are described here. First, a survey in the optical and near-infrared wavelength range for distant clusters of galaxies yielded candidates for the most distant clusters known today. Second, combining deep radio imaging with datasets across the entire electromagnetic spectrum enables the study of the properties of the faint radio population with an emphasis on dust-enshrouded massive star forming galaxies and dust-obscured QSO as well as the characterization of the environment around peculiar radio galaxies.

Establishing catalogues of astronomical objects is the oldest tool at the disposal of astronomical researchers. Systematic cataloging of celestial objects was necessary to deduce the periodic phenomena on the sky throughout the year, a major interest in early Egypt and Mesopotamia. The first true catalogue of stars was prepared by the Greek astronomer Hipparchus from Nicaea as early as 135 BC. Another well-known survey is the Messier catalogue, published in 1784 by Charles Messier. He was a comet hunter and catalogued nebulae which might be mistaken for comets. With these few examples it is already clear that surveys come in two different flavors: Complete catalogues, listing all known objects on the sky or in selected areas, and catalogues of special objects, like comets or galaxies.

Modern examples of surveys most widely used by present day astronomers are the National Geographic Society – Palomar Observatory Sky Survey (POSS) secured on photographic plates between 1948 and 1958 in two filters with the Palomar 48-inch Schmidt telescope and the Sloan Digital Sky Survey (SDSS) completed in June 2005, taken with a CCD camera and five filters. Obviously, these surveys are general purpose tools. Based on these, subsets for different purposes have been extracted, e.g. the Abell catalogue of clusters of galaxies is based on a visual inspection of the Palomar survey plates.

A fundamental aspect of modern astronomy is the extension of the observations beyond the visual range. The first wavelength range explored beyond the optical was the radio band and again a major tool was a radio survey, the 3rd Cambridge catalogue. In 1963 the visual identification of its sources led to the discovery of a new class of objects – quasars. Today we have catalogues at hand spanning the whole frequency range from the radio to the energetic gamma-rays. Of course, parts of these cannot be observed from the earth's surface but need the telescope to be launched into space, like the ROSAT X-ray satellite. It was built under the leadership of the MPI for extraterrestrische Physik in Garching and performed the first all-sky X-ray survey in the early 1990s.

It is only natural to extend the survey tool also to a combination of observations in different wavebands. Optical identifications of radio or X-ray sources, as mentioned above, are only a first step. Based on the nature of the objects under study a combination of observations in several wavebands has a highly discriminative power, enabling the reliable selection of a given class of objects. This contribution to the Annual Report will describe in detail this last approach, deep multi-color surveys conducted at MPIA. From the various projects currently pursued within this framework we select two examples: (A) HIROCS, a search for distant clusters and (B) COSMOS, a large international collaborative effort towards understanding the formation and evolution of galaxies over cosmic time.

A. HIROCS – a Search for the Most Distant Clusters of Galaxies

The Heidelberg InfraRed/Optical Cluster Survey (HIROCS) is part of the extragalactic keyproject MANOS (MPI for Astronomy Near-infrared Optical Surveys) and aims at the detection of the most distant clusters of galaxies. Following the motivation of the survey, a detailed description of the layout of the survey is given. First results show that HIROCS is indeed able to find clusters in the targeted redshift range.

Why Search for Distant Clusters?

Matter is not distributed homogeneously in the universe. Galaxies are arranged in filaments and sheets enclosing large voids and build up what we call large-scale structure in the universe. Clusters of galaxies are the most massive, gravitationally bound entities within these structures we know. According to our current understanding of structure formation, galaxies and clusters of galaxies form from initial density fluctuations. These fluctuations were produced at early times by inflation of quantum fluctuations to macroscopic scales. Galaxy sized structures form first; clusters of galaxies later

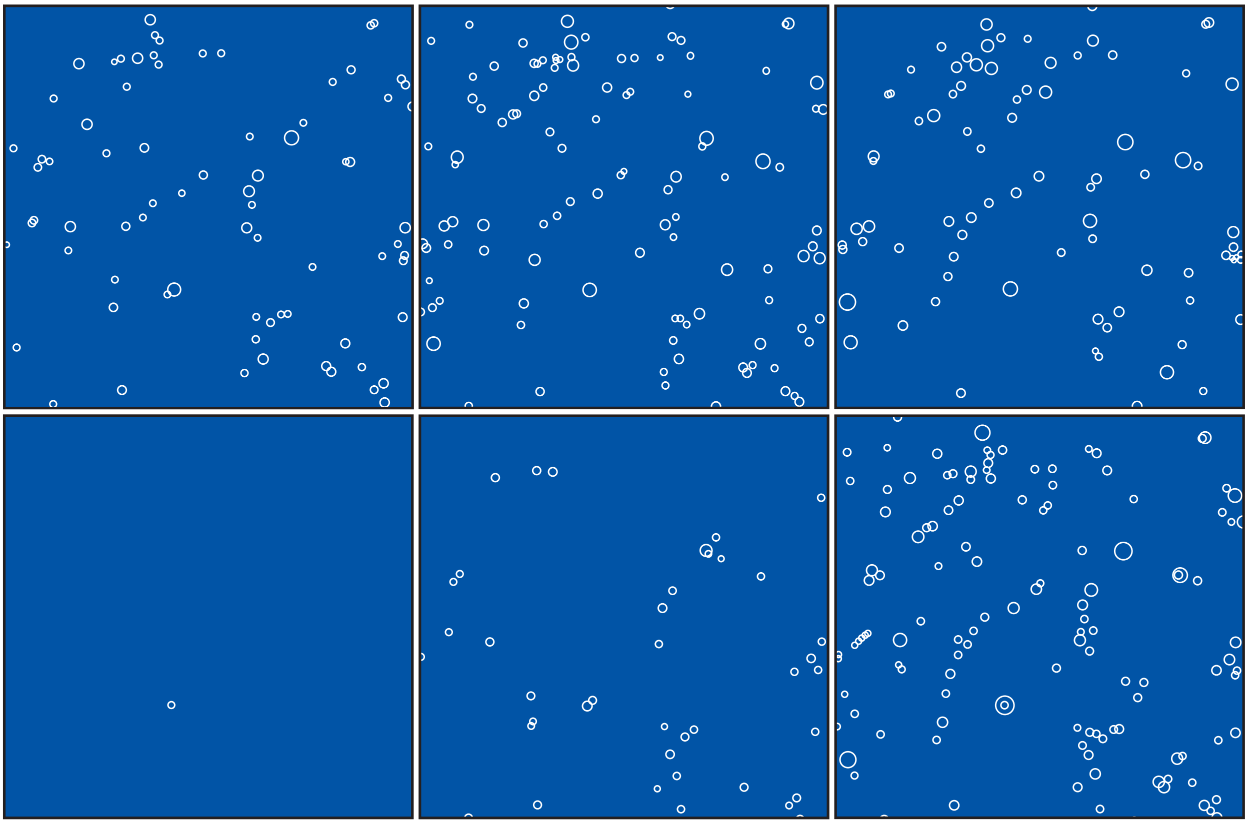


Fig. III.4.1: The influence of the cosmological model on the evolution of gravitational clustering was simulated by Borgani, Guzzo (Nature 2001) using an N-body code with about two million particles. The upper panels are for a flat low-density model with $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$, and the lower panels show results for an Einstein-de-Sitter model (EdS) with $\Omega_m = 1$ as an extreme case for a high-matter density universe. Columns show X-ray emitting clusters as circles at three redshift snapshots of 0, 0.6 and 1.4 (*right to left*) with each panel extending over a region with sides of 250 h^{-1} Mpc and thickness of 75 h^{-1} Mpc (co-moving with the cosmic expansion). The size of the circles is proportional to the temperature of the X-ray emitting plasma. The cluster density today at redshift zero was set to be equal for both models. In a low-density universe clusters have to form early.

assemble from galaxies. Dark matter dominates the gravitational potential of the largest structures into which the smaller lumps (galaxies) fall, creating a cluster of galaxies. From this brief description it is evident that the details of cluster formation depend critically on the cosmological model assumed. Looking at the growth of the initial density perturbations with time one has to consider two counter-acting effects: gravitational collapse vs. cosmological expansion. In a high-density universe with the matter density being equal to the critical density the time scales for both effects are the same at all times. In a low-matter density universe this equality only holds for the time shortly after the big bang. At later epochs, when the self-gravity of the Universe has become negligible, the cosmic expansion overtakes the fluctuation growth and eventually the growth of fluctuations comes to a halt. In 2001 Stefano Borgani and Luigi Guzzo published a simulation which compares the expected number densities of rich clusters as a function of redshift for universes with different matter densities (Fig. III.4.1). The simulations were normalized in such a way as to correctly provide the present day cluster density. Following the arguments above, clusters are formed relatively early in a low matter density universe, i.e. one expects to see rich clusters also at large lookback times, i.e. at high redshifts. For a high matter density, the clusters formed late in the evolution of the universe rendering them rare at high redshifts. Thus a measurement of the number density of clusters as manifestations of successful fluctuation growth as a function of redshift puts constraints on the matter density in the universe.

Besides this cosmological motivation to search for the most distant clusters there is also the aspect of galaxy evolution. Galaxy clusters are ideal laboratories to study the evolution of galaxies as a population by using the universe as a time-machine (see footnote on redshift). In the simplest division galaxies come in two flavors: Star-forming disk galaxies have a blue color and elliptical galaxies show an evolved, old red stellar population. It is well known that elliptical galaxies prefer dense environments like clusters or even their dense cores, whereas disk galaxies live in looser contact to their neighbours. This morphology-density relation, discovered 1980 by Alan Dressler, seems to be already established at a redshift of about 1 albeit in a somewhat different form. As elliptical galaxies are believed to be the result of merging disk galaxies there must be an earlier epoch where this merging happened in clusters. In their seminal paper, Harvey Butcher and Gus Oemler showed in 1984 that the fraction of blue galaxies in clusters is a strong function of redshift, with the blue galaxies more abundant at earlier times. HUBBLE-Space-Telescope observations have shown that the blue galaxies in clusters are predominantly star-forming spirals with a large fraction of disturbed, interacting and thus probably merging galaxies. Finding galaxy clusters at the highest possible redshifts will thus certainly allow us a glimpse of the childhood of galaxies in clusters.

Currently known distant clusters of galaxies, i.e. those with redshifts above unity, are rare. Only about a handful are well studied and, except for one, they were exclusively discovered due to their X-ray emission (see Fig. III.4.13, p. 93). The source of X-ray radiation from clusters is an extremely hot (10 to 100 Million degrees) plasma permeating the cluster, trapped in the deep potential well of the cluster's dark matter. It is not at all clear that these X-ray emitting clusters are typical at these redshifts. A search for distant clusters concentrating on the detection of the cluster galaxies' stellar light instead of the plasma's X-ray emission will show if and how the two selection methods are biased.

Based on all these considerations we started in 2002 at MPIA to design a survey for distant clusters of galaxies with redshifts up to 1.5. By then the large-area imagers for the prime-focus of Calar Alto's 3.5 m telescope, LAICA for the optical and OMEGA 2000 for the infrared wavelength range, were about to go into operation. These instruments would be needed to conduct such a survey within a reasonable observing time.

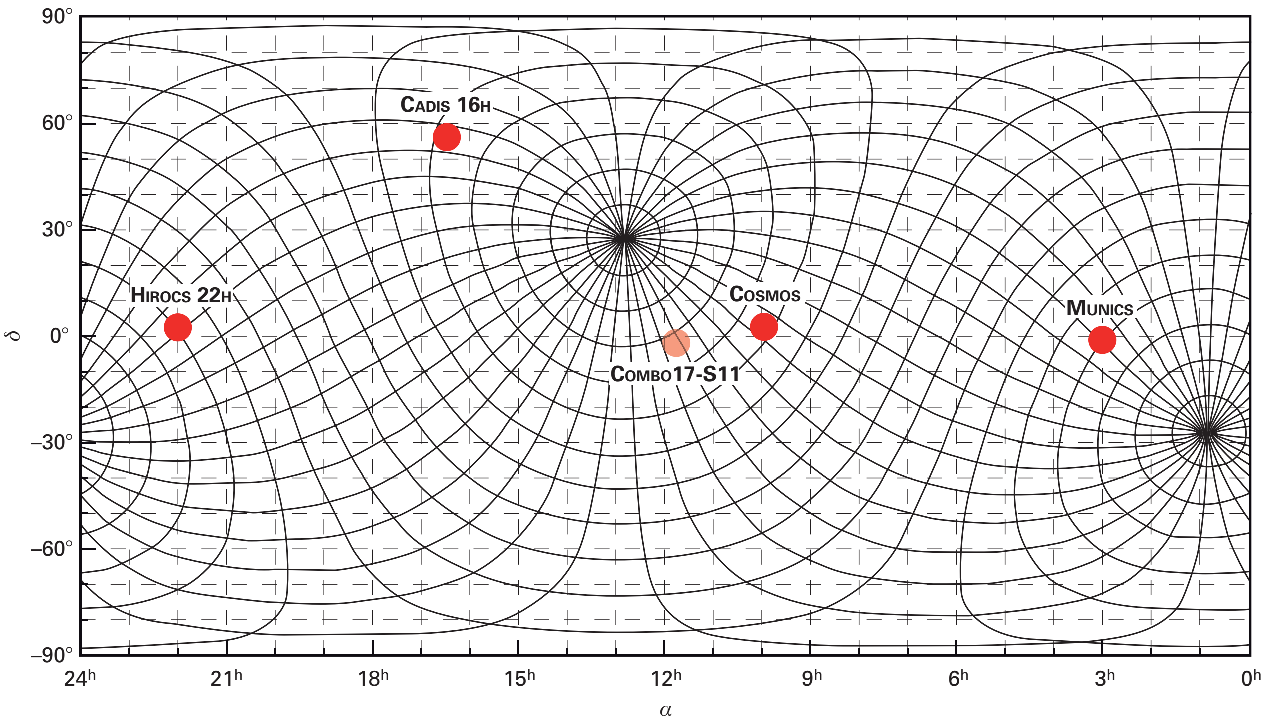
Survey Specification

It was clear from the beginning that such a survey would be a major effort for the next years to come. Due to the large commitment in telescope time the project was declared a keyproject of MPIA's department "Galaxies and Cosmology". The first task to accomplish was a detailed specification of the survey: What area has to be covered? Where to look? Which filters are needed? How deep do the exposures have to be to detect clusters at redshifts beyond unity? How will we isolate the cluster candidates?

Area to be Surveyed

From the beginning the survey was restricted to the aspect of the evolution of the galaxy population in clusters. Derivation of cosmological parameters would require a

Fig. III.4.2: Positions of the HIROCS survey fields on the sky. The overlaid curves are lines of constant galactic latitude and longitude. The fields are all at high galactic latitude, i.e. away from the plane of the Milky Way.



considerably larger area to be covered and will be attempted by other groups and other means, e.g. by surveys exploiting the Sunyaev-Zel'dovich effect. To study the evolution of the galaxy populations a sample of clusters is needed that covers at least two distinctly different redshift ranges. In order to be statistically significant, a minimum of 25 clusters is needed for each range. Thus we have to aim at a cluster sample of 50 or more clusters at redshifts above unity. As this redshift range was terra incognita we had to resort to model calculations. Bartelmann and White (2002) had estimated the number of clusters with redshifts larger than one expected in the Sloan Digital Sky Survey (see above). Their estimate of an expected 5 clusters per square degree meant that our survey will have to cover at least 10 square degrees.

Where to Look

The survey fields had to fulfill the following criteria: 1) location near the celestial equator to enable follow-up observations with large telescopes from both hemispheres, 2) low interstellar absorption in our Milky Way, 3) no bright stars in the field of view, as their scattered light halo would render a large part of the image unusable. We settled on the 4 fields shown in Fig. III.4.2. Three of the fields contain areas already surveyed by other projects so we can exploit their results at least for calibration purposes: The 3h-field covers also the MUNICS field and we collaborate with our colleagues from Munich in acquiring a common data pool. The 10h-field is the COSMOS field (see below, p. 94), for which a large international consortium establishes a multi-wavelength database including HUBBLE-Space-Telescope data. The 16h-field is the only field accessible only from the northern hemisphere, which was chosen because it is one of the CADIS fields, where a large set of spectroscopic observations are available. To be able to observe throughout the year the gap between the 16h and the 3h-field was filled with a new HIROCS field at approximately 22h in Right Ascension.

Each field is $1° \times 3°$ in extent except for the COSMOS field. This will allow us to trace any galaxy overdensity due to large-scale structure and hopefully discriminate it from a real cluster. However, none of our cameras can image such a large area in one shot: LAICA needs 4 shots to cover one square degree and OMEGA 2000 needs 16 exposures. This adds a new dimension to our data reduction procedures. In our previous surveys like CADIS or COMBO-17 each field was covered by a single exposure. Now that we have to mosaic our fields, the individual exposures contributing to the different patches of the mosaic are no longer taken under the same conditions regarding seeing, sky background and atmospheric transmission. To cope with this various extensions to our reduction software had to be made, normalizing the mosaic tiles to one another. Only then we are able to use our existing extensive software package for further analysis.

How Do We Find the Clusters?

Assuming that the data are in hand, how can distant clusters be isolated? Looking at a deep image of the sky with myriads of faint galaxies (Fig. III.4.3) this task is reminiscent of finding the apocryphal needle in the haystack. At lower redshift, e.g. in Abell's catalogue of nearby clusters, one can simply look for overdensities of bright galaxies. At higher redshifts the contrast of clusters in deep images against the many faint fore- and background galaxies deteriorates rapidly making it impossible to find clusters merely on the grounds of the galaxies' surface density. Additional information has to be employed. The distance of a galaxy from us, i.e. its redshift, is an important piece of information, allowing direct elimination of back- and foreground galaxies.

Here, the MPIA's experience from the CADIS and COMBO-17 projects comes into play. Over the years we have developed tools to use images taken in many different filters across the visible wavelength range to construct a low resolution spectrum for each object in the field. Comparing this spectrum with a library of template spectra for stars, galaxies and quasars allows us to select the best fitting library spectrum and thus the most likely object class. For galaxies and quasars the libraries must, of course, also include the set of template spectra for the whole range of redshifts to be surveyed. In the end, this procedure of multi-colour classification assigns an object class and a so-called photometric redshift (in contrast to a spectroscopic redshift derived from a spectrum taken with a spectrograph) for all objects in the field brighter than a certain limiting magnitude. For fainter objects the procedure becomes more and more unreliable. Photometric redshifts have now become a common tool in extragalactic multi-colour surveys.

Given the photometric redshift and the position on the sky for each galaxy in a survey field one can now isolate clusters truly in 3D-space, overcoming the above mentioned contrast problem. The idea is as follows. For each galaxy with photometric redshift information one can calculate the radius which will be spanned on the sky by a typical cluster radius (the Abell radius) at this redshift. Within this circle around the galaxy, one then calculates for all other galaxies with photometric redshifts the redshift difference to this galaxy. Redshift differences correspond to differences in distance. This way the true local galaxy volume density can be derived for each galaxy in the sample. An examination of the statistical distribution of these galaxy densities points to galaxies living in over-dense regions. These are the clusters we are looking for.

Photometric redshifts are necessarily less accurate than redshifts derived from "real" spectra and they become less accurate the more one reduces the number of filters in the survey. For CADIS and COMBO-17, 16 and 17 filters were used, respectively. To use such a large number of filters is absolutely unrealistic for a survey

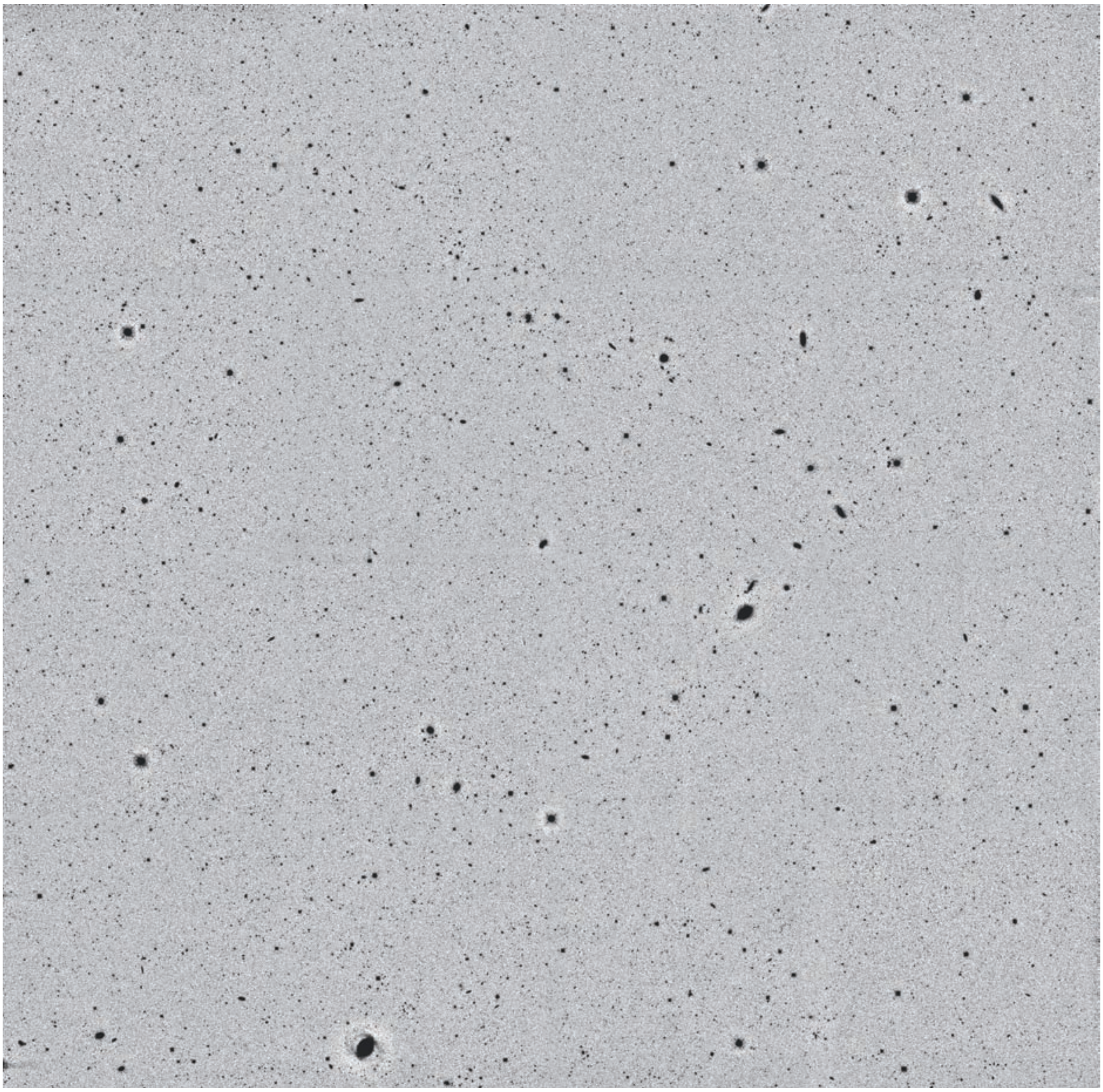


Fig. III.4.3: Full mosaic ($1° \times 1°$) of 4×4 OMEGA 2000 H-band images of the 3h-field containing more than 75 000 objects with signal-to-noise ratio larger than 3. Each individual image is the sum of 50 single frames, which are slightly shifted in position (dithered) to always place the objects on different pixels of the detector. Each of these again is the sum of 20 exposures with 3 seconds integration time. These 20 images are taken at the same telescope position and already added up in the data acquisition computer. Otherwise the data rate to disk would be too high to cope with. The total integration time for this mosaic is thus $(16 \times 50 \times 20 \times 3)$ seconds $= 13.3$ hours.

covering 10 square degrees with the instruments and the telescope time available. The number of filters has thus to be optimized.

Which Filters Are Needed?

As mentioned above, rich clusters are dominated by a population of red elliptical galaxies. These spectra exhibit a characteristic feature, the so called 4000-Å-break, where the flux rises by about a factor of 2 (see Fig. III.4.4). The strongest signal in the multi-color classification of elliptical galaxies comes from two filters straddling this break. If one wants to push a survey out to redshifts well beyond unity, at least one infrared band has to be included. To minimize the number of filters in the optical range we started with the full set of 16 CADIS filters for one field and performed an object classification. Then the number of filters was reduced and the classification ran again. The results were compared with the original classification especially in terms of the errors of

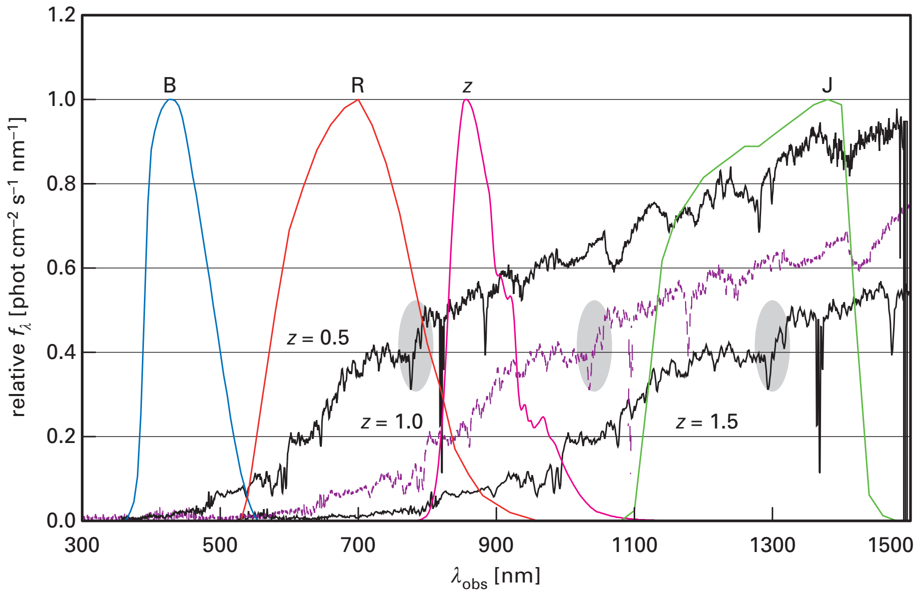


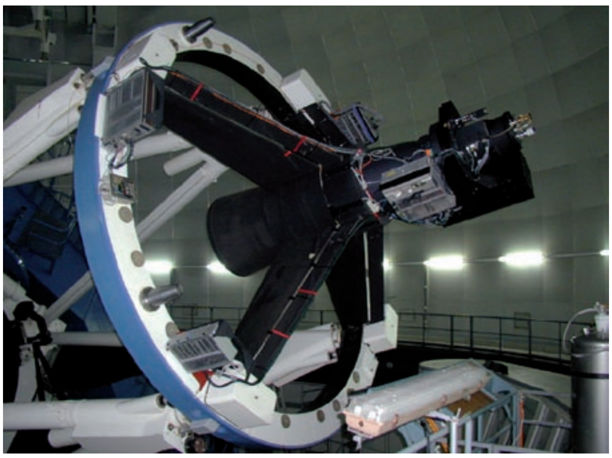
Fig. III.4.4: Spectrum of an elliptical galaxy at three different redshifts. The position of the 4000-Å-break is marked by the grey ellipse. Locations of the filters straddling the break at each redshift are indicated by their transmission curves. For redshifts above unity an infrared band is mandatory to securely identify galaxies by their 4000-Å-break.

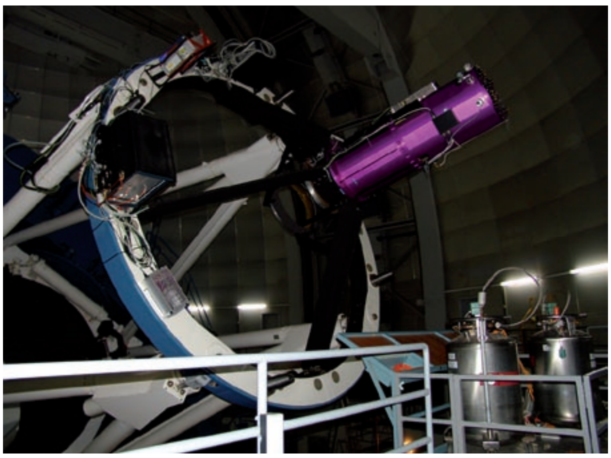
the photometric redshifts. It turned out that with the five broad filters *B*, *R*, *i*, *z* plus the infrared band *J* a reliable classification was still possible. Even a cluster candidate that happened to lie in this field at a redshift of about 0.6 could be recovered with the reduced filter set. For the actual survey we decided to replace the *J*- by the *H*-band. At a redshift of 1.5 the J-band is only just above the 4000-Å-break, so the use of the *H*-band would eventually allow pushing the redshift limit even beyond 1.5.

Exposure Times Needed

To calculate the exposure time needed to achieve a predefined signal-to-noise ratio requires knowledge of the complete instrumental setup (atmosphere, telescope, and instrument), the form of the emitted object spectrum, the luminosity of the object and its distance to us. Based on these the number of photons detected from the object as well as the noise introduced from the sky background can be calculated as a function of exposure time. The instrumental data are easiest to get. They are usually made available on the web page of the observatory. The distance to reach is set by the redshift limit of 1.5 for the survey. For the luminosity and the spectrum of the objects we had to make reasonable assumptions, which were based on the results of the Combo-17 survey. However, as Combo-17 did not include an infrared band, it only found galaxies out to a redshift of about 1. To extrapolate from here to a redshift of 1.5 we used the following strategy.

Fig. III.4.5: Laica (*left*) and Omega 2000 (*right*) in the prime focus of the 3.5 m telescope on Calar Alto. See annual reports 2001 and 2003 for details about these instruments.





In a rich cluster the number of galaxies with a given luminosity is distributed over luminosity according to the so-called Schechter luminosity function. It shows an exponential cutoff at the bright end and a power-law slope at the faint end; the turn-over point between these two branches occurs at a typical luminosity termed L^*. To recognize a cluster as such, one has to probe the luminosity function well beyond L^* into the fainter part. Otherwise only very few cluster members would be covered and the cluster nature would not be recognizable. Thus we decided to probe one magnitude deeper than L^* which for typical clusters in our neighborhood would include about 20 to 50 cluster members. As was shown by Bell et al. (2004) from the COMBO-17 data, L^* varies with redshift. From this work a value of L^* in the *B*-band of – 22 mag was derived for a redshift of 1.5. Concerning the spectral shape one has to keep in mind that the spectrum of a present-day elliptical galaxy is not typical for one at redshift 1.5. The stars in the galaxy were much younger then and thus the composite spectrum of the ensemble of stars was different. As a spectral energy distribution we have selected the reddest spectrum found on average at the highest redshifts in COMBO-17.

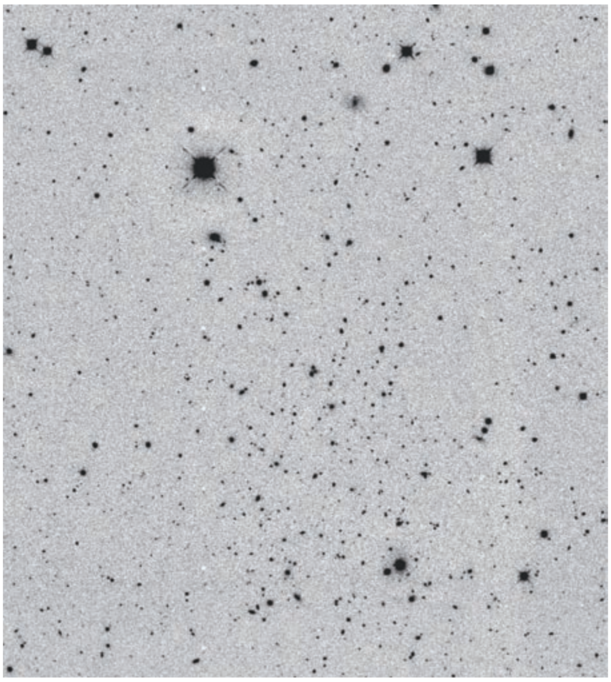
Combining all this information we could calculate the exposure time necessary to detect an elliptical galaxy 1 mag fainter than L^* at a redshift of 1.5. Together with the field size for each instrument one could then derive the total integration time required. Typical values for observing efficiency finally lead to a total telescope time required for HIROCS of 7.6 nights to cover one square degree in all five filters. Assuming that for the COSMOS field the optical data are all publicly available, we would need 73 clear nights on the 3.5 m-telescope on Calar Alto to complete the survey.

Current Status of HIROCS

HIROCS started with first observations in July 2002 using LAICA (Fig. III.4.5). Optical observations were supplemented since December of the same year by the Wide-Field-Imager on the 2.2 m telescope on La Silla. OMEGA 2000 was commissioned in 2003; the first science run took place in September of the same year. Since then the infrared data came in regularly. There were, however, serious delays with the optical data due to technical problems with LAICA and the 3.5 m telescope. Also weather losses hampered the observations on La Silla. We had hoped to have covered 6.6 square degrees in all 5 filters by the end of 2006. This goal was not completely accomplished, again due to bad weather. We still need 21 hours with OMEGA 2000 and 17 hours with LAICA which now have to be scheduled in 2007.

The first full square degree covered with all filters became available for the 3h-field. We have used these data to develop the software necessary to treat these data properly. As mentioned above, special care has to be taken of the photometric properties of mosaics. Also the large optical distortion in LAICA required special treatment. All these tools are now available and the first reduction was performed.

Fig. III.4.6: Part of an OMEGA 2000 *H* image with over-density of faint objects at center (*top*). In a color composite prepared from the R, z, and H images these objects are seen as a cloud of red galaxies in the center (*bottom*). The two bright stars appearing greenish are about 3′ apart; North is up, East to the left.



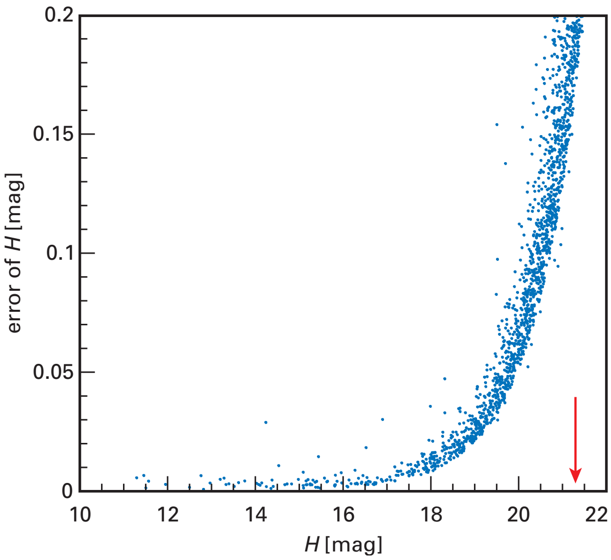


Fig. III.4.7: Distribution of magnitude errors for the *H*-band as a function of *H*-magnitude. Only every 30th object is plotted for clarity. The width of the distribution is mainly determined by the different depths of the 16 tiles of the mosaic. The limiting magnitude (5σ-level, corresponding to $\Delta H = 0.2$ mag) can be read off as 21.3 mag (*red arrow*), fainter than the originally planned goal of 20.9 mag as the seeing during the observations was better than expected. At the bright end the photometric error is well below 1 %.

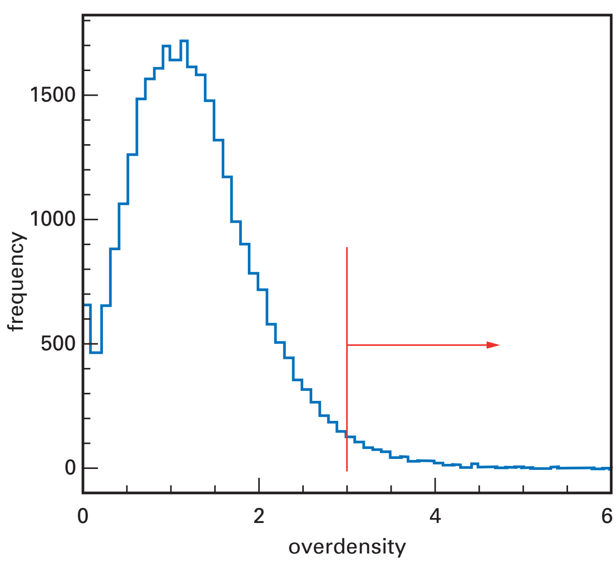


Fig. III.4.8: Distribution of the normalized local object densities. To select the cluster candidates a cut at an overdensity of 3 (red arrow) was used.

First Results

A rich cluster at intermediate redshift

Already during the reduction of the *H*-band data, we noticed an over-density of faint objects in one of the OMEGA 2000 images by eye (Fig. III.4.6). A quick-look reduction showed it to be at a redshift of about 0.7, which was later refined by the final reduction to 0.61.

First search on a full data set

By summer 2006 all software tools were ready and data in five filters for the first square-degree patch in the 3h-field had been reduced. Recently acquired data for some tiles in some filters were not included yet, however. But we could go ahead and perform the first search for high redshift clusters following the strategy outlined above. The final data product to work with is a table with one row for each object and the columns giving the parameters measured for each object like position on the sky, shape, fluxes measured in the various wavebands, and results of the multi-color classification like object class and redshift. On this table the tools from the MIDAS table system could be applied to plot results and perform selection operations based on the object parameters. This table contained 145 000 objects in 0.96 square degrees. For 137 000 of them a photometric redshift could be derived, for 36 600 of these the accuracy was better than 0.1. The first thing to verify was that the estimate of the exposure time needed to reach the desired limiting magnitude had been correct. In most filters it even turned out to be somewhat conservative (Fig. III.4.7).

To isolate cluster candidates in the data table the number of objects has to be reduced by a stepwise selection process according to various object properties. The first selection is done by overdensity. For each galaxy with a photometric redshift the local object density is calculated as outlined above and entered into the table. A histogram of the overdensities for all galaxies is given in Fig. III.4.8. In this first step all objects living in regions of overdensities higher than 3 are selected. Clusters are isolated on a plot of the location of the selected objects on the sky (Fig. III.4.9). Clumps of galaxies in overdense regions point to the cluster candidates.

A look at Fig. III.4.9 shows that indeed there are numerous clumps of objects. Some of them are certainly spurious (like the satellite trails) and have to be eliminated one by one. At this stage we looked at the most prominent concentrations manually. Without any further selection the most prominent concentration at [1200, – 750] is the cluster already identified visually (Fig. III.4.9, left). As we look for the most distant clusters the selection in the next step was for overdense regions comprised of galaxies with photometric redshifts larger than unity (Fig. III.4.9, right). The first candidate we chose for a closer inspection is the region around [500, – 1600] in the bottom central region. The selection of objects was pushed further by only selecting objects lying within this region, i.e. in the interval $300 < x < 655$ and $-1730 < y < -1480$. Now the number of objects selected has shrunk to only 31 (out of a total of 145 000). The distribution of

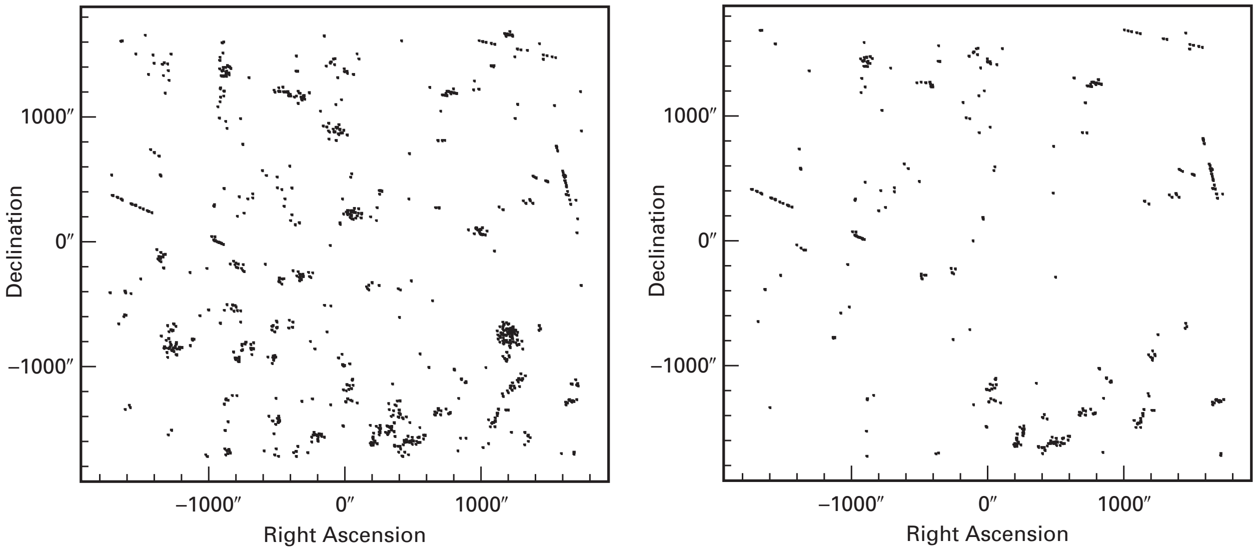


Fig. III.4.9: Location of galaxies living in overdense regions on the sky. All redshifts are plotted on the left, only galaxies with redshift larger than 1 on the right panel. Some spurious signals like satellite tracks have not been removed. The cluster found visually is very prominent in the left panel at [1200, – 750]. The strongest signal in the right panel at [500, – 1600] is the cluster at a redshift of 1.25.

the photometric redshifts for these remaining galaxies (Fig. III.4.10) shows this to be indeed a cluster candidate at a redshift of about 1.24. The width of the distribution is what we expect from the redshift accuracies. Further support that we have found a real cluster is given by the excellent fit of our photometric data points to the template spectra. An example is given in Fig. III.4.11.

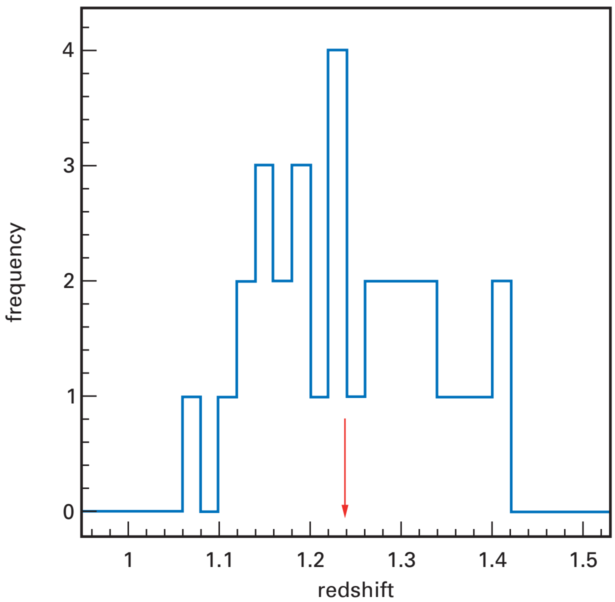


Fig. III.4.10: Distribution of photometric redshifts for the first HIROCS cluster candidate at a redshift above unity. The average redshift is 1.24 ± 0.02 (scatter for the 31 objects is 0.093 in redshift).

Fig. III.4.11: Best-fitting template spectrum (*green*) for one of the members of the cluster at redshift 1.24. The photometric redshift of this particular galaxy was determined as 1.26 ± 0.14. The photometric measurements in our 5 filters are given by the black crosses, whose width indicates the filter width and the height the photometric error. This galaxy has an R-band Vega magnitude of 24.8 mag.

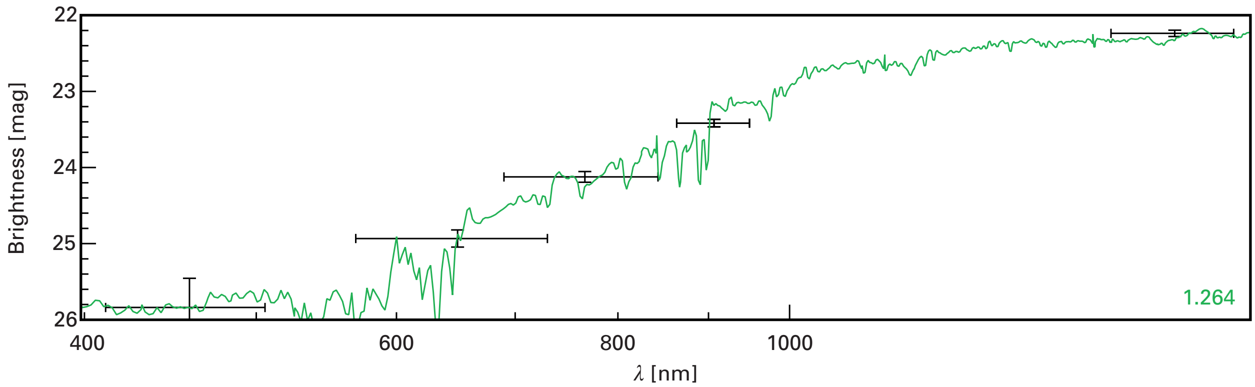


Fig. III.4.12: False color image prepared from the R, z and H images shows the cluster candidate at redshift 1.24 as a concentration of (weak!) red galaxies in the center.

A false color image of this region, prepared from the R, z, and H image shows the cluster as a concentration of faint red galaxies (Fig. III.4.12). Without the redshift information from the multi-color classification it would not have been possible to find this cluster.

Another candidate was found close-by on the sky with an even higher redshift of 1.35 ± 0.02. It is, however, less rich in galaxies (and thus mass) and thus less impressive in appearance. In the meantime the data acquisition for the first square degree of the 3h-field is essentially complete and the images are reduced with a software version optimized further based on the experience gained in the first round of data analysis. Thus the final list of cluster candidates for this field will soon be available.

How do these redshifts compare with the most distant clusters published thus far? The cone diagram in Fig. III.4.13 shows the distribution of known clusters over redshift, coded by the discovery method. HIROCS clusters are amongst the most distant clusters currently known. But it is also evident that other projects like UKIDSS (a survey at infrared wavelengths with the UKIRT 3.8 m telescope on Mauna Kea, that will cover a larger area to fainter magnitudes than HIROCS in three filters) or those using the SPITZER space telescope are tough competitors in finding galaxy clusters by means of their optical/infrared emission of stellar light.

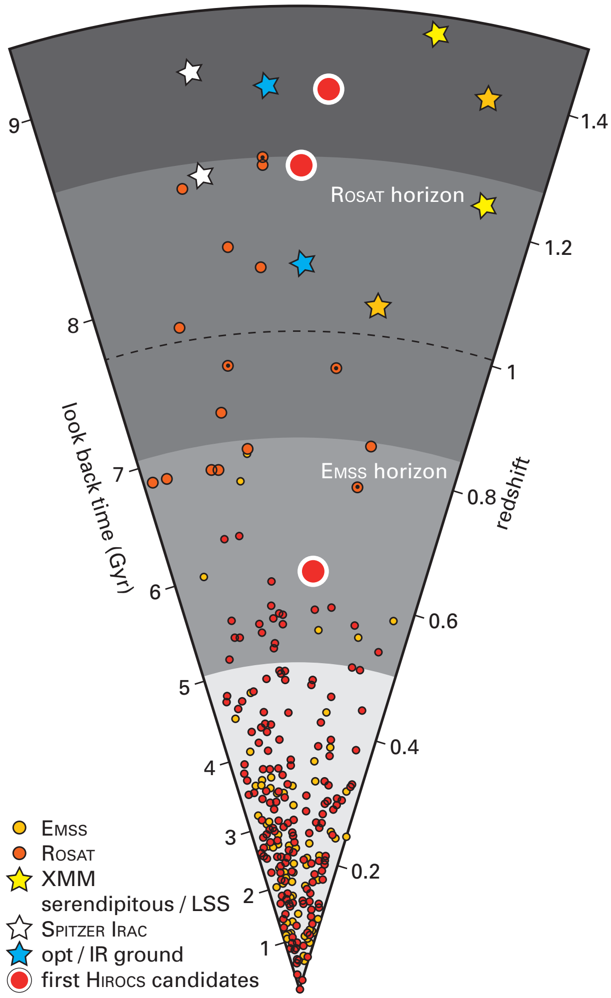


Fig. III.4.13: Distribution of currently known clusters in redshift space. EMSS, ROSAT and XMM mark clusters detected by their X-ray emission. Optically selected clusters at low redshift (like the Abell clusters) are omitted. (Updated from Mullis, Ringberg Workshop 2005)

Outlook

Having demonstrated the ability to find high-redshift clusters of galaxies in the deep multi-color survey HIROCS, which includes an infrared band, we hope to establish a sizeable sample of such objects for further investigation with large telescopes like the VLT and the LBT in the near future. Their detailed study will shed light onto whether the clusters found by searches for concentrations of stellar light are different from those found in deep X-ray surveys. Investigations of the galaxy populations in the distant clusters and a comparison with their counterparts at low redshift will certainly provide important ingredients for our understanding of the evolution of galaxies in clusters and in general.

Hermann-Josef Röser, Hans Hippelein,
Kris Blindert, Michael Zatloukal, together with
Siegfried Falter (Köln) and Christian Wolf (Oxford)

B. Cosmos – Studying the Cosmic Evolution of Galaxies and Black Holes

Resulting from synergetic theoretical and observational efforts, our understanding of the formation and evolution of galaxies and their large-scale structures (LSS) has advanced enormously over the past decade. Deep observational studies using the Hubble Space Telescope (HST) and the largest ground based telescopes have probed galaxy and AGN populations back to redshift $z = 6$ when the universe had aged less than 1 billion of its current 13 billion years. Just as remarkable is the enormous success of numerical simulations for ΛCDM models in reproducing many of the current LSS characteristics, all starting from an initial, nearly uniform, hot universe.

The deep imaging surveys using the Hubble space telescope (HDF, Goods, Gems, HUDF) have provided exquisite imaging of galaxy populations in narrow cones out to $z \sim 5-6$. Ground-based multi-band imaging and spectroscopy provide redshifts and hence cosmic ages for these populations. Most briefly, the early universe galaxies were more irregular/interacting than at present and the overall cosmic star formation rate probably peaked at $z \sim 1-3$ with 10 – 30 times the current rates. Although some large scale structure and clustering of the luminous, high redshift galaxies is in evidence, it is the theoretical simulations which have so far best characterized (or at least hypothesized) the larger scale, dark matter structure (see Fig. III.4.14).

In fact, the major gap which exists in our current understanding is the coupling between the LSS and the evolution of luminous galaxies. The relations between the cosmic mass distribution, environment and galaxy properties (morphology, size, and age) have no strong empirical constraints beyond redshift $z{\sim}0.5$. The rate of galaxy evolution and the morphological mix are thought to be strongly dependent on galaxy environment (LSS), but this is well established only for the local Universe (e.g. the Sloan Digital Sky Survey). Substantial LSS occurs on scales up to ~100Mpc at low redshift, including voids, filaments, groups and clusters. Adequately mapping galaxy evolution over the full range of environments and redshifts therefore requires data covering wide areas coupled with accurate spectroscopic redshifts ($\Delta z/(1+z) \leq 0.01$) for the line-of-sight discrimination in the LSS. The Cosmos project is a pan-chromatic imaging and spectroscopic survey designed to probe galaxy and SMBH evolution as a function of cosmic environment.

Cosmos – The Cosmic Evolution Survey

The international pan-chromatic Cosmos survey (P.I.: Nick Scoville, California Institute of Technology) is the first survey encompassing a sufficiently large area that it can address the coupled evolution of LSS, galaxies, star formation and AGN. The equatorial field of the

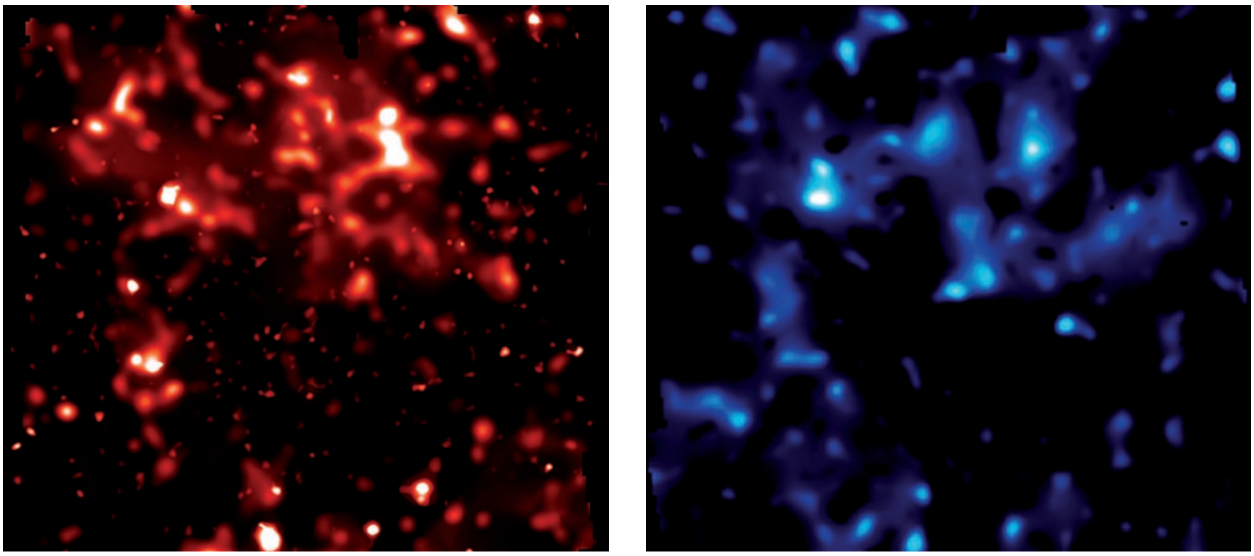


Fig. III.4.14: Two false-color images compare the distribution of normal matter (*red, left*) with dark matter (*blue, right*) in the Cosmos field. The brightness of clumps corresponds to the density of mass. The comparison of dark matter and normal matter will provide critical observational underpinnings to future theories for how structure formed in the evolving universe under the relentless pull of gravity. Dark matter is an invisible form of matter comprising the bulk of the universe's mass. Because the dark matter can't be seen directly, its distribution on the sky is measured via weak gravitational lensing. This is the distortion of light from distant galaxies (rather like the effect of a funhouse mirror), due to the gravitational warping of space by dark matter along our line of sight. Constructing the entire map required the measurement of the shapes of half a million background galaxies. The distribution of the visible matter was derived from the distribution of the light coming from galaxies and the hot gas present in galaxies cluster which emits in the X-ray regime.

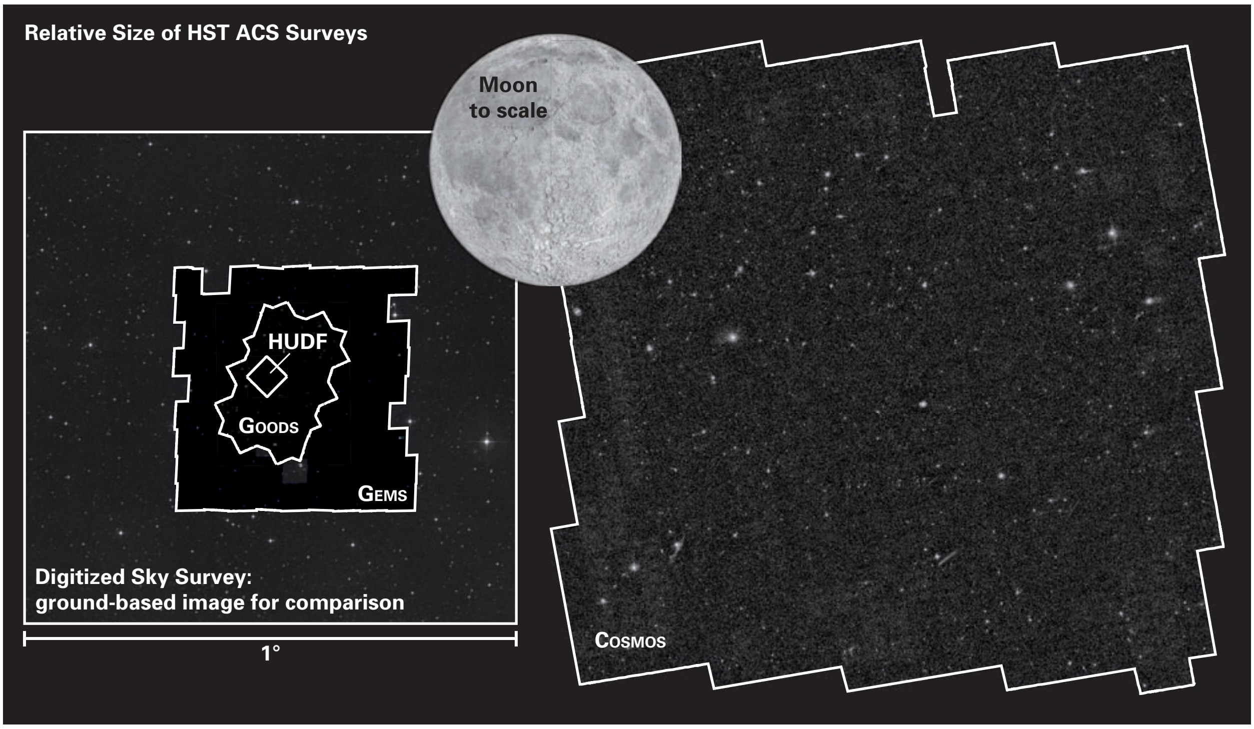


Fig. III.4.15: Since HUBBLE Space Telescope (HST) has a narrow field of view, which is only a fraction of the angular diameter of the Moon, mosaic images need to be assembled to survey comparatively larger areas of sky to address a wide range of galaxy evolution and cosmological questions. The Cosmic Evolution Survey (COSMOS) is the largest HUBBLE mosaic of the sky. It covers two square degrees of sky. By comparison, the Earth's moon is one-half degree across. Several other HST survey fields are shown for comparison and nested inside the one-degree width of sky in the southern constellation Fornax. Going from shallower to the deepest images: GEMS – Galaxy Evolution from Morphology and Spectral Energy Distributions, GOODS (Great Observatories Origins Deep Survey), HUDF (HUBBLE Ultra Deep Field).

COSMOS project offers the critical advantage of allowing all major observatories from both hemispheres to join forces in this endeavor: COSMOS is the largest HST survey ever undertaken (590 orbits) – imaging an equatorial, $\sim 2° \times 2°$ field with single-orbit I-band exposures (Fig. III.4.15). Extensive multi-wavelength ground and space-based observations of this field have been gathered, and more are anticipated, spanning the entire spectrum from X-ray, UV, optical/IR, mid-infrared, mm/submm to radio with extremely high sensitivity imaging and vast spectroscopy. These make the COSMOS field an excellent resource for observational cosmology and galaxy evolution studies in the important redshift range $0.5 < z < 3$, a time span covering about 75 % of the lifetime of the universe.

This full spectrum approach is required to probe the coupled evolution of young and old stellar populations, starbursts, the interstellar medium (molecular and ionized components), super-massive black holes, AGN, and dark matter environment. The multi-wavelength approach is also necessitated by the fact that light from different cosmic epochs is differentially redshifted and the presence of dust obscuration in many of the most rapidly-evolving galactic regions. The large areal coverage of COSMOS is motivated to sample the largest structures existing in the local universe – at $z = 1$, 1°.4 implies co-moving ~ 90 Mpc – since smaller area coverage leads to severe cosmic variance.

The key issues of the COSMOS survey include: (a) follow the assembly of galaxies, clusters and dark matter on scales up to such a the local Coma cluster of galaxies,

Fig. III.4.16: The Very Large Array (VLA) of the National Radio Astronomy Observatory (NRAO) was used to image the COSMOS field at 1.4 GHz (20 cm). On over 45 days the field was observed for 6 hrs each. (Image courtesy of NRAO/AUI).

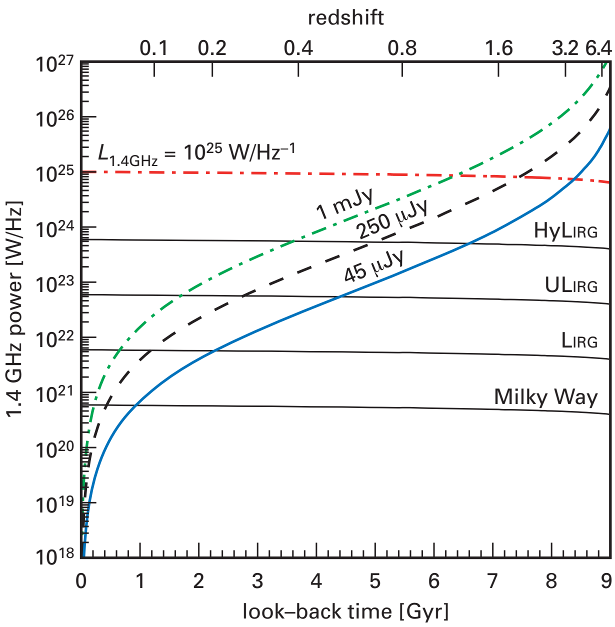


Fig. III.4.17: Comparison of the detection limit of the VLA-COSMOS survey to other large radio surveys at 1.4 GHz as a function of radio luminosity (power) and look-back time (or redshift). The horizontal lines indicate the threshold for different classes of star forming galaxies from a few solar masses per year (Milky Way) to several hundred solar masses per year (Ultra-Luminous Infrared Galaxies – ULIRGS). In addition, the dividing line above which all radio emission must be due to an AGN is indicated as well.

(b) trace the evolution of galaxy morphology, galactic merging and star formation, and (c) study the evolution of AGN, and the relationship between black hole growth and galaxy evolution–all as a function of LSS environment and redshift. COSMOS detects roughly 2 000 000 galaxies and AGN, sampling a volume in the high redshift universe approaching that sampled locally by the Sloan Digital Sky Survey. With this large number of objects at hand, the growth of galaxies, AGN and dark matter structure can be accurately traced throughout most of the cosmic history.

The VLA-COSMOS Survey

The radio source counts above the milli-Jansky level are dominated by radio galaxies and quasars powered by active galactic nuclei (AGN) in elliptical host galaxies. However, deep radio surveys at 1.4 GHz show an upturn in the integrated source counts at sub-mJy levels revealing the presence of a population of faint radio sources far in excess of those expected from the high luminosity radio galaxies and quasars which dominate at higher fluxes. While radio sources with relatively bright optical counterparts are starburst galaxies, the ones with fainter optical counterparts are often redder than expected for early type galaxies. Recent detailed multi-wavelength follow-up of faint radio sources showed a mixture of active star forming galaxies and AGN hosts. However, the exact mixture of the different populations (high-z AGN, intermediate-z post starburst, low-z emission line galaxies) as a function of radio flux is not very well established, especially for the faintest radio sources observable to-date.

In order to investigate the true nature and evolution of the microJy population it is necessary to couple deep radio observations with high quality imaging and spectroscopic data from other wavelengths covering as much of the electromagnetic spectrum as possible. For the radio observations at 1.4 GHz, it was essential to match the typical resolution for optical-NIR ground-based data of $\sim 1''$ to fully exploit the COSMOS database. Therefore observations with the NRAO Very Large Array (VLA, Fig. III.4.16) were conducted in the A-array that provides a resolution of about $1''\!.5$ (FWHM) at 1.4 GHz. Mosaicking is necessary to cover the large area of the COSMOS field. The VLA-COSMOS survey consists of the pilot project (testing the VLA mosaicking capabilities), the large project (imaging the full COSMOS field, Fig. III.4.17) and the ongoing deep project (focusing on the central $1° \times 2°$ and the very dusty star forming galaxies detected in the (sub-)millimeter regime–see below).

The COSMOS field was mapped at 1.4 GHz with the VLA in A + C configuration as part of the VLA-COSMOS survey (PI: Eva Schinnerer) resulting in the by far largest areal coverage at its sensitivity and angular resolution (Fig. III.4.18). The catalog of about 3500 detected sources combined with the COSMOS multi-wavelength data provides the currently best dataset with which to study the faint radio source population, including rare objects such as radio galaxies.

The VLA-COSMOS radio observations were matched to the overall depth of the multi-wavelength COSMOS data in order to study a range of issues related to the history of star formation, the growth of super-massive black holes, and the spatial clustering of galaxies. Its specific goals are studying the evolution of radio-loud AGN as a function of environment, including a comparison to X-ray AGN and clusters and a search for type-II radio QSOs, a dust-unbiased survey of star forming galaxies as revealed in the sub-mJy radio source population, considering the evolution of the radio-FIR correlation out to $z \sim 1$ through a comparison with the SPITZER data, and of extreme, high redshift starbursts as seen in the millimeter COSMOS survey.

The ongoing spectroscopic surveys within the COSMOS project are targeting well-defined samples of radio sources in order to provide spectra for about 2000 optical counterparts. This will be the largest sample of faint radio sources with spectral information for the foreseeable future. All data obtained by the COSMOS collaboration will be made available to the public. Thus final reduced

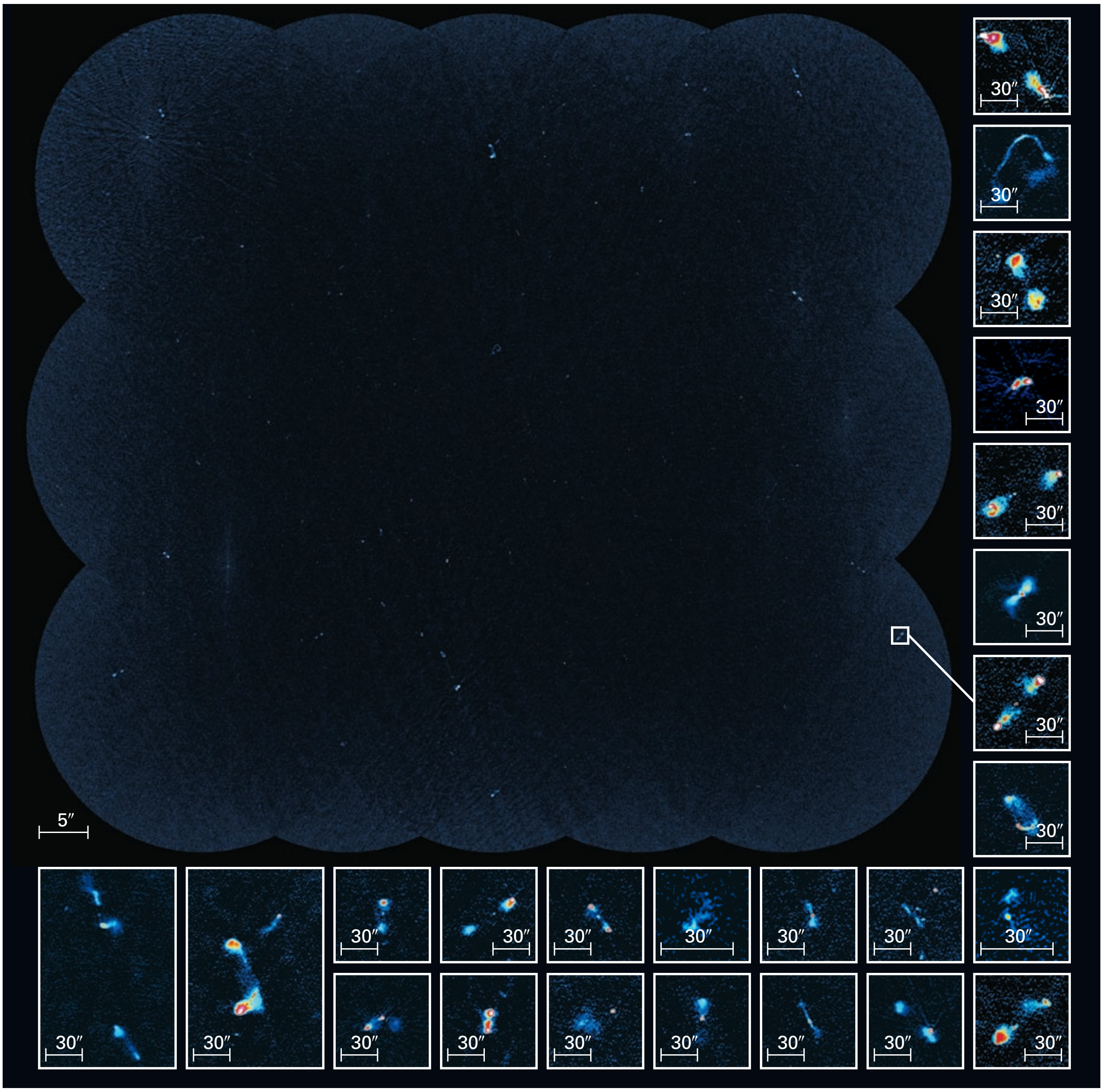


Fig. III.4.18: The COSMOS field as seen at 1.4 GHz. The image consists of 23 separate images, each the size of the full moon. While not immediately apparent in the overall view, it contains about 3600 sources most of them point-like, and about 60 radio galaxies (see small panels to the right and bottom).

and calibrated data of the VLA-COSMOS pilot and large project can already be found in the COSMOS web-archive.

Before one can use the VLA-COSMOS sample for scientific applications, it is essential to characterize the faint radio sources (Fig. III.4.19). For this purpose, we are currently developing a method to robustly sort the radio sources into star forming and AGN galaxies based on the COSMOS multi-wavelength database. Our method is calibrated in the local universe. We classify the VLA-COSMOS radio population into (a) stars, (b) quasars, (c) obscured AGN and (d) star forming galaxies. For identifying the first two types of objects we predominantly make use of the high resolution images obtained with HST. Namely both, stars and quasars have point-like appearance in high resolution optical images. However, disentangling obscured and low luminosity AGN (i.e. Seyfert and LINER galaxies) from star forming galaxies is a much more difficult task. Nonetheless, it was shown that the UV to IR spectral energy distribution (SED) is a one parameter family, and in particular that the emission line fluxes, characteristic for star formation and/or AGN activity, are well correlated with the rest-frame color indices of galaxies. Hence, we use the galaxies' rest-frame color properties, obtained by fitting the observed SEDs with stellar synthesis models, in order to identify star

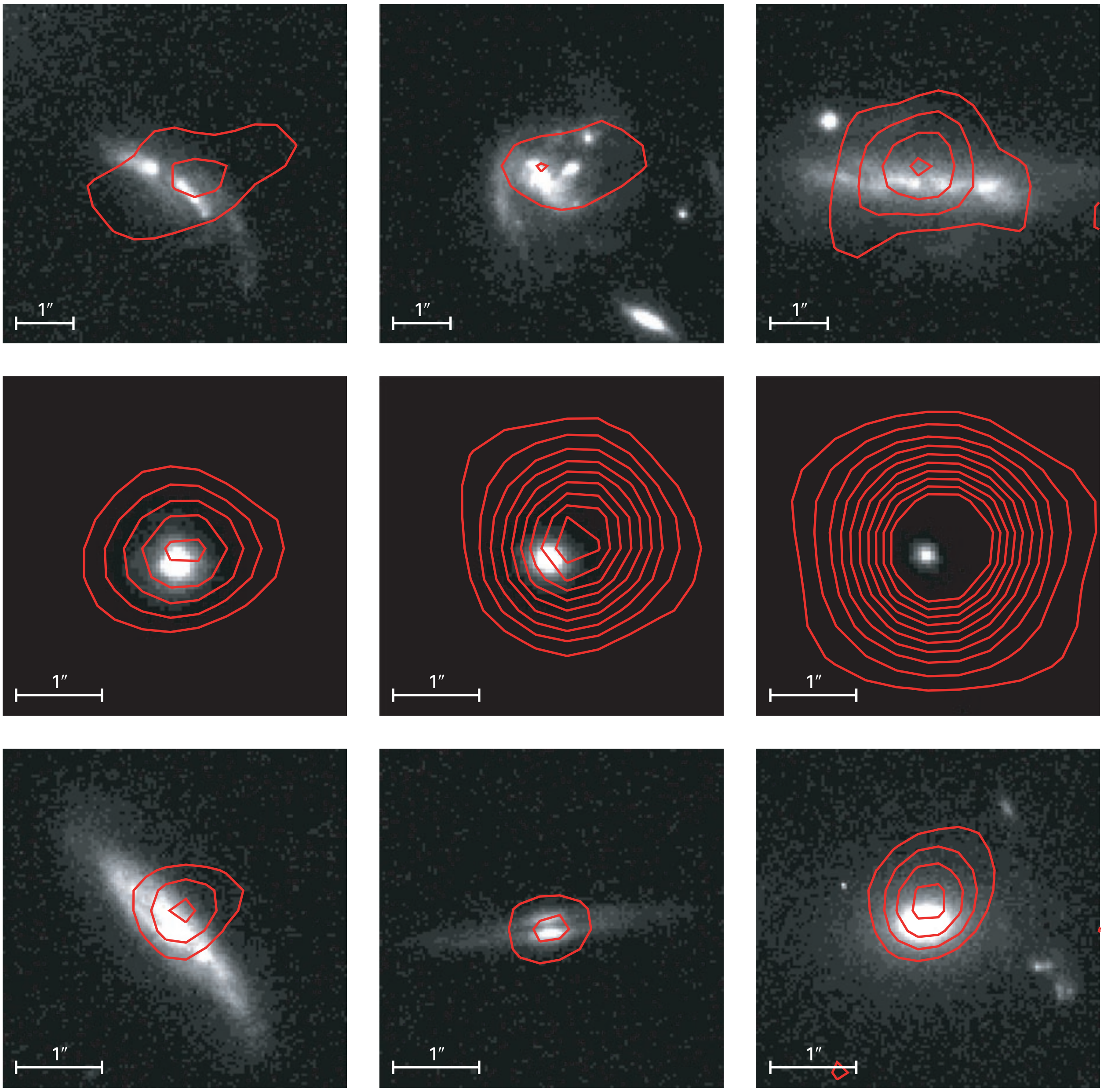


Fig. III.4.19: Examples of optical counterparts to radio sources in the VLA-Cosmos catalog. The morphology as imaged with the HST (grey-scale) can be used for the closer targets to classify the origin of the radio emission (contours; starting at 3 sigma in steps of 2 sigma). *Top:* Star forming galaxies where the radio emission is coinciding with the galactic disk and its spiral arms in which the young stars are born. *Below:* Galaxies containing an AGN, where either the active nucleus is obvious in the optical image (such as type 1 quasars) or the method described in the text classified them as AGN and the morphology of their host galaxies is consistent with early type galaxies.

forming and AGN galaxies in our VLA-Cosmos source sample. Fig. III.4.20 outlines this method showing local universe galaxies from our control sample, which we use for the calibration of our classification method.

The Star Formation View

The radio luminosity of local galaxies is well-correlated with their star formation rate, and needs, unlike optical tracers, no correction for dust obscuration (Fig. III.4.21). Thus radio sources with correct identification (as star forming galaxies) can be independently used to estimate the star formation history (of the luminous sources). While the evolution of the cosmic star formation history traced by optical surveys bears the large uncertainty of dust corrections, deep VLA observations of the Cosmos field do provide a unique, unobscured look at star forming galaxies and highly extincted galaxies in the full range of environment. This is especially true in combination with the deep (sub)mm data and deep Spitzer infrared imaging to which the high resolution

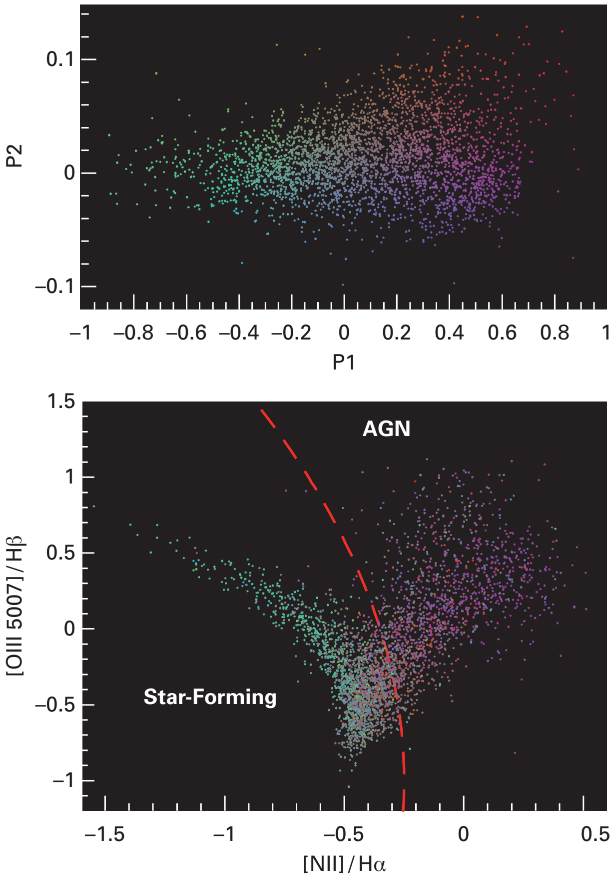


Fig. III.4.20: *Top:* Distribution of ~ 3000 SDSS/NVSS galaxies from the "main" spectroscopic sample in the plane spanned by two rest frame colors: P1 and P2. Each dot represents a galaxy, and the color code is determined by the position of a galaxy in this diagram. *Bottom:* The distribution of galaxies in the Baldwin-Phillips-Terlevich (BPT) diagram, constructed with emission line strength ratios and commonly used as a diagnostic tool for the separation of AGN and star forming galaxies. The dashed line separates the regions populated by star forming galaxies and AGN. The dots (each dot again represents one galaxy) are colored using P1 and P2 as shown above. Note how well star forming galaxies can be separated from AGN ones by using the rest frame color P1.

of the VLA images provides means to properly identify the optical counterparts of these luminous infrared galaxies.

One immediate goal for the Cosmos group at MPIA is to use the VLA radio data to trace the cosmological star formation history and to test the Fir/radio correlation at high redshifts. Recent work using deep radio data confirms the trend of rising star formation rate between $z = 0$ and $z = 1$, however the derived values still have large error bars. A key uncertainty is the contribution of AGN to the faint radio population, with estimates ranging from 20 % to 80 % for surveys down to 40 Jy. Thus our new method to characterize this population should result in much better estimates.

Secondly, the (far)IR-radio correlation for star forming galaxies appears to hold out to high redshift. However, the current number of star forming sources detected at 1.4 GHz is small above $z = 0.5$. A thorough understanding of the IR-radio correlation out to higher redshifts is important, as it has been widely used as a distance measure for sub-mm sources without any optical counterparts. Also, an important question for active star forming galaxies is the role of mergers, in particular at higher redshift. The Fir imaging alone will lack sufficient resolution to address this issue, while the optical imaging will suffer from the standard problem of obscuration in these very dusty systems. Only arcsecond resolution radio data such as from VLA-Cosmos will allow the determination of the spatial distribution of star formation in dusty starbursts on scales relevant for merging galaxies (~10 kpc).

Thirdly, sub-millimeter and millimeter wide field imaging surveys with Scuba and Mambo have revealed a population of active star forming galaxies at high redshifts also referred to as sub-millimeter galaxies (SMGs). These objects dominate the far-IR background, and current models suggest that this population may represent the formation of spheroidal galaxies at redshifts between 2 and 5, constituting about half of the total amount of cosmic star formation from the Big Bang to the present. This observation caused a significant revision to the optically derived star formation history of the Universe, with the addition of a population of highly reddened active star forming galaxies at high z, and follow-up mass estimates of the submillimeter sources placed new constraints on galaxy formation models. Clearly, a good understanding of SMGs is crucial to further our knowledge of galaxy formation and evolution. Due to the large beams of (sub-)millimeter telescopes it has been a tedious process to identify the counterparts to the SMGs at optical, infrared or radio wavelengths. Therefore, a concerted effort to combine Spitzer data with deep optical, X-ray, and radio observations over sufficiently large angular scales is required to gain deeper insight into these enigmatic systems. This is a project pursued in collaboration with the group of Prof. Bertoldi from the Alfa at Bonn University.

Finally, one can use the VLA-Cosmos image to estimate the radio emission from a certain class of objects, e.g. star forming galaxies at a redshift of $z = 5.7$ (identified via their bright Lyman Alpha line emission) when the universe was still very young. While none of the about 100 $z = 5.7$ star forming galaxies had a radio counterpart, we "stacked" cut-outs of these objects from the radio image to produce the average image of such a galaxy in the radio emission. However, no signal was detected in this average radio image either implying that the star formation rate in these objects is similar to what is observed in local star forming galaxies. This stacking technique can be easily applied to other samples of galaxies to search for star formation that is obscured by dust.

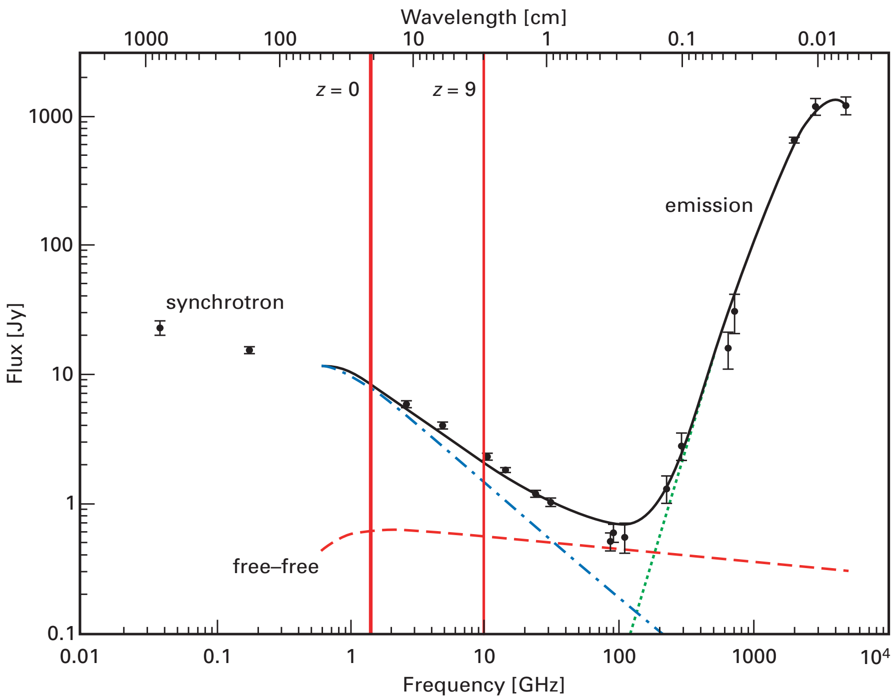


Fig. III.4.21: Sketch of the components comprising the spectral energy distribution at radio and infrared wavelengths (adapted from Condon 1992). The radio emission observed at 1.4 GHz consists mainly of synchrotron emission at $z = 0$. At a higher redshift the observed frequency becomes higher, this means that also Bremsstrahlung (free-free emission) from heavily obscured star forming regions might contribute to the observed flux.

The AGN View

Only a large field and deep radio survey can provide information about the currently highly uncertain evolution of faint radio-detected AGN. The fundamental problem in the study of the evolution of radio-loud AGN has been that samples are drawn from either very wide field, but very shallow surveys, or very deep, but very small field surveys. The former are limited at high redshifts to only extreme luminosity sources, while the latter are plagued by relatively small number statistics and number variance. The VLA-Cosmos survey was designed to enable the study of the demographics and evolution of AGN by encompassing a large cosmological volume and by providing good statistics on both radio-loud and radio-quiet AGN as a function of redshift. Its sensitivity is adequate to detect relatively weak (FRI) radio AGN to very high redshift ($z \sim 6$) while providing a large number (~ 1000) of AGN sources. At lower redshift, $z \sim 1$, a significant fraction of radio-quiet but not radio-silent, optically-selected QSOs should be still observable. Moreover, questions regarding redshift evolution of radio galaxies, their parent galaxy properties, and environmental dependencies can be addressed. Highly luminous radio-loud objects such as Cygnus A should be observable out to their epoch of formation if such objects did exist back then.

Within the framework of the Cosmos project, our group at MPIA is concentrating on studying the properties of un-obscured (type 1) and obscured (type 2) quasars, in particular, their host galaxies. The different AGN selection methods (X-ray, optical, IR, radio) can be combined effectively to produce samples of AGN at intermediate redshifts ($1 \leq z \leq 3$) based on specific selection criteria as well as the necessary control samples of inactive galaxies, all with coherent and similar datasets. This research takes advantage of the synergy between the many Cosmos datasets and expertise available.

One aspect of the Cosmos group at MPIA is the characterization of the dominating stellar components of type 1 and 2 AGN host galaxies at $z < 1.1$ and a possible dependence on nuclear radio emission. Studies of the host galaxies of type 1 quasars are notoriously difficult due to the presence of the bright AGN nucleus which often outshines the stellar light coming from the host galaxy (see Fig. III.4.22). The large sample sizes will allow us to study the expected enhanced presence of young stellar populations as a function of luminosity, morphology, radio emission properties, and the presence of interaction signs, in comparison to local galaxies. We also plan to study the morphology of AGN host galaxies, with an emphasis on the presence of interactions and the evolution of these parameters with cosmic time.

Recently, the question of the true number of obscured (type 2) to un-obscured (type 1) quasars received new attention. In the purely geometric model, the difference between these two types is solely due to the orientation

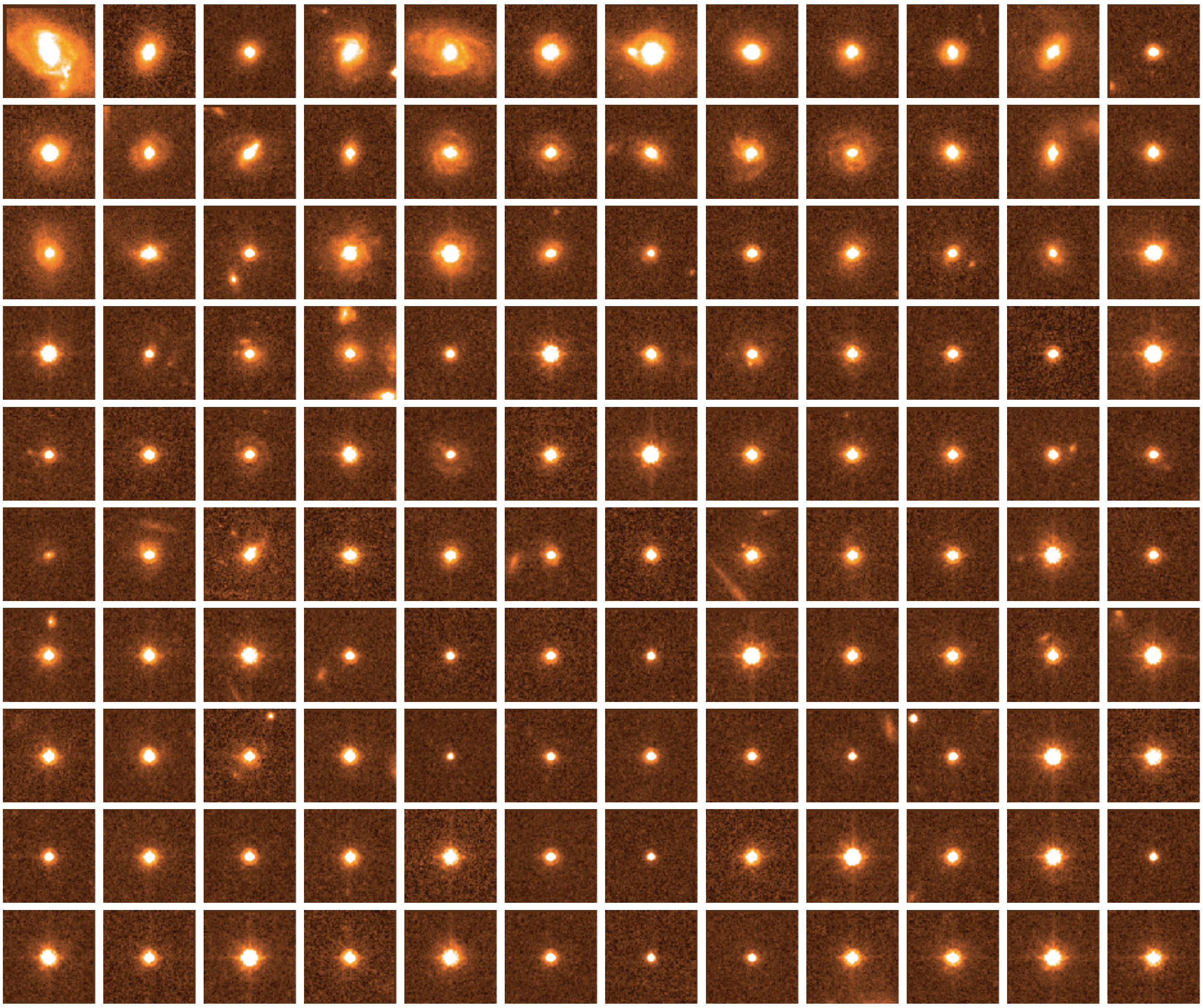


Fig. III.4.22: A sample of 120 type 1 AGN with their host galaxies present in the Cosmos field. The HST cut-outs are sorted by redshift with the closest objects being in the top left corner and the most distant ones in the bottom right.

of the accreting black hole and its dusty torus with respect to the observer. However, an evolutionary scenario for the difference has been suggested as well: the strong correlation between black hole mass and bulge mass in low-z galaxies has been used to argue that the energetic output of quasar feedback is believed to terminate star formation in the host galaxy by heating and expelling the gas necessary to form young stars, and is a potentially important component in current models of galaxy formation. Before the gas is expelled, the quasar is believed to be heavily obscured by the gas and dust in the star forming galaxy, while after the gas is expelled, quasars are only obscured if our line of sight is blocked by the dusty torus around the accretion disk (a.k.a. the unified scheme). There is now mounting evidence that the ratio of type 1 to type 2 quasars is not 1:1 as expected from the geometrical model and that indeed different types of obscured quasars are observed. This new additional class of type 2 quasars might instead be obscured by a starburst host galaxy. A sketch of this scheme showing un-obscured quasars as well as the two types of obscured quasars is shown in Fig. III.4.23. The sketch shows quasars hosted by starburst hosts, responsible for the obscuration (c and d), we call these host-obscured quasars. With time, the quasars clear the dust, leaving evolved dust-free galaxies where the obscuration (or lack of) depends in the orientation of the torus (a and b). We are using the VLA-Cosmos data together with the Spitzer data to define a sample of obscured type 2 quasars at a redshift of $z \sim 2$ which can be used to address this open question.

In short, the pan-chromatic Cosmos dataset not only allows the unbiased selection of quasars and less luminous AGN, but also provides the information required to study their properties as a function of wavelength. In addition, we used the VLA-Cosmos catalog to find unusual objects worth detailed case studies. One such example is the Wide Angle Tail (Wat) radio galaxy CWat-01 which is located at a redshift of $z \sim 0.22$.

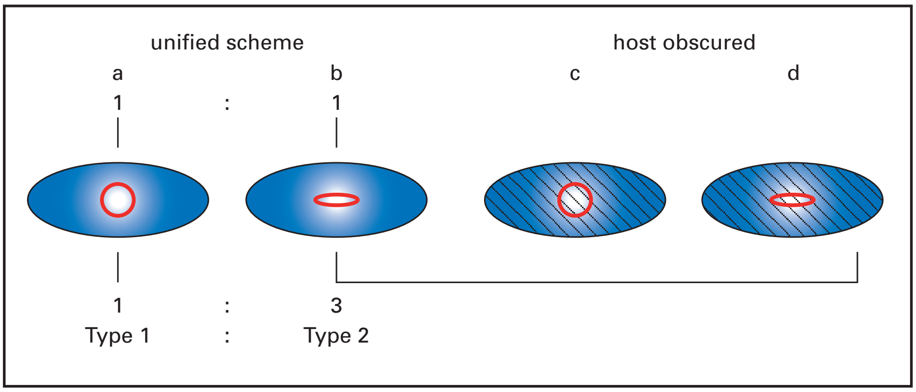


Fig. III.4.23: Sketch showing the proposed distribution of unobscured (type 1) and obscured (type 2) AGN. In the unified scheme where the sole orientation of the torus around the AGN is causing the difference (a and b) a ratio of 1 : 1 is expected. However, the observed ratio appears to be closer to 1 : 3 at a redshift of $z \sim 2$, suggesting that in addition to the pure geometrical difference an evolutionary component (here: massive dusty star formation in the host itself) is causing obscuration as well.

Fig. III.4.24: Color composite showing the environment of the wide angle tail radio galaxy CWAT-01 which lies at a redshift of $z \sim 0.2$. The COSMOS datasets revealed evidence for this apparently forming large structure (see text for details). The rainbow colors show the four X-ray detected galaxy clusters, while the optical images are shown as an RGB image with early type galaxies being reddish in color and disk galaxies appearing blue. CWAT-01 is located in the bottom left cluster and shows radio jets which are bent in a wide C-shape.

Our detailed analysis combining the radio data with the optical and X-ray datasets from COSMOS revealed CWAT-01 to be part of a very complex large-scale structure representing a cluster assembly with an extend of ~ 2 Mpc. Fig. III.4.24 shows the distribution of emission from different parts of the electromagnetic spectrum within the cluster assembly area. The diffuse X-ray emission reveals that the CWAT-01 parent cluster is only one of the poor clusters encompassed in a larger cluster structure. The cluster assembly contains a minimum of four X-ray luminous clusters within ~ 2 Mpc distance. In addition, our search for galaxy over-densities indicates that there is at least one more loose group on the outskirts of the X-ray cluster assembly but not detected in the X-rays. The misalignment between the direction of the jets of CWAT-01 and the elongation of the X-ray emission suggests that the cluster has had no time yet to (dynamically) relax. Numerical simulations of cluster

evolution show that at $z = 0.2$ a final massive cluster is just being built at the intersection of filaments by the accretion of matter from numerous filaments. Therefore, our results strongly indicate that we are witnessing the formation of a large cluster from an assembly of multiple clusters, consistent with the hierarchical scenario of structure formation.

What's next?

Multi-wavelength surveys are ideal to test our current cosmological models in multiple ways by comparing actual observational facts to theoretical predictions. For example, as in the case of HIROCS, the number of galaxy clusters expected to be already in place when the universe had half its current age. The VLA-COSMOS survey will provide important insights on the faint radio population as well as the radio derived star formation and/or AGN properties of many different types of objects. The existence of such pan-chromatic datasets is paramount for future instruments by providing interesting targets to observe, but also to help designing the instruments themselves.

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Knud Jahnke, Alejo Martinez Sansigre,
Irini Sakelliou together with
Chris Carilli (NRAO, Socorro),
Nick Scoville (CalTech),
Marco Bondi and Paolo Ciliegi (INAF, Bologna),
Frank Bertoldi (ALFA, Bonn)
and the VLA-COSMOS team and COSMOS collaboration

IV. Instrumental Developments and Projects

IV.1 New Technology Developments

With telescopes venturing into the 8 m class and beyond, the size, mass and complexity of astronomical instrumentation systems has also increased. Consequently the importance of light-weight construction is growing. In order to satisfy the often extreme technical requirements, innovative technologies and methods must be applied. However, this is not a one-way street leading from technology into research – novel technical developments in astronomical instrument construction are also viewed with keen interest in industry. This mutual relationship concerning technology transfer will be explained below using some concrete examples.

Tremendous progress has been made in the past few years – not only regarding to the development and construction of modern large-scale telescopes, but also with respect to the development of instrumentation systems for astronomy. Extremely high accuracy is called for here. And new technologies must constantly be developed, as astronomers want to use the new instruments to advance ever deeper into the infrared spectral range: The complex optics, mechanisms, detectors and other components are required to operate faultlessly at extremely low temperatures below – 200 °C. Here, we highlight a few developments at MPIA in this area.

Carbon Fiber Reinforced Plastic (CFRP) Materials for the Interferometry Instrument LINC-NIRVANA

LINC-NIRVANA is an imaging interferometer for the Large Binocular Telescope (LBT) that combines the radiation from the two 8 m primary mirrors. It will deliver the spatial resolution of a 23 m telescope. Fig. IV.1.1 shows a computer model of LN on the instrument platform of the LBT.

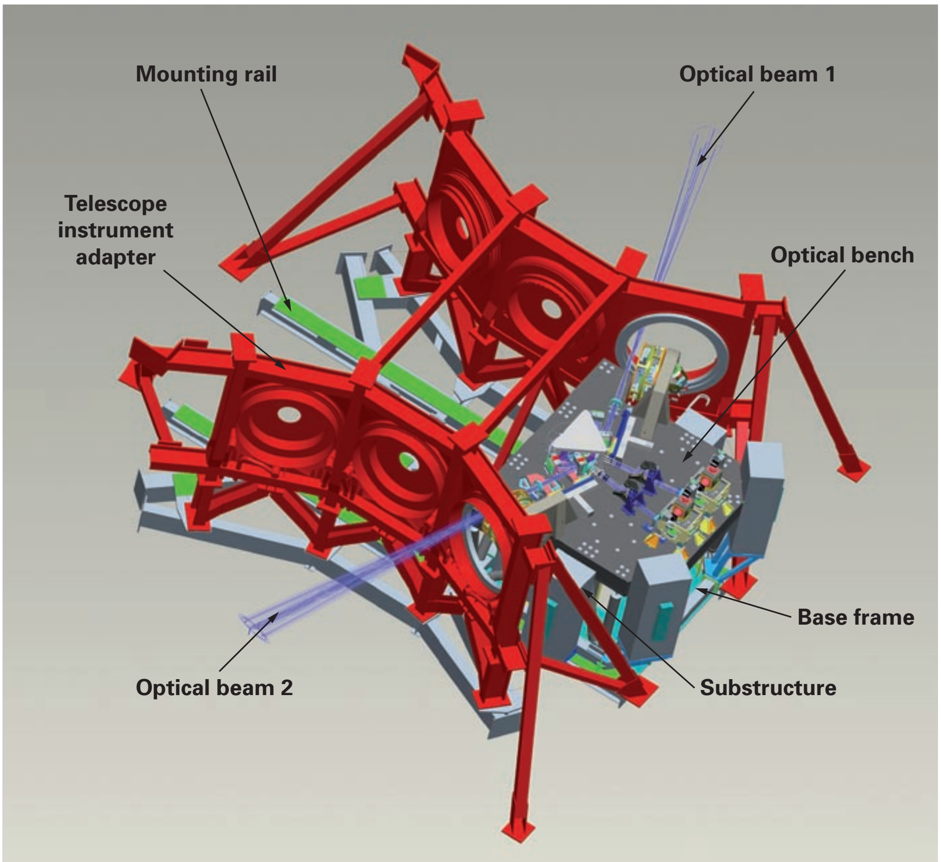


Fig. IV.1.1: LINC-NIRVANA mounted on the LBT.

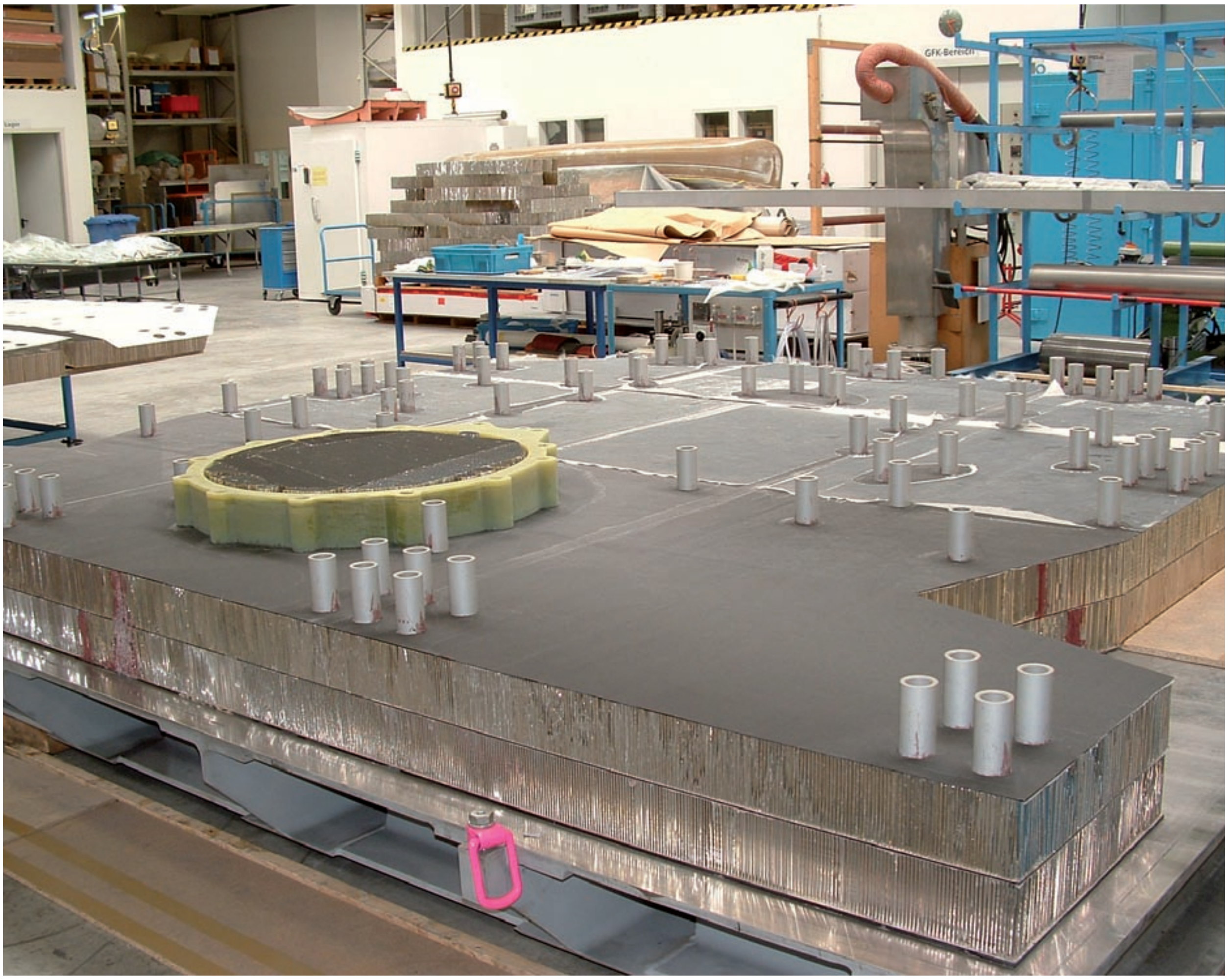


Fig. IV.1.2: Layer structure of the mounting plate at INVENT, Braunschweig.

All components of the instrument are mounted to a plate that is linked to the telescope via a supporting structure. The plate and the supporting structure must comply with the following requirements:

- High rigidity
- High accuracy of the attachment points
- High thermal stability
- Improved attenuation properties
- Minimum weight

Suitable materials for this platform are not readily available, but the excellent properties of CFRP are capable of satisfying these requirements. The support structures for the LINC-NIRVANA instrument were developed in cooperation with the private firms Ingenieurbüro Schlossmacher, Unterschleißheim, and INVENT, Braunschweig. Fig. IV.1.2 shows the structure of the individual layers (high-strength aluminum honeycombs alternating with CFRP intermediate layers) of the mounting plate.

The following properties of the laminated CFRP product were achieved in our construction (values for steel in brackets for comparison):

- Modulus of elasticity $E_x = E_y = 132\ (+200)$ GPa
- Coefficient of expansion $\alpha_x = \alpha_y = -0.37\ (+10) \times 10^{-6}\,\mathrm{K}$
- Density ϱ(CFRP) = 1.7 (7.9) g/cm³

The extremely low coefficient of expansion, which guarantees an excellent thermal stability of the instrument, is particularly noteworthy here. This is especially important, because in contrast to other interferometry experiments, LN is mounted directly to the telescope rather than in a lab with a steady temperature.

The mechanical and thermal properties of the supporting structure were simulated with the aid of computer models. The load tests carried out on a test body at the University of the German Armed Forces in Munich have confirmed the correctness of the computer model.

Fig. IV.1.3 shows the finished construction in the MPIA construction hall. The CFRP components (black) have been attached to a base frame (blue). The support tubes and the plate are linked via stainless steel joints (manufactured at the MPIA). The entire unit is fixed to a

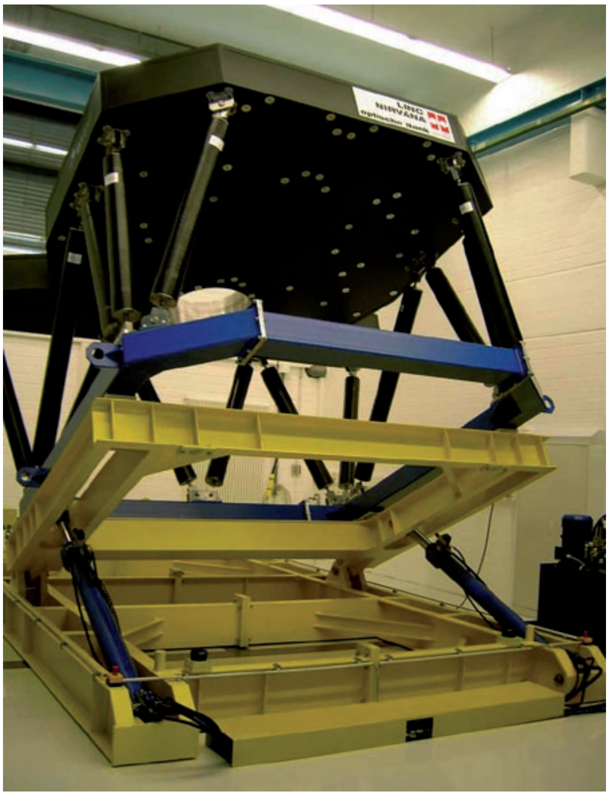


Fig. IV.1.3: The supporting structure of LINC-NIRVANA in the MPIA's construction hall.

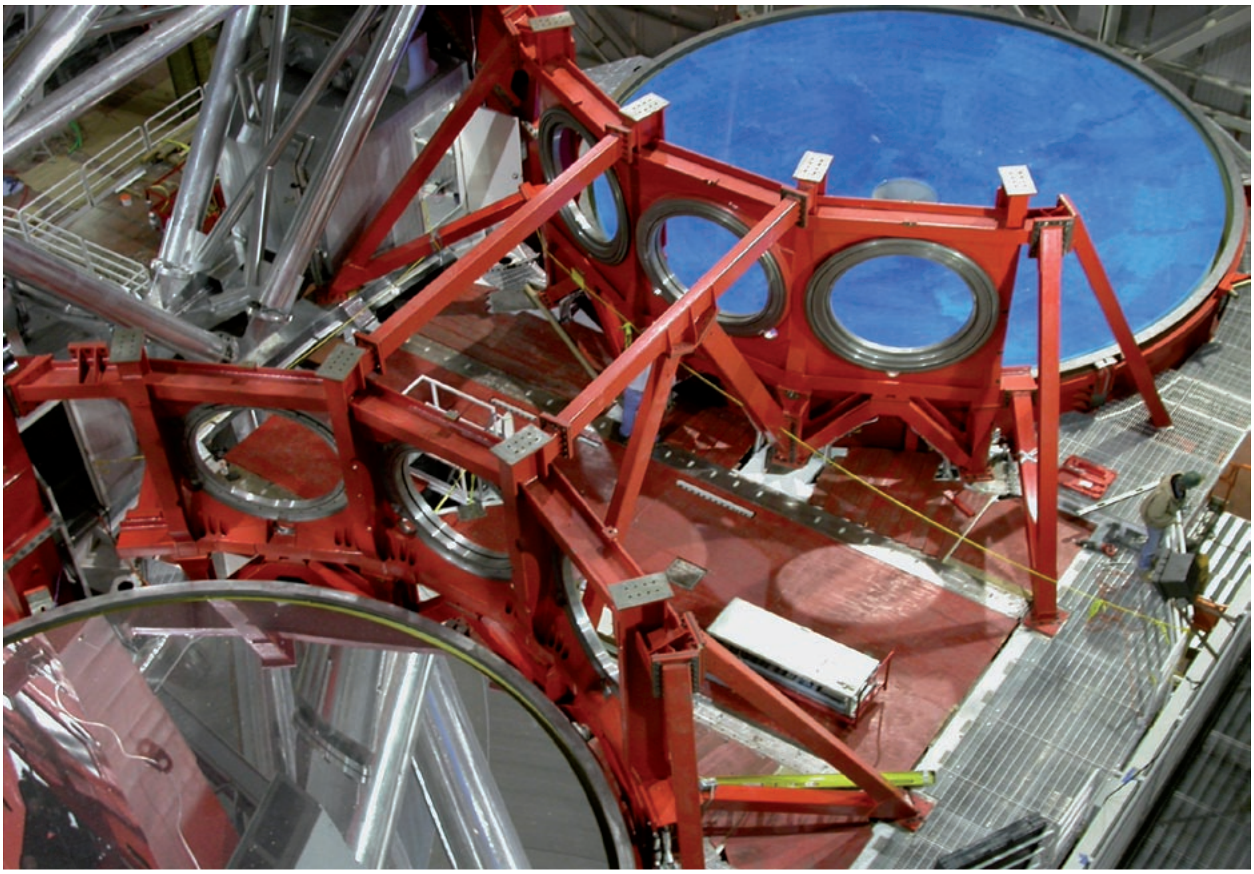
tilting frame (yellow) capable of simulating the telescope movements. Larger CFRP components are to be found in aviation and space technology only.

Deformation Measurements at the LBT

In order to define the proper dimensions of LINC-NIRVANA, it is important to know how the telescope construction responds in various telescope positions. Deformation cannot be entirely prevented given the size of the structures. Fig. IV.1.4 shows the LBT instrument platform to which LN will be attached.

In ship construction, a method for measuring large structures has become established, which can also be used for our purposes. For this method (photogrammetry), very precise target marks are placed on the object to be measured. It is then photographed from various angles using a digital camera. Afterwards, special software calculates the exact positions of the measurement marks, thus detecting changes at various telescope positions. These measurements were planned and performed together with the Fraunhofer Anwendungszentrum Großstrukturen in der Produktionstechnik, Rostock. Fig. IV.1.6 shows the shooting technology from an elevated

Fig. IV.1.4: The LBT instrument platform



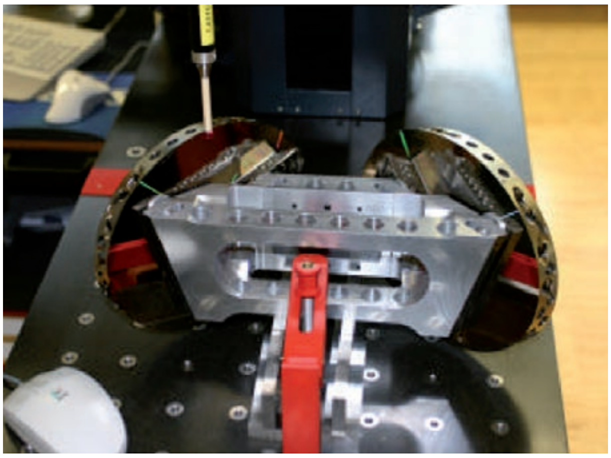


Fig. IV.1.5: The mirror assembly for the LN instrument.

working platform (above), with the target marks stored in the computer and the individual camera positions shown below. The lines of sight towards the individual target marks are shown for two camera locations.

New Mirror Material for LINC-NIRVANA

Demands concerning the production of complex optical surfaces are currently growing, and especially the requirements on the component surfaces. Ultra-precision processing (diamond turning and milling) offers the possibility of manufacturing optical systems made of metal, such as aluminum, copper or nickel, with complex surface shapes. While the requirements on form stability made by applications in the infrared range are satisfied by this method, the roughness and true shape attainable by this machining process are not sufficient for shorter wavelengths. As a result, fine polishing or compensation polishing of the components has to be carried out subsequently. This process is preferably performed using aluminum substrates equipped with an amorphous nickel phosphor layer (NiP). One disadvantage of this material combination is the considerable difference in thermal expansion between aluminum (23.8 ppm/K) and the NiP layer (12 ppm/K). If the optical parts are subject to temperature change in practice, the corresponding bimetal effect will result in tensions and deformation with a potential impact on the optical quality. By using an expansion-adjusted alloy such as Dispal (AlSi35, CE13F) with almost the same characteristic value as NiP (12.8 ppm/K), this disadvantage can be eliminated. Other advantages of this material combination include its improved rigidity and a higher modulus of elasticity of the Al-Si alloy.

Fig. IV.1.5 shows a double mirror developed for the LN instrument together with the Fraunhofer-Institut für Feinmechanik und Optik, Jena. A joint patent application has been filed for this method.

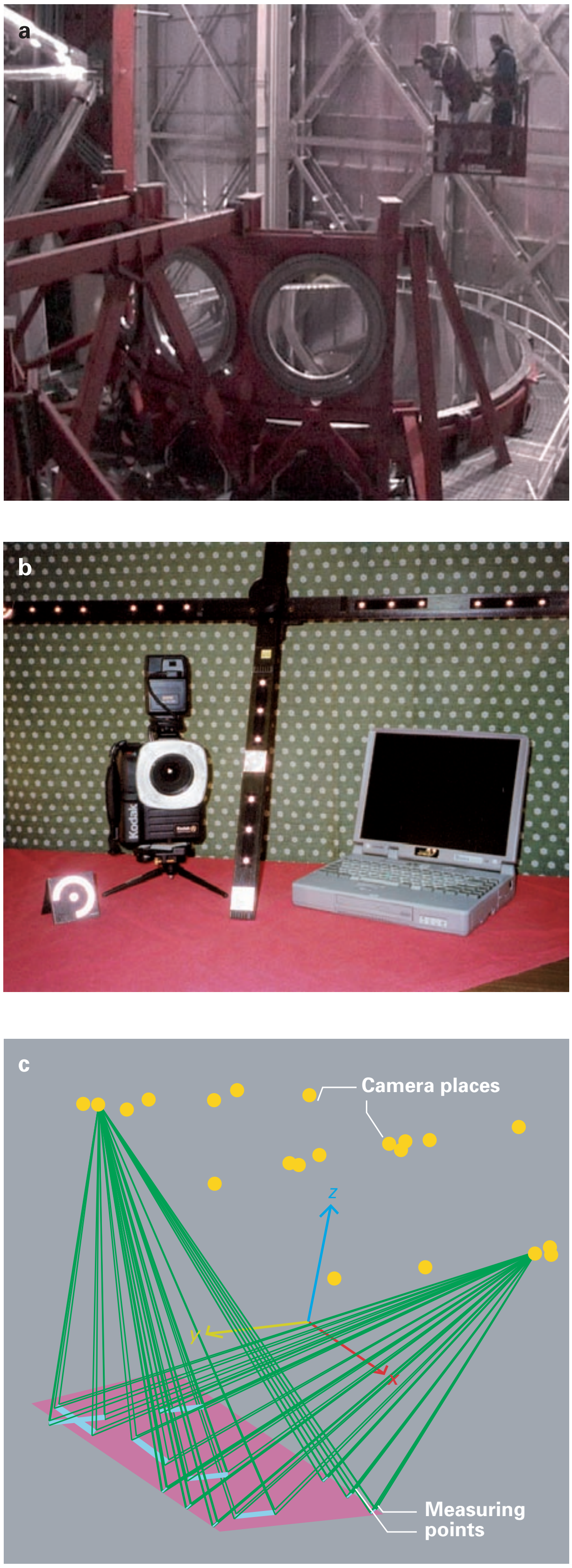


Fig. IV.1.6: *Above:* Taking pictures of the target marks from the elevated working platform; *below:* representation of the data in the computer.

Gearbox for Cryogenic Temperatures

Gearboxes for applications at temperatures below – 200 °C are virtually unavailable on the market. For this reason only direct drives are used in most cases at cryogenic temperatures.

Under "normal" operating conditions, the harmonic drive gearing has proven to be efficient. It ensures a high step-down ratio at small size. This gear design was modified at the MPIA so that it can also be used at extreme temperatures. All moving parts received a hard metal coat (dry lubrication), the bearing seat was adjusted, and the aluminum housing was replaced with a steel housing.

Fig. IV.1.7 shows the individual gear components. The hard metal coat is clearly detectable by the dark-gray color of individual components. A long-term test at 200 °C has shown that the modified gear box performs its intended function. Fig. IV.1.8 shows the test set-up with a stepper motor attached. This is a rotary actuator for a filter wheel to be used in an infrared wavefront sensor (Fig. IV.1.9).

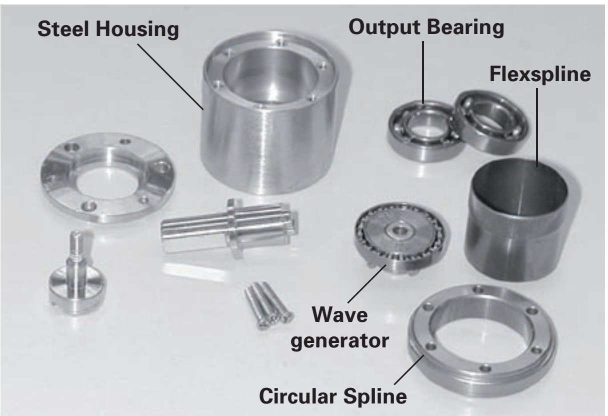


Fig. IV.1.7: Components for the harmonic drive gearing.

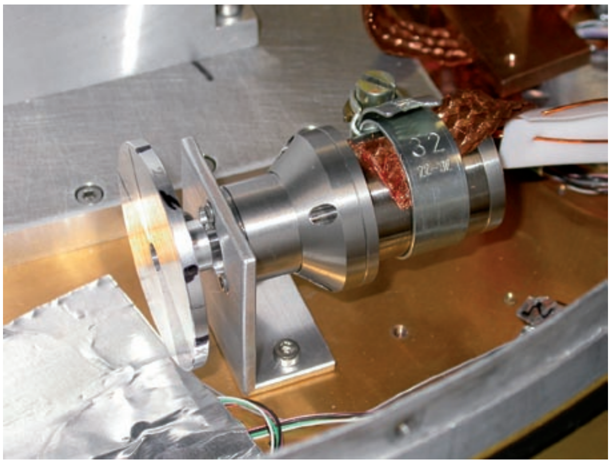


Fig. IV.1.8: Test set-up of the harmonic drive gearbox with stepper motor for – 200 °C.

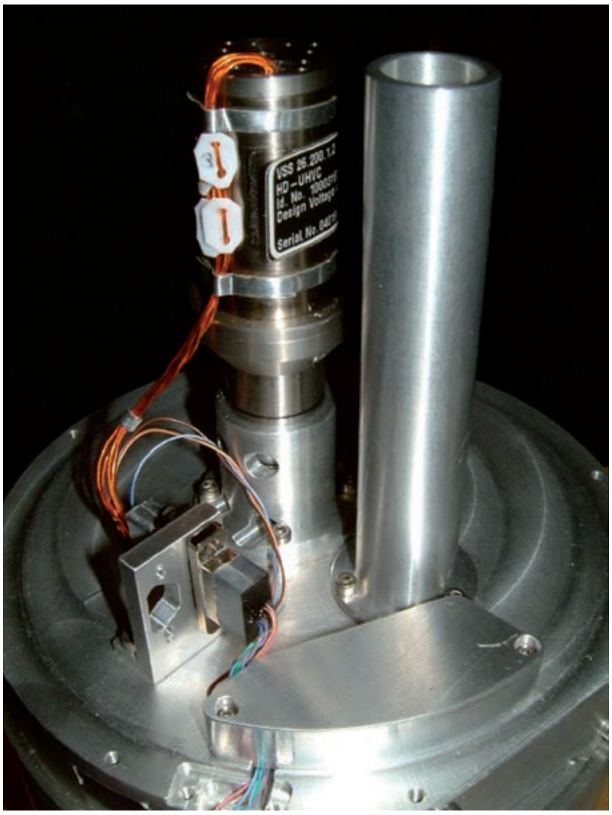


Fig. IV.1.9: Filter wheel actuator of the infrared wavefront sensor.

The activities at the MPIA have aroused great interest at Harmonic Drive AG, Limburg. In addition to being used for astronomical instruments, there are other commercial fields of application at extra-low temperatures or applications in which grease lubrication of the gear boxes is not possible. The activities at the MPIA were described in the internal newsletter of Harmonic Drive AG, "Newdrive", issue 26 (Fig. IV.1.10).

Conclusions

As demonstrated by the examples outlined above, the construction of astronomical instruments and its occasionally extreme requirements are not the only ones to benefit from the rapidly increasing technological development. Industry is often stimulated to provide maximum performance. It is not always easy to convince our partners from industry of the feasibility of a project.

If certain components or methods are not available on the market, the cooperation between the MPIA and highly specialized companies also triggers new developments, which are met with great interest from the industrial partners afterwards. A prime example of this trend is the development of the Zerodur glass-ceramic material for astronomical mirrors. Today this material can be found in any modern kitchen.

Nummer 25 • November 2005 • 8. Jahrgang

Harmonic Drive AG

newdrive

Das News-Magazin der Harmonic Drive AG

Kaltes Licht aus dem All

Am Himmel spielen sich existenzielle Dramen ab – allerdings von uns meist unbemerkt: Riesige Sonnen explodieren in gewaltigen Lichtblitzen oder hauchen ihr Leben als farbenprächtige Nebel aus, während in anderen Regionen des Alls zur gleichen Zeit neue Sterne entstehen.

So besteht unser Universum neben Sternen und Planeten zu einem großen Teil aus dünnen Gaswolken, der so genannten interstellaren Materie. Diese Wolken, die vor allem Wasserstoff enthalten, sind so kalt, dass sie kein sichtbares Licht emittieren; sie lassen sich daher mit einem optischen Teleskop nicht beobachten, zum Ärger der Weltraumforscher, die damit auf eine wichtige Informationsquelle verzichten müssen. Sie senden aber Infrarot- und hochfrequente Radiowellen aus, die sich mit entsprechenden Teleskopen problemlos auffangen ließen – wäre da nicht die Erdatmosphäre …

Aus interstellarer Materie können unter geeigneten Bedingungen neue Sterne entstehen. Die Erforschung der Frühstadien der Sternentstehung und -entwicklung ist ein typisches Arbeitsgebiet der IR-Astronomie. Infrarot-Astronomie erlebt zurzeit einen Aufschwung. So werden beispielsweise hochpräzise Antriebe in Instrumenten bei kryogenen Temperaturen unter 80 K verwendet, um Detektoren auszurichten, mit denen Bildrotationen kompensiert werden, sowie Spiegel, Filter und andere optische Komponenten zu bewegen. Die Positioniergenauigkeit für Linearantriebe liegt dabei bei 1 – 2 µm und bei Rotationsantrieben bei wenigen Winkelsekunden. Solche Prozesse untersuchen Wissenschaftler des Heidelberger Max-Planck-Instituts für Astronomie (MPIA), das sich mit der Erforschung des Universums in optischen und infraroten Spektralbereichen widmet (www.mpia.de).

Für Antriebsaufgaben in Vakuumanwendungen steht man vor der Aufgabe einen geeigneten Antrieb zu konstruieren, eine in der Regel rotatorische Bewegung mit Hilfe einer Drehdurchführung in den Vakuumbehälter zu übertragen und Antrieb und Drehdurchführung mit möglichst geringem Aufwand miteinander zu verbinden.

Laut Ralf-Rainer Rohloff vom MPIA macht es keinen Sinn, AC- oder DC-Motoren in kalter Umgebung zu verwenden, da diese ein Encoder-Feedback erfordern, um die tatsächliche Position zu erfassen. Encoder für kryogene Applikationen sind jedoch derzeit am Markt nicht verfügbar. Tests am MPIA haben gezeigt, dass sich für einen Rotationsantrieb im Betrieb bei 80 K (-193°C) ein Phytron-Schrittmotor in Kombination mit einem Harmonic Drive Getriebe eignet. Wave Generator, Flexspline und Circular Spline des standard Harmonic Drive Getriebes wurden mit Wolfram-Disulfid beschichtet, um die Fettschmierung zu ersetzen, das Aluminium-Gehäuse wegen differierenden Wärmeausdehnungskoeffizienten bei niedrigen Temperaturen durch ein neues aus Edelstahl ersetzt. Dieser Rotationsantrieb wurde über einen längeren Zeitraum getestet bei nahe – 200°C und erreicht die geforderte Lebensdauer.

Kryogene Antriebe für den sofortigen Einsatz hat man nicht mal „eben so auf Lager". Daher hat das MPIA in Heidelberg Aktuatoren für lineare und kreisförmige Bewegungen entwickelt. Informationen über verwendbare Werkstoffe, Trockenschmierung und Komponenten wie Motoren, Mikroschalter und Resolver für diese Temperaturbereiche sind in der Literatur kaum zu finden. So wurden groß angelegte Experimente und Tests durchgeführt, um Antriebe auf ihre Einsatzmöglichkeit unter kryogenen Temperaturen zu qualifizieren. Antriebe vom MPIA mit Harmonic Drive Technologie werden zurzeit in einer Reihe von bahnbrechenden Teleskopen, wie z. B. dem Large Binocular Telescope (LBT) eingesetzt. Dieses riesige Teleskop, das auf dem Mount Graham in Arizona, USA, kurz vor der Fertigstellung steht, sammelt Licht aus dem Universum mit zwei riesigen Spiegeln, jeweils 8,4 m im Durchmesser. Nach der Fertigstellung wird das LBT das weltweit stärkste Teleskop in Bezug auf Lichterfassungsvermögen sein. Bis jetzt unsichtbare Himmelskörper werden damit zum ersten Mal sichtbar.

Seit 1979 liefert das Calar-Alto-Observatorium bahnbrechende Erkenntnisse. Auch die neuen Techniken der Infrarot-Astronomie kommen hier zum Einsatz.

Quelle: MPIA Heidelberg

Der Kryo-Aktuator bestehend aus einem Phytron-Schrittmotor und Harmonic Drive Getriebebox

Die beschichteten Komponenten des Harmonic Drive Getriebes beim MPIE

Pyramir, der Infrarot-Wavefront-Sensor, mit Harmonic Drive UHVC, in dem 3,5 m Teleskop Calar-Alto (rechts)

Die Infrarot-Astronomie

Bei Untersuchungen der Wärmeverteilung im Sonnenspektrum (er wollte Filter gegen die allzu große Hitzestrahlung der Sonne entwerfen) fand der Astronom F. W. Herschel die unterschiedlichen Temperaturen der Spektralfarben. Rot hatte eine höhere Temperatur als die anderen Farben.

Aber oberhalb des roten Bereiches, wo sich keine Farbe mehr abbildete, ließ sich eine noch höhere Temperatur messen. Damit war Herschel die Entdeckung der infraroten Strahlung gelungen, welche den Bereich von 0,001 bis 1 mm belegt.

Bei der Anwendung der Infrarottechnik gibt es allerdings einige Probleme zu lösen. Lässt die Lufthülle um unseren Planeten sichtbares Licht noch mehr oder weniger ungehindert passieren, wirkt sie beispielsweise für Infrarotstrahlung aus dem All wie die Augenklappe eines Piraten. Um trotzdem zu brauchbaren Ergebnissen zu kommen, arbeiten die Astronomen auf hohen Bergen, mittels Ballons (welche bis zu 50 km Höhe fliegen können), mit Detektoren in Flugzeugen oder – und das ist die beste Lösung – mit Infrarot-Satelliten.

Ein weiteres Problem ist nämlich die Tatsache, dass alle warmen Objekte im Infraroten strahlen, also auch Gegenstände unseres täglichen Lebens und die Astronomen selber. Außerdem stört die Hintergrundstrahlung des Weltalls. Die Erfassung der Infrarotstrahlung erfordert daher die Kühlung der Messapparatur auf kryogene Temperaturen. Für die Astronomen bedeutet dies, dass Teleskope, Zusatzgeräte und sie selbst irgendwie abgeschirmt werden müssen, weil sie sonst die Ergebnisse verfälschen können.

Infrarot-Detektoren sowie die Mechanismen im Inneren der Instrumente werden im Hochvakuum unter kryogenen Temperaturen eingesetzt. Durch die zunehmende Anwendung tiefer Temperaturen in der Forschung, Energietechnik und im Weltraum besteht der Bedarf an elektrischen Antrieben und Positioniersystemen, die auch unter kryotechnischen Bedingungen, also bei tiefen Temperaturen und im Vakuum, funktionstüchtig sind und darüber hinaus einer Reihe von erhöhten Anforderungen genügen: insbesondere Betriebssicherheit, Miniaturisierung, geringste Wärmeentwicklung sowie geringe akustische und elektrische Störpegel.

Fig. IV.1.10: The report on the cooperation with the MPIA in the company newsletter of Harmonic Drive AG.

In the future, more joint projects will be carried out together with partners from industry. The MPIA will mainly contribute its experience in the field of extra-low temperatures.

Ralf-Rainer Rohloff, Harald Baumeister, Monica Ebert, Norbert Münch, Vianak Naranjo

IV.2 First Light for PARSEC: The Laser of the VLT Laser Guide Star Facility

PARSEC, a joint project by MPE (Garching) and MPIA (Heidelberg), is the name of the sodium line laser, which routinely produces a high quality 10 – 20 Watts continuous wave output beam, about 10 000 times more powerful than a class 2 laser pointer.

Adaptive optics (AO) systems are now indispensable on all fully developed and competitive 8 – 10 m class telescopes. They cancel out atmospheric optical disturbances typically in the near-infrared wavelengths regime. In order to work, AO systems need a reference source for wavefront analysis. Sufficiently bright natural guide stars close to the scientific object are required, which limits the usage of AO systems to about a few percent of the sky. The solution to this problem is an artificial star projected on the sky by a powerful laser.

The project of building the VLT Laser Guide Star Facility (LGSF) was started in 2000. The LGSF has three main components: a projection telescope behind the VLT's secondary mirror, a fiber beam relay from the laser control room to the projection telescope, and a high power sodium laser.

On 28 January 2006, at 23:07 local time, a laser beam of several watts was launched from Yepun, the fourth 8.2 m Unit Telescope of the Very Large Telescope, producing an artificial star, 90 km up in the atmosphere. Despite this star being about 20 times fainter than the faintest star that can be seen with the unaided eye, it is bright enough for the adaptive optics to measure and correct the atmosphere's blurring effect. The event was the culmination of many years of collaborative work by a team of scientists and engineers from ESO and the MPIs for Extraterrestrial Physics in Garching and for Astronomy in Heidelberg, Germany.

Fig. IV.2.1: First light of the VLT Laser Guide Star. (Credit: Stefan Seip)

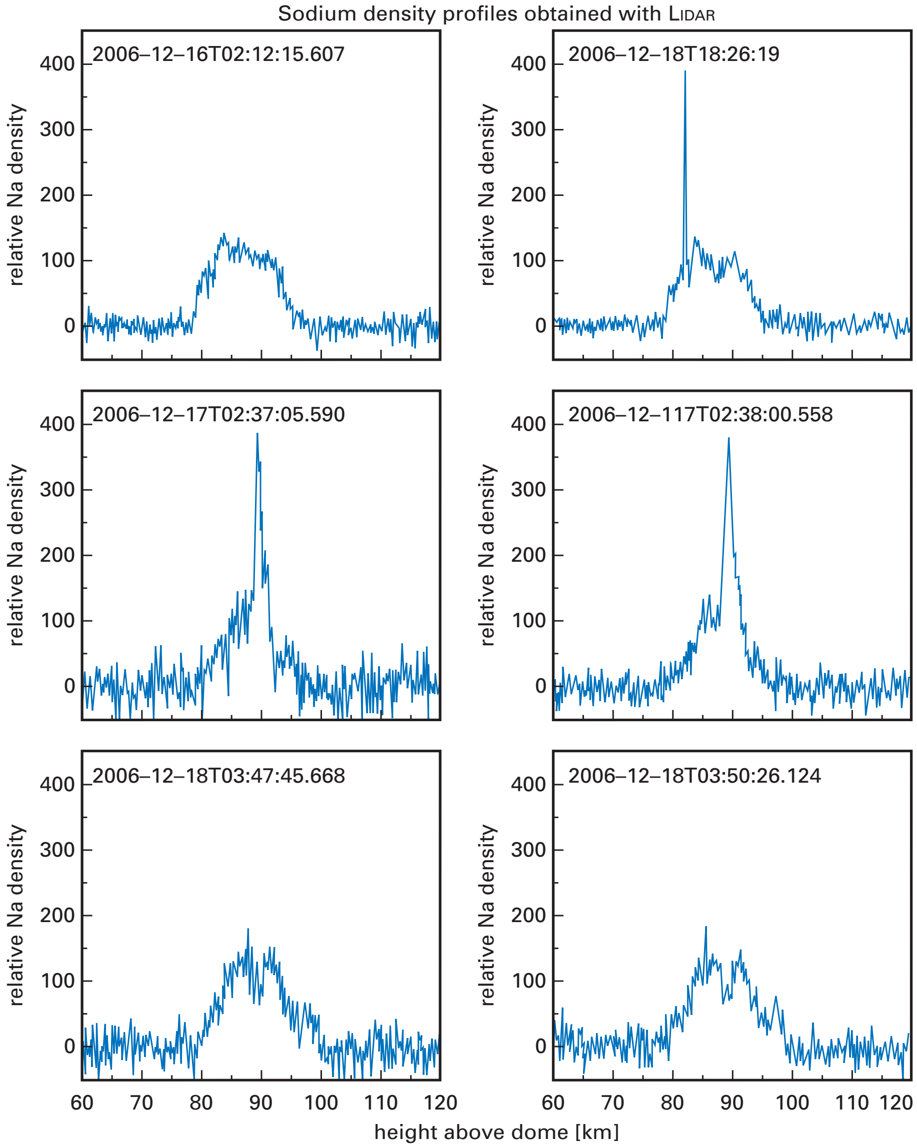


Fig. IV.2.2: Sodium densities above Paranal as measured with LIDAR.

After more than one month of integration on site with the invaluable support of the Paranal Observatory staff, the VLT Laser Guide Star Facility saw First Light and propagated into the sky a 50 cm wide, vivid, beautifully yellow beam. (Fig. IV.2.1.)

Even though first light was quite successful, there was a problem in focusing the laser guide star (LGS). This could be identified as a misalignment inside the laser launch telescope and was fixed in autumn 2006. In December 2006 the commissioning of the LGSF with the adaptive optics instrument NACO continued. At the time of writing this article, NACO with LGS routinely delivers an angular resolution in *K*-band images below 0.1 arcseconds.

The integrated LIDAR (LIght Detection And Ranging, laser radar) system, which was part of MPIA's contribution to PARSEC, was commissioned in 2006, too. First results of measured sodium densities above Paranal observatory are shown in Fig. IV.2.2.

Meteoric ablation is regarded as the dominant source of all mesospheric alcali atoms including sodium. The sodium layer typically stretches from 80 to 100 km hight with a peak near the mesopause at 90 km, the Na column density is of the order of 5×10^{13} atoms per square meter. The sodium abundance can vary on short time scales as well as have seasonal changes. Spikes in the LIDAR profile can be attributed to evaporation of meteoroids containing sodium. The PARSEC LIDAR profiler serves two purposes: 1) as a diagnostic tool for the expected LGS return flux, and 2) to calibrate the focus offset of the wavefront sensor.

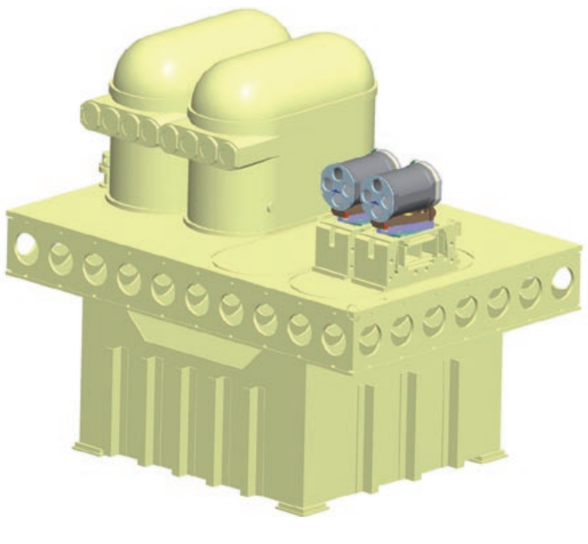
Stefan Hippler, Wolfgang Brandner, Thomas Henning, Udo Neumann, Hans-Walter Rix

IV.3 ESPRI – Exoplanet Search with PRIMA

In only two years from now the high-precision astrometric facility PRIMA (Phase Referenced Imaging and Micro-arcsecond Astrometry) will be available at the Very Large Telescope Interferometer (VLTI) of the European Southern Observatory (ESO). One of the key components for PRIMA, the Differential Delay Lines, are being developed at MPIA, in collaboration with the Landessternwarte Heidelberg and the Observatoire de Geneve. When completed, MPIA researchers will use PRIMA to perform a large astrometric survey to search for extrasolar planets.

PRIMA will enable the VLT interferometer to simultaneously observe two stars that are separated by up to 30 arcseconds. Like in adaptive optics observations, one star can be used as a reference to stabilize the interferometric phase, while the other star can then be observed without the perturbations by the atmosphere. When this technique is used to measure very precisely the separation between two stars (astrometry), one can detect the gravitational wobble (astrometric signal) that would be caused by an (unseen) planet orbiting that star. When equipped with Differential Delay Lines, PRIMA will be able to reach an astrometric accuracy of 10 μarcsec (which corresponds to 2 cm on the moon when viewed from earth). This precision will enable the detection of extrasolar planets down to the mass of Uranus around nearby stars.

Fig. IV.3.1: System view (model) of the Differential Delay Lines, with optical bench, vacuum vessels with entrance windows, and cat's eye retro-reflector telescopes on high-precision linear translation stages.



Although until today most extrasolar planets have been detected with the radial velocity technique, the astrometric method is very complementary because it is more sensitive to planets with orbital periods longer than one year. In particular, the astrometric method can also be used to search for planets around stars which are less suitable for radial-velocity searches because their spectral lines are too broad or not stable enough (e.g., young and active stars that rotate very fast).

The MPIA Heidelberg, Landessternwarte Heidelberg, and the Geneva Observatory (Switzerland) are cooperating in a consortium that has agreed with ESO to build and deliver the Differential Delay Lines for PRIMA, to develop the astrometric data reduction software, and then to carry out an astrometric planet search program at the VLTI with the Auxiliary Telescopes (ATs) in the near-infrared *K*-band.

In terms of hardware developments, MPIA is primarily in charge of designing and building the cat's eye retro-reflector telescopes for the DDLs. The DDLs will compensate optical path differences between the two stars of up to 12 cm with an accuracy of one nanometer (dynamic range of 10^8!) in connection with a two-stage linear motion mechanism and a laser-metrology system, and placed on a stable optical bench in a vacuum tank. The most difficult technical challenge is to keep sub-arcsecond stability over the full motion range. In summer 2006 we successfully passed the Final Design Review for the DDLs at ESO. After performing a technical feasibility study in collaboration with the IOF Fraunhofer institute in Jena, we have contracted the company AXSYS in Detroit to build the cat's eye telescopes. We are currently furbishing a new optical laboratory at MPIA and expect to receive and test the first cat's eye optics in summer 2007.

Other no less important activities in the ESPRI project are the development of the PRIMA Astrometric Operation and Software tools (PAOS), the establishment of a full error budget, and the scientific preparation of the planet search program. MPIA participates in the first task and leads the latter two. Commissioning of the instrument and its astrometric mode is foreseen for the second half of 2008, such that the scientific program "Exoplanet Search with PRIMA" can start in early 2009.

Harald Baumeister, Peter Bizenberger,
Uwe Graser (PM), Thomas Henning (PI),
Ralf Launhardt (PS), Johny Setiawan,
Robert Tubbs, Karl Wagner.
Partners: Observatoire de Geneve,
Landessternwarte Heidelberg-Königstuhl,
ESO, Garching

IV.4 SPHERE – Direct Imaging of Extrasolar Planets

SPHERE – Spectroscopic and Polarimetric High-Contrast Exoplanet Research – is the name of 2nd generation VLT instrument for direct imaging of extrasolar planets at the VLT. It will be composed of an extreme adaptive optics system – using a deformable mirror with 1600 actuators and running at a loop frequency of 1.5 kHz, dedicated coronagraphs, and three focal plane instruments. These are the differential polarimeter ZIMPOL operating at visual wavelengths, an integral field spectrograph working in the *Y*- and *J*-band, and a versatile NIR differential imager essentially similar to CONICA – SDI.

The kick-off for SPHERE's phase B was held in Paris in March 2006. PDR is planned for May 2007. Sphere is being built by a consortium of 13 European institutes with the Laboratoire d'Astrophysique et Observatoire de Grenoble being the P.I. institute and MPIA the Co-P.I. institute. MPIA's prime responsibility in the project is the data reduction and handling software, essentially everything between and including the target list and the final list of candidate detections, data reduction and analysis. Additionally, MPIA is providing some hardware components, like a detector motion stage for the near-infrared imager, atmospheric dispersion correctors and field/pupil de-rotators.

SPHERE is currently expected to cost about 174 FTE and 6 million Euro hardware, including some FP6-funded components. MPIA's contribution is planned to be 18 FTE and 500 000 Euro, resulting in a 10 percent share in the project. The number of guaranteed observing nights generated by the effort is expected to be 260. A large, common survey for exoplanets carried out jointly by the consortium is currently planned to fill most of the garanteed nights. Detailed preparations of this survey are under way.

Markus Feldt (Co-P.I.) and the SPHERE consortium:
Laboratoire d'Astrophysique de Grenoble,
Laboratoire d'Astrophysique de Marseille,
Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique,
Laboratoire Universitaire d'Astrophysique de Nice,
Istituto Nazionale di Astrofisica,
Eidgenössische Technische Hochschule Zürich,
Observatoire de Genève,
Universität van Amsterdam,
Office National d'Etudes et de Recherches Aérospatiales,
Stichting Astronomisch Onderzoek in Nederland,
ESO Garching

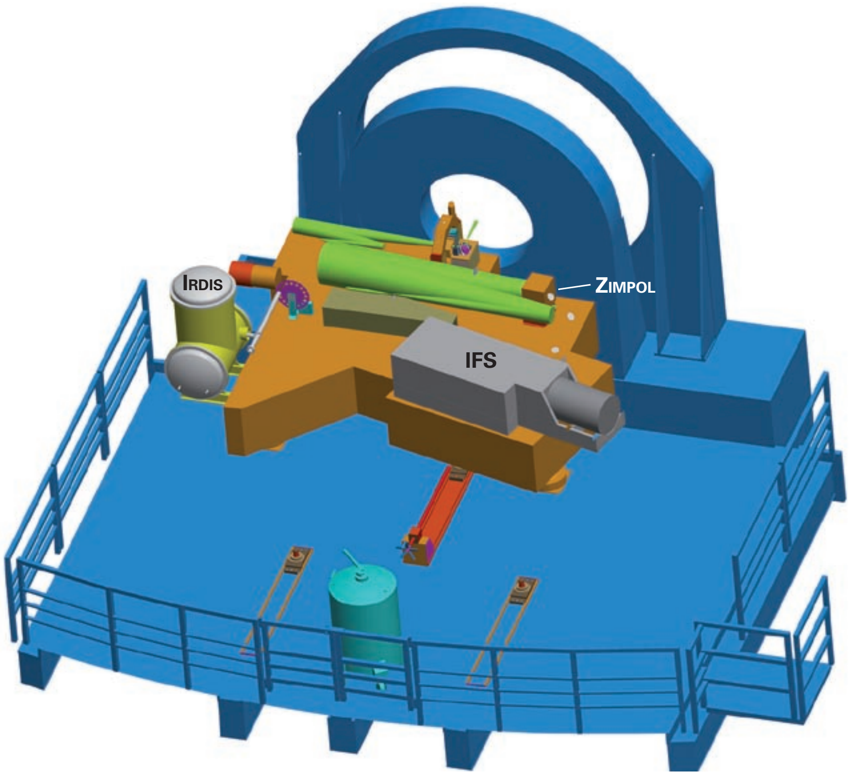


Fig. IV.4.1: SPHERE at the Nasmyth platform of the VLT.

IV.5 Linc-Nirvana

The Linc-Nirvana instrument is an imaging coherent beam combiner for the Large Binocular Telescope (LBT). Sitting at one of the central shared foci of the LBT, Linc-Nirvana will combine the light from the two, 8.4 meter primary mirrors, producing true, panoramic imagery with the spatial resolution of a single 23 meter telescope. The MPIA is leading a consortium of four institutes that are constructing Linc-Nirvana. Our other partners include the Istituto Nazionale di Astrofisica (Italy), the University of Köln, and the Max Planck Institute for Radioastronomy in Bonn.

The Linc-Nirvana team achieved a number of important milestones in 2006. The most visible of these is the commencement of component integration into the larger instrument. This involves installation on the large optical bench in the MPIA clean room and subsequent performance testing and verification. One important activity is to ensure that Linc-Nirvana will deliver high quality imagery, even when the telescope is tipped over from vertical. The large hydraulic flexure-testing platform allows us to measure performance at all angles between the zenith and the horizon.

Several individual subsystems entered the integration and verification phase in 2006. These included the warm fore-optics, various component mounts and stages, and the large vacuum cryostat, which will hold the science and fringe-tracking detectors.

Fig. IV.5.2: MPIA engineer Sebastian Egner adjusts the connection points of the vacuum cryogen lines on the Linc-Nirvana cryostat.

The cryostat presents a particularly interesting technical challenge for MPIA engineers. In addition to providing a cold (77 K or – 196 °C), light-tight environment for the sensitive detectors, the cryostat must provide a variety of mechanical functions while minimizing electrical interference and vibrations, which can be deadly to interferometric measurements.

These requirements have led to a number of innovative technical solutions for the cryostat. For example, the science detector must rotate to follow the astronomical target, yet motors typically cause unacceptable electrical interference. To combat this problem, the Linc-Nirvana

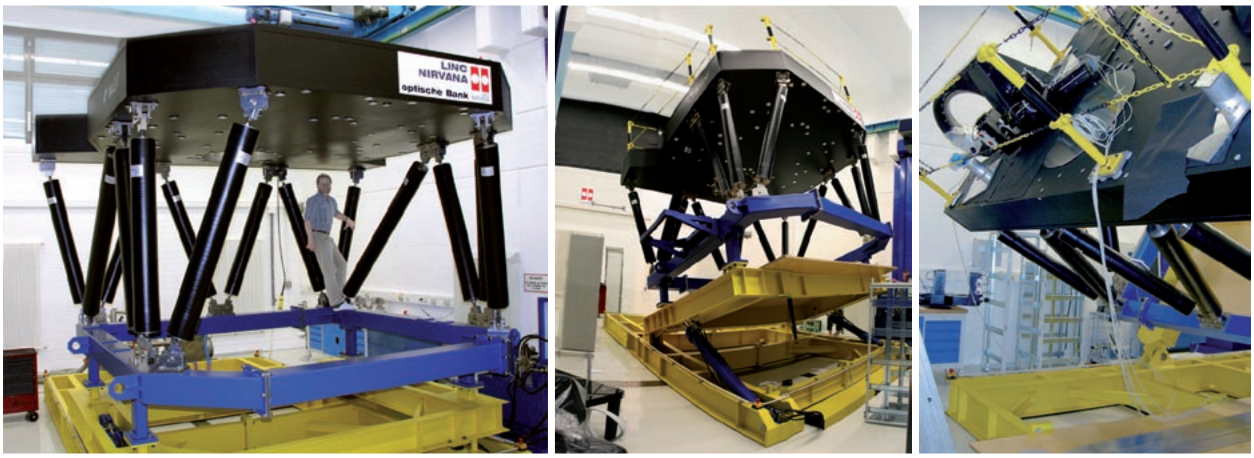


Fig. IV.5.1: *Left:* The Linc-Nirvana optical bench in zenith-pointing orientation). *Center:* To examine flexure effects, the hydraulic rams can tilt the entire instrument. *Right:* testing of opto-mechanical components takes place on the top of the bench.

Fig. IV.5.3: The analog motor drive and prototype cryogenic rotation mechanism. (Vianak Naranjo)

Fig. IV.5.4: The remote mechanical cooler for the LINC-NIRVANA cryostat.

team developed a unique analog motor drive, which significantly suppresses the current spikes that cause interference with the detector.

Vibrations are another key technological challenge. Typical modern cryostats use mechanical coolers to reach the low temperatures needed for infrared operations. Unfortunately, mechanical coolers produce mechanical vibrations. Motions of LINC-NIRVANA's optical components by a fraction of the wavelength of light can destroy the delicate interference needed to achieve maximum spatial resolution. Low vibration mechanical coolers exist, but they simply don't have the cooling capacity to chill LINC-NIRVANA's large cryostat.

Working with a commercial partner, MPIA engineers are pioneering a new way of cooling large astronomical instruments. The key insight was to isolate the mechanical cooler from the vibration-sensitive components. LINC-NIRVANA's cooler will be installed one level below the dome floor with other "dirty" systems such as fans, hydraulic pumps, etc. The cooler refrigerates a transport medium, in this case gaseous helium, to approximately 60 K, and an impeller forces the gas through approximately 40 meters of insulated pipe to the instrument. The helium line enters the vacuum vessel and wraps around a large, cylindrical heat exchanger, which in turn cools the optical components and detectors.

Assembly, integration, and testing of LINC-NIRVANA will continue through 2007 and 2008. In the meantime, progress continues on the LBT itself. The commissioning of binocular operation and installation of the adaptive secondary mirrors are important milestones during this period. LINC-NIRVANA will arrive on Mt. Graham in 2009, and soon thereafter, MPIA astronomers can begin exploiting this unique observational capability.

Harald Baumeister, Jürgen Berwein, Mario Biz, Armin Böhm, Luis Borelli, Florian Briegel, Mario Brix, Fulvio De Bonis, Sebastian Egner, Wolfgang Gässler, Bernhard Grimm, Stefan Hanke, Tom Herbst (PI), Frank Kittmann, Martin Kürster (PM), Lucas Labadie, Werner Laun, Ulrich Mall, Lars Mohr, Vianak Naranjo, Aleksey Pavlov, Hans-Walter Rix, Ralf-Rainer Rohloff, Eva Schinner, Joachim-Johannes Schmidt, Clemens Storz

IV.6 LUCIFER I/II for the LBT

The first of the two identical NIR imager/spectrographs LUCIFER I/II for the LBT is nearing completion: During 2006 all opto- and cryo-mechanical parts were manufactured and delivered (except for some narrow band filters, which will be delivered by the end of February 2007). The cold structure including the cooling and pre-cooling system has been implemented in LUCIFER I. Optical components have been integrated into their mechanical mounts, and these mounts have been integrated into the cryostat. LN2 pre-cooling and closed cycle main cooling systems have successfully been tested. At the end of 2006 LUCIFER I was nearly completely assembled, with first detector tests planned for February 2007. LUCIFER I has been attached to the telescope simulator for the first tests (see Fig. IV.6.1).

In parallel, the MOS-unit has been integrated into LUCIFER II and tested at MPE (Garching). First delivery of the MOS unit and test integration into a fully assembled LUCIFER will be done in February 2007.

Installation and commissioning time of LUCIFER I at the LBT is now planned for December 2007. The second LUCIFER instrument will follow about one year later.

Rainer Lenzen

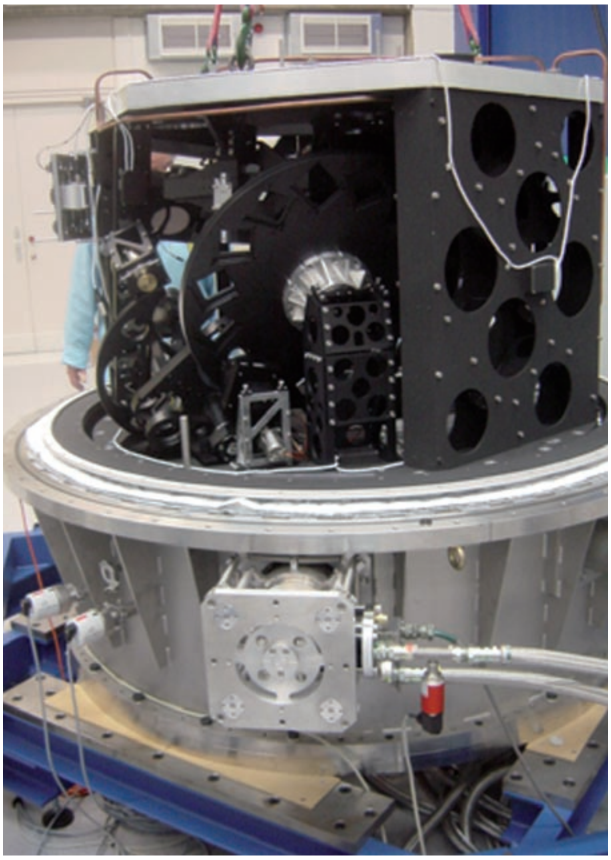


Fig. IV.6.2: LUCIFER I during the assembling procedure at the MPIA. The partly assembled cryogenic structure is entering the front part of the cryostat (entrance window on the bottom, not visible). The two large filter-wheels can be clearly seen.

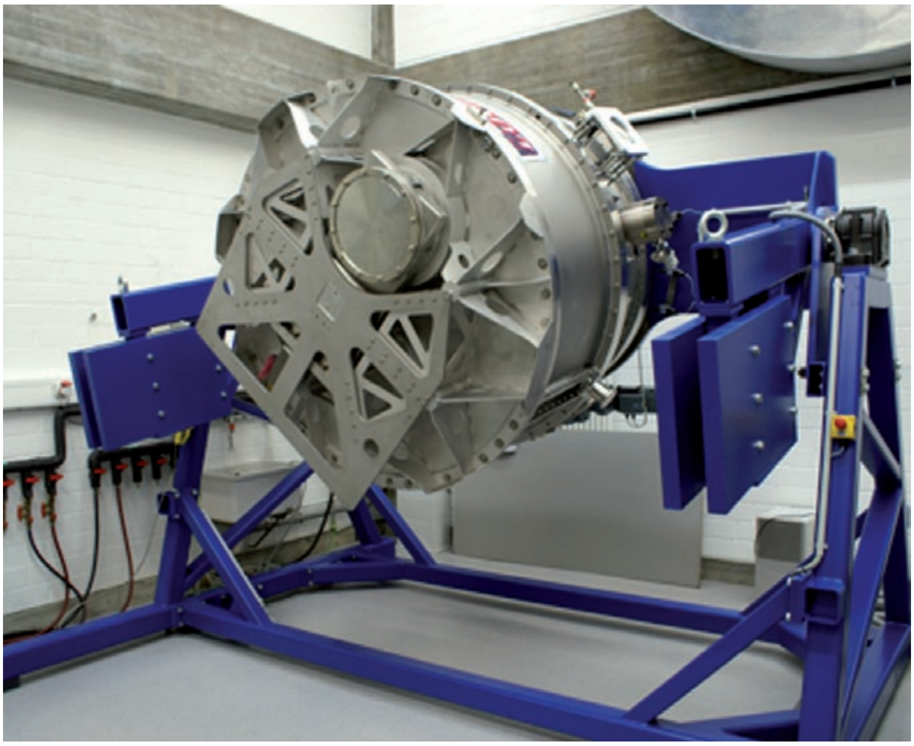


Fig. IV.6.1: LUCIFER I attached to the telescope simulator at the MPIA. On the rear side the large valve, which allows mask exchange at cryogenic temperatures, can be seen.

IV. 7 AstraLux – Diffraction Limited Imaging at Visible Wavelengths

The angular resolution achieved with ground based telescopes is usually limited by atmospheric optical turbulence. There are basically two ways to avoid this limitation: one is to observe from above the earth atmosphere using space observatories, the other consists in using "adaptive optics" which compensate in real time the rapid deformations of the astronomical images produced by the variable atmospheric conditions. Here we present the new instrument AstraLux, which is now in use at the Calar Alto 2.2 m telescope and makes use of a third method, called "Lucky Imaging".

For very brief periods, imaging through the atmosphere can deliver much sharper images compared to long exposure seeing limited images. While the latter ones typically show an angular resolution of about 1 arcsec, the point spread function of the short exposure images consists of speckles with an full width at half maximum (FWHM) matching the diffraction limit of the telescope.

AstraLux is based on Lucky Imaging, a method to select among many rapid short exposure images for example the best 1%, 5%, or 10%. These images are then stacked together with a shift-and-add technique to create the final image. On a 2.2 m telescope like the one on Calar Alto, Lucky Imaging can and does reach the diffraction limit of the telescope: 0.085 arcsec at 900 nm wavelength.

First light with AstraLux at the Calar Alto 2.2 m telescope was in July 2006. The AstraLux instrument is based on an electron multiplying, thinned and back-illuminated CCD which is operated in frame transfer mode and capable of running at 34 frames per second when reading the full 512×512 pixel frame. The camera is situated at the Cassegrain focus of the telescope, behind a simple Barlow lens which changes the focal ratio from *f*/8 to *f*/32 in order to get an image scale of 46.4 mas/pixel. This provides Nyquist sampling at $\lambda \approx 1\ \mu$m, and slightly undersamples the theoretical point spread function at the typical observation wavelengths of 700 – 950 nm. With the exception of the mount needed to attach the camera to the telescope, all components were bought off-the-shelf, making AstraLux a simple and cheap instrument, taking only six months from the first idea to first light.

While even professional astronomers sometimes worry about the shear amount of data thrown away or not used, typically 95 %, the results obtained with Lucky Imaging are manifold. Lucky Imaging can provide high

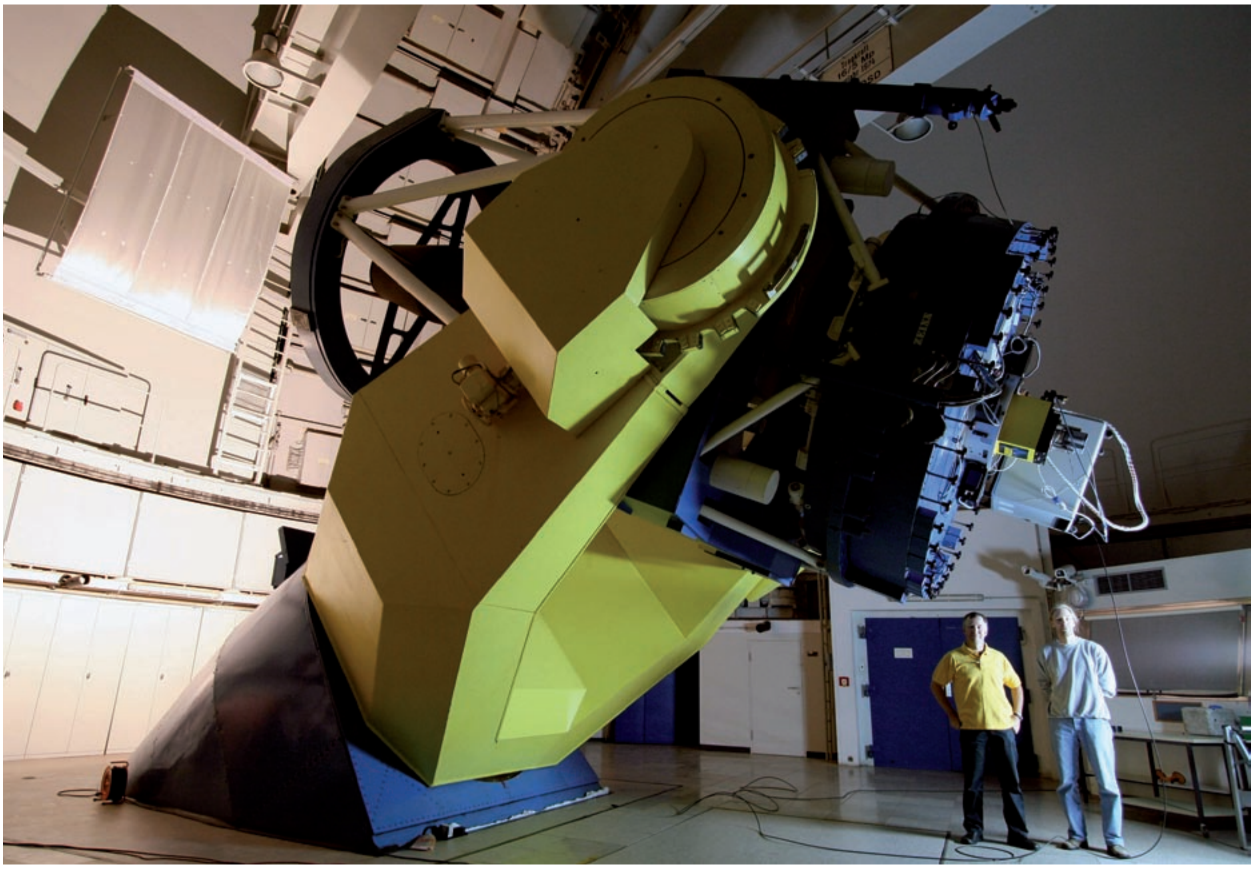


Fig. IV.7.1: The AstraLux camera mounted at the Calar Alto 2.2 m telescope, with Stefan Hippler (*left*) and Felix Hormuth (*right*).

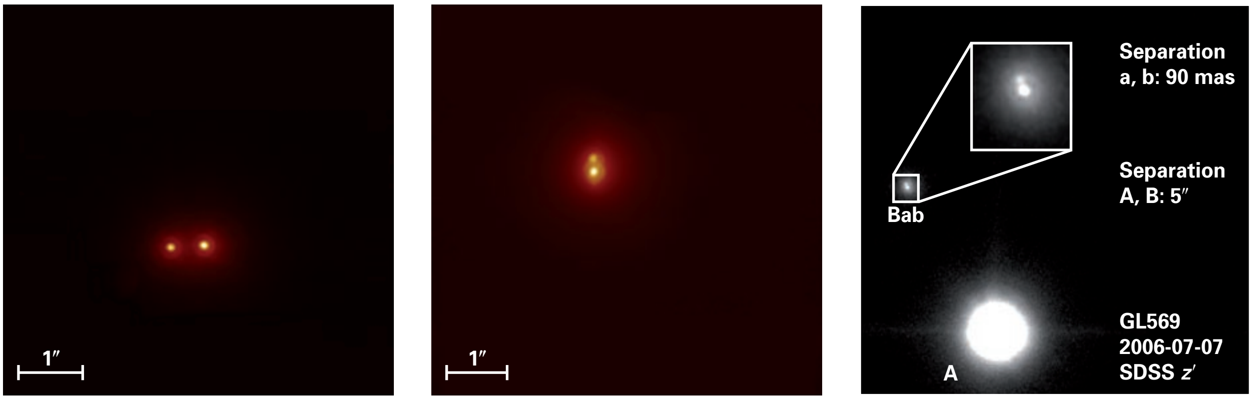


Fig. IV.7.2: First light images obtained with ASTRALUX at the Calar Alto 2.2 m telescope in July 2006. *Left:* the binary WDS 14139 + 2906, separation: 520 mas, brighter component: $V = 7.6$ mag, seeing 0.8 arcsec. *Center:* the binary WDS 15420 + 0027, separation 200 milliarcsec, brightest component: $V = 8.2$ mag, seeing 0.9 arcsec. *Right:* the multiple system GL 569. The M dwarf (A) is accompanied by a brown dwarf, which is resolved here into two components separated by only 90 milli-arcseconds. This image is based on a 5 % selection from 15 000 frames with 15 ms exposure.

angular resolution at visible wavelength on a 2-m-class telescope, typically around 100 milli-arcseconds. The "best of" selection process increases the signal-to-noise ratio of point sources compared to the seeing limited case with 100 % flux. Because of the selection effect, the iso-planatic patch found in Lucky Imaging is larger compared to the one in adaptive optics corrected images. The reference star needed for Lucky Imaging can be as faint as $I = 15.5$ mag on a 2.2 m telescope, which is very similar to the limiting magnitude of near-infrared adaptive optics systems. Costs and complexity of Lucky Imaging are orders of magnitude less than for adaptive optics systems.

Figures IV.7.2 and IV.7.3 show results obtained during the very first observing nights.

Stefan Hippler, Felix Hormuth,
Wolfgang Brandner, Karl Wagner,
Thomas Henning

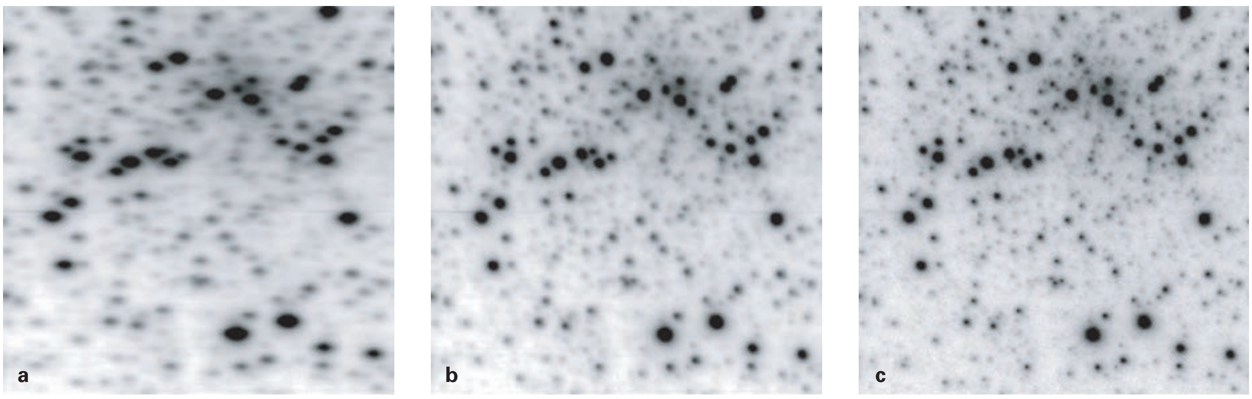


Fig. IV.7.3: The dense core of the globular cluster M15, a case study for Lucky Imaging. The images show from left to right, *a)* the seeing limited image (due to a periodic error of the telescope tracking the stars appear elongated, FWHA = 730 × 430 mas), *b)* a tip-tilt corrected image, and *c)* the Lucky Imaging result, based on the best 250 out of 5000 images. The total integration time was 15 seconds. The stellar FWHM is 110 milli-arcseconds. The field of view is 24 × 24 arcseconds.

IV.8 PANIC – The Panoramic Near Infrared Camera

This project will equip the 2.2 m telescope at the CAHA observatory with a state-of-the-art competitive wide field imager for the near infrared. Such an instrument was selected by astronomers at the Instituto de Astrofísica de Andalucía (IAA) and at the MPIA, which started to build PANIC in a joint project in September 2006. Mechanics, electronics and read-out of the detectors is theresponsibility of MPIA. Optical design and software is done by IAA.The current schedule aims at a preliminary design review in July 2007 and first light at the telescope in the second half of 2009.

Since the main applications of the instrument will be wide-field imaging, the image scale was set to 0.45 arcsec/pixel, which results in a field of view of 0.5 by 0.5 degrees with a 4 K × 4 K detector. The spectral range extends from *z*-band (0.82 mm) to *K*-band (2.42 mm).

Two major restrictions have to be met at the Ritchey-Chrétien focus of the 2.2 m telescope: the mechanical length of the instrument must not exceed 160 cm, and its weight at the focus is limited to 300 kg. The length limit can be easily met by folding the instrument. The weight limit will require the use of light-weight materials and weight reduction by constructive means.

The optical design of the instrument is shown in Fig. IV.8.1. Three flat mirrors fold the instrument, such that the length limit is met and most of the hardware in the cryostat is located near the focal plane in order to minimize the torque on the telescope. The optical design is purely dioptric; the encircled energy is > 80 % within 1 pixel radius over the whole field and spectral range. The distortion is less than 0.5 %. An image of the entrance pupil within the optical path allows one to use a cold aperture stop and so reduce the thermal background of the instrument. The cryostat will have a 60 liter liquid nitrogen tank to ensure an estimated holding time of 36 hours. Three filter wheels can house 21 filters.

Four HAWAII-2RG detectors will be mounted in one array with a minimal gap of about 12 pixel. PANIC will thus have a very convenient footprint. The read-out electronics will be a new generation of the standard MPIA ROE, which is currently being developed. It will allow fast and low-noise read-out.

The software will include a GUI for easy control of the instrument as well as macros to ease observations. A data quick-look, including bias and flat field correction as well as stacking of images and distortion correction, will allow one to control of the quality of the data obtained already during observations. We will also supply a data reduction pipeline and an archiving system.

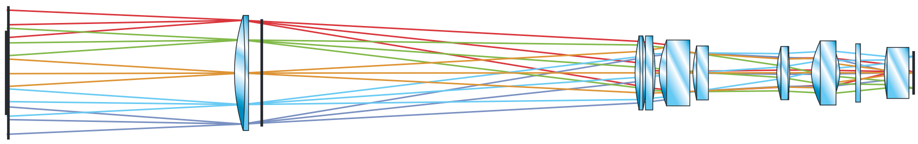


Fig. IV.8.1: The optical design for Panic. The entrance window, which has some optical power, is located before the focal plane of the telescope. An image of the entrance pupil is formed after the first group of lenses. The length of the optical train is about 160 cm.

Josef W. Fried, Werner Laun,
Ralf-Rainer Rohloff, Bernhard Grimm,
Ulrich Mall, Vianak Naranjo,
in cooperation with colleagues of the IAA, Granada

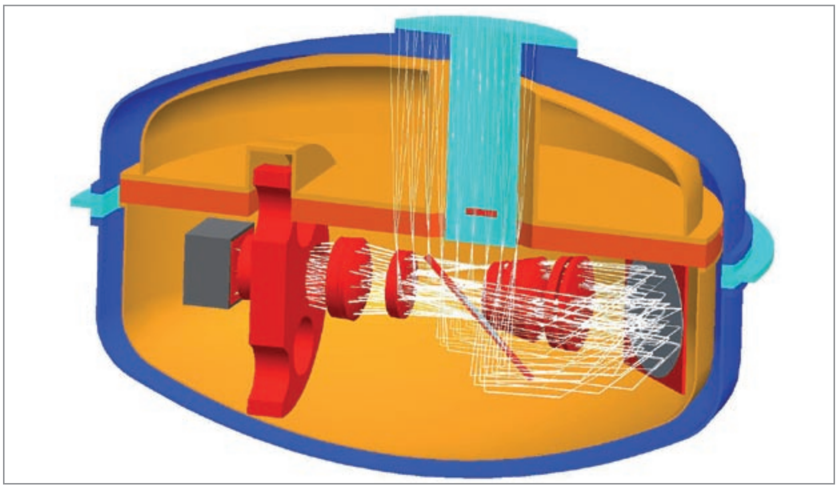


Fig. IV.8.2: A design study for the layout of the instrument. A compact design results from the use of 3 folding mirrors. The vacuum can is shown in blue, the nitrogen vessel in ochre, the optical elements and the filter wheels are shown in red, the optical bench in light red and the detector in grey.

IV.9 Pyramir – a New Wavefront Sensor for Alfa

Pyramir is a new wavefront sensor for the AO system Alfa at the 3.5 m telescope at Calar Alto Observatory in Spain. It is based on the pyramid principle – essentially an extension of the Foucault wavefront test and expected to be superior to a Shack-Hartmann sensor at the same photon rate. The advantage is supposed to be played out once the Strehl number increases above about 20 % at the sensing wavelength. Hence Pyramir, operating in the Nir where Alfa's correction is most effective and high Strehl numbers are easily reached, should be able to prove or disprove this prediction.

In 2006 Pyramir had several commissioning runs at the 3.5 m telescope on Calar Alto. Successful closed-loop operation was achieved with *K*-band Strehl ratios of up to 40 % on the sky. Systematic tests were undertaken to determine the linear range of the sensor, find an optimized mode set, measure modal crosstalk, and determine the sensitivity to static aberrations present in the system. The proof/disproof of its superiority over Shack-Hartmann sensing is still pending, since the on-sky observations are not yet sufficient in number for a conclusive result. This is additionally complicated by the terminal failure of the visual Shack-Hartmann sensor's communication links. This device is now de-commissioned and Pyramir may become Alfa's only wavefront sensor, provided another successful commissioning period can be completed in early 2007.

Markus Feldt

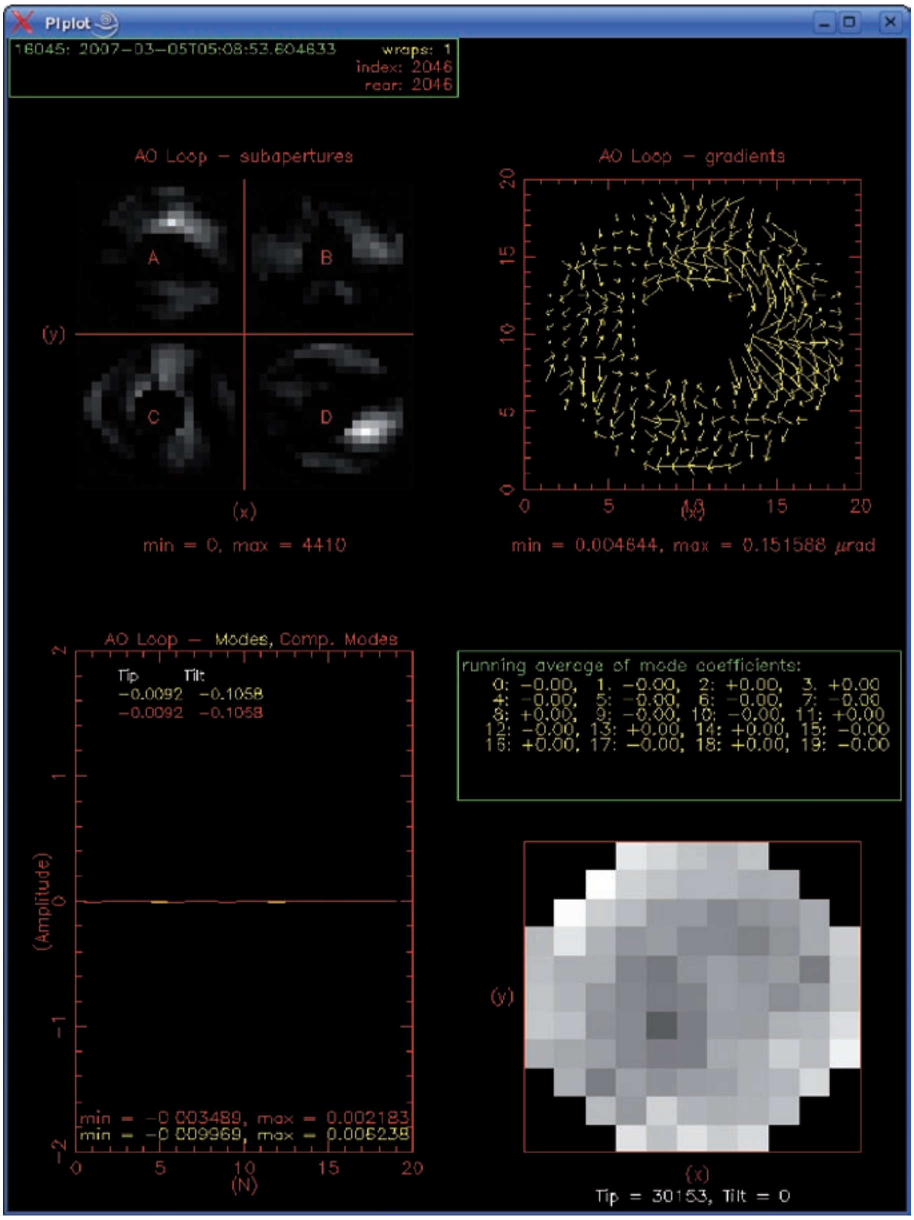


Fig. IV.9.1: Display of Pyramir's real-time control loop. *Upper left:* the four pupil images of the pyramid sensor. *Upper right:* the wavefront gradients derived from the pupil images. *Lower left:* the aberration modes, and *lower right:* the correction signal applied to the deformable mirror. The image was taken with the AO loop closed, thus only residuals of the aberrations are visible. The Strehl number is about 70 percent.

IV.10 E-ELT – the European Extremely Large Telescope

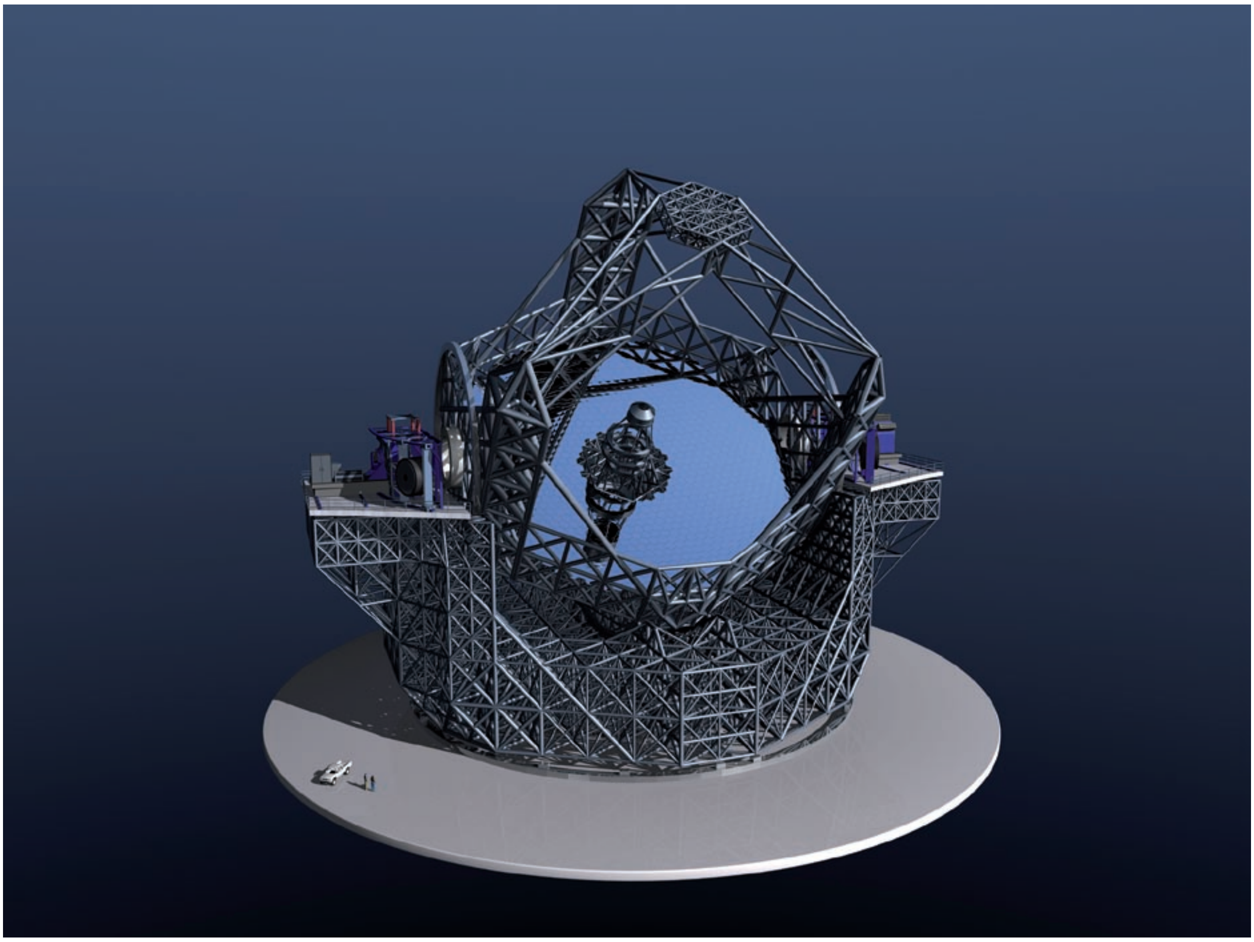
With the VLT nearing full implementation and operation, the time has come to plan the "next step". Defined as ground-based telescopes with diameters in the range 20 – 100 meters, the Extremely Large Telescopes (ELT) are conceived to provide this next leap in humankind's capability to observe the cosmos. European plans for an ELT evolved considerably during 2006, and the MPIA continued to be at the center of scientific and technical planning for the European ELT (E-ELT).

The end of 2005 saw the completion of the 100 meter OWL telescope design study. Although quite successful in many respects, the OWL review panel considered a 100 m optical telescope as too ambitious within a realistic budget and time envelope. As a result, the European Southern Observatory (ESO) launched a re-examination of European science priorities and technical capability in December of 2005. A total of five working groups in Science, Telescope Design, Adaptive Optics, Instrumentation, and Site Selection studied options for the E-ELT during the first four months of 2006. The MPIA was well represented on these panels, including members and chairs on three of the five panels.

ESO formed the European ELT Project Office in June of 2006 in order to advance the telescope to a point where it could enter the detailed design phase. To ensure that the results would meet the future observational needs of European astronomers, ESO also established the European ELT Science and Engineering (ESE) committee. This body, formed from the leadership of the five working groups and additional highly qualified astronomers, will provide guidance and oversight for the entire E-ELT project. The MPIA has significant participation and input to the ESE panel: two of the twelve ESE committee members, including the Co-chair, are from the Institute.

On the technical side, the MPIA was a co-investigator institute in the MIDIR study, an effort to identify the optimal design for a mid-infrared camera/spectrograph for the E-ELT. This research, partially funded by the European FP6 Program, led to a combined imager and spectrograph with integral field capability. It would operate in the wavelength range 3 – 20 μm at diffraction limited spatial resolution and moderate to high spectral

Fig. IV.10.1: Preliminary engineering drawing of the European ELT. The current baseline is a five mirror optical design with a 42 meter diameter segmented primary.



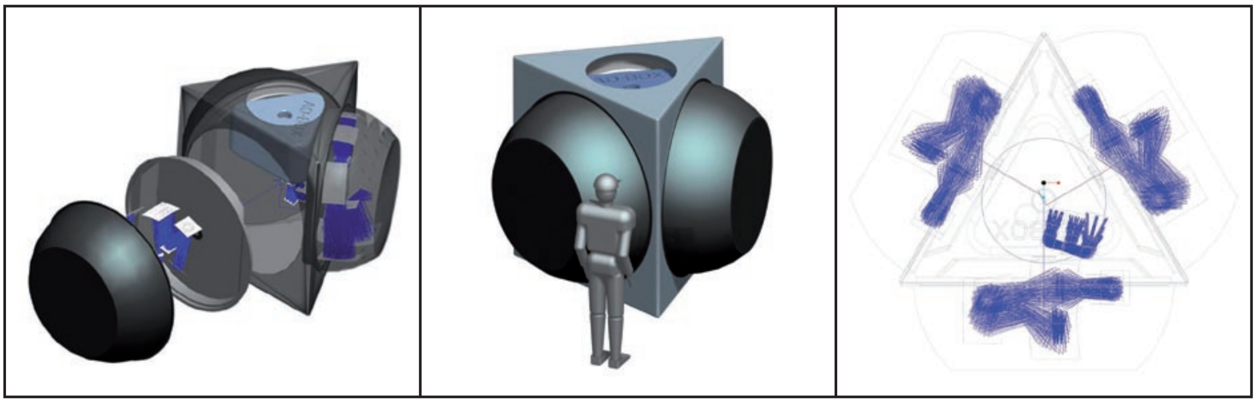


Fig. IV.10.2: Partially exploded view (*left*), for size comparison (mid), and optical design (*right*) of the MidIR instrument. The lines trace the optical paths of the imager (center) and the three modular spectrographic channels (surrounding the central triangle).

resolution. Because it places relatively modest demands on the wavefront quality delivered by the E-ELT, MidIR would make an excellent choice for the first-light instrument complement.

Finally, the proceedings of an MPIA-organized workshop on ELT instrumentation were published in April 2006. The almost 300 pages of the proceedings capture our understanding of how to address the challenge of equipping these giant telescopes with the most scientifically productive instrumentation possible.

Wolfgang Brandner, Wolfgang Gässler, Roland Gredel, Tom Herbst, Rainer Lenzen

IV.11 Herschel Before Launch

In 2008, the European Space Agency (Esa) will launch the Herschel Space Observatory. The 3.5 m telescope will be operated about 1.5 million kilometers away from the Earth and perform observations in the far-infrared and submillimeter range. The MPIA is engaged in the development of Herschel's Pacs instrument, a camera and spectrometer for wavelengths from 60 to 210 µm.

One Rocket – Two Observatories

When Esa's two pioneering deep space observatories Planck and Herschel lift off from French Guyana aboard a single Ariane-5 rocket (Fig. IV.11.1) in autumn 2008, both satellites will be targeting the far-infrared and (sub)millimetre range of the electromagnetic spectrum that is blocked from reaching Earth by our atmosphere. The two vehicles will separate shortly after launch and proceed independently to different orbits about the second Lagrange point of the Earth-Sun system (L2).

While Planck will map anisotropies of the Cosmic Microwave Background – the remnants of the radiation that filled the Universe immediately after the Big Bang some 14 billion years ago – with improved sensitivity and angular resolution, the Herschel satellite is designed to explore the "cool Universe" during its nominal 3.5 year mission lifetime.

A significant fraction of the Universe consists of gas and dust that is far too cold to radiate in visible light or at even shorter wavelengths. Such cold material is associated with the earliest evolutionary stages of galaxies, stars in formation, circumstellar disks that may form planets, and the atmospheres of comets packed with complex organic molecules. The continuum emission from such dust enshrouded objects peaks in the Herschel wavelength range, and gases with temperatures between 10 and a few hundred K emit their brightest molecular and atomic emission lines here. In addition, the optical extinction of dust in such sources can be extremely large. At far infrared and sub-mm wavelengths, where the cold matter radiates most strongly, and in addition the extinction is much smaller, one can directly study the associated physical phenomena.

To achieve its scientific goals, Herschel is equipped with a 3.5 m mirror and marks the beginning of a new generation of "space giants". With its approximately 7.5 m height and 4.3 m width, this space telescope is bigger than any of its predecessors; its science payload consists of three instruments: Pacs and Spire are both cameras and spectrometers that will allow Herschel to take pictures in six different "colours" in the far-infrared, and Hifi is a spectrometer with extremely high resolution.

Previous space-based infrared telescopes have had neither the sensitivity and spatial resolution nor the ability of Herschel's three instruments to explore comprehensively this important part of the spectrum. HERSCHEL will bridge the gap between what can be observed with ground-based facilities and earlier space missions, such as ESA's Infrared Space Observatory (ISO) operating in the years 1995 – 1998 and NASA's ongoing SPITZER mission.

A Cryogenic Mission

In order to achieve the high sensitivity that is needed to measure the faint heat signatures of the "cold" part of the cosmos, the detectors on HERSCHEL are operated at very low and stable temperatures down to only a few tenths of a degree above the absolute zero point at – 273 ºC. The shared optical bench that carries all three instruments is contained within a large cryostat (Fig. IV.11.2) in order to maintain the low temperature. Some 2300 litres of liquid helium (at 1.7 K) will be used during the mission for primary cooling. To reach the very lowest temperatures, individual detectors are equipped with additional, specialised cooling systems.

The 3.5 m Mirror

HERSCHEL's 3.5 m primary mirror – made using a novel silicon carbide technology – is so large that it was built by joining twelve pieces together into one single piece. As can be seen in Fig. IV.11.1, the mirror diameter just fits into the nose cone of the ARIANE-5 rocket.

Because of its large size, the mirror is located outside the HERSCHEL cryostat. Protected by a fixed sunshade, the telescope will radiatively cool to an operational temperature in the vicinity of – 193 °C. Even under these frigid conditions the thermal radiation background from the telescope is large compared to the brightness of the observed astronomical sources. To extract their faint signals, sophisticated observing methods have to be implemented.

Location: L2

To provide the necessary cold and stable environment, HERSCHEL will be positioned at the second Lagrange point (commonly known as L2). There, 1.5 million km from Earth on the prolongation of the line Sun – Earth, the satellite will feel the joint attractive forces of Sun and Earth, and despite its larger distance to the Sun it will orbit the Sun with the same angular velocity as the Earth (Fig. IV.11.3). Consequently, the Sun, Earth and Moon as intense sources of both straylight and thermal modulation are always locked in the same region of the sky which greatly reduces their negative effects on the observatory. Therefore, during the whole mission, we will see HERSCHEL from Earth always in anti-solar direction, which offers stable radio links to Earth and unbroken observing time.

Although the point L2 is a solution of the three-body problem of celestial mechanics, HERSCHEL will not be stationed exactly at that point. There are at least three arguments against it: 1. L2 is a metastable point, that is, smallest perturbations will drive a satellite away from there (comparable to a pencil standing "stably" on a fingertip); 2. for stationing, braking maneuvers would have to be carried out directly at L2; 3. because the Earth lies in between, the satellite would experience solar eclipses, which would interrupt its energy supply.

Fig. IV.11.1: The nose cone of the ARIANE-5 launcher with the HERSCHEL (*top*) and PLANCK (*bottom*) observatories. Important parts of both spacecraft are identical, greatly reducing development costs. (ESA/AOES Medialab)

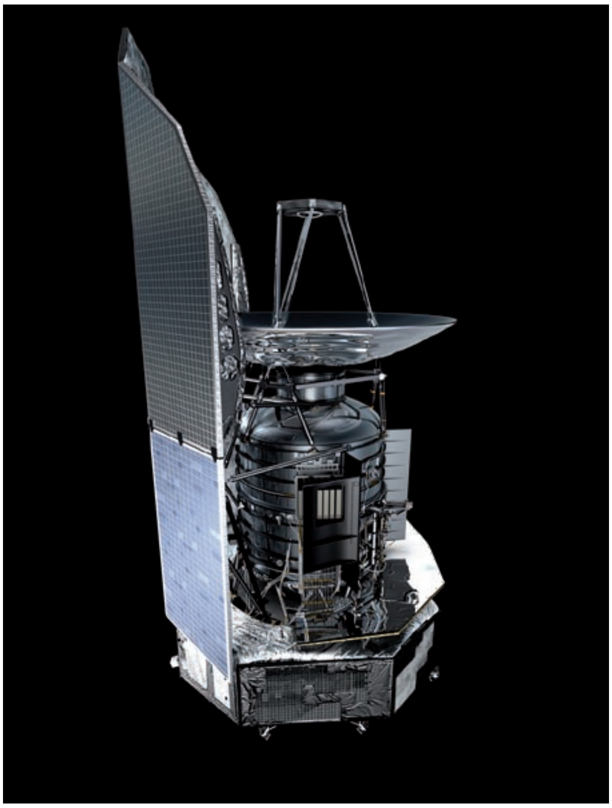


Fig. IV.11.2: The HERSCHEL spacecraft is 7.5 m high and 4 m × 4 m across, with a launch mass of 3.3 t. The Payload Module consists of the telescope and the cryostat. Inside the cryostat is the optical bench carrying the parts of the instruments that need to be cooled. A sun shield protects the telescope and cryostat from solar heating and prevents stray light from Earth entering the telescope; it also carries solar cells to generate the power for the spacecraft.

Therefore, loop-shaped Lissajous orbits around L2 are chosen in practice. The larger the diameter of these loops around L2, the easier the orbital maneuvers during closing-in and later orbit corrections. A limit is set, however, by the scattered-light requirements which limit the deviation from L2 as seen from Earth to some 30°. The HERSCHEL spacecraft will be placed in a large "halo" orbit around L2, with an amplitude of about 700 000 km and a period of approximately 178 days. The deviation from L2 as seen from Earth will be up to 30°.

The PACS Instrument

The Photoconducting Array Camera and Spectrometer (PACS) provides HERSCHEL with far-infrared imaging and spectroscopic capabilities in the range from 60 to 210 micrometers. It employs four detector arrays, two bolometer arrays and two Ge:Ga photoconductor arrays. The bolometer arrays are dedicated to photometry, while the photoconductor arrays are to be employed exclusively for spectroscopy. PACS can be operated either as an imaging photometer, or as an integral field line spectrometer. The MPIA is the largest co-investigator institute participating in the PACS instrument, which is being developed jointly by eleven European institutes under the leadership of MPE Garching.

A Chopper for PACS

To precisely measure the small signal of a cosmic source against the large thermal background signal of the warm HERSCHEL telescope, PACS employs a focal plane chopper. This device (Fig. IV.11.4) is a 30 mm "tipping" ("chopping") mirror comparing two neighbouring sections of the sky with a square-wave modulation with frequencies up to 10 Hz. By subtracting the background radiation, which is supposed to be identical in both fields, the brightness of the cosmic source can be extracted.

The chopper is one of MPIA's important contributions to PACS. After a successful prototyping phase at the institute, the company Carl Zeiss, Oberkochen, has been selected as industrial contractor for building the flight models of the chopper. With the delivery of the second flight unit, the contract between MPIA and Carl Zeiss successfully ended on April 25, 2006.

In order to test the chopper thoroughly, several models had to be manufactured: A lifetime model successfully passed 650 million chopper movements at an operating temperature of – 270 °C, and other models had to withstand strong vibration loads of up to 30 times Earth's gravity, simulating an ARIANE-5 launch, or had to survive seven cold-warm cycles (– 270 °C → + 300 °C → – 270 °C).

Although the first flight model delivered to MPE in Summer 2005 already met all of the demanding technical requirements, the final flight spare showed even better performance. Its electrical power dissipation could be reduced to one thousandth of a Watt – saving the supply of liquid helium aboard HERSCHEL and extending its lifetime. It was therefore decided to integrate this final model into the flight unit of the PACS instrument.

Flight spares are built to substitute flight models in the case of damage or other problems with the flight model, reducing launch delays and their enormous associated costs. Unfortunately, such an event became reality for the PACS chopper: On October 31, 2006 one of the flex pivots which suspend the chopper mirror along its rotation axis broke during the first cold test within the final ground calibration campaign of the PACS instrument.

A detailed investigation allowed us to identify the reason for this fatal accident: The chopper was highly overloaded by too large drive currents from the instrument electronics and their software control loop (which was not the responsibility of MPIA) which led to the mechanical destruction of the chopper. Finite element calculations confirmed that the observed break of one blade of the flex pivot happened exactly at the position where these electromechanical overloads predict them to occur.

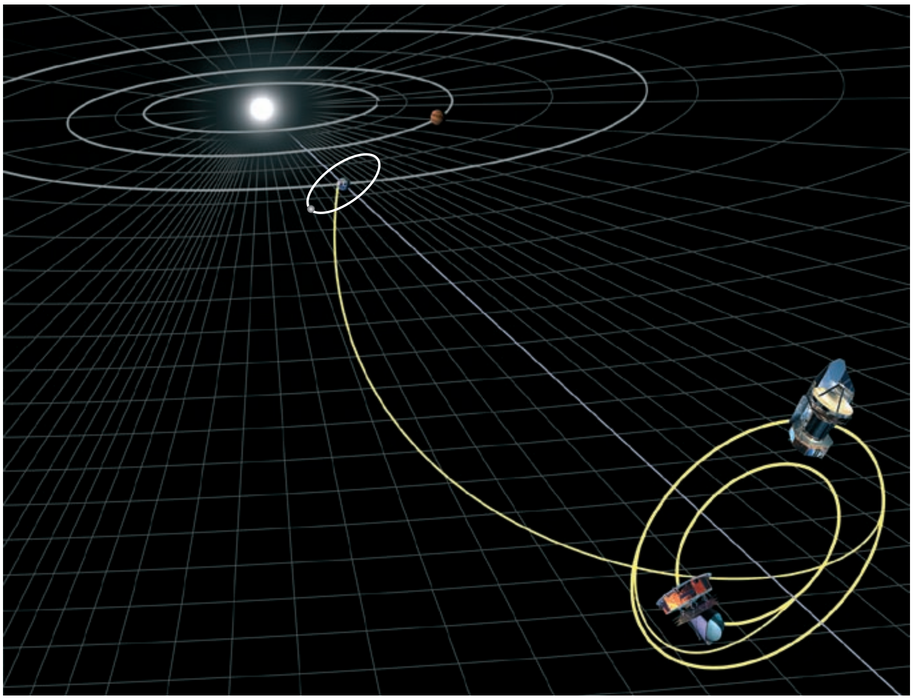


Fig. IV.11.3: HERSCHEL and PLANCK will orbit L2 in large Lissajous orbits at about 1.5 million km from Earth. The position opposite from the Sun, Earth and Moon provides stable thermal conditions and uninterrupted radio communications. (ESA/AOES Medialab)

Meanwhile, the original flight model of the chopper has been built into PACS and, with support of MPIA, precautions have been implemented to avoid damage to the only currently remaining model.

The Ge:Ga Detectors

The MPIA is also responsible for the characterization of the PACS far-infrared low stressed Gallium doped Germanium (Ge:Ga) detectors used in the integral field spectrometers of the PACS instrument (Fig. IV.11.5). The test facility allows simulation of the in-flight operational conditions of the arrays and provides accurate IR fluxes by means of external/internal black bodies and calibrated cold attenuation filters. During the year 2006 the complete characterizations of the 16×25 pixel Ge:Ga-cameras for the flight model and for the flight spare model were carried out.

Ideally the photodetectors generate a current proportional to the incident infrared flux. However, the continuous radiation environment at the L2 orbit generates additional charge carriers in the Ge:Ga crystals inducing changes in the properties of the detectors and the integrating read-out electronics, which have a significant influence on the performance of the detectors.

A major issue with Ge:Ga detectors used in previous space missions such as IRAS (1983), ISO (1995 – 1998) and SPITZER (ongoing since 2003) to explore the far-infrared sky has been tracking the responsivity drifts to maintain accurate calibration. For PACS, the goal is to determine the optimal operating parameters for the operation at the L2 orbit, the best curing method, curing frequency and calibration procedure in order to reach a high absolute photometric accuracy in the far infrared (~ 1 %).

In order to study the relevant effects (the radiation-induced changes in responsivity and noise, and the transient behaviour) on ground, a ^{137}Cs gamma-ray source is used to simulate the impact of the steady cosmic irradiation at L2 on the photoconductor arrays. Measurements without irradiation are highly reproducible. Experimental simulation of the radiation environment using a ^{137}Cs-source is a promising technique for studying the effects of ionizing radiation expected at L2.

In addition, detailed simulations of the impact of galactic cosmic rays onto PACS have been performed by modelling the photoconductors geometrically and applying a GEANT4 code. Complementary to long term gamma irradiation tests, proton tests have also been performed, simulating the proton flux expected at HERSCHEL's L2 orbit, including solar flare events.

Instrument Control Center

The work for the actual instrument is drawing to a close at MPIA, and the tests and development of the ground observatory are reaching the final stages. Scientists from Heidelberg were heavily involved in the cold tests of the PACS flight model at MPE in Garching. For these tests, procedures were designed and an extended data analysis

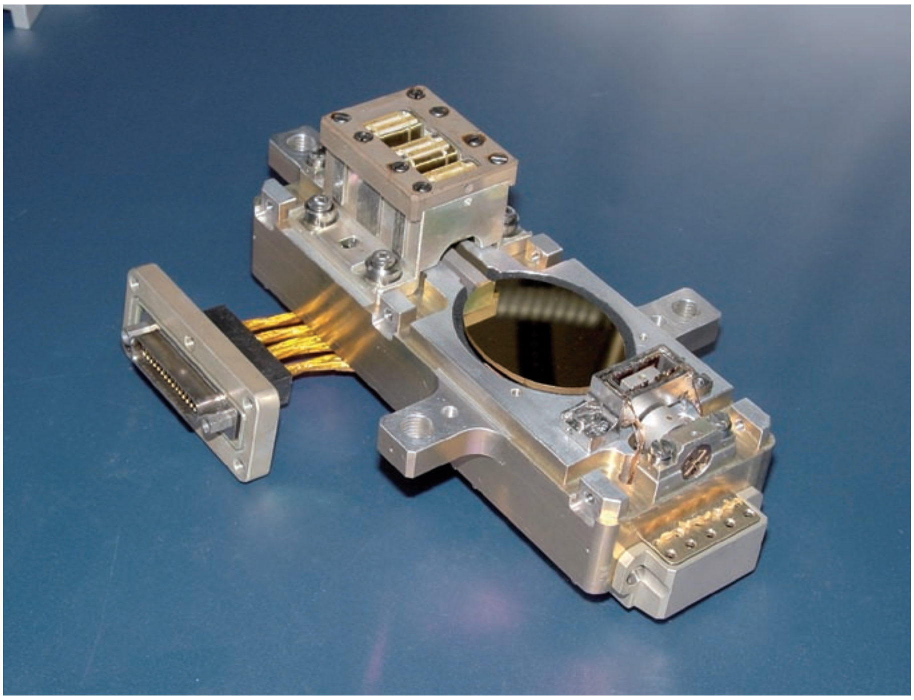


Fig. IV.11.4: Flight spare of the PACS focal plane chopper. The gold-plated mirror has a maximum diameter of 32 mm. To the left, one of the suspensions in a CuBe flexural pivot can be seen, and to the right, the three coil forms for the high-purity Al wires. Within the instrument, the chopper is housed inside an infrared-black enclosure with baffles, which have been removed for this image.

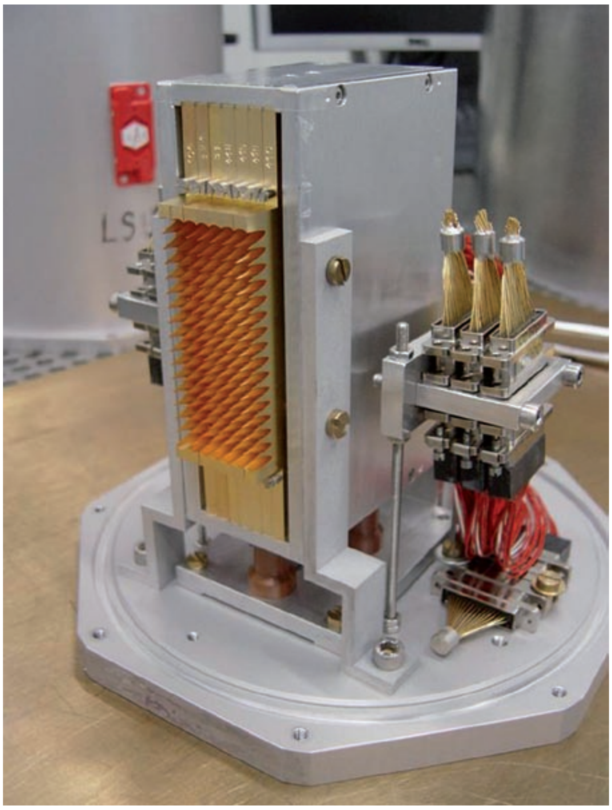


Fig. IV.11.5: Seven detector rows with 16 pixels each of a camera for the PACS spectrometer unit. The light funnels in front of the Ge:Ga pixels are visible.

was carried out. Naturally, the focus of the contributions from Heidelberg was on detectors, chopper, and calibration.

Moreover, MPIA is contributing to the design of the scientific observing templates for future users of the HERSCHEL Observatory and has taken on a leading role in the development of the interactive data analysis for PACS.

Two-thirds of HERSCHEL's observation time will be available to the worldwide scientific community, with the remaining time reserved for the spacecraft's science and instrument teams. For their contributions to the development of the PACS instrument, scientists at MPIA are granted 290 hours of guaranteed observing time with HERSCHEL. Most of the time will be included in two large high-priority key-projects: 1. quasars at high redshifts, and 2. early stages of star formation. Further shares in MPIA's guaranteed time will go into the participation in other key projects such as luminous galaxies, supernovae, and protoplanetary disks.

Oliver Krause, Dietrich Lemke, Stephan Birkmann, Helmut Dannerbauer, Ulrich Grözinger, Thomas Henning, Ralph Hofferbert, Ulrich Klaas, Jürgen Schreiber, Jutta Stegmaier, Manfred Stickel, Markus Nielbock, Jeroen Bouwman

IV.12 Instruments for the JWST

The James Webb Space Telescope (JWST) will be the successor to the already legendary HUBBLE Space Telescope. Following a warm launch in 2013, it will be operated for a lifetime of 5 – 10 years. It will be equipped with four scientific instruments. MPIA is responsible for the development of both grating wheels and the filter wheel for the mid-infrared instrument MIRI and contributes to the development of optical wheel mechanisms for the near-infrared spectrograph NIRSPEC.

More than 1000 people are currently engaged in the flagship mission JWST, the premier space observatory for the next decade which is jointly developed by the US, European and Canadian Space Agencies (NASA, ESA and CSA).

JWST has four main science themes: the end of the Dark Ages: first light and reionization, the assembly of galaxies, the birth of stars and protoplanetary systems, and finally planetary systems and the origins of life. These studies in the high-redshift, dust-enshrouded, and cool universe will be conducted in the infrared spectral region.

The 6.5-m primary mirror of the JWST will allow acquisition of infrared images that will be as sharp as those taken by the smaller HUBBLE mirror in the optical range. To avoid blinding of the sensitive cameras by its own thermal radiation, the primary mirror is cooled radiatively to – 230 °C. This passive cooling is possible at the Lagrangian Point L2 at 1.5 million km anti-solar distance from Earth. NASA is responsible for the JWST satellite which will be launched aboard an European ARIANE-5 rocket.

JWST is equipped with four scientific instruments. The near-infrared camera (NIRCAM) covers the wavelength range from 0.6 to 5 μm. The camera can image fields of 4.4 arcmin × 2.2 arcmin in several broad- and narrow-band filters and can be used as a coronagraph. At the same time it serves as a wavefront sensor for the observatory, measuring the alignment of the 18 mirror pieces of the 6.5 m primary mirror.

While NIRCAM is funded and built by the US, the near infared spectrograph NIRSPEC is developed by ESA and built by Astrium, Germany. NIRSPEC allows multi-object spectrosccopy of more than 100 objects within its field of 3 arcmin × 3 arcmin.

MIRI, a camera with coronagraph and spectrometer for the mid-infrared range (5 to 28 μm), is built by a consortium of 21 European institutes, with NASA providing detectors and the cryogenic cooler.

The forth instrument, the Fine Guidance Sensor (FGS) is provided by the Canadian Space Agency. The FGS contains a dedicated Guider and a Tunable Filter Camera, which allows narrow band imaging in the range from 1.6 to 4.9 μm.

Common to all focal-plane instruments is that they have to be operated in a cryo-vacuum. For NIRCAM and NIRSPEC a temperature of – 240 °C suffices. MIRI has to be cooled below – 260 °C so that its own thermal emission will not outshine the cosmic infrared radiation.

Another common property of the instruments is that all of them have large optical exchange wheels with numerous gratings, filters, beam splitters, mirrors, prisms and coronagraphic masks mounted on them. Although every space technician is anxious to avoid mechanisms like these wheels (... may fail ...), powerful scientific instruments without moving parts are not feasible.

Because of previous successful mechanisms developed for the European space telescopes ISO and HERSCHEL, our institute was well prepared for these high-risk challenges and the institute has been involved in the development of wheel mechanisms for MIRI and NIRSPEC since 2002.

All mechanisms are based on a ratchet principle (see Fig. IV.12.2) first flown aboard ISO: small ball bearings are mounted at the periphery of the wheel. Their number corresponds to the quantity of optical elements. A wedge-shaped element on a moving lever latches between two

Fig. IV.12.1: Structure Thermal Model (STM) of the MIRI instrument. The STM provided an early mechanical qualification of the Primary Structure, and is used to characterise gravity release and alignment repeatability from warm to cold (77 K) and to validate the thermal instrument model. The STM is later refurbished with additional mirrors and delivered to NASA for use during tests of the Integrated Science Instrument Module. (MIRI consortium)

ball bearings, thus locating the position of the wheel with a repeatability of ~ 1 arcsec. The central motor is a torque motor without a transmission. The exact position is carried out mechanically without electric power by the spring torsion of the ratchet system. This drive concept avoids feedback from an electrical position sensor and holding currents since positioning is always carried out mechanically with great reliability.

Within the European MIRI consortium the MPIA is responsible for the development of both grating wheels and the filter wheel. After a tendering procedure in 2005, the MPIA selected the offer by ZEISS for the building of the qualification and flight models.

Basis for the collaboration with ZEISS has been the experience gained at MPIA in developing and testing prototypes of the mechanisms. Extended cryogenic tests have been conducted on these development models, leading to significant improvements such as a new ratchet geometry and a more reliable position indicator. The critical central ball bearing successfully performed a lifetime test with more than 25 000 full rotations at a temperature of – 265 °C.

These development models will also be built into a verification model (VM) of the MIRI instrument. The VM is used to verify key aspects of instrument performance as well as integration and alignment sufficiently early to avoid major cost and scheduling problems in the event of detected problems requiring extensive FM modifications. It contains the flight optical design without optics channels fully populated, the DM mechanisms, and a complete Focal Plane System with flight-like detectors and software.

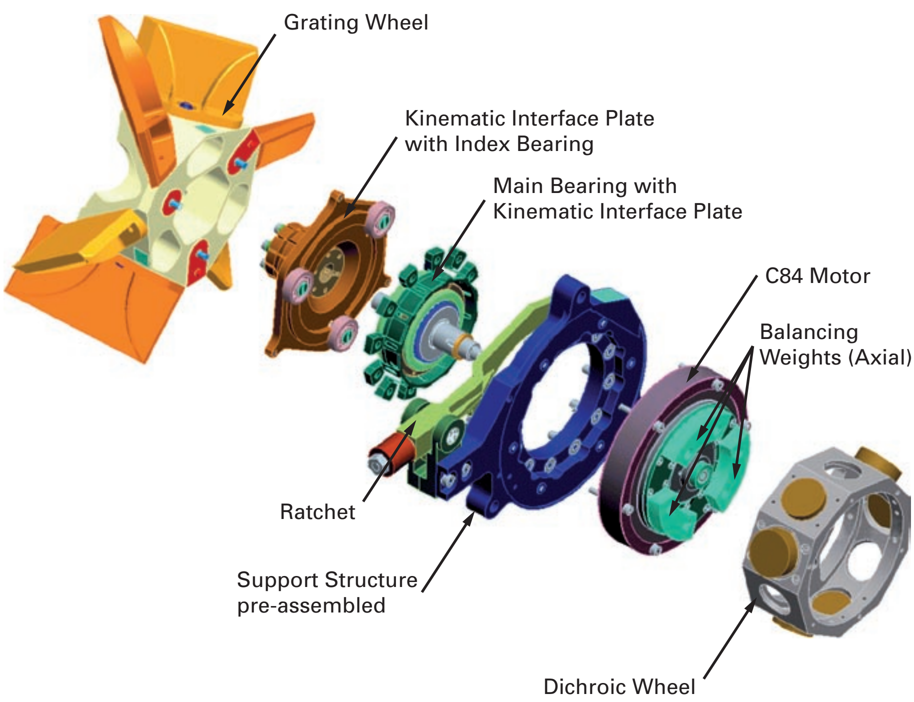
Following a test readiness review with participation of the MIRI-consortium, ESA, DLR and ZEISS at MPIA in August 2006, the two VM grating wheel mechanisms and the filter wheel mechanisms were fully tested and delivered to the consortium partners ATC, Edinburgh, and CEA, Saclay, in October and December 2006.

The MIRI wheel mechanisms successfully passed a series of subsystem Critical Design Reviews (CDR) in the reporting year. Several hundred technical items, which have been identified in the review process, were solved and led to an updated design of the flight and qualification models. This design was presented during the MIRI Optical System CDR on December 6 and 7.

MPIA is also participating in the development of the grating and filter wheels for NIRSPEC. Although the institute is also collaborating in this project with ZEISS, the roles here are reversed: MPIA contributes as a subcontractor to the development of the grating and filter wheels for NIRSPEC. In the consortium led by ZEISS, MPIA is responsible for the development of the electric components (motors, position sensors, harness). In the reporting year, the mechanisms successfully passed their subsystem Preliminary Design Review.

Progress has been made in the development of a two-dimensional tilt and position sensor system for the grating wheel, which is capable of measuring the grating orientation with a resolution of 0.3 arcsec. A breadboard

Fig. IV.12.2: Grating and dichroic wheel mechanism for the Mid-Infrared Instrument (MIRI). Two such mechanisms are employed in the spectrometer unit of MIRI. The wheel is moved by a central torque motor and positioned with a detent latching into the index bearings outer race. The mechanism has a diameter of 14 cm and a total mass of 1.6 kg (wheel mass 1 kg).



system consisting of moving permanent magnets and fixed magnetoresistive elements was implemented and succesfully tested in the cryo-vacuum.

Oliver Krause, Thomas Henning, Dietrich Lemke, Ulrich Grözinger, Ralph Hofferbert, Armin Huber, Sven Kuhlmann, Armin Böhm, Monica Ebert, Bernhard Grimm, Stefan Meister, José R. Ramos, Ralf-Rainer Rohloff, Alexandra Bohm, Hannelore Heißler, Friedrich Müller, Silvia Scheithauer, Christian Schwab, Thomas Blümchen

IV.13 – The GAIA Galactic Survey Mission

GAIA is Europe's flagship space mission in the next decade. It is an all sky astrometric and photometric survey complete to magnitude $G = 20$ ($V = 20 - 22$), observing some 10^9 stars, half a million quasars and a few million galaxies. GAIA will achieve an astrometric accuracy of 12 – 25 mas (microarcseconds) at $G = 15$ (providing a distance accuracy of 1 – 2 percent at a distance of 1 kpc) and 100 – 300 mas at $G = 20$. These numbers are also the approximate proper motion (tangential velocity) accuracy in mas/year.

The astrometry provides five dimensions of the six dimensional phase space (three spatial and three velocity coordinates). The sixth component is provided by the onboard radial velocity spectrograph. This gathers spectra at a resolution of 11 500 around the CaII triplet, providing a velocity precision of 1 – 15 km/s for all stars brighter than about $V = 17$. Astrometry and photometry are obtained using a broad ("white light") band (G). To characterize the sources (which are detected in real time), each is observed via low dispersion prism spectrophotometry over the range 330 – 1000 nm with a dispersion between 3 and 30 nm/pixel. In addition to permitting a broad classification, we will use these data

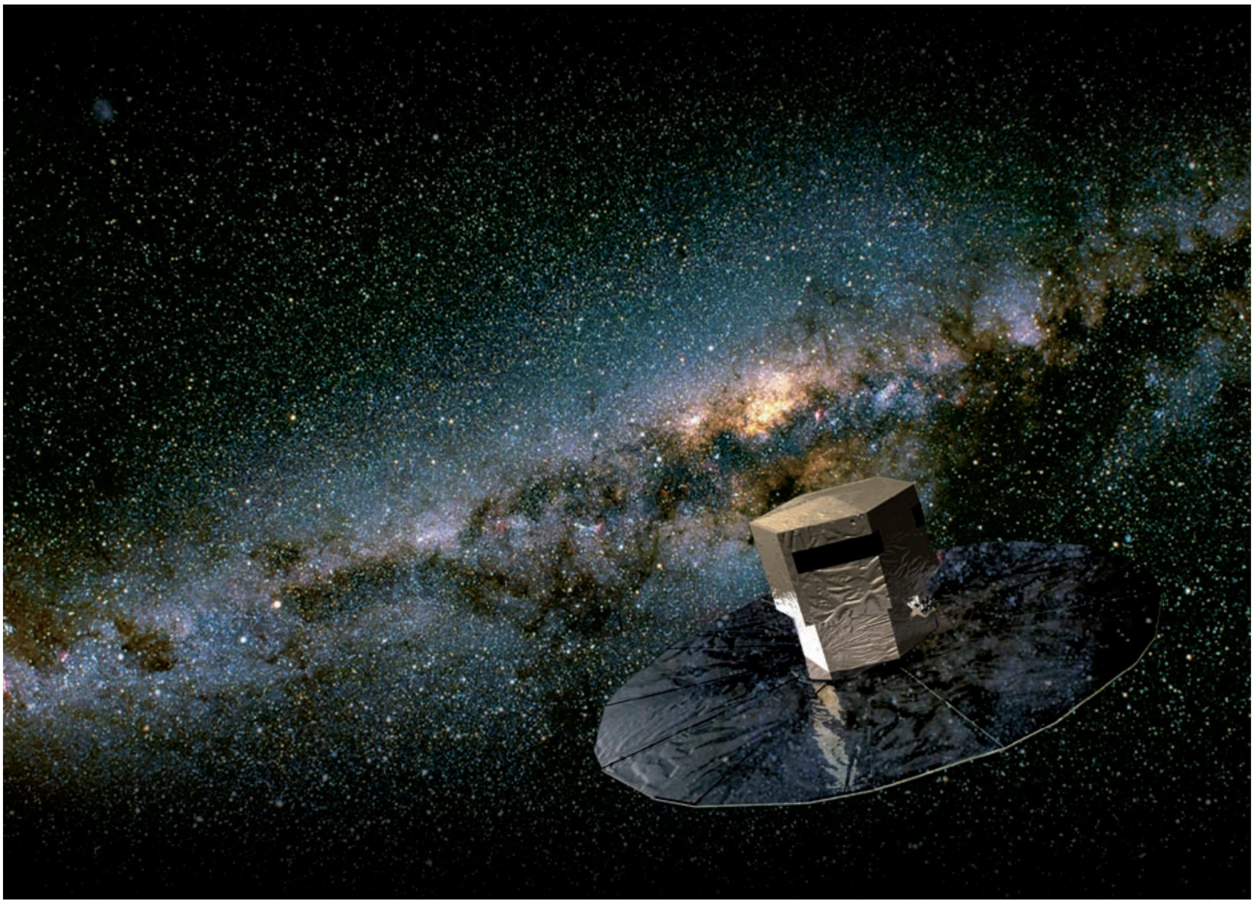


Fig. IV.13.1: When launched at the end of 2011, GAIA will undertake the largest and most accurate astrometric survey of the Galaxy ever attempted. It will observe over one billion stars with an astrometric accuracy of up to 10 microarcseconds and obtain high and low resolution optical and near-infrared spectroscopy of all sources. A DLR-funded team at the MPIA is leading the effort within the GAIA Data Processing and Analysis Consortium (DPAC) to physically characterize the stars, galaxies, quasars and asteroids which GAIA observes.

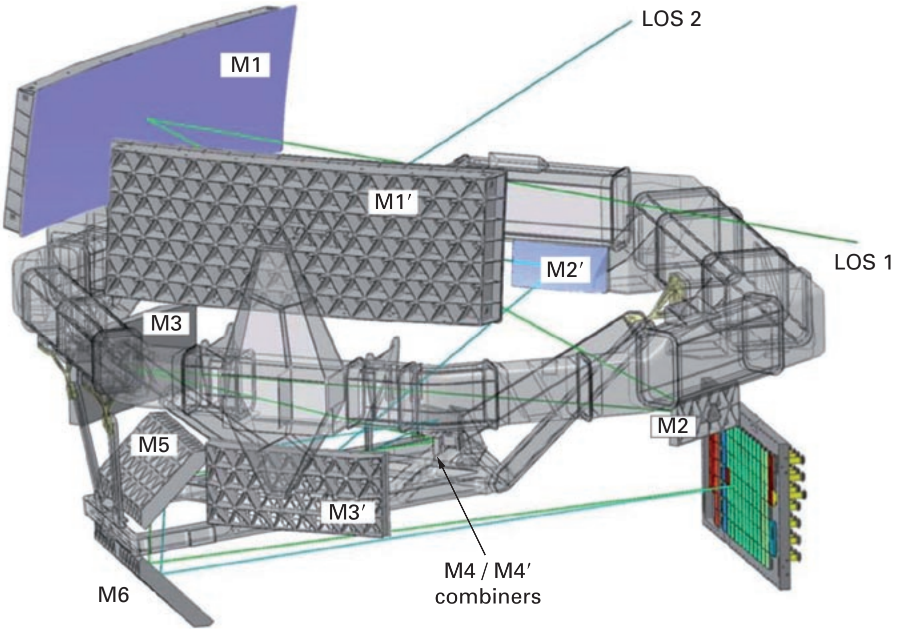


Fig. IV.13.2: The GAIA telescope. In order to construct a rigid and accurate astrometric reference frame, GAIA observes simultaneously in two viewing direction via the two primary mirrors M1 and M1'. Their light is combined (at M4/M4') and superimposed on a single focal plane. To achieve high accuracy, the payload must be extremely stable; thermal and mechanical perturbations must be reduced to extremely small values. (Graphic: EADS Astrium)

Fig. IV.13.3: Flat mirrors are used to fold the optical path to reduce the volume occupied by the instrument (to allow it to fit within the launcher fairing). The focal plane is split into three parts. Unfiltered light reaches the first part, the so-called "Astrometric Field" (AF). Very high signal-to-noise ratio images are collected here: the on-ground processing allows an accurate determination of the centroids – and thus the positions – of the stellar images. In the second part of the focal plane the light is dispersed by the two photometer prisms to deliver low resolution spectra, used for classification and physical parametrization. In the final part of the plane, light is reimaged by a grating spectrometer. This delivers high resolution spectra over a narrow wavelength range for determining radial velocities. (Graphic: EADS Astrium)

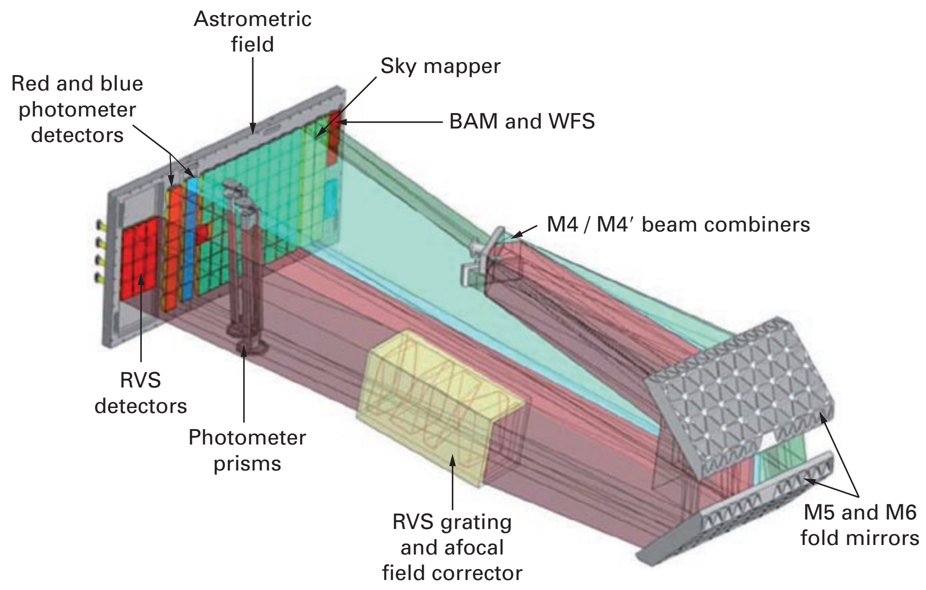


Fig. IV.13.4: The GAIA focal plane showing the CCD layout in more detail. The "AF" CCDs receive the undispersed light. BP and RP measure the dispersed light from the blue and red photometric prisms. The three columns of RVS (Radial Velocity Spectrograph) CCDs detect the high resolution spectra. GAIA continuously rotates such that each star transits the plane.

to estimate stellar astrophysical parameters including effective temperature, surface gravity, metallicity, alpha element abundance and the line-of-sight extinction to stars individually.

The impressive astrometric accuracy of GAIA is better illustrated when convolved with a model of the Galaxy. This shows that GAIA will yield distances with an accuracy of 1 percent or better for 11 million stars. This compares to fewer than 200 stars with have a parallax of this accuracy obtained from HIPPARCOS, all of which lie within 10 pc. Some 100 000 stars will have a distance accuracy better than 0.1 percent and about 150 million better than 10 percent. GAIA goes far beyond anything we currently have in both accuracy and statistics. Distance estimates are vital to almost every aspect of astrophysics because they provide determinations of intrinsic (rather than apparent) luminosities and convert angular scales and velocities to physical quantities. Furthermore, astrometry is the only way of obtaining distances without making assumptions about the source. GAIA will allow us to construct a six dimensional phase space map for hundreds of millions of stars in the Galaxy. Combined with measurements of the physical properties of all sources this will allow us to address a range of astronomical issues including the distribution of dark matter, the cosmic distance ladder, stellar structure and evolution, the stellar mass-luminosity relation, Near-Earth Objects, exoplanetary systems and General Relativity.

GAIA is a fully funded ESA mission due for launch in late 2011. With a nominal mission duration of five years and three years planned for post-mission processing, the final catalogue will be available in about 2020. It is the only large scale, high-accuracy astrometry mission under construction.

ESA is responsible for the construction, launch and operation of the satellite and its instruments. Unlike most missions, such as PLANCK, HERSCHEL and Mars Express, GAIA does not have any PI-instruments. This is because the "instruments" cannot be separated from the "telescope" in the conventional way that they are for, say, JWST. Instead, the scientific payload must be built as a single integrated whole to very high levels of accuracy and stability. The main task of the scientific community is the data processing.

GAIA is a self-calibrating instrument, meaning that an accurate astrometric calibration is obtained from the science data themselves via a massive global iterative solution of a few hundred million simultaneous equations. The accurate astrometry must be tied to a rigid and precise reference frame, stable at the level of a microarcsecond. To achieve this, GAIA continuously observes the sky in quasi-great circles. The 80 or so measurements of each individual object are then mixed up across time and position in the raw data. (The raw data will total 100 Terabytes (10^{14} bytes). The processing initially increases this to around 1 Petabyte (10^{15} bytes).

Partly for this reason, the GAIA data processing is considerably more complex than that involved in other missions or astronomical surveys. It includes many tasks beyond the global astrometric solution, including modelling the satellite's attitude, calibrating the 100 CCDs, calibrating the response and dispersion of the spectrographs, modelling and compensating for radiation damage, determining astrometric orbits for binary stars and exoplanets, and detecting and characterizing stellar variability, to mention just a few. The effort (and cost) necessary for the data processing alone is the equivalent to building several large instruments, and is a major part of the mission.

To address this challenge, the scientific community has set up the GAIA Data Processing and Analysis Consortium (DPAC) to process, analyse and publish all of the GAIA data, that is, to extract astrometric, photometric, spectroscopic and astrophysical parameters on well over one billion stars, galaxies, quasars and solar system objects. The DPAC is organized around nine "Coordination Units" (CUs), each of which is responsible for the development and operation of the data processing software and hardware.

One of these CUs, CU8 "Astrophysical Parameters", is lead by Coryn Bailer-Jones at the MPIA. CU8 is responsible for classifying everything which Gaia observes and for determining their intrinsic astrophysical parameters. The CU comprises about 60 scientists spread over 17 institutes in 8 countries, with a total full time equivalent of about 15 (to increase with time). Since the beginning of 2006, the MPIA hosts a DLR-funded group of three full-time scientists' positions (two of which are already filled) plus the group leader, responsible for the core aspects of CU8. This includes management of the CU, definition of the system architecture, development and maintenance of the data model, and in particular research into and development of machine learning algorithms to address some of the key classification tasks. The work is an interesting interdisciplinary challenge on the boundary between astronomy, computer science and statistical data analysis. The software is being developed in Java and the development takes advantage of standard tools (e.g. Eclipse, Subversion and Mantis) as well as machine learning algorithms such as Support Vector Machines. Software development takes place in six-monthly development cycles which permits the production of prototype algorithms which are successively improved.

Coryn A. L. Bailer-Jones,
Carola Tiede, Kester Smith

V People and Events

V.1 The Institute Adds Another Floor

On September 29th, the staff of the MPIA and prominent guests celebrated the addition of another floor to its main building. The completion of the new top floor now offers office space for nearly 50 more scientists and students.

During the past years, number and size of projects at the MPIA have grown rapidly. An increasing number of staff members, diploma and Ph.D. students from all over the world means finding room for all of them to work. This led to the first expansion of the main building, since it was built in 1975. In the last months before the expansion was completed, some staff members even had to be accommodated in temporary quarters in front of the main entrance.

In 1977, the institute's building had been awarded the Prize of the Association of German Architects. Hence, it became clear in early discussions with the Max Planck Society in 2004 that finding the right style for the addition to the existing building was mandatory. After the building permit was obtained, the first meeting to discuss the construction took place with architects, engineers and builders in November 2005. But by April 7, 2006 we were already able to celebrate the topping-out ceremony. An additional 47 desks in 19 new offices are now available to the MPIA after the completion of the construction measures. Another meeting room was also added, which was desperately needed. The complete building also underwent extensive, urgently needed improvements to the fire protection requirements during the building phase.

Opening Ceremony with Special Guests

The event began with a guided tour through the Institute for the guests. The opening celebration was part of the summer party at the MPIA. The newly elected Lord Mayor of Heidelberg, Eckart Würzner, was one of the prominent guests to visit the Königstuhl.

The party was an occasion for the management of the MPIA to thank all those who had made the construction possible. This included the Max Planck Society, the architects' company Hauss, Walla and Partners, the other companies and tradesmen involved, representatives of various authorities and the fire department. Last, but not least, the technical service crew of the MPIA were

Fig. V.1.1: Construction on the Institute grounds continued for several months, but it was worth the effort.

Fig. V.1.2: The addition to the building provides office space for nearly 50 staff members.

thanked for their unfailing assistance and all members of the staff for the patience they showed during the building phase.

Just a few days after the opening ceremony, the temporary quarters were removed and the situation in the over-filled offices could be relieved. But it also became obvious that the additional space will not be sufficient for long. Nevertheless, no matter how one looks at it, the new addition of another floor has significantly improved the work situation at the MPIA.

Klaus Jäger

Fig. V.1.3: The President of the Max Planck Society, Peter Gruss (*2nd from left*) inspects the construction and enjoys the exceptional view from the roof of the MPIA. He was accompanied by Director Hans-Walter Rix, Scientific Coordinator Klaus Jäger and the Head of Administration, Mathias Voss.

Fig. V.1.4: Heidelberg's new Lord Mayor, Eckart Würzner, was very interested in the research being done at the MPIA. Here Oliver Krause (*left*) demonstrates how a filter wheel, designed for space, works.

V.2 New Junior Research Groups at the Institute

In recent years, our Institute has grown rapidly. Here we briefly present four new junior research groups.

Eric Bell: Massive Galaxy Evolution.

With its Emmy Noether Program, the German Research Foundation (DFG) supports young scientists, offering them the opportunity to establish their own junior research groups. In 2004 and 2005 three such groups were established at the MPIA, led by Sebastian Wolf (Protoplanetary Disks), Coryn Bailer-Jones (Formation and Properties of Sub-stellar Objects), and Henrik Beuther (Massive Star Formation). In 2006, a fourth junior research group was established at the MPIA, led by Eric Bell.

Eric Bell studied physics and astronomy at the University of Glasgow and received his PhD from the University of Durham, in the UK. Subsequently, he worked as a postdoctoral research assistant at the University of Arizona. He came to the MPIA in 2002, funded by the European Union Research Training Network "Spectroscopic and Imaging Surveys for Cosmology".

Fig. V.2.1: Eric Bell

His research group at the MPIA studies the evolution of the massive galaxy population.

One of the most important research topics of the group will be to understand the role of galaxy mergers in driving the growth of the massive galaxy population. Galaxy formation models predict that mergers between massive galaxies are the main mechanism by which the most massive galaxies have grown in the last 8 billion years, since thew epoch of $z = 1$. Testing this prediction has proven challenging, owing to the rarity of galaxy mergers, difficulties in reliably identifying ongoing mergers, and an inability to robustly estimate the timescale over which one can identify galaxy mergers. Two PhD students, Rosalind Skelton and Aday Robaina, are working on state-of-the art observational surveys and theoretical models to resolve these challenges, providing an important test of current galaxy formation models.

Another focus of the research group is to explore the relationship between where stars form, and where they end up. This involves the refining and characterization of methods to estimate the stellar masses and star formation rates of galaxies from their multi-wavelength spectral energy distributions. These accurate measurements of mass and star formation rate can then be used to understand in which type of galaxy, and in which environments, stars form. These methods will be developed, tested and refined on large survey datasets, such as the Sloan Digital Sky Survey and the COMBO-17 survey. This effort involves a postdoc, Anna Gallazzi, and a PhD student to start in 2007.

Cornelis Dullemond: From Cosmic Dust to Planetary Building Blocks.

The great advances of infrared and (sub-)millimeter wave telescopes and instruments in recent years have opened a new window on research of planet formation. By studying the spectra and images of the protoplanetary disks surrounding many young stars it has become possible to find evidence of the very first steps of the planet formation process: the growth of from sub-micron-scale dust grains to centimeter-size aggregates and beyond. This has kindled renewed international interest into the question how these early stages of how planet formation take place, how these processes affect the later assembly of planets, and how they link to primitive material in our solar system such as asteroids and comets.

These questions involve a broad range of scientific disciplines, including astrochemistry, astromineralogy, the physics of aggregation and sticking (including laboratory

Fig. V.2.2: Cornelis Dullemond

collision experiments), the physics of the structure and evolution of protoplanetary disks and the physics of particle motion in turbulent media. So far, only moderate collaboration between these fields has taken place. The MPIA is involved in two efforts to improve this situation.

Firstly, in October 2006, the German Science Foundation (DFG) approved a Forschergruppe network, which aims to bring together scientists from all these disciplines in a closely knit collaborative effort to solve this problem from a broad perspective. The Forschergruppe is lead by Willy Kley from the University of Tübingen, Cornelis P. Dullemond from the MPIA and Mario Trieloff from the University of Heidelberg. In addition, it involves researchers from the Technical University of Braunschweig and the University of Münster. The MPIA is involved in two PhD projects. One is a collaboration between Hubert Klahr from MPIA and Willy Kley from Tübingen and aims to get a better understanding of the expected collision velocities between particles in a protoplanetary disk. The other one is a collaboration between Sebastian Wolf and Cornelis P. Dullemond and is charged with finding links between the Forschergruppe results and various observational aspects of protoplanetary disks.

Secondly, in December 2006 a new independent junior research group (Selbstständige Nachwuchsgruppen, SNWG) has been established at the MPIA, led by Cornelis P. Dullemond. This group is funded by the Max Planck Society under the SNWG program, which is to some degree a Max Planck equivalent to the DFG Emmy Noether program. Within the SNWG the Max Planck Society invites applications from outstanding young scientists in all fields of research pursued by the Max Planck Society. Successful applicants have demonstrated the ability to perform excellent research. They are offered an Independent Junior Research Group Leader position including a five-year grant (research positions, budget, investments) at a Max Planck Institute of their choice. It is the second such group at the MPIA, the first one having been led by Frank van den Bosch since 2005.

The new group will be primarily involved in the theoretical numerical modeling of the large-scale aggregation process itself. It intends to clarify what the observations of dust in protoplanetary disks, which can only probe grains with a size up to 1 cm, tell about the non-observable growth from 1 cm to macroscopic objects. It also aims to understand how the growth process can break the so-called meter-size barrier which is the size range in which aggregates tend to get easily destroyed in mutual high-speed collisions.

To do this modeling correctly it has to be based on realistic physical input parameters for which the group will rely on collaborations within the above mentioned Forschergruppe. These data include experimental results from aggregate collisions performed in the laboratories in Braunschweig and Münster, theoretical impact collisions performed in Tübingen, mineralogical data and models from the University of Heidelberg and data from computer simulations of turbulence at the MPIA.

Cristina Afonso: Search for Transiting Extrasolar Planets.

Cristina Afonso was awarded a W2 position for 5 years within the “Special Program for Excellent Young Women Researchers” of the Max-Planck Society. This program offers young women researchers the opportunity to establish their own research group.

Cristina Afonso studied Physics Engineering at the University of Lisbon, Portugal. After a Masters in Astrophysics & Astronomy at the Observatoire de Meudon, France, she obtained a PhD degree at the University of Paris VII. Her PhD was done at the Centre d’Énergie Nucleaire, Saclay, France, focusing on the “Detection of Microlensing events toward the Galactic Center”. Subsequently, she worked as a postdoctoral research assistant for two years at New Mexico State University, USA, and another year at Nasa Ames Research Center on a search program for extrasolar planets with the transit method. She then came to the MPIA in 2004 with a Humboldt fellowship to pursue her research in the domain of extrasolar planets.

The research group is currently being built and will be fully established mid 2007. The main task will be to work on the Pan-Planets project, a search for transiting

Fig. V.2.3: Cristina Afonso

Fig. V.2.4: Eva Schinnerer

extrasolar planets with a camera of 7 square degrees field of view mounted on the 1.8 m Pan-STARRS1 telescope, located at Lure Observatory on Haleakala on the Maui island in Hawaii.

In the last decade, the search for extrasolar planets has established itself as a major research field in Astronomy and promises to be one of the main science drivers for decades to come. Planetary transits yield many properties, namely mass and radius of the host star, along with the radius and inclination angle of the planet. The radius of planets can only be determined from transiting planets, representing the principal motivation and strength of the transit technique. A radius measurement is an important quantity, since it allows to constrain the evolutionary and migration history of the planet and to infer its composition and atmosphere through evolutionary models.

The Pan-Planets project is expected to find more than 100 Jupiter-like planets after 3.5 years of operation. This will certainly shed new light on the statistics and characteristics of extrasolar planetary systems.

Eva Schinnerer: Evolution of Galaxies from High Redshifts to Today.

Eva Schinnerer leads a second group within the "Special Program for Excellent Young Women Researchers" of the Max-Planck Society. She is dealing with a number of key studies related to the evolution of galaxies from high redshifts to the nearby galaxies using radio, millimeter and infrared observations. One of the main research topics, the fueling of galactic nuclei, was already described in the 2004 annual report (chapter III.4). Another major effort, the COSMOS project, will be presented in section III.4 of this 2006 annual report.

Eva Schinnerer obtained her PhD in 1999 at the Ludwig Maximilians University, Munich in the infrared/sub-mm group of Reinhard Genzel at the MPE. From 1999 – 2002 she was Post-doctoral scholar in the Owens Valley Radio Astronomy group at the California Institute of Technology, after that a Jansky Fellow of the National Radio Astronomy Observatory at the Array Operations Center in Socorro, New Mexico, until 2004. Subsequently she changed to the MPIA, where in 2005 she obtained a position from the "Special Program for Excellent Young Women Researchers" of the Max Planck Society.

The long wavelength range from the radio to the infrared is ideal to study processes related to star formation and active galactic nuclei. In particular, observations of the molecular gas kinematics are key to understanding how galactic centers (and their central massive objects, such as black holes or compact stellar clusters) are fueled and, thus, how nuclear activity might be able to occur. Millimetric interferometers, such as the PdBI and (in the future) ALMA, are used to observe the line emission of CO and other molecules to probe the molecular gas properties at highest angular and spectral resolution in nearby galaxies. These observations provide the necessary constraints for theoretical models of the gas dynamics in galaxies and its role in the secular evolution of galaxies, in particular the ongoing NUGA (Nuclei of Galaxies) project.

In order to understand how star formation and AGN activity is changing over time, it is necessary to study large samples of galaxies via look-back surveys, such as the Cosmic Evolution Survey (COSMOS; PI: Scoville). The ongoing pan-chromatic COSMOS survey has the unique advantage that complementary data from the X-ray to the radio regime already exists. The radio observations of the COSMOS field (PI: Schinnerer) were done at the VLA and provide a unbiased look at massive star forming galaxies and AGN without obscuration by dust.

Vernesa Smolcic (PhD student) has been deeply involved in the reduction and analysis of the VLA-COSMOS observations and is now focussing on the properties of the faint radio population which consists of massive star forming galaxies at intermediate redshifts as well as radio-loud AGN galaxies out to high redshift. Once all star forming galaxies have been identified, these will be used to estimate the dust-obscured cosmic star formation density, as radio emission is not affected by extinction. The post-docs Knud Jahnke and Alejo Martinez Sansigre are both working on the evolution of obscured and unobscured AGN using the COSMOS datasets.

Knud Jahnke is studying the properties of the host galaxies of type 1 quasars and their change over time to test whether black holes and galactic bulges co-evolve or not. Alejo Martinez Sansigre's main interest lies in the most obscured AGN at a redshift of $z \approx 2$. These enigmatic objetcs seem to be more abundant than previously expected and come in two flavours: one in which the obscuration of the central AGN is solely due to the orientation of the torus and one in which dusty material associated with massive star formation within the galactic disk is blocking our view onto the black hole.

The HI-NUGA project complements the study of the kinematics of the molecular gas in the central kiloparsec done by the NUGA project (annual report 2004, chapter III.4) by observations of the atomic HI gas in the outer disk. The PhD student Sebastian Haan is leading the analysis of the HI data obtained with the VLA. The aim of his PhD project is to study the gas transport from the outskirts to the very center in a sample of nearby active galaxies. Furthermore, it will include the modeling of the observed gas kinematics using N-body codes allowing, for the first time, a detailed comparison between data and dynamical models over several orders of spatial scales.

V.3 International Max Planck Research School Begins

Training young scientists is of elementary importance for the future of science, research and innovation in Germany. For this reason, in the year 2000 the Max Planck Society, together with the german Universities, set up a network of graduate schools. At the "International Max Planck Research Schools" (IMPRS) students with their first qualified degree but before receiving a doctorate have the opportunity to obtain structured scientific training combined with excellent possibilities for doing research.

The IMPRS for Astronomy and Cosmic Physics at the University of Heidelberg was founded in 2005 and has successfully completed its first "year of operation". As a mutual initiative by the MPIA, the departments of Astrophysics and Particle Physics of the MPI for Nuclear Physics and the three institutes of the Center for Astronomy at the University of Heidelberg (ZAH), it offers a wide range of modern research opportunities for PhD students from all over the world.

The MPIA is especially active in the following fields of research: Planet and star formation, extrasolar planets, substellar objects, development and dynamics of galaxies, active galactic nuclei, gravitational lensing, cosmology, structure formation, dark matter and the development of ground-based and space-supported astronomical instrumentation.

Together with the university, a structured, technical training program was introduced in English language consisting of basic and advanced lectures and the IMPRS seminar, complemented by soft skill courses for key qualifications such as presentation techniques.

The first round of applications in 2005 attracted as many as 17 PhD students to the IMPRS. In the second year, the number increased to 23, which was the original target to be achieved after three years as a long-term average. In the new round of applications for 2007, it seems that this successful tendency will continue: the number of applicants and, above all, the number of excellent candi-

Fig. V.3.1: The poster for the IMPRS Summer School.

dates has again increased. Fig. V.3.2. gives an overview of the number of applicants and their origins. The percentage of foreign students was 85 percent in 2006. One very positive aspect of the international recruitment of IMPRS PhD students is the high number of women; at almost 50 percent, this is extraordinary in Germany.

A highlight of the IMPRS year 2006 was the first Summer School – the first summer program in Heidelberg ever of its kind. The topic "Physics of the Interstellar Medium" was chosen by professors to attract PhD students working in this field. The School was organized by Christian Feldt and Thomas Henning, who was also one of the speakers. From abroad, two recognized experts with a high international reputation in their fields gave lectures – Leo Blitz from the University of California in Berkley and Robert Williams from the HUBBLE Space Telescope Science Institute in Baltimore. In addition to these main lectures, the Heidelberg colleagues presented their research activities in short "Science Talks".

From approximately 95 candidates for participation in the Summer School, roughly 55 from all over the world were selected to attend, as well as 25 students from Heidelberg. About 30 of the international students, particularly PhD students from South America or Eastern Europe, could only participate after applying for travel grants. However, there were also participants who came all the way from Japan or Australia – even without grants – which is further proof of the popularity of the project!

In addition to the academic program, there were also extensive extracurricular activities, where participants could get to know each other better and enjoy Heidelberg

Fig. V.3.2: The statistics on applicants from 2005 to 2007. The continents from which students come are marked in color. It is noteworthy that many applicants have already had quite international careers. A young man from India, for example, might have received his degree in the United States, whereas a Pakistani his in Sweden. The shortlist includes the best candidates for doing their PhD at the IMPRS. The number of applicants has also been broken down into male (m) and female (f).

IMPRS applications – statistics 2005-2007

Year	Nationalities	Europe/West	Europe/East	Asia	America/Latin	America/North	Arabia	Africa
2005	Applicants	Italy 14	Russia 4	India 6	Chile 3	Canada 3	Iran 2	Ethiopia 1
	82	Germany 11	Ukraine 3	China PR 4	Argentina 2	Mexico 2	Lebanon 1	
	55m, 27f	Greece 2	Poland 2	Korea 3	Pakistan 2	Hong Kong 1	Egypt 1	Turkey 1
New members 17		UK 2	Slovakia 2	Croatia 1	Malaysia 1	Philippines 1	Indonesia 1	Taiwan 1
		Austria 2	Portugal 1	Spain 1	Sweden 1			
	33 shortlisted	Germany 4						
	20m, 13f	Europe/W 10	Europe/E 6	Asia 6	America/L 4	America/N 3		
2006	Applicants	Italy 13	Bulgaria 2	India 12	Argentina 3	Canada 2	Iran 4	South Africa 2
	90	Germany 12	Romania 2	Taiwan 3	Chile 3	USA 1	Lebanon 1	Egypt 1
	56m, 34f	Spain 5	Ukraine 2	Pakistan 2	Brazil 1	Ecuador 1	Turkey 1	
New members 23		UK 3	Hungary 1	Korea 1	Bangladesh 1	Mexico 1	Peru 1	
		Austria 1	Poland 1	Russia 1	Indonesia 1	Thailand 1		
		Finland 1	France 1	Ireland 1	Czech Rep. 1			
	43 shortlisted	Germany 6						
	27m, 16f	Europe/W 12	Europe/E 4	Asia 12	America/L 5	America/N 2	Arabia 1	Africa 1
2007	Applicants	Germany 24	Hungary 3	India 9	Mexico 4	Canada 2	Iran 6	Algeria 2
	108	Italy 10	Russia 3	Taiwan 7	Chile 4	USA 1	Lebanon 1	Egypt 1
	60m, 48f	Italy-Chile 1	Turkey 2	China PR 4	(Chile-Italy 1)			
New members ??		Spain 5	Georgia 1	Indonesia 1	Columbia 2			
		France 3	Romania 1	Thailand 1				
		Greece 3	Portugal 3	UK 2	Austria 1	Cyprus 1	Denmark 1	Norway 1
	67 shortlisted	Germany 12						
	34m, 33f	Europe/W 22	Europe/E 5	Asia 13	America/L 8	America/N 2	Arabia 3	Africa 2

Fig. V.3.3: IMPRS students at the Neckarwiese.

and surroundings, such as: a visit to the MPIA laboratories with a guided tour and German beer and food to top it off; a boat trip along the Neckar River to Neckarsteinach, a tour of the Castle; and lastly, the final lecture in the historic Alte Aula (old auditorium) were events that combined both fun and culture (Fig. V.3.3.).

As the IMPRS Summer School is to take place every year, plans were made directly after the 2006 session for the next year – topic: The Milky Way.

Christian Fendt

V.4 Small Symposia on the Future of Astronomy and Cosmology

In which direction is astronomy developing? What will be the new topics for research? In order to deal with these questions more closely, the MPIA initiated a series of four mini-symposia, to which 21 prominent speakers were invited.

In the past two decades, hardly any other field of science has gone through as turbulent a development as astronomy. This is mainly due to the tremendous advancements made concerning instrumentation and the possibilities for observation throughout the complete electromagnetic spectrum. And the development continues. The planning for the Extremely Large Telescope (ELT) is making progress, and totally new possibilities are within reach through the LBT, Herschel, Planck, Gaia, JWST and Alma observatories. These facilities will provide many research fields with new momentum. The objective of the mini-symposia was to fathom out this potential.

In the symposium entitled *Extrasolar Planet Searches* given on October 11th, Michael Liu (from the University of Hawaii), Andrzej Udalski (University of Warsaw), Sara Seager (Carnegie Observatory) and Didier Queloz (University of Geneva) reported on the various methods of searching for extrasolar planets. Other topics of discussion were the very different types of planets that have already been found outside the solar system and those expected to be found in the future. Since the discovery of an extrasolar planet in the year 1995, more than 200 further planets have been identified, several of them even in planetary systems. Due to the extremely small angular distance of a planet to its parent star at an extreme difference in brightness between both objects, up to now all previously discovered extrasolar planets have been only indirectly identified, with the exception of a few controversial cases. Despite the technical advancements to be expected in the future, directly capturing an image of an extrasolar planet will remain a great challenge. Indirect methods, for example on the basis of transit observations or by exploiting the micro-lensing effect, will presumably become more important. The types of planets that have already been found are quite remarkable. The frequent discoveries made initially using the Doppler method showed primarily very massive, Jupiter-like planets with relatively tight orbits, i.e. at a short distance from the central star. These so-called "hot Jupiters" pose a mystery to scientists. In particular, the question was discussed as to how the existence of hot Jupiters is compatible with common theories of planet formation.

The discovery and the closer investigation of earth-like extrasolar planets is of increasing importance. Therefore, astrobiology is becoming increasingly significant. This became clear at the small symposium held on May 29th entitled *Highlights in Astrochemistry and Astrobiology*, in which Eric Herbst (Ohio State University), Ewine van Dishoeck (University of Leiden), Geoffrey Blake (Cal Tech), Anne Dutrey (Bordeaux observatory), Edwin Bergin (University of Michigan) and Jim Kasting (Penn State University) were guest lecturers. The search for planets similar to Earth brings into discussion the question of the probability of life outside our solar system and

Fig. V.4.1: Hans-Walter Rix welcomes the guests at one of the four symposia.

Fig. V.4.2: The audience listens attentively to one of the fascinating lectures.

its possible detection. However, this is only part of the complete field of work. Topics such as the formation of complex molecules in the interstellar medium, the composition of comets and meteorites, or the astrochemical composition and evolution of protoplanetary disks are also included and bring this field of research more and more into the foreground of scientific attention.

Without the formation of stars, there would be no planetary systems, and until we fully understand the mechanisms of star formation, many questions related to planets will remain unanswered. The title of the small symposium on July 10th, *Star Formation from Galactic to Cosmological Scales*, reveals that the investigation of star formation increasingly combines several fields once handled separately because of the spatial scales. Eva Grebel, (University of Basel), Tom Abel (KIPAC Stanford), Andrea Ferrara (SISSA), Volker Springel (MPA Garching), Daniela Calzetti (STScI) and Jay Gallagher (University of Wisconsin) explained how detailed studies of star formation and evolution in our Milky Way System and in various types of near galaxies can provide important clues for understanding the history of star formation in the entire Universe. These findings have to be taken into account within models of galaxy evolution as well, and thus have to be included in the current simulations of cosmological structures, some of which were shown in impressive presentations at the symposium.

A basic understanding of the processes in our own galaxy also includes the precise knowledge of its morphological structure and dynamics. Ever since the investigation of our Milky Way began, astronomers had to deal with one major problem: we are part of the Galaxy and therefore in a poor location for getting a general overview. Another issue is the interstellar dust blocking our view into certain areas of the Galaxy. At the mini- symposium *The Milky Way* on May 31st, Steve Majewski (University of Virginia), Amina Helmi (Kapteyn Astronomical Institute), Wyn Evans (Cambridge University), Rodrigo Ibata (Strasbourg Observatory), and Michael Perryman (ESTEC) reported on the progress achieved and expected in the area of the cartography of the Milky Way. The GAIA mission will open up a new approach here by enabling highly precise astrometry of approximately one billion stars. The investigation of our galaxy has already received new impulses in the past few years. The discovery of new satellite galaxies and tidal streams, which were created through the interactions between satellite galaxies and the Milky Way system, has decisively changed and extended our image of the dynamic processes occurring in the Galaxy. The observation of our next largest neighbor, the Andromeda galaxy (M 31), has long been used to learn more about our own stellar system; if the previous concepts prove true, these observations will increasingly show that M 31 really is in some sense a twin to our own galaxy.

The four small symposia made it quite clear that our knowledge – even in the classic, long-studied fields – has virtually exploded, and new research fields – like the search for exoplanets have found their way from speculation to real science. The MPIA would like to thank all speakers again for having made possible the four mini-symposia, in which many visitors from outside the Institute also participated.

Klaus Jäger

V.5 Conferences, Workshops, and Symposia

Apart from the Minisymposia, described in the preceding chapter, the MPIA organized a number of conferences, workshops and symposia within as well as outside the institute. In the following we describe two of these events in detail, a complete list follows at the end of this chapter.

Dwarf Galaxies as Astrophysical and Cosmological Probes

March 12 to 17, 2006, astronomers from all around the world met at Ringberg Castle to discuss an important class of galaxies, the dwarf galaxies (the most common type of galaxies in the universe). The meeting was organized by Fabian Walter (MPIA) and Alberto Bolatto (UC Berkeley) and sponsored by the MPIA and the Max Planck Society. Over 50 scientists attended the meeting from universities in North America, Europe and Australia.

The broad field of dwarf galaxies is rapidly evolving and the meeting brought together international experts (both observers and theoreticians) to discuss the latest scientific results. Dwarf galaxies provide unique opportunities to learn about several aspects of galaxy formation. A number of talks were presented to discuss the stellar content of the dwarf galaxies. Resolved stellar population studies of Local Group dwarf galaxies, for example, reveal their chemical enrichment and star formation history. Also debated at the workshop was the role of the interstellar medium, since nearby dwarf galaxies are ideal laboratories to investigate both how stars form out of gas in environments deficient in heavy elements as well as how, in turn, violent star formation shapes the ambient interstellar medium.

In a more cosmological context, studies of our own Galaxy and M 31 have revealed the ubiquitous presence of substructure, attributed to the recent incorporation of dwarf galaxies, which is suggestive of hierarchical build-up via mergers and accretion. At the same time, however, accounting for the numbers, internal structure, and properties of dwarf galaxies has been one of the thorniest problems for theories of galaxy formation based on Cold

Fig. V.5.1: The participants of the workshop on Dwarf Galaxies as Astrophysical and Cosmological Probes, in front of Ringberg Castle.

Dark Matter (as discussed in talks given by the theorists who attended the meeting).

In summary, truly remarkable progress has been made in recent years in the study of these faint systems using state-of-the-art telescopes such as Spitzer, HST, Chandra, and large ground-based observatories. Great progress has been made, as well, in extending the capabilities of numerical and semi-analytic simulation techniques in order to make detailed predictions of dwarf galaxy properties. Many new observational results were presented by the speakers and a number of important topics in dwarf galaxy research have been identified, to be tackled in the coming years.

One thing became more clear than ever at this meeting: it is necessary to understand the detailed physics at work in dwarf galaxies before one can attempt to understand bigger galaxies. Given the next generation of instrumentation and telescopes on the horizon there clearly is a bright future for these faint objects.

Fig. V.5.2: Social life and discussions during candle light dinner.

Transiting Extrasolar Planets

From September 25th through September 28th, 2006, an international workshop on transiting extrasolar planets took place at the MPIA. The workshop highlighted current research and future plans for this field, and the event was well attended, with 55 contributions from 99 delegates in 14 countries. During the workshop, we were lucky to hear of the discovery of two new planets using the transit method. Cristina Afonso and David Weldrake from the MPIA organized the workshop.

The search for extrasolar planets as a whole has established itself as a major research field in Astronomy in the last decade, and promises to be one of the main science drivers for decades to come. An important subset of this involves looking for transiting extrasolar planets, a field which is rapidly expanding with growing international interest and investment, as exemplified by the multinational audience who attended the workshop.

The search for transiting extrasolar planets is one of the youngest and most active areas of modern astrophysics. Many groups from many countries are involved in the development and use of instrumentation specifically designed to look for the periodic dimming of a star caused by an orbiting planet. The future is bright for the discovery of many new transiting planets, with increasing MPIA investment toward this end.

Planetary transits yield many properties, namely the true planetary mass (when coupled with radial velocity measurements), along with the radius and orbital inclination of the planet, as well as the mass and radius of the host star. The transit technique has come to fruition in recent years, with the detection of 14 Jupiter-mass extrasolar transiting planets in close-in orbits (< 0.05 AU). Transits provide the only method with which to calculate the radius of a planet, representing the principal motivation and strength of the transit technique. A radius measurement is an important quantity, since it allows to constrain the evolutionary and migration history of the planet and to infer its composition and atmosphere through evolutionary models.

The workshop was intended to address several topics related to transit astronomy, in order to offer a global overview of the status of the field, regarding observational strategies, methods to select transits, as well as detections and characterization of planets. Moreover, the workshop offered a discussion platform for new approaches, methodologies, and the issue of radial velocity follow-up observations for fainter host stars – an issue of increasing importance as more transit candidates are identified.

The difficulties of transit detection were addressed, presenting the methods currently available to produce exceedingly accurate brightness measurements of the stars, and removal of systematic trends or effects that are caused by the weather that change the quality of the data. A large discussion was held on how to differentiate planets from binary stars, a topic of great importance as more transit candidates are identified in current work. The statistics of transit detection were also highlighted, offering insight into the observational reasons behind why only 14 planets have been found to date.

Many current and future surveys were announced and their most recent results were presented at the workshop, including the Pan-planets project of which MPIA is involved. This, along with other ultra-wide-field deep surveys, will revolutionize transit detection in the next few years, with hundreds of new planets expected to be found. Many searches are underway targeting both specific star clusters and the general galactic field. We are currently at the tip of the transit iceberg.

Two new planets, Wasp-1 and Wasp-2, were announced during the workshop, and subsequently had their radii accurately measured less than a day later, with live transit observations appearing during one of the contributions – to the amazement of the audience!

Both the observation and theory of known transiting planets were also well represented, with talks addressing the internal structure and atmospheres of the planets, including a new and impressive observation of the secondary eclipse of a transiting planet, when it disappears behind the star, revealed for the first time by the space telescope SPITZER.

The workshop was a vital forum for presenting the current status of global transit astronomy, and served as a trigger for lengthy discussions among delegates for future collaborations and ideas. As a direct result of this workshop it was decided to hold regular meetings around the world for the community to keep up to date on this rapidly expanding and evolving field of astrophysics.

Table. V.5.1: All conferences, workshops etc. organized by the MPIA

Title	Location	Date
3rd MPIA Student Workshop	Brixlegg, Österreich	February 18 – 22
Planet Formation and Evolution Studies: Various Approaches – One Goal	MPIA	March 1 – 3
Dwarf Galaxies as Astrophysical and Cosmological Probes	Schloss Ringberg	March 12 – 17
"Carbon in Space"	Villa Vigoni, Como	May 22 – 25
Highlights in Astrochemistry and Astrobiology	MPIA	May 29
The Milky Way	MPIA	May 31
Star Formation from Galactic to Cosmological Scales	MPIA	July 10
EPoS 2006 – The Early Phase of Star Formation	Schloss Ringberg	August 28 – September 1
From Dust to Planetesimals	Schloss Ringberg	September 11 – 15
Transiting Extrasolar Planets	MPIA	September 25 – 28
IMPRS Summer School "Physics of the Interstellar Medium"	Heidelberg	September 25 – 29
Extrasolar Planet Searches	MPIA	October 11
Planets Network Meeting "EU PLANETS: The Next Generation"	MPIA	October 26 – 27
The Formation of Low-Mass Protostars and Proto-Brown Dwarfs	Pasadena	November 7
GEMS/STAGES Collaboration Meeting	MPIA	November 29 – Dec. 1
9th MHD-Days 2006	MPIA	December 4 – 5

V.6 Highlights of Public and Educational Outreach

This year the MPIA again implemented many projects and activities designed at giving the public, especially pupils and students, an idea of the research being done at the Institute. Luckily, astronomy seems to appeal to many people. However two events exceeded even our expectations.

The activities at the MPIA concerning public outreach again included a wide variety of events in 2006. Whether it was a lecture held at a planetarium out of town, at clubs or other public events – or tours of our Institute (there were 36 guided tours with 840 visitors in 2006) for prominent delegations or visitors from schools, companies, institutes or universities – we always were rewarded with a pleasing response. Also included were special workshops for young girls at *Girls' Day* or BOGY (high school job orientation program), which fill the gap between classic public relations work and purely vocational training measures.

In addition to our own in-house magazine *Sterne und Weltraum* (Stars and Space), the press releases and the annual report also successfully contributed to attracting attention to the Institute through various media, reaching a variety of target groups. In 2006 the leaflet containing information on our Institute for visitors was updated and our website newly designed. At its meeting in September, the Board of Trustees was also very impressed with our outreach work and acknowledged that the Institute has a good concept for presenting itself to the public without neglecting its core duties.

In addition to these continuous activities for the press and publicity, the Max Planck Institute for Astronomy also participated in larger nationwide events and exhibitions and occasionally organized special activities such as open house. We will certainly long remember two of the events in the year 2006 – the *Long Night of the Museums* and our new public lecture series *Astronomy on Sunday Morning*.

Long Night of the Museums

"From our open house, we know that thousands of people have an avid interest in astronomy. In view of the diverse alternatives, I am still positively surprised that so many visitors did not shy the tiresome journey up the mountain. There was a time when we had to ask the organizers to interrupt the bus coming up here because we could not deal with the crowds." This somewhat sobering excerpt from an interview given by the organizer of the Long Night at MPIA in the Rhein-Neckar-Zeitung gives you just a vague impression of the dramatic events that went on during that night at the Königstuhl. The term "state of emergency" would be phrasing it more appropriately!

Fig. V.6.1: Girls' Day: Monica Ebert, our staff member from the engineering department, explains her work to the visibly enthusiastic participants.

Fig. V.6.2: The tasty results of the “Cold Show” experiments – cooking with liquid nitrogen – were also quite popular with the girls.

For years now, the annual Night of Museums has been staged in the Rhine-Neckar metropolitan area. On March 18th, 2006, more than 100 cultural institutions opened their doors in Heidelberg, Mannheim and Ludwigshafen – mainly museums, but also research institutes.

This year the MPIA featured a small program with films, lectures, guided tours at the telescope and several experiments. Together with the Astronomy School from the neighboring State Observatory Heidelberg, a special program just for children and adolescents was offered.

The event was to be hosted under the motto “Small but precious”. Because our open house had only been staged a few months before (with over 5000 visitors!), we tried to keep the expenses down – as we expected only few visitors due to the arduous journey up the mountain and the abundance of attractive alternatives. We were very wrong.

At 5 p.m. – one hour before the Night of Museums officially started – an endless line formed in front of

Fig. V.6.3: Several children draw pictures of their experiences at the Night of the Museums.

Fig. V.6.3: The MPIA was packed during the Long Night of the Museums.

our doors, and approximately two hours later we had to do something to stop the flow of visitors immediately. Every area open to the public in the Institute was filled to the brim with visitors. So we asked the organizers to stop bringing up any visitors, and the bus leaving every 10 minutes was only used to transport guests back down to the valley. The Heidelberger Bergbahn (funicular railway) also was asked not to bring any further guests up to the mountain. Lines had also formed at the station at the foot of the mountain.

The enthusiasm was overwhelming. The lecture hall was overcrowded until past midnight, so that we improvised and added additional lectures in a smaller lecture hall to the program to quench our visitors' thirst for knowledge. The visitors patiently waited long hours and risked missing out on other events of the Night of the Museums. Most of them stayed on the mountain far into the night. Even at three in the morning the visitors didn't mind waiting for a tour of the 70 cm telescope. "Then we'll just have to walk back down to Heidelberg," was the answer we received when we reminded visitors that the last bus to town was leaving.

All in all, there were 3000 to 4000 visitors on the Königstuhl that evening. Thanks to the great patience on the part of the guests, the professional assistance from the security guards hired for the event, and the unflagging loyalty of the small team of students and staff at the MPIA, the night was very successful despite the crowds, and there were no unpleasant incidents. To sum it all up: All of our staff were truly exhausted at the end of this long night, but very happy.

Astronomy on Sunday Morning

A while ago, some people at the MPIA had the idea of hosting a series of lectures for the public in which the scientists of the Institute could present topics from our research at the MPIA in the context of current astronomy in simple, generally understandable language. This series of lectures was to take place on Sunday mornings in the summer months, offering visitors an opportunity to listen to an interesting lecture and combine it with a mountain walk on the popular Königstuhl.

Because of the great interest on the part of the public during the Night of the Museums and at the open house in the fall of 2005, we thought it would make sense to restrict the number of visitors right from the start. It was arranged to sell a limited number of tickets at a location in downtown Heidelberg.

Doubts that the time and effort to reach the Königsstuhl at such an hour would not attract many people were dispelled right from the start. When Hans-Walter Rix opened the lectures series with his talk on black holes on June 11, it could already be anticipated that the entire series would also be a huge success. And so it was – the lecture hall was almost always filled with 100 or even more guests – even when the weather was poor and it didn't look as if people would want to go for a walk before or afterwards on Heidelberg's "home mountain". After eight lectures on planets, stars, galaxies, space-supported astronomy and possible life in the universe, the first run of the Sunday morning lectures came to a successful close. Because it was so popular, it will be repeated in the year 2007.

Klaus Jäger

V.7 Ernst Patzer Prize for Vernesa Smolcic and Catherine Heymans

The Ernst Patzer Prize for the promotion of young scientists receives its funds from the Ernst Patzer Foundation, which was founded by the widow of philosopher and art lover Ernst Patzer. This foundation was created to promote and support science and research, mainly in the field of astronomy. It awards grants to promising young scientists and researchers at the MPIA. Prizes are given to young scientists who have achieved the best refereed publications during their PhD studies and/or their post-doc phase at the MPIA. The nominations are appraised by a panel of experts specially appointed for this task made up of two scientists from the MPIA as well as an external scientist. The two laureates of the year 2006 each received € 2000.

Vernesa Smolcic studied in Zagreb, Croatia. In 2004 she came to the MPIA to do her PhD and is also a student at the International Max Planck Research School (IMPRS). She received the Patzer Prize for the best refereed publication of a doctorate student at the Institute in 2006. Within the framework of an international collaboration, Smolcic describes in her publication a "tadpole galaxy" discovered in the large COSMOS field. This galaxy, named CWAT-01, has two radio jets with lengths of 685 000 and 520 000 light years which arch off at an angle of 100°. Photographs taken with the HUBBLE Space Telescope show that this is an elliptic galaxy. Using hydrodynamic models, Smolcic and her co-workers found that the bent jets occurred because the galaxy moves at 300 to 550 km/s relative to intergalactic gas. For galaxies in relaxed clusters, this velocity is unusually high. Further studies in the x-ray range revealed that CWAT-01 belongs to a galaxy cluster that is colliding with another cluster before our very eyes. Moreover, not far away there are at least two more galaxy clusters. The entire group is part of an even larger structure. Astronomers will presumably witness how several small galaxy clusters fuse into a huge cluster that will turn out to have approximately one-fifth of the mass of the Coma galaxy cluster.

Catherine Heymans studied in Great Britain and received her doctorate from Oxford University. In 2003 she came to the MPIA as a post-doc, where she mainly worked in the GEMS (Galaxy Evolution from Morphology and Spectral Energy Distribution) project on the development of galaxies. Her main field of research, however, is devoted to the weak gravitational lensing effect which has developed over the past years into a new instrument for investigating dark matter. Catherine Heymans performed her award-winning work within the framework of the

Fig. V.7.1: Vernesa Smolcic

Fig. V.7.2: Catherine Heymans with her daughter Molly

Shear Testing Programme (STEP). This is an international project aimed at achieving an improved analysis of current and future sky surveys. To make this possible, a deep sky image was simulated on the computer as it would be seen through a ground-based telescope. Various methods for analyzing the inherently visible weak gravitational lensing effects were applied to this image and then compared with each other. Calibration uncertainties, which are a weakness of more or less all methods, became evident during this simulation. However, the first results show that it should be possible to relatively precisely (within a few percent) determine the distortions of the galaxy images caused by the weak gravitational lensing effect. Catherine Heymans is meanwhile continuing her research within the framework of the STEP project at the University of British Columbia in Canada.

V.8 The Center for Astronomy at the University of Heidelberg – New Perspectives for Research

An interview with Joachim Wambsganss, the managing Director of the Center for Astronomy of the University of Heidelberg, and Matthias Bartelmann, the Dean of the Department of Physics and Astronomy of the University of Heidelberg.

The Center for Astronomy of the University of Heidelberg (Zentrum für Astronomie der Universität Heidelberg, ZAH) was officially founded on January 1st, 2005. Three astronomical institutes with a total of approx. 150 employees combined their activities in this new institution: the Astronomisches Rechen-Institut, (ARI) and the Heidelberg-Königstuhl State Observatory (Landessternwarte Königstuhl, LSW), which had so far been directly controlled by the Ministry of Science, Research and Arts as state institutions, as well as the Institute of Theoretical Astrophysics of the University of Heidelberg (Institut für Theoretische Astrophysik, ITA). A decisive step had thus been completed to bundle Heidelberg's non-MPG astronomical research capacity, with the long-term goal of turning the ZAH into a competitive research institution. Through close cooperation between the ZAH and the Max Planck Institutes for Astronomy and for Nuclear Physics, astronomers from Heidelberg have attained a leading position in Germany. Astronomy "made in Heidelberg" has also gained ground by international standards. At the opening of the ZAH, Baden-Württemberg's Minister of Science, Peter Frankenberg, said, "At the University of Heidelberg, the potential is created for bundling the resources through a scientific point of crystallization and with the necessary critical mass up to the point that astronomic research in Heidelberg is able to maintain at a top position in Germany." The teaching and research activities of the ZAH are closely linked to the Department of Physics and Astronomy and the Heidelberg Max-Planck Institutes focused on astronomy. This cooperation, which is already well established based on a joint special research area (Sonderforschungsbereich), receives additional impetus from the Heidelberg-based International Max-Planck-Research School for Astronomy and Cosmic Physics (IMPRS).

Question: What initiated the idea born to unite the three astronomical institutes?

Joachim Wambsganss: The original idea dates back to the year 1997 when the state government commissioned an evaluation of all astronomical institutes in Baden-Württemberg. It became a current issue when we realized

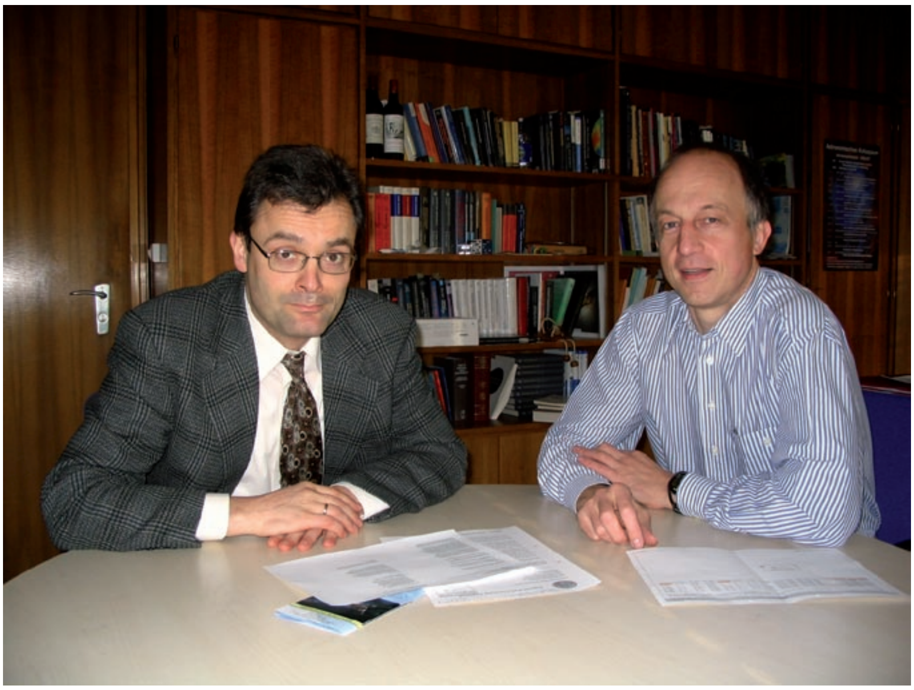


Fig. V.8.1: Believe in the positive approach of astronomical research in Heidelberg: Matthias Bartelmann, the Dean of the Department of Physics and Astronomy, and Joachim Wambsganss, the managing Director of the Center for Astronomy at the University of Heidelberg.

that both directors of the ARI, Prof. Roland Wielen, and of the LSW, Prof. Immo Appenzeller, would all be retiring almost at the same time, in the years 2004 and 2005, respectively. Even during the negotiations concerning my appointment as successor to Prof. Wielen, the potential combination of the institutes was an important issue.

At that time, were there any concrete plans for this unification?

JW: No, various models involving different levels of independence of the individual institutes were initially discussed. Then the ministry suggested combining all three institutes in a center that would then be integrated into the university.

What stance did you take on this proposal?

JW: To me, this made sense. In my opinion, it was important, however, that no jobs be lost from astronomical research. None of the three institutes should become the university's "job quarry". In addition, the department itself had first to be convinced of this concept. However, we managed to do that in several rounds of negotiations.

Is the ZAH completely integrated into the department?

JW: At the moment, the ZAH is directly controlled by the rectorate and does not belong to a department. However, all of the professors and researchers of the ZAH are members of the Department of Physics and Astronomy.

Matthias Bartelmann: The fact that the ZAH does not belong to a department gives us more freedom to move in some areas than we would otherwise have as part of a department.

Does this solution benefit all?

JW: I believe that everybody benefits from it – the three institutes as well as the department. Relatively small state institutes such as the former LSW and ARI are always at risk of being closed. Even in the course of the negotiations in 2004, I had said that the ZAH solution would be beneficial to all parties involved, practically a "win-win-win-win-win situation"; and today I am still convinced that this is the case.

Was the ZAH initially set up for a limited period of time?

JW: The agreement on targets made by the state and the university stipulates that there will be an evaluation after five years. Then, we will see whether or not the model is declared successful.

MB: I am not worried about this evaluation at all. Cooperation between astronomers from the former three institute has substantially improved, and we have received large research projects, such as the SFB/Transregio 33, "The dark universe". And we filed an application for an excellence cluster only recently. In addition, we received a graduate school for fundamental physics of which IMPRS is just one component. Although its coordination is the responsibility of the MPIA, however, this school was only made possible in cooperation with the university, i.e. with the ZAH and the department.

Let's return to the cooperation with the MPIA later. First I would like to ask you: What have the consequences of establishing the ZAH been so far?

JW: First, contacts between staff members have substantially improved. In the near future, the institutes will also move together physically in terms of buildings. It is planned that ITA, ARI and some sections of theoretical physics will be jointly accommodated in the building of the Institute of Physics, Philosophenweg 12. As soon as the Institute of Physics moves to a new building in the Neuenheimer Feld, some of the theoretical physicists and all of the astronomers – with the exception of those from the LSW – will be united under the same roof. Then, we will have a single library and a single administration. After all, it does make a difference whether your colleague is working 20 minutes away in another part of town or just two doors down the hall. And the LSW is located right next to the MPIA.

MB: We have also gained a lot of flexibility. In case of financial bottlenecks, we can help each other out much more easily, and make joint decisions on positions and especially concerning the appointment of professors. Formerly, this would not have been possible, or it would have been extremely difficult.

The size of the ZAH is probably also an advantage for attracting good people.

MB: Undoubtedly. We have many different fields of research within the ZAH. Although this was also the case before the ZAH was founded, we now decide jointly as to whom we want to appoint as professor. And for the new staff members, it is important to find many colleagues and many opportunities for exchange at the ZAH. We have just appointed two new professors we were absolutely keen on having join us. They probably would not have come to one of the small institutes we had before. We have exceeded the critical mass! That is a very important point.

JW: Two new professor's positions could not have been created without a reallocation of other positions when the ARI and the LSW were integrated into the university. In this way, we now have seven full professorships for

Fig. V.8.2: The ZAH logo.

astronomy at the ZAH. This is the highest number at any university in Germany.

MB: The critical mass is a very important point. For example, as an ITA staff member, I am working on the Planck satellite project, whereas the ARI is strongly involved in Gaia, and LSW in the LBT. Now, we can claim that the ZAH has a stake in Planck, Gaia and LBT. This has suddenly added to the weight and visibility of the University of Heidelberg both nationally and internationally. And our opportunities have substantially improved, for example, to receive an Emmy Noether Independent Junior Research Group. This is a very important DFG promotion program for young researchers.

JW: In addition to these tangible, quantitative aspects, I have also identified a very positive personal experience. Spirits are very high, people get along very well, discussing openly and pulling together. To me, one of the most important aspects at the ZAH is the fact that it offers a pleasant scientific atmosphere. I believe that this is a basic requirement for good joint research.

MB: And this is actually true for the entire department.

How did the physicists at the university respond to the foundation of the ZAH, what has changed?

MB: The physicists really welcomed the involvement of the ZAH astronomers in the life of the department. Myself, I am giving introductory lectures in theoretical physics because I really want to see all of the students, not only the seniors, attending lectures in astronomy. Now, astronomers also take part in colloquia on physics, supervise training groups, tutorials, etc. This was not the case before, and it signifies a clear enrichment for both sides, astronomers and the department.

JW: Some astronomers initially had to overcome their skepticism to participate in basic training for students of physics. But now, most of them are really enthusiastic about it.

MB: The physicists also believe that the expansion of astronomy in Heidelberg means a large benefit for the university. A survey among physics students has recently shown that one third started their academic education here because they were interested in cosmology, another third came to Heidelberg to study astrophysics, and the last third favored quantum physics. This shows quite clearly how important cosmology and astrophysics are to young physicists.

So, educating students and improving research are progressing well?

JW: Many things have improved. The conditions and opportunities over here are really good for students and postgraduates. However, the bottleneck is always encountered at the post-doc level. There are hardly any postdoc positions, and permanent positions are still much too rare. All of the young scientists working under third-party funding schemes are forced to continually apply for other positions, including positions abroad. As soon as they are accepted elsewhere, they are gone.

Would tenure track positions help?

JW: Naturally. To me, they are a kind of long-term position with a probationary period, which is converted to permanent in 80 to 90 per cent of all cases.

In parallel to the founding of the ZAH, the curriculum was also submitted to substantial changes.

MB: I strongly favored and achieved the introduction of a four-hour lecture on theoretical astrophysics. It will complement the previous introductory lecture to general astronomy. In addition, we have made sure that a set of lectures on astrophysics was developed on the basis of theoretical astrophysics. And finally, we had to adapt our curricula to the new bachelor/master system. For this purpose, physicists and astronomers had to sit down together to scrutinize the entire curriculum and decide: What is necessary, what is not? A very useful and sensible discussion. We took entire subjects totally apart and rebuilt them in new combinations. One result was, for example, that there will be a lecture on mathematics for physicists. Quite importantly, theoretical physics will be taught beginning with the first semester for bachelors-to-be, which will be done in connection with the mathematical methods required for this purpose. Anyone who wants to can go to astronomy lectures as a minor subject from the very beginning. And last but not least, the course of studies for future teachers will also change. All in all, this was a huge task, but I think that we have done a good job at the department.

Did the foundation of the ZAH also change the relationship between astronomers of the former three institutes on the one hand and researchers at MPIA on the other?

JW: I think, the relationship has been traditionally very good. The new, quite stimulating climate found at the ZAH also has its positive effects on cooperation with MPIA, though. The IMPRS is a great success which we have been able to achieve only through joint efforts. Besides, last summer we jointly worked out a preliminary application for an excellence cluster entitled "Heidelberg CASTLE – Cluster of ASTrophysicaL Excellence". This could only be done based on the broad astronomical research done here. The list of main applicants is divided approximately in half between members of the two MPIs in Heidelberg and the university.

MB: The graduate school for fundamental physics has been in operation since November 1st, 2006 with contributions from physicists and astronomers. Its term is limited to five years and it receives one million euro of funding per year from the excellence initiative. However, we are hoping to obtain subsequent financing. IMPRS is part of this graduate school. If our application for the excellence cluster is granted, we would receive 6.5 million euros for this program. Some 70 positions could be financed from this money. This would be a huge benefit for us. But still, one should bear in mind that the whole amount paid by the excellence initiative to the successful universities in Munich only just corresponds to the library budget of Harvard University.

JW: In this context, the recently approved DFG research group on "Planet formation" should also be mentioned. It is made up of the MPIA and Heidelberg University as well as institutes in Tübingen, Braunschweig and Münster. And we should not forget the DFG special research area 439, "Galaxies in the young universe".

Can you mention a number of concrete projects that represent the close cooperation between the MPIA and ZAH?

JW: In addition to the projects already mentioned, the future GAIA astrometry space mission is a good example. German project management is performed by the ARI, while the MPIA researchers are dealing with data evaluation issues and some other scientific aspects. The joint research work on the SDSS-SEGUE project can currently be considered a successful preliminary step for just such a collaboration. We already mentioned the LBT in which the state observatory and the MPIA are strongly involved. Then, there are some fields of research that are being dealt with on a cross-institutional level, such as the search for exoplanets with the microlensing effect and with transits, or the PanSTARRS-1 project performing repeated surveys of large parts of the sky with gigantic CCD cameras.

MB: It is quite obvious: the opportunities for interaction have clearly improved by integrating the three astronomical institutes under the roof of the university and through closer cooperation of staff members at the ZAH and within the department. At the same time, we have gained flexibility in the allocation of material funding and also in winning students, postgraduates, postdocs and professors. I am sure that this is the right approach. After two years of reorganization and substantial changes in the department, however, I am now hoping for a quieter period so that we can better concentrate on what we are actually supposed to be doing – research and teaching.

The questions were asked by
Thomas Bührke and Jakob Staude

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Interns: Brenner (until 28.2.), Eggert (until 28.2.), Feger (15.2. until 31.8.), Immer (17.7. until 31.10.), Jakob (until 31.8.), König (until 28.2.), Meschke (since 18.4.), Oberrauner (1.3. until 31.8.), Salonen (since 1.9.), Schrödel (since 1.9.), Stricker (1.3. until 31.8.)

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Department: Planet and Star Formation
Director: Thomas Henning

Infrared Space Astronomy: Oliver Krause / Dietrich Lemke, Stephan Birkmann, Thomas Blümchen, Jeroen Bouwman, Helmut Dannerbauer, Ulrich Grözinger, Martin Hennemann, Jörn Hinz, Ralph Hofferbert, Armin Huber, Ulrich Klaas, Ernest Krmpotic, Sven Kuhlmann, Friedrich Müller, Markus Nielbock, Silvia Scheithauer, Jürgen Schreiber, Christian Schwab, Jutta Stegmaier, Manfred Stickel

Star Formation: Thomas Henning, Aurora Aguilar Sicilia, David Butler, Andrés Carmona, Xuepeng Chen, Markus Feldt, Miwa Goto, Attila Juhasz, Ralf Launhardt, Rainer Lenzen, Hendrik Linz, Laszlo Mosoni, Yaroslav Pavlyuchenkov, Diethard Peter, Sascha Quanz, Thorsten Ratzka, Veronica Roccatagliata, Dmitri Semenov, Mark Swain, Robert Tubbs, Roy van Boekel, Antonin Vasyunin

Brown Dwarfs / Exoplanets: Reinhard Mundt, Cristina Afonso, Alessandro Berton, José Caballero, Wolfgang Brandner, Matilde Fernandez, Kerstin Geissler, Bertrand Goldmann, Markus Janson, Viki Joergens, Florian Rodler, Jens Rodmann, Victoria Rodriguez Ledesma, Johny Setiawan, David Weldrake

Theory (SP): Hubertus Klahr, Frithjof Brauer, Frank Dettenrieder, Cornelis Dullemond, Natalia Dziourkevitch, Ovidiu Furdiu, Patrick Glaschke, Anders Johansen, Rolf Kuiper, Stefan Umbreit

Laboratory Astrophysics: Friedrich Huisken, Marco Arold, Olivier Debieu, Cornelia Jäger, Gael Rouillé, Angela Staicu

Frontiers of Interferometry in Germany (FRINGE): Thomas Henning, Uwe Graser, Ralf Launhardt, Thorsten Ratzka, Jürgen Steinacker

AO Laboratory: Wolfgang Brandner, Alessandro Berton, David Butler, Fulvio De Bonis, Markus Feldt, Dimitrios Gouliermis, Stefan Hippler, Felix Hormuth, Micaela Stumpf

Emmy-Noether-Group I ("The Evolution of Circumstellar Discs to Planetary Systems"): Sebastian Wolf, Kacper Kornet, Alexander Schegerer

Emmy-Noether-Group II ("Properties and Formation of Substellarer Objects"): Coryn Bailer-Jones, Steve Boudreault, Paola Re Fiorentin

Emmy-Noether-Group III ("The Formation of Massive Stars"): Hendrik Beuther, Cassandra Fallscheer, Javier Rodon

MPG Junior Research Group: Cornelis Dullemond (in the process of organization)

Special Program for the Promotion of Excellent Female Scientists: Cristina Afonso (in the process of organization)

Department: Galaxies and Cosmology
Director: Hans-Walter Rix

Structure and Dynamics of Galaxies: Hans-Walter Rix, Josef Fried, Matthew Coleman, Jelte De Jong, Anna Pasquali, Nicolas Martin, Rainer Klement, Nadine NeuMayer, Domenico Tamburro, Sergey Koposov, Xiangxiang Xue; Coryn Bailer-Jones (GAIA Project Group), Johan Holmberg, Carola Tiede, Paola Re Fiorentin

Stellar Populations and Star Formation: Fabian Walter, Ioannis Bagetakos, Frank Bigiel, John Cannon, Kirsten Kraiberg Knudsen, Adam Leroy, Dominik Riechers, Hélène Roussel; Thomas Herbst (Head), Mayken Gustafsson, Lucas Labadie

Evolution of Galaxies and Cosmology: Eric Bell (Emmy Noether Group "Massive Galaxy Evolution"), Marco Barden, Isabel Franco, Dörte Mehlert, Xianzhong Zheng, Anna Gallazzi, Rosalind Skelton, Aday Robaina, Boris

Häussler; Klaus Meisenheimer, Hermann-Josef Röser, Hans Hippelein, Siegfried Falter, Irini Sakelliou, Kris Blindert, Isabel Franco, Hélène Nicol, Michael Zatloukal

Active Galactic Nuclei: Klaus Meisenheimer, Christian Fendt, Sebastian Jester, Almudena Prieto, Marc Schartmann, Konrad Tristram; Eva Schinnerer (Special Program for the Promotion of Excellent Female Scientists), Sebastian Haan, Knud Jahnke, Alejo Martinez Sansigre, Vernesa Smolcic

Theory – Formation of Galaxies and Large Scale Structure: Rachel Somerville, Fabio Fontanot, Akimi Fujita, Andrea Maccio, Christian Maulbetsch; Frank van den Bosch (Independent Junior Group), Marcello Cacciato, Xi Kang, Surhud More, Ramin Skibba

Instrumental Developments: Thomas Herbst, Hermann–Josef Röser, Josef Fried, Wolfgang Gässler, Sebastian Egner, Stefan Hanke, Lucas Labadie, Eva Meyer

Cooperation with Industrial Companies

4D electronic GmbH, Bretten
ABB (ehem. Hartmann+Braun), Alzenau
ADR, Paris
Advanced Office Deutschland GmbH, Bochum
Agilent Technologies, Böblingen
Almet–AMB, Mannheim
Alternate, Linden
Althen GmbH, Kelkheim/Ts.
America II OPE GmbH, Mönchengladbach
Amphenol–Tuchel Electronics, Heilbronn
Angst+Pfister, Mörfelden
APE Elektronik, Kuppenheim
Arthur Henninger, Karlsruhe
ASKnet AXSYS, Karlsruhe
Auer Paul GmbH, Mannheim
Axsys Technologies, Rochester Hills
bacuplast GmbH, Remscheid–Lüttringhausen
baier Digitaldruck, Heidelberg
Barth, Leimen
Bechtle, Neckarsulm
Bectronic GmbH, Derschen
Best Power Technology, Erlangen
Beta Layout, Arbergen
Beuth Verlag GmbH, Berlin
Bieri Engineering, Winterthur
Binder Elektronik GmbH, Sinsheim
Binder Magnete, Villingen–Schwenningen
Blässinger, Stuttgart
Bohnenstiel, Heidelberg
Böllhoff GmbH, Winnenden
Börsig, Neckarsulm
Bubenzer Bremsen, Kirchen–Wehrbach
Buerma Werner Machauer KG, Stuttgart
BueroMix, Mannheim
Bürklin OHG, München
Cancom, Bad Homburg
CAB, Karlsruhe
CAP, CNC+Coating Technik, Zell. a. H.
Cadillac–Plastic, Viernheim
CAM–Center GmbH, Nidderau
Carl Roth, Karlsruhe
Carl Zeiss, 3D Automation GmbH, Essingen bei Aalen
Carl Zeiss, Optronics GmbH, Oberkochen
Caspar Gleitlager GmbH, Flein
Cherry Mikroschalter, Auerbach
Christiani, Konstanz
C&K Components, Neuried b. München
Coating–Plast, Schriesheim
Com Pro, Stuttgart
Compumess Electronik, Unterschleissheim
ComputaCenter, Kerpen–Sindorf
Comtronic GmbH, Heiligkreuzsteinach
Conrad Electronic, Hirschau
Creasco GmbH, Gilching
Cryophysics, Darmstadt
Dannewitz, Linsengericht
DataTranslation GmbH, Bietigheim–Bissingen
db electronic Daniel Böck GmbH, Ehringshausen
Dell–Computer GmbH, Frankfurt
Delta–V, Wuppertal
Deltron Components GmbH, Nied b. München
Deti, Meckesheim
Dicronite UTE Pohl GmbH, Iserlohn
Digi–Key, Enschede
DMG–Service, Pfronten
DPV Elektronik, Eppingen
druckerDruck, Bietigheim
Dürkes & Obermayer, Heidelberg
Dyna Systems NCH, Mörfelden–Walldorf
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
EMS Elektrometall, Schwanenmühle
ERNI Electronics GmbH, Adelberg
eurodis Enatechnik, Quickborn
Europa–Lehrmittel Verlag, Haan–Gruiten
Eurostor, Filderstadt
EWF, Eppingen
Faber Industrietechnik GmbH, Mannheim
Farben Specht, Bammental
Farnell Electronic Services, Möglingen
Farnell InOne GmbH, Oberhaching
FCT Electronic, München
Fels Spedition, Heidelberg
Fisba, St. Gallen
Fischer Elektronik, Lüdenscheid
FPS–Werkzeugmaschinen GmbH, Otterfing
Frank GmbH International
Franke, Aalen
Fresemann Andreas, Dörpen
Fritz Faulhaber, Schönaich
Future Electronics Deutschland, Unterföhring
GAD GmbH, Dresden
Ganter, Walldorf
Garlock GmbH, Neuss

Geier Metall–u. Stahlhandel, MA
Genoma Normteile, Hameln
Gerwah Präzision GmbH, Grosswallstadt
GFI Elektro GmbH, Heidelberg
GLT, Pforzheim
Göttle, Königsbrunn
Goodfellow, Hamilton ON, Canada
Gould Nicolet Messtechnik, Dietzenbach
Grandpair, Heidelberg
Grulms–Pneumatik, Grünstadt
GRW, Würzburg
Gummi Körner, Eppelheim
Gummi–Plast Schild, Gernsheim
Gutekunst, Pfalzgrafenweiler
Häcker, Weinsberg
Häfele Leiterplattentechnik, Schriessheim
Hahn u. Kolb GmbH, Oberursel
Handelsvertretung Schaffland, Leverkusen
Heidenhain Dr. Johannes GmbH, Traunreut
Heinrich Wietholt GmbH, Velen
Helukabel, Hemmingen
Hema, Mannheim
Herose GmbH, Bad Oldeslohe
Herz, Leister Geräte, Neuwied
Hewlett–Packard Direkt, Böblingen
Hilger und Kern, Mannheim
Hilma–Römheld GmbH, Hilchenbach
HKi GmbH, Weinheim
HM Industrieservice, Waghäusel
Hommel–Hercules Werkzeughandel, Viernheim
Hormuth, Heidelberg
Horn, Stutensee
Horst Göbel, Ludwigshafen
Horst Pfau, Mannheim
HOT Electronic, Taufkirchen
HTF Elektro, Mannheim
Huber+Suhner GmbH, Taufkirchen
Hummer+Riess, Nürnberg
IBF Mikroelektronik, Oldenburg
IDS Innomic GmbH, Salzwedel
Jenaer Messtechnik GmbH, Jena
IFI Ingeni büro f. IC Techno, Wertheim
Infrared Labs, Tucson, USA
Inkos, Reute/Breisgau
Inotec electronics GmbH. Lauffen a. N.
Invent GmbH, Braunschweig
iSystem, Dachau
Jacobi Eloxal, Altlussheim
Jarmyn, Limburg
Joisten+Kettenbaum, Bergisch Gladbach
Kaiser+Kraft GmbH, Stuttgart
Kaufmann, Crailsheim
Kerb-Konus-Vertriebs-GmbH, Amberg
Kniel, Karlsruhe
Knürr, München
Kugler, Salem
Kurt Noor & Co, Viernheim
KVT Canespa, Langenhagen
Labelident GmbH, Schweinfurt
Laflow Reinraumtechnik GmbH, Blaubeuren
Lambda Electronics, Achern
Laser Components GmbH, Olching
Laser Vison, Fürth
Layher, Güglingen
Lemo Electronik, München
Leybold Vakuum GmbH, Köln
Lineartechnik Korb, Korb
LPKF CAD/CAM Systeme, Garbsen
LWS–Technik GmbH & Co, Heilbronn
Macrotron, München
Mädler, Stuttgart
Mankiewicz, Hamburg
MathWorks, Ismaning
Matsuo Electronics Europe, Eschborn
Matsushita Automation, Holzkirchen
Maxim Ges. f. elektronische integrierte Bausteine, Planegg
Menges electronic, Dortmund
Mentor, Erkrath
Metrofunkkabel–Union GmbH, Berlin
Mitsubishi–Electric, Weiterstadt
MGV Stromversorgung, München
Möller–Wedel Optical GmbH, Wedel
Mönninghoff, Bochum
Moll, Bleche und Verarbeitung, Hirschberg
MSC Vertriebs GmbH, Stutensee
MTI, Baden–Baden
MTS Systemtechnik GmbH, Mertingen
Munz, Lohmar
Nanotec, Finsing
Newport, Darmstadt
Nickel Schalt– und Messgeräte, Villingen–Schwenningen
Niedergesess, Sandhausen
Nies Elektronic GmbH, Frankfurt/M.
Noesse Datentechnik, Leverkusen
Noor, Viernheim
Nova Electronik, Pulheim
Oberhausen, Ketsch
OpenStorage, Wiesbaden
Optima Research, Detroit
Orglmeister Industriemesstechnik, Walluf
Otto Faber, Mannheim
Otto Ganter, Furtwangen
OWIS, Staufen
Parametric Technology, München
Parcom, CH–Flurlingen
pbe Electronic, Elmshorn
PCE Group oHG, Meschede
Pfeiffer Adolf GmbH, Mannheim
Pfeiffer Vakuum GmbH, Asslar
Pfister Büro, Leimen
Phonix Contact GmbH & Co, Blomberg
Physik Instrumente (PI) GmbH & Co. KG, Karlsruhe/Waldbronn
Polytec GmbH, Waldbronn
Phytec Messtechnik, Maynz
Phytron, Gröbenzell
PI, Karlsruhe
PINK Vakuumtechnik GmbH, Wertheim
Plastipol, Runkel
POG, Gera
ProCom, Eislingen
Prout Services+Handware GmbH, Darmstadt
PSI Tronix, Tulare, California, USA
PSC, Saarbrücken
Pühl A. GmbH, Plettenberg
Püschel Electronik, Mannheim
Radiall, Rödermark
RALA, Ludwigshafen
Räder Gangl, München
Rau–Messtechnik, Kelkheim
RED Regional Electronic Distribution, Rodgau–Jügesheim
Reeg, Wiesloch
Reichelt Elektronik, Sande
Reinhold Halbeck, Offenhausen
Reith, Mannheim
Retronic, Ronneburg
Rexim, Maulbronn
Riegler & Co. kG, Bad Urach
Riekert & Sprenger, Wertheim
Rittal GmbH+Co. KG, Herborn
Roland Häfele Leiterplattentechnik, Schriesheim
Roth Carl GmbH, Karlsruhe
RS Components GmbH, Mörfelden–Walldorf
RSP GmbH, Mannheim
Rudolf, Heidelberg
Rütgers, Mannheim
Rufenach Vertriebs–GmbH, Heidelberg
Rutronik, Ispringen
Sartorius, Ratingen
Sasco, Putzbrunn
Sauter–Cumulus GmbH, Freiburg

Scantec, Planegg
Schaffner Elektronik, Karlsruhe
Schlossmacher Ingenieurbüro, Unterschleissheim
Schrauben–Jäger AG
Schulz Bürozentrum GmbH, München
Schuricht, Fellbach–Schmiden
Schwab Holz–Zentrum, Hockenheim
Schweizer Elektroisolierungsstoffe, Mannheim
SCT Servo Control Technology, Taunusstein
SE Spezial–Electronic, Bückeburg
Seifert mtm Systems, Ennepetal
Siemens IC–Center, Mannheim
Sigmann Elektronik GmbH, Hüffenhardt
SolidLine AG, Walluf
Spaeter, Viernheim
Sphinx, Laudenbach
Spindler & Hoyer, Göttingen
Spoerle Electronic, Dreieich
Stahlschlüssel Wegst GmbH, Marbach
Straschu Leiterplatten, Oldenburg
Steinbach Ingenieurbüro, Jena
Suco–Scheuffele, Bietigheim–Bissingen
Synatron, Hallbergmoos
Tandler, Brauen
Tautz GmbH, Gladbeck
Team Arrow, Untereisesheim
Teldix GmbH, Heidelberg
Testo, Lenzkirch
THK, Düsseldorf
Thorlabs, Grünberg
ThyssenKrupp Schulte, GmbH, Düsseldorf
TMS Test– und Messsysteme, Herxheim/Hayna
TopCart, Erzhausen
Tower Electronic Components, Schriesheim
Transtec, Tübingen
Trivit AG, Ravensburg
TS–Optoelectronic, München
TWK–Elektronik, Karlsruhe
Vacuumschmelze, Hanau
VBE Baustoff+Eisen GmbH, Heidelberg
Vero Electronics, Bremen
Vision Engineering, Emmering
W. & W. Schenk, Maulbronn
Wamser Buero Service, Mannheim
Werner Curt GmbH & Co. KG, Heidelberg
Wika, Klingenberg
Wikotec, Bramsche
Wilhelm Gassert, Schriesheim
Witter GmbH, Heidelberg
WS CAD Electronik, Berk Kirchen
RS Components, Mörfelden–Walldorf
RSP–GmbH, Mannheim
Rudolf, Heidelberg
Rufenach Vertriebs–GmbH, Heidelberg
Rütgers, Mannheim
Sasco Holz, Dreieich
Sauter–Cumulus GmbH
Sartorius, Ratingen
Sasco, Putzbrunn
Scantec, Germering
Scantec, Planegg
Schaffner Elektronik, Karlsruhe
Schlossmacher Ingenieurbüro
Schrauben–Jäger AG
Schwab Holz–Zentrum
Schulz Bürozentrum GmbH
Schuricht, Fellbach–Schmiden
Schweizer Elektroisolierungsstoffe, Mannheim
SCT Servo Control Technology, Taunusstein
SE Spezial–Electronic, Bückeburg
Seifert mtm Systems, Ennepetal
Senior Berghöfer, Kassel
Siemens IC–Center, Mannheim
Sinus Elektronik, Untereisesheim
SolidLine AG
Spaeter, Viernheim
Spindler & Hoyer, Göttingen
Spoerle Electronic, Dreieich
Stahlschlüssel Wegst GmbH
Steinbach M. Ingenieurbüro
Straschu Leiterplatten, Oldenburg
Suco–Scheuffele, Bietigheim–Bissingen
Tafelmaier, Rosenheim
Tautz GmbH
Tandler, Brauen
Teldix GmbH
Telemeter Electronic, Donauwörth
THK, Düsseldorf
Thorlabs, Gruenberg
ThyssenKrupp Schulte
TMS Test– und Meßsysteme, Herxheim/Hayna
Tower Electronic Components, Schriesheim
Trivit AG
TS–Optoelectronic, München
TWK–Elektronik, Karlsruhe
Vacuumschmelze, Hanau
VBE Baustoff+Eisen, Heidelberg
Varian Deutschland GmbH, Darmstadt
Vereinigte Baustoff–und Eisen GmbH
Vero Electronics, Bremen
Vision Engineering, Emmering
W. & W. Schenk, Maulbronn
Werner Curt GmbH&Co. Heidelberg
Wietholt Heinrich GmbH
Wika, Klingenberg
Witter GmbH, Heidelberg
Wikotec, Bramsche WMM, Andechs
Wilhelm Gassert, Schriesheim
Witzenmann GmbH, Pforzheim
WS CAD Electronik, Berk Kirchen
Würth Elektronik GmbH & CO., Künzelsau
Yamaichi Electronics, München

Teaching Activities

Winter Term 2005/2006

C. Dullemond: The Formation of Stars and Planets (lecture)

Ch. Fendt: Introduction to Astronomy and Astrophysics I/II (IMPRS lecture)

Ch. Fendt, K. Meisenheimer, H.-W. Rix: Current Research Topics in Astrophysics (IMPRS seminar, with W. Duschl, ZAH)

J. Fried: Galaxies (lecture with tutorial, with B. Fuchs, ZAH)

H.-W. Rix: Introduction to Astronomy and Astrophysics I/II (IMPRS lecture with tutorial, with A. Just, R. Spurzem, ZAH)

H.-J. Röser, M. Stickel: Introduction to Astronomy and Astrophysics, III (seminar, with J. Wambsganss, ZAH)

S. Wolf, Th. Henning: Protoplanetary Disks (lecture)

Summer Term 2006

H. Beuther, Th. Henning: Star Formation (lecture)

Ch. Fendt, K. Meisenheimer: Current Research Topics in Astrophysics (IMPRS seminar, advanced seminar, with W. Duschl und J. Wambsganss, ZAH)

Th. Henning: Physics of Star Formation (advanced seminar)

K. Meisenheimer, R. Mundt, H.-J. Röser: Introduction to Astronomy and Astrophysics, III (seminar, with J. Krautter, ZAH)

H.-J. Röser, M. Stickel: Galaxies in the early Universe (advanced seminar)

Winter Term 2006/2007

H. Beuther, Ch. Fendt: Outflows and Jets: Theory and Observations (lecture, IMPRS)

Ch. Fendt, K. Meisenheimer, H.-W. Rix: Current Research Topics in Astrophysics (IMPRS seminar, advanced seminar with J. Wambsganss, ZAH)

J. Fried: Galaxies (lecture with tutorial, with B. Fuchs, ZAH)

Th. Henning: Substellar Objects – Extrasolar Planets and Brown Dwarfs (lecture, with B. Goldmann, ZAH)

Th. Henning: Physics of Star Formation (advanced seminar)

K. Meisenheimer: Sources of High Energy Radiation (advanced seminar, with M. Camenzind, S. Wagner, ZAH, and J. G. Kirk, MPIK)

H.-J. Röser: Introduction to Astronomy and Astrophysics, III (seminar, with J. Heidt, LSW und J. Wambsganss, ZAH)

Conferences, Scientific and Popular Talks

Conferences Organized

Conferences Organized at the Institute:

Third MPIA Student Workshop, Brixlegg, 18–22 February (Organization: S. Quanz, J. Stegmaier, M. B. Stumpf)

Workshop "Planet Formation and Evolution Studies: Various Approaches – One Goal", MPIA, 1–3 March (Organization: S. Wolf and M. Trieloff, University of Heidelberg)

Workshop "Dwarf Galaxies as Astrophysical and Cosmological Probes", Schloss Ringberg, 12–17 March (Organization: F. Walter, R. Somerville, J. Cannon, F. Biegiel und D. Riechers)

Workshop "Carbon in Space", Villa Vigoni, Loveno di Menaggio, Como, 22–25 May (Organization: F. Huisken, Th. Henning, and L. Colangeli)

Minisymposium "Highlights in Astrochemistry and Astrobiology", 29 May (Organisation: R. Gredel, Th. Henning, K. Jäger)

Minisymposium "The Milky Way", 31 May (Organization: H.-W. Rix, K. Jäger)

Minisymposium "Star Formation from Galactic to Cosmological Scales", 10 July (Organisation: R. Sommerville, K. Jäger)

Progress meeting LBTO/LINC–NIRVANA/LBT–SW MPIA, 24 July (Organisation: M. Kürster)

Workshop "The Early Phase of Star Formation", EPoS 2006, Schloss Schloss Ringberg, 28 August–1 September (Organization: J. Steinacker and A. Bacmann/Bordeaux)

Workshop "From Dust to Planetesimals", Schloss Ringberg, 11–15 September (Organization: C. Dullemond, H. Klahr)

Workshop "Transiting Extrasolar Planets", MPIA, 25–28 September, (Organization: C. Afonso, Th. Henning, David Weldrake)

IMPRS Summer School "Physics of the Interstellar Medium", Heidelberg, 25–29 September (Organization: Ch. Fendt, Th. Henning)

Minisymposium "Extrasolar Planet Searches", MPIA, October 11 (Organization: T. Herbst, K. Jäger, R. Launhardt, S. Wolf)

The 2nd PSF Workshop, Mont Sainte-Odile (France), 23–26 October (Organization: A. Carmona, D. Gouliermis, J. Setiawan, R. van Boekel)

LINC–NIRVANA Consortium Meeting, MPIA, 26 October (Organization: M. Kürster)

Planets Network Meeting "EU PLANETS: The Next Generation", MPIA, 26–27 October (Organization: H. Klahr)

Workshop "The Formation of Low-Mass Protostars and Proto–Brown Dwarfs", Pasadena, 7 November (organized by J. Steinacker, J. Eislöffel / TLS)

GEMS/STAGES Collaboration Meeting, MPIA, 29 November–1 December

9th MHD Days, MPIA, December 4–5 (Organization: N. Dziourkevitch, A. Johansen, H. Klahr)

2nd Meeting of the GAIA Data Processing and Analysis Consortium Coordination Unit 8 (Astrophysical Parameters), MPIA, 6–7 December (Chair: C. Bailer-Jones)

Other Conferences Organized:

C. Bailer-Jones: IAUnion General Assembly, Prague, August, Joint Discussion "Exploiting Large Surveys for Galactic Astronomy", Co-chair of the SOC; First Meeting of the GAIA Data Processing and Analysis Consortium Coordination Unit 8 (Astrophysical Parameters), Nizza, 16–17 March (Chair);

W. Gässler: "Adaptive Optics at the LBT – Upgrades and their Science Drivers", Florence, 30–31 October

R. Gredel: "Towards the European ELT", Marseille, 27 November–1 December (SOC Member)

Th. Henning: Conference "Electromagnetic and Light Scattering by Non–sperical Particles", St. Petersburg, 5–9 June

M. Kürster: LINC–NIRVANA Consortium Meeting, MPIfR, Bonn, 24–25 April

D. Lemke: SPIE – Astronomical Telescopes and Instrumentation: Optomechanical Technologies for Astronomy Orlando, Florida, USA, 24 – 31 May (Chair); Lunar Observatory Workshop, Bremen, 23–24 November (SOC Member)

H.-W. Rix: Lorentz Center Workshop "Dissecting the Milky Way", Leiden, 6–10 November (with A. Helmi/ Groningen)

E. Schinnerer: Workshop on "The LINC–NIRVANA Science Case", Bologna, 28 February

J. Steinacker: "The Formation of Low-Mass Protostars and Proto-Brown Dwarfs", Pasadena, 7 November

S. Wolf: Workshop "MATISSE Science Cases", Nizza, 27 March; Workshop of the Radiative Transfer Working Group of the European Interferometry Initiative, Paris, 22–23 June; MATISSE Science Team Workshop, Nizza, 17 November

Invited Lectures

C. Bailer-Jones: Zentrum für Astronomie, Universität Heidelberg, January (invited lecture); Armagh Observatory, Northern Ireland, May (invited lecture); Lorentz Center workshop "Dissecting the Milky Way", Leiden, November (invited lecture)

H. Beuther: "Complex Molecules in Space Present status and prospects with ALMA", Aarhus, 8–11 May (invited lecture); Max-Planck-Institute for Radioastronomy, Bonn, June 2006 (colloquium); IAU Symposium 237 "Triggered star formation in a turbulent ISM", Prague, August 14–18 (Invited review); EPoS 2006, "The early phase of star formation", Schloss Ringberg, Germany, 28 August – 1 September (invited lecture); ELBA 2006 "2nd European School on Jets from Young Stars: High Angular Resolution Observations", Marciana Marina, 4–8 September (invited review); Harvard–Smithsonian Center for Astrophysics, Cambridge, USA, November (colloquim); University of Gainsville, Florida, USA, November (colloquium); University of Heidelberg, December (colloquium)

H. Dannerbauer: ESO, Garching, 25 April (colloquium); Sterrewacht Leiden 21 November, (colloquium)

Ch. Fendt: "IMPRS Summer School: Physics of the interstellar medium", Heidelberg, 25–29 September (invited lecture)

R. Gredel: "Towards the European ELT", Marseille, 27 November – 1 December (invited lecture)

Th. Henning: ETH Zürich, 7 February (colloquium); University of Münster, 9 February, (colloquium); University of Basel, 14 February (colloquium); Observatoire de Strasbourg, 17 March (colloquium); Meeting "Interstellar Dust: from Fundamental Studies to Astrophysical Models", Les Houches, 1–5 May (invited lecture); Workshop "Carbon in Space", Lugano, 23–25 May (invited lecture); Nobel Symposium "Cosmic Chemistry and Molecular Astrophysics", Stockholm, 10–15 June (invited lecture); 69th Meteoritical Society Meeting, "Dust in Protoplanetary Disks", Zürich, 6–11 August (invited lecture); Summer School "Physics of the Interstellar Medium", Heidelberg, 25–29 September (invited lecture); Workshop "From Dust to Planetesimals", Schloss Ringberg, 11–15 September (invited lecture); Summer School "Physical Processes in Circumstellar Disks around Young Stars", Portugal, 18–23 September (invited lecture); ARENA–Meeting, Roscoff, 16–19 October (invited lecture); University of Düsseldorf, 14 December (colloquium)

F. Huisken: University of Regensburg, 30 January (colloquium); NASA Laboratory Astrophysics Workshop, Las Vegas, 14–16 February (invited lecture); European Workshop NanoLum IV, Tübingen, 15–16 May (invited lecture); International Workshop on *Carbon in Space*, Villa Vigoni, Loveno di Menaggio, Como, Italy, 22–25 May (invited lecture); Max Planck Institute for Nuclear Physics, Heidelberg, 14 June (invited lecture); Institut für Physikalische Hochtechnologien, Jena, 21 June (invited lecture); Workshop "Silicon-based dust in Space" of the DFG – Forschergruppe Laborastrophysik, Jena, 7 July (invited lecture); European Workshop NanoLum V, Troyes, France, 13–14 October (invited lecture)

C. Jäger: International Workshop on Carbon in Space, Villa Vigoni, Loveno di Menaggio, Como, 22–25 May (invited lecture)

S. Jester: Cambridge (GB), 2 February (colloquium); Portsmouth, 27 April (colloquium); Heidelberg, 5 May (colloquium); Conference "Challenges of Relativistic Jets", Cracow, 25 June – 1 July (invited lecture)

A. Johansen: University of Tübingen, February (colloquium); American Museum of Natural History, May (colloquium); Princeton University, June (colloquium);

U. Klaas: colloquium on Infrared Space Missions in the Far-Infrared and their Legacy to the Virtual Observatory, Konkoly Observatory, Budapest, May 11 (invited lecture); Helsinki Observatory, November 1 (colloquium);

ISO Legacy Colloqium, ESAC, Villafranca, Spain, 13 December (invited lecture)

H. Klahr: Jet Propulsion Laboratory, Pasadena, June (colloquium); American Museum of Natural History, July (colloquium); Workshop "From Dust to Planetesimals", Schloss Ringberg, 11–15 September (invited review); Queen Mary University, London (colloquium); University of Tokyo, December (colloquium); University of Kyoto, December (colloquium)

O. Krause: SPIE – Astronomical Telescopes and Instrumentation: Optomechanical Technologies for Astronomy, Orlando, Florida, USA, 24–31 May (invited lecture); AAS #208, 4 – 8 June (invited lecture)

R. Launhardt: TLS Tautenburg, December (invited lecture)

D. Lemke: colloquium on Infrared Space Missions in the Far–Infrared and their Legacy to the Virtual Observatory, Konkoly Observatory, Budapest, Hungary, 11 May (invited lecture); SPIE – Astronomical Telescopes and Instrumentation: Optomechanical Technologies for Astronomy, Orlando, Florida, 24 –31 May (invited lecture); Lunar Observatory Workshop, Bremen, 23–24 November (invited lecture); ISO Legacy Colloqium, ESAC, Villafranca, Spain, 13 December (invited lecture)

A. Pasquali: Strasbourg Observatory, 24 November (invited Seminar); GAIA CU5 meeting, Barcelona, 13–14 December (invited lecture)

Th. Ratzka: SPIE – Astronomical Telescopes and Instrumentation Conference 6268: "Advances in Stellar Interferometry", Orlando, Florida, 24–31 May (invited lecture)

P. Re Fiorentin: Osservatory Astronomico di Torino, 5 January (invited lecture); Santa Fe, New Mexico, 25 March (invited lecture)

H.-W. Rix: Winter 2006 Aspen Astrophysics Conference "Local Group Cosmology", Aspen/Colorado, 7 February (invited lecture); Tufts/CfA/MIT Cosmology Seminar, CfA Harvard, Cambridge, USA, 25 April (invited lecture); Physics colloquium MIT, Boston, 27 April (invited lecture); Ringberg – Symposium "Perspectives of Research", Schloss Ringberg, 3–5 May (invited lecture); MPIfR, Bonn, 12 May (invited lecture); IAC, Teneriffa, 16 May (invited lecture); Conference "Towards the European ELT", Marseille, 28 November (invited lecture)

H. Roussel: CEA/Saclay, France, spring (Seminar); Workshop "Dust and gas in ULIRGs: tracing star formation and black hole growth at the centers of ultraluminous infrared galaxies", Cornell University, USA, 19–22 June (invited lecture)

E. Schinnerer: Nobel Symposium "Cosmic Chemistry and Molecular Astrophysic", Soedertuna, Sweden, 10–15 June (invited lecture); "Mapping the Galaxy and Nearby Galaxies", Ishigaki Island, Japan, 25–30 June, (invited lecture); MPIfR, Bonn, 8 December (colloquium)

D. A. Semenov: MPI für Kernphysik, Heidelberg, 14 July (invited lecture); "Molecular databases for HERSCHEL, ALMA and SOFIA", Lorentz Center, Leiden, 6–8 December (invited lecture)

J. Steinacker: University of Heidelberg, ARI, 27 April (colloquium); Les Houches School on "Interstellar Dust Properties: From Fundamental Studies to Astronomical Models", May 1 (invited lecture); First Heidelberg Astronomy Summer School "Physics of the Interstellar Medium", Heidelberg, 27 June (invited); "Grand Challenge Problems in Computational Astrophysics Reunion Conference I", Lake Arrowhead 10 December (invited)

Ch. Tapken: Observatoire de Geneve, 9 February (colloquium)

K. Tristram: Euro Summer School "Observation and Data Reduction with the Very Large Telescope Interferometer", Goutelas (France), 4–16 June (invited lecture);

R. van Boekel: SPIE – Astronomical Telescopes and Instrumentation, Conference 6268 "Advances in Stellar Interferometry", Orlando, Florida, 24–31 May (invited lecture); "The Third Conference on the Development of Extra–solar Planetary Science", Tokyo, 11–13 December (invited lecture); University of Tokyo, 14 December (colloquium); ISAS/JAXA, Tokyo, 19 December (colloquium)

F. Walter: "From *z*-Machines to ALMA: (Sub)Millimeter Spectroscopy of Galaxies", NRAO, Charlottesville, 12–14 January (invited lecture); ESO Garching, 9 February (colloquium lecture); IAU General Assembly, Prague, 13–19 August (invited lecture); "Science with ALMA: a new era for Astrophysics", Madrid, 13–17 November (invited lecture)

S. Wolf: PLANET EU–RTN network Training School "Detection and Characterization of Exoplanets: Observational Challenges for the next Decade", Geneve, 28–30 June (invited lecture); COSPAR, Symposium "Advances in FIR and submm Astrophysics", Bejing, China, 16–18 July (invited lecture); IoA Conference "The Planet–Disc Connection", Cambridge (UK), 17–21 July (invited lecture); 2nd pan–STARRS International Conference "Science with ALMA", Madrid, 13–16 November (invited lecture)

Conferences and Meetings Attended, Scientific Talks and Poster Contributions

C. Afonso: Training School "Detection and Characterisation of Exoplanets", Observatoire de Genève, Geneva, Switzerland, 28–30 June; International Transiting Extrasolar Planets Workshop, MPIA, September, 25–28 (lecture); Planets Network Meeting "EU Planets: the Next Generation", MPIA, 26–27 October, (lecture)

C. Bailer-Jones: 3rd GAIA Data Analysis Coordination Committee meeting, Nizza, 19–20 January; 16th GAIA Science Team meeting, ESTEC, Netherlands, 20–21 February; 4th GAIA Data Analysis Coordination Committee meeting, Lund, 23–24 May; IAU General Assembly, Prague, August (invited/contributed lecture); 1st meeting of the GAIA Data Processing and Analysis Consortium Executive Meeting, ESAC, Spain, 21–22 September; 18th GAIA Science Team meeting, ESTEC, Netherlands, 5–6 October

M. Barden: "Galaxies and Structures through Cosmic Times", Venedig, 26–31 March (poster)

H. Baumeister: SPIE – Astronomical Telescopes and Instrumentation Conference "Millimeter and Submillimeter Detectors and Instrumentation for Astronomy III", Orlando, Florida, USA, 24–31 May (poster)

J. Berwein: SPIE – Astronomical Telescopes and Instrumentation, Orlando, 25–30 May (lecture); Conference: ADASS 2006 (Astronomical Data Analysis Software & Systems XVI), Tucson, 15–18 October (poster)

F. Bigiel: "Dwarf Galaxies as Astrophysical and Cosmological Probes", Rinberg Castle, 12–17 March; IAU General Assembly, Prague, August (poster)

F. Briegel: SPIE – Astronomical Telescopes and Instrumentation, Orlando, 25–30 May (poster); Conference: ADASS 2006 (Astronomical Data Analysis Software & Systems XVI), Tucson, 15–18 October (lecture)

S. Birkmann: SPIE – Astronomical Telescopes and Instrumentation Conference "Millimeter and Submillimeter Detectors and Instrumentation for Astronomy III", Orlando, Florida, USA, 24–31 May (lecture)

W. Brandner: 4th Planet Formation Workshop, Heidelberg, 1–3 March; Keck Science Meeting, Irvine, CA, 15 September

A. Carmona: VLTI Summer School, Chateau Goutelas, France, 5–16 June, "Physical Processes in Circumstellar Disks", Vidago, Portugal, 18–23 September (lecture); Center of Astrophysics of Porto University, 29 September (lecture); "The 2nd PSF workshop", Mont Sainte-Odile (France), 23–26 October; 24th Jerusalem Winter School in Theoretical Physics "The Lives of Low mass Stars and their Planetary Systems", The Hebrew Unversity of Jerusalem, 27 December – 5 January (lecture)

H. Dannerbauer: Conference "Galaxies and Structures through Cosmic Times", Venedig, 26–31 March (poster); Radiaton Workshop, MPIA, May

J. de Jong: Institute of Astronomy, Cambridge, UK, 19 January (colloquium); workshop "Deconstructing the Local Group", Aspen, USA, 25 June – 2 July (lecture); workshop "Dissecting the Milky Way", Leiden, November 6–10 (lecture); IAU Symp. 241 "Stellar Populations as Building Blocks of Galaxies", La Palma, 10–15 December (lecture)

N. Drurkyevich: JPL, Pasadena, July (lecture); Workshop "From Dust to Planetesimals", Schloss Ringberg, 11–15 September (lecture); PSF Workshop, Monte St. Odile, October (lecture); 9th MHD Day, MPIA, 4–5 December (lecture); EU Network Planets Meeting, MPIA, 26–27 October

C. Dullemond: Technische Hochschule Braunschweig, 10 Ja-nuary (colloquium); University of Florence, 21 February (colloquium); Workshop "From Dust to Planetesimals", Schloss Ringberg, 11–15 September (lecture); 4th Planet Formation Workshop, Heidelberg, 1–3 March (lecture)

S. Egner: SPIE – Astronomical Telescopes and Instrumentation Conference "Millimeter and Submillimeter Detectors and Instrumentation for Astronomy III", Orlando, Florida, USA, 24–31 May (three posters)

F. Fontanot: Seventh Italian Conference on Active Galactic Nuclei: "Fenomenologia degli AGN, evoluzione e processi di formazione delle galassie", Montagnana (Padova), 23–26 May (lecture); Conference Deep 06 "At the Edge of the Universe", Sintra, Portugal, 9–13 October (lecture)

W. Gässler: LBT Software workshop, Tuscon, 1–5 October

A. Gallazzi: IAU Symposium 241 "Stellar populations as building blocks of galaxies", La Palma, 10–16 December (lecture)

P. Glaschke: "The 2nd PSF workshop", Mont Sainte-Odile (France), 23–26 October (lecture)

B. Goldman: Journées de la SF2A, Paris, 26–30 June (poster)

D. Gouliermis: Symposium "Massive Stars: From Pop III and GRBs to the Milky Way", STScI, Baltimore, 8–11 May, (poster); Minisymposium "The Milky Way", MPIA, Heidelberg, 31 May; IAU XXVI General Assembly, Prague, 14–22 August, (poster, Press Release); 2nd PSF Department Workshop, Mont Sainte-Odile, 23–26 October (lecture)

R. Gredel: Faraday Discussion 133, St. Jacut de la Mer, 24–26 April; "Carbon in Space", Villa Vigoni, 22–25 May (lecture); ELT Conference, ESO Garching, 27–28 April (lecture); OPTICON in FP7, UKATC, Edinburgh, 21–22 June; 2nd NEON archive school, Garching, 1–8 September (lecture)

B. Häussler: MPIA Student Workshop, Brixlegg, 18–22 February (2 lectures); "Cosmic Frontiers", Durham, GB, July 31 – August 8 (poster); IAU Symposium 235 "Galaxy Evolution along the HUBBLE time", Prague, 14–17 August (poster); Fall Mini–Workshop "Galaxy Mergers: From the Local Universe to the Red Sequence", 4–6 October, Baltimore (poster); "At the Edge of the Universe", 9–13 October, Sintra, Portugal (poster); Royal Observatory, Edinurgh, October 23 (invited lecture); GEMS Meeting, MPIA, November 29 – December 1 (2 lectures)

S. Hahn: IAU Symposium 235 "Galaxy Evolution Across the HUBBLE Time", Prague, (poster)

S. Hanke: SPIE Conference on Astronomical Telescopes and Instrumentation Orlando, Florida, 24–31 May

M. Hennemann: IAU XXVIth General Assembly, Prague, 14–25 August (poster); EPoS 2006, "The Early Phase of Star Formation", Schloss Ringberg, 28 August – 1 September (poster)

K. Jäger: "Universe Awareness for Young Children" (UNAWE), ARI, Heidelberg, 5 April

K. Jahnke: 207th AAS meeting, Washington, 8–12 January (poster); "Galaxies and Structures through Cosmic Times", Venedig, 26–31 March (lecture); IV Potsdam Thinkshop "The role of black holes in galaxy formation and Evolution", September 11 (lecture); COSMOS collaboration meeting, Schloss Ringberg, 24–29 September (lecture)

S. Jester: RAS National Astronomy Meeting 2006, University of Leicester, 3–7 April (poster); 6th Microquasar Workshop, Como, 18–22 September (lecture); Oxford, 24 October (colloquium); Workshop "Coronae of Stars and Accretion Disks", Bonn, 12/13 December; 9th MHD days at MPIA (lecture)

A. Johansen: "Planet Formation and Evolution Studies", Heidelberg, March (lecture); "Pencil Code Workshop", Copenhagen, July (lecture); "From Dust to Planetesimals", Schloss Ringberg, September (lecture); "The 2nd PSF workshop", Mont Sainte-Odile (France), 23 – 26 October (lecture); "PLANETS Network meeting", Heidelberg, October (lecture)

F. Kittmann: Conference: ADASS 2006 (Astronomical Data Analysis Software & Systems XVI), Tucson, 15–18 October (lecture)

H. Klahr: 4th Planet Formation Workshop, Heidelberg, March; Conference "The Planet-Disk Connection", Cambridge, March (lecture); IAU Symposium 239 "Convection in Astrophysics", Prague, July (lecture); "The 2nd PSF workshop", Mont Sainte-Odile (France), 23–26 October (lecture); EU Network Meeting PLANETS, Heidelberg, October (lecture); The Third Meeting of Exoplanet Research, Tokyo, December (lecture)

R. Klement: Workshop "Dissecting The Milky Way", Leiden, November

K. Knudsen: IRAM, Grenoble, February (Seminar); "Cosmic Frontiers", Durham, 31 July – 4 August (poster); IAU General Assembly, Prague, August (poster); "Science with ALMA: a new ear for Astrophysics", Madrid, 13–17 November

K. Kornet: "Planet Formation and Evolution Studies: Various Approaches – One Goal", Heidelberg, 1–3 March, (lecture); Planet EU–RTN School & Network Meeting: Detection and Characterization of Exoplanets, Genève, 28–30 June (poster); Workshop "From Dust to Planetesimals", Schloss Ringberg, 11–15 September (lecture); Planets Network Meeting "EU PLANETS: The Next Generation", Heidelberg, 26–27 October (poster)

S. E. Koposov: IAU XVI General Assembly, Prague, August (three posters); "Astronomical Data Ananlysis Software and Systems, XVI", Tucson, September (poster); International Virtual Observatory Alliance interoperation meeting, Moscow, September (lecture)

E. Krmpotic: GALEV06, "Studying Galaxy Evolution with SPITZER and HERSCHEL", Agios Nikolaos, Crete, 28 May – 2 June (poster)

J. Kurk: "Galaxies and structures through cosmic times" Venedig, 27–31 March (poster); IAU XXVIth General Assembly, Prague, 14–18 August (lecture)

L. Labadie: SPIE – Astronomical Telescopes and Instrumentation Conference "Millimeter and Submillimeter Detectors and Instrumentation for Astronomy III", Orlando, Florida, USA, 24–31 May (lecture); COSPAR Meeting 2006 – General Assembly, Beijing, 16–23 July

R. Launhardt: "The Early Phase of Star Formation", EPoS 2006, Schloss Ringberg, 28 August – 1 September (lecture)

R. Lenzen: "Towards the European ELT", Marseille, 27 November – 1 December (poster); SPIE Conference "Astronomical Telescopes and Instrumentation", Orlando, 24–31 May (poster)

A. Martinez: COSMOS collaboration meeting, Schloss Ringberg, September (lecture); "The Central Engine of Active Galactic Nuclei", Xi'an, China, October (lecture); SPITZER Science Center, Pasadena, December (Seminar)

N. Martin: "Dissecting the Milky Way", Leiden, 6–10 November (lecture); "Stellar populations as building blocks of galaxies", La Palma, 11–15 December

E. Meyer: SPIE – Astronomical Telescopes and Instrumentation, Conference 6268 "Advances in Stellar Interferometry", Orlando, Florida, 24–31 May (poster)

R. Mundt: Workshop "Transiting Extrasolar Planets", MPIA, 25–28 September

A. Pavlov: SPIE – Astronomical Telescopes and Instrumentation, Orlando, 25–30 May (lecture); Conference: ADASS 2006 (Astronomical Data Analysis Software & Systems XVI), Tucson, 15–18 October (lecture)

S. P. Quanz: "From Dust to Planetesimals", Schloss Ringberg, 11–15 September (lecture)

P. Re Fiorentin: SEGUE meeting at ARI, Hei-delberg, 14 March (lecture); SDSS–II Collaboration Meeting, Santa Fe, New Mexico, 23–29 March (lecture); Summer School in Statistics for Astronomers and Physicists II, "Statistical Challenges in Modern Astronomy", State College–Pennsylvania State University, 5–15 June; GAIA CU8 Meeting, MPIA Heidelberg, 6–7 December

C. A. Riechers: 207th Meeting of the American Astronomical Society, Washington DC, USA, 8–12 January (poster); ALMA Conference "From z – Machines to ALMA: (Sub)Millimeter Spectroscopy of Galaxies", Charlottesville, USA 13–14 January (lecture); DFG Summer School "Evolution of galaxies and their large – scale environment", Bad Honnef, 2–7 July; XXVIth General Assembly of the IAU, Prague, 14–25 August (2 posters); ALMA Conference "Science with ALMA: a new era for Astrophysics", Madrid, Spain, 13–17 November (poster)

H.-W. Rix: SEGUE Workshop, Santa Fe, 27 March (lecture); DUNE Workshop, Saclay, 13 October (lecture); Lorentz Center Workshop "Dissecting the Milky Way", Leiden, 6–10 November (lecture)

F. Rodler: 4th Planet Formation Workshop, Heidelberg, 1–3 March; Conference "Precision Spectroscopy in Astrophysics", Aveiro, Portugal (poster); Planets

Network Meeting "EU PLANETS: The Next Generation", Heidelberg; "The 2nd PSF workshop", Mont Sainte-Odile (France), 23–26 October (lecture)

R.-R. Rohloff: SPIE Astronomical Telescopes and Instrumentation Symposium, Orlando, Florida, 24–31 May (lecture)

Ch. Ruhland: GEMS/STAGES Workshop, MPIA, 29 November–1 December (lecture)

A. Schegerer: Headquarters of the Submillimeter Array, Hilo, 14 April (lecture); Workshop "From Dust to Planetesimals", Schloss Ringberg, 11–15 September (lecture)

M. Schartmann: "The History of Nuclear Black Holes in Galaxies", Cambridge, MA, 15–18 May (poster)

E. Schinnerer: 207th Meeting of the American Astronomical Society, Washington, DC, 8–12 January (lecture); ALMA Workshop "From z–Machines to ALMA: (Sub)Millimeter Spectroscopy of Galaxies", Charlottesville, Virginia, 12–13 January (lecture); "Galaxies and Structures through Cosmic Times", Venedig, 26–21 March (lecture); IAU Symposium 235 "Galaxy Evolution across the HUBBLE Time", Prague, 14–18 August (poster); COSMOS Team Meeting, Schloss Ringberg, 24–29 September (lecture), "Science with ALMA: A New Era for Astrophysics", Madrid, 13–17 November (poster)

D. A. Semenov: 4th Planet Formation Workshop, MPIA Heidelberg, 1–3 March (poster); Faraday Discussion 133 "Chemical Evolution of the Universe", St. Jacut de la Mer, France, 24–26 April (poster), "Complex Molecules in Space – Present Status and Prospects with ALMA", Aarhus, Denmark, 8–11 May (three posters); 9th Conference on Electromagnetic and Light Scattering by Nonspherical Particles, Saint-Petersburg, 5–9 June (poster); "Science with ALMA: a new era for Astrophysics", Madrid, 11–13 November (three posters)

J. Setiawan: Geneva Planet School, Geneva, 24–26 June (poster); "Precision Spectroscopy in Astrophysics", Aveiro (Portugal), 11–15 September (lecture, poster); "Transit Extrasolar Planets", MPIA Heidelberg, 25–29 September (poster)

J. Stegmaier: Radiation Workshop, MPIA, May (lecture); SPIE – Astronomical Telescopes and Instrumentation: Optomechanical Technologies for Astronomy, Orlando, Florida, 24–31 May (lecture)

J. Steinacker: Spring Meeting of the Deutsche Physikalische Gesellschaft, Heidelberg, 15 March (lecture); "AstroGrid – D science from robotic telescopes to GRAPE boards", C&C Research Laboratories, NEC Europe Ltd., St. Augustin, 21 April (Seminar); "The Early Phase of Star Formation", EPoS 2006, Schloss Ringberg, 29 August (lecture); Observatoire de Bordeaux, 17 October (Seminar); "The 2nd PSF workshop", Mont Sainte-Odile (France), 23–26 October (lecture)

M. Stumpf: 4th Planet Formation Workshop, Heidelberg, 1–3 March (lecture); XXVIth General Assambly of the IAU, Prague, 14–25 August; NEON Archive Summer School, ESO Garching, 30 August – 9 September (lecture); "Cool Stars 14", Pasadena, 5–10 November (lecture)

Ch. Tapken: "Cosmic Frontiers", Durham, 31 July – 8 August; "At the Edge of the Universe", Sintra, Portugal, 9–13 October (poster)

C. Tiede: Conference "Astronomical Data Analysis Software & Systems", Tucson, 15–18 October (lecture)

K. Tristram: The Fourth Harvard–Smithsonian Conference on Theoretical Astrophysics "The History of Nuclear Black Holes in Galaxies", 15–18 May, Harvard University, Cambridge, MA (poster); IAU Symposium 238 "Black Holes", Prague, 21–25 August (lecture)

R. van Boekel: SPIE – Astronomical Telescopes and Instrumentation, Conference 6268 "Advances in Stellar Interferometry", Orlando, Florida, 24–31 May (lecture); Conference "From dust to planetesimals", Schloss Ringberg, 11–15 September (lecture)

F. Walter: AAS meeting, Washington, 8–12 January (poster); "Mapping the Galaxy and Nearby Galaxies", Ishigaki Island, 26–30 June, (lecture); IAU General Assembly, Prague, 13–19 August (lecture)

S. Wolf: 4th Planet Formation Workshop "Planet Formation and Evolution Studies: Various Approaches – One Goal", Heidelberg, 1–3 March (lecture); Conference "Visions for Infrared Astronomy", Paris, 20–22 March (lecture); British German Symposium "Frontiers of Science", Alexander von Humboldt–Stiftung/Junge Akademie, Wyboston, Bedfordshire (UK), 30 March – 2 April (poster); Conference "Complex Molecules in Space – Present Status and Prospects of ALMA", Aarhus (Denmark), 8–11 May; Conference "Karrierewege in Wissenschaft in Forschung" (BMBF/DFG), Berlin, 4–5 October; SEE–COAST Science Team Meeting, Geneva, 5 October (lecture); MATISSE Kick–off Meeting, Nizza (France), 16 November (lecture); Conference "Towards the European ELT", Marseille, 27 November – 6 December (lecture); Symposium zur Vorstellung der Nachwuchsgruppenleiter, University of Heidelberg, 12–13 December (lecture)

Lecture Series

Ch. Fendt: "The Properties of Galaxies", Summer School SPP 1177 "Evolution of Galaxies and their Large-scale Environment", Bad Honnef, 2–7. July

Popular Talks

H. Beuther: Astronomy on Sunday Morning, MPIA, 2 June: "The formation of stars – about Brown Dwarfs and Blue Giants"

S. Birkmann: Astronomy on Sunday Morning, MPIA, 9 July, "Life in the universe – are we alone?"

S. Hanke: Astronomiekreis der Universität Stuttgart, 6 December, "The Large Binocular Telescope and LINC–NIRVANA"

B. Häussler: Long Night of Museums, Heidelberg, 18 March, "From the Big Bang until today: a short history of the universe", Astronomy on Sunday Morning, MPIA, 18 June, "From the Big Bang until ... : a short history of the universe"

Th. Henning: "The discovery of new worlds – extrasolar planetary systems", Göttingen, 7 March

K. Janke: Planetarium Mannheim, 17 February: "Galaxies, quasars, black holes"; Volkshochschule Rüsselsheim, 15 September: "Galaxies, quasars, black holes"

K. Jäger: Speech at the inauguration ot the new telescope of the MPI for Informatics, Saarbrücken. 20 July, "Galaxies and gigabytes – astronomy in the age of giant telescopes"; Long Night of Museums, MPIA, 18 March, "Galaxies and gigabytes – astronomy in the age of giant telescopes"; Girls' Day, MPIA, 27 April, "The sky in the computer – virtual planetaria"; Astronomy on Sunday Morning, MPIA, 23 July "Fascinating pictures producing knowledge – results from HUBBLE"; Förderkreis Planetarium Göttingen, 10 October, "The riddle of quasars"; BOGY (MPI/LSW), 23 October, "Telescopes and observational techniques"; Planetarium Mannheim, 27 October, "Fascinating pictures producing knowledge – results from HUBBLE"

O. Krause: Astronomy on Sunday Morning, MPIA, 30 July, "Higher, faster, further – satellites in astronomy"

D. Lemke: Sternenfreunde Nordenham, 15. June, "Atacama, Antarctica, Moon, *L2* – a voyage to the observatories of the future"

R. Lenzen: HS Mannheim: "Five years Very Large Telescope: development and utilization"

S. P. Quanz: Long Night of Museums, Heidelberg, 18 March, "The solar system – a voyage to the nine (?) planets"; Anne-Frank-Schule, Eschwege, February, "Origin, present and future of matter and energy"

H.-W. Rix: Planetarium Mannheim, 20 January: "Look back at the big bang"; Förderkreis Planetarium Göttingen, 21 February: "Redder, deeper, sharper – the future of observational astropnomy"; Interview, WDR, Studio Mannheim, 24 February; Astronomy on Sunday Morning, MPIA, 11 June: "Black holes: the brightest objects in the universe"

A. Sicilia Aguilar: Antalya (Turkey), 28 March, "Dusty stars, newborn planets and eclipses in other solar Systems"

J. Stegmaier: Manfred-Sauer-Stiftung, Lobbach, November, "Falling stars"

J. Steinacker: Long Night of Museums, Heidelberg, 18 March, "The secret of star formation"

M. Stickel: Starkenburg–Sternwarte, Heppenheim, 14 March, "Supernovae and the accelerated expansion of the universe"

Ch. Tapken: Long Night of Museums, Heidelberg, 18 March, "The secrets of galaxies"

Fabian Walter: Astronomy on Sunday Morning, MPIA, 16 July: "The Milky Way and its sisters"

Sebastian Wolf: Astronomy on Sunday Morning, MPIA, 25 June: "Planets – near our Sun and near other stars"

Service in Committees

C. Bailer-Jones: Co–chair of the GAIA Data Analysis Coordination Committee; member of the GAIA Science Team; member of the GAIA Data Processing and Analysis Consortium; Leader of the Subconsortiums "Astrophysical Parameters" im GAIA Data Processing and Analysis Consortium; member of the Scientific Organizing Committee of Commission 45 (Stellar Classification) of the International Astronomical Union

W. Brandner: member of the ESO Adaptive Optics Working Group, ESO Observing Programme Committee Panelist, representative of the employees in the Max Planck Society in the Chemistry, Physics and Technology Section, member of the ASTRONET Panel C, Referee of Observing Proposals for Taiwan's share of CFHT, member of the MPIA Student Selection Committee, of the Calar Alto Scientific Advisory Committee, of the PanSTARRS 1 Science Council, of the Heidelberg Astronomical colloquium Selection Committee

B. Goldman: member of the Calar Alto TAC

D. Gouliermis: GALEX GI Program Cycle 3 Peer Review, Towson MD, USA, September

R. Gredel: member of the OPTICON board, OPTICON executive committee, ELT working group 3 – site characterisation, ELT ESE – Science and Engineering working group

Th. Henning: member of the the ESO Strategic Planning Group; member of the SOFIA Science Council; member of the European ALMA Board; chair of the German Interferometry Centre FRINGE; President of the Science Council of the European Interferometry Initiative; Co–Chair of the DFG Researchers Group "Laboratory Astrophysics", chair of the LBT–Beteiligungsgesellschaft (until August); member of the Board of Directors LBT

Corporation (until August); member of the Pan–STARRS1 Board; co-chair of the Advisory Council of the Kiepenheuer Institute for Solar Physics, Freiburg; Co–I of the IR instruments FIFI I–LS (SOFIA), PACS (HERSCHEL), MIRI (JWST), SPHERE (VLT), PRIMA–DDL (VLTI); MATISSE (VLTI); member of the Astronomische Gesellschaft, of the Deutsche Physikalische Gesellschaft and the Deutsche Akademie der Naturforscher Leopoldina

K. Jäger: Collaboration in the CAHA Executive Committee and in the LBT Beteiligungsgesellschaft, member of the ARENA Information and Communication Unit and of the LBT–PR Committee

U. Klaas: member of the ISO Active Archive Coordination Committee as representative of the ISOPHOT Data Center at the MPIA; member of the HERSCHEL Calibration Steering Group, Representative of the PACS Instrument Control Centre Calibration Working Group, Chair of the Library Committee at the Institute

K. Knudsen: member of the Advisory Council of IDA (Instrument Center for Danish Astrophysics)

O. Krause: member of the SPITZER Time Allocation Review Panel

M. Kürster: member of the IAU Working Group "Extrasolar Planets", member of the Organizing Committee for the Creation of IAU Commission 53, "Extrasolar Planets"

R. Launhardt: member of the Board of the Ernst Patzer Foundation

Ch. Leinert: member of the VLTI subpanel in the ESO Science and Technical Committee

D. Lemke: member of the MIRI Steering Committee (advisor of the DLR)

R. Lenzen: member of the TAC for the ESO/MPG 2.2 m Telescope at La Silla, representative of the disabled persons at the Institut, Safety Officer (science)

H.-W. Rix: Chair of the Advisory Council of the Astrophysical Institute at Potsdam (AIP); member of the Kuratoriums of the AIP; member of the Board of Trustees of the Astronomisches Rechen-Institut Heidelberg (ARI); member of the ESO Visiting Committee; member of the Board of the Large Binocular Telescope Corporation (LBTC); member of the Board of the Large Binocular Telescope Beteiligungsgesellschaft (LBTB); member of the Board of OPTICON; member of the JWST/NIRSPEC Science Team; member of the BMBF Advisory Committee "Astrophysics and Astroparticle Physics"; member of the DFG Emmy Noether Committee; member of the DFG Experts Advisory Board

H.-J. Röser: member of the TAC for the ESO/MPG 2.2 m Telescope at La Silla

J. Staude: member of the Jury for the national contest "Jugend forscht"

E. Schinnerer: member of the Patzer Prize Comitees, referee for the VLA/VLBA at the National Radio Astronomy Observatory, Equal Opportunity Commissioner at the Institute

K. Tristram: Students representative in the Chemistry, Physics and Technology Section Section in the Max Planck Society (PhDnet)

F. Walter: Referee for NRAO, member of the IRAM Program committee

S. Wolf: member of the ESO OPC Observing Programmes Committee; P79/2006); Advisor of the ESO Observing Programmes Committee. Panel C "ISM, Star Formation and Planetary Systems", Chair of the Panel C1 in ESO Period P79, Co-chair of Panel C1 in ESO Period P78; European Interferometry Initiative (EII) Working Group "Radiative Transfer Codes for modelling targets of long baseline optical and infrared interferometry", chair since 12/2005; Second Generation mid-infrared interferometric VLTI instrument MATISSE, Co-PI und Project Scientist since 11/2005; member of the Science Teams for VSI/VITRUV (Second generation imaging near-IR interferometer for the VLTI); Referee for Astrophysical Journal, Astronomy and Astrophysics and Planetary Sciences Review Series (University of Arizona Press); SOC member of the IOA Conference "The Planet-Disc Connection", Cambridge (UK), July; member of the Strategic Time Allocation Committee (STAC) at the MPIA

Further Activities

In the Advanced Practical Course in Physics at the University of Heidelberg, Stephan Birkmann, Martin Hennemann, Sascha Quanz, Marc Schartmann, Jutta Stegmaier and Konrad Tristram were responsible for the experiment "FP30 – CCD photometry in modern astronomy"; Stefan Hippler, Felix Hormuth, Anders Johansen, and Daniel Meschke were responsible for "FP36 – wavefront analysis with a Shack-Hartmann sensor".

Michael Zatloukal and Rainer Klement assisted at the Practical Course in Astronomy and Astrophysics (Astronomisches Praktikum) for students in astronomy at the Landessternwarte.

Practical courses for schoolboys and -girls (BOGY) were organized by Klaus Meisenheimer and carried out in October 23. – 27. with the help of Nadine Neumayer, Wolfgang Sauer, Marc Schartmann, Jutta Stegmaier (MPIA), and of Ulrich Bastian, Michael Biermann, Holger Mandel (ZAH)

The Undergraduate Research Projects (Miniforschungsprojekte) at the MPIA were organized by Sebastian Wolf with the help of numerous colleagues.

The Girls' Day at the MPIA (27 April) was organized by Eva Schinnerer with the help of 35 colleagues.

Klaus Jäger organized at the MPIA our share of the "Long Night of Museums" (18 March) with the help of 20 colleagues.

Sascha P. Quanz and Jutta Stegmaier organized the series of eight public lectures "Astronomy at Sunday Morning" which were held at the MPIA during the summer term.

Jakob Staude, assisted by Axel M. Quetz, edited the 44. annual volume of the monthly magazine "Sterne und Weltraum".

In the course of the year, 840 visitors in 36 groups were given a guided tour through the MPIA. (Axel M. Quetz, Stephan Brinkmann, and others)

The Board of Trustees held a meeting at the MPIA on September, 28.

In June, Christian Fendt, Klaus Meisenheimer and Klaus Jäger (MPIA), together with Cecilia Scorza de Appl (LSW), assisted at "Explore Science" (in Mannheim), weeklong event for schoolboys and –girls in the region.

The MPIA participated in the "Euroscience Open Forum" (ESOF) on July 15.–19. in Munich (Th. Henning, K. Jäger)

Since July, Wolfgang Brandner was visiting professor at the University of California, Los Angeles.

During the year under report, various actions were taken at the MPIA in order to improve compatibility of profession and family, as for instance the establishment of a baby office for young scientists, the creation of possibilities to work at home for familiar reasons, an improved exchange of informations about matters concerning the compatibility of profession and family. In order to further improve the working conditions at the MPIA, these actions will be continuously developed.

Prizes

In the year under report, the Ernst Patzer Prize for the Promotion of Young Scientists was awarded twice:

to Vernesa Smolcic from Croatia, a PhD student at the International Max Planck Research School (IMPRS) for Astronomy and Cosmic Physics, for the publication of a paper on the Tadpole Galaxy CWAT – 01;

to Catherine Heymans from Great Britain, who worked at the MPIA as Postdoc within the GEMS project, for a paper on the weak gravitational lens effect.

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