Max-Planck-Institut für Astronomie

Heidelberg-Königstuhl

Annual Report 2000

MAX-PLANCK-GESELLSCHAFT

Cover Picture:
The domes of the Calar Alto Observatory. From left to right: 2.2 m telescope, 1.23 m telescope, 3.5 m telescope and Schmidt telescope.

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Max-Planck-Institute for Astronomy

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Prof. Hans-Walter Rix (since 1.8. 2000)

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The MPIA currently employs a staff of approximately 187 (including externally funded positions). There are 35 scientists and 39 junior and visiting scientists. Students of the Faculty of Physics and Astronomy of the University of Heidelberg work on dissertations at the degree and doctorate level in the Institute. Apprentices are constantly undergoing training in the Institute's workshops.

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I General

I.1 Research Goals at MPIA

The Calar Alto Observatory

In 1967, the Senate of the Max Planck Society decided to establish the Max Planck Institute for Astronomy in Heidelberg with the intention to enable astronomical research in Germany to catch up with international standards. Two years later, the Institute commenced its work in temporary accommodation on the Königstuhl, and in 1975 it moved into its new buildings (Fig. I.1). The MPIA was assigned with the construction and operation of two competitive observatories, one in the northern and one in the southern hemisphere. For the northern site, the Calar Alto Mountain (height: 2168 meters), in the province of Almería southern Spain, was chosen, offering good climatic and meteorological conditions for astronomical observations. In 1972, the German-Spanish Astronomical Center (DSAZ) was established, generally known as the **Calar Alto Observatory**.

Between 1975 and 1984 the 1.2m reflector financed by the German Research Society (DFG) as well as the 2.2m and the 3.5m telescopes started operation on Calar Alto (Fig. I.2). The 80cm Schmidt reflector was transferred from the Hamburg Observatory. The site also hosts a Spanish 1.5m telescope which is operated by the Observatorio Nacional de Madrid and does not belong to DSAZ. The original plans to build a southern observatory on the Gamsberg in Namibia could not be realized for political reasons. The 2.2 m telescope intended for this location has instead been loaned to the European Southern Observatory (ESO) for a period of 25 years. Since 1984, it has been in operation on La Silla in Chile where 25% of its observing time is granted to astronomers within the Max Planck Society.

Operating the Calar Alto Observatory is currently one of the major tasks of the MPIA. This includes the constant optimization of the telescopes' efficiency. With the Calar Alto Observatory, the MPIA commands one of the two most significant observatories in Europe. Participation in international observatories

Fig. I.1: The Max Planck Institute for Astronomy in Heidelberg

Fig. I.2: The domes of the telescopes on Calar Alto. From left to right: the Spanish 1.5 m telescope, the Schmidt telescope, the 1.23 m telescope, the 2.2 m telescope and the 3.5 m telescope.

and scientific space projects is also of central importance. Building new instruments for ground-based or space telescopes is a major part of MPIA's activities (Chapter III). For this purpose, the Institute is equipped with ultra-modern precision mechanics and electronics workshops. Data obtained with these instruments are analyzed in Heidelberg. Research is concentrated on the "classical" optical and the infrared spectral range.

International Cooperation in Ground-based Astronomy

Under the coordinating leadership of the MPIA, the high-resolution infrared camera CONICA is presently being built for the ESO **Very Large Telescope** (VLT) on Cerro Paranal in Chile which will be the world's largest observatory. Work on the construction of MIDI, an interferometry instrument for the VLT (Fig. I.3), is also in progress. From 2002, this promising instrument will make it possible for the first time to couple interferometrically two large telescopes for infrared observations.

Moreover, the MPIA has a significant partecipation in the **Large Binocular Telescope** (LBT, Fig. I.4). The LBT is a kind of double telescope, with two mirrors of 8.4 m diameter each fixed on a common mount. Together, the two mirrors have a light-gathering power equivalent to a single 11.8 m mirror. This will make the LBT the world's most powerful single telescope after its commissioning, currently planned for 2004. The double telescope will particularly be used for interferometric observations. In this case, its spatial resolution will correspond to that of a single mirror 22.8 m across. The LBT is being built by an American-Italian-German consortium on Mount Graham in Arizona, USA.

Within the "LBT Participation Group" (LBTB) the MPIA together with the MPI for Extraterrestrial Physics in Garching, the MPI for Radio Astronomy in Bonn, the Potsdam Astrophysical Institute and the Heidelberg State Observatory will have a 25% share in the costs and use of the LBT. As executive institute of the LBTB, the MPIA has contributed considerably to the final definition of the instruments. In the year under report, the Institute has additionally taken over the presidency of the Scientific Advisory Board of the LBT.

Under the leadership of the Heidelberg State Observatory, the German partners are building the LUCIFER near-infrared spectrograph for the LBT. For this instrument, MPIA will deliver the entire detector package and develop the cooling concept. Integration and tests of the instrument will be performed at the Institute's laboratories.

At the same time, planning for the LBT interferometer, which will be equipped with adaptive optics, is in full swing. The optics of the Beam Combiner (LINC) are beind designed at the MPIA. This device will allow interferometry in the wavelength range between 0.6 µm and 2.2 µm, requiring an optical design of the highest standards. Conception has started in the year under report. In addition, an informal consortium was formed with colleagues from the University of Cologne and the Osservatorio Astrofisica di Arcetri (Florence).

The MAX (Mid-Infrared Array eXpandable) infrared camera built at MPIA has been operating for several years at one of the largest telescopes in the northern hemisphere, the British 3.9 m telescope **United Kingdom Infrared Telescope** (UKIRT) on the island of Hawaii. Astronomers at MPIA have a fixed fraction of observing time at this telescope. UKIRT permits excellent observations in the infrared range.

The MPIA is also participating in the **Sloan Digital Sky Survey** (SDSS). This is the most extensive digital sky survey currently in progress, imaging about a quarter of the entire sky in five wavelength ranges with a mosaic CCD camera. The final catalogue will

Fig. I.3: From 2002, it will be possible to couple interferometrically two of the four large telescopes of the VLT. The Institute is participating in this project with the construction of the MIDI instrument.

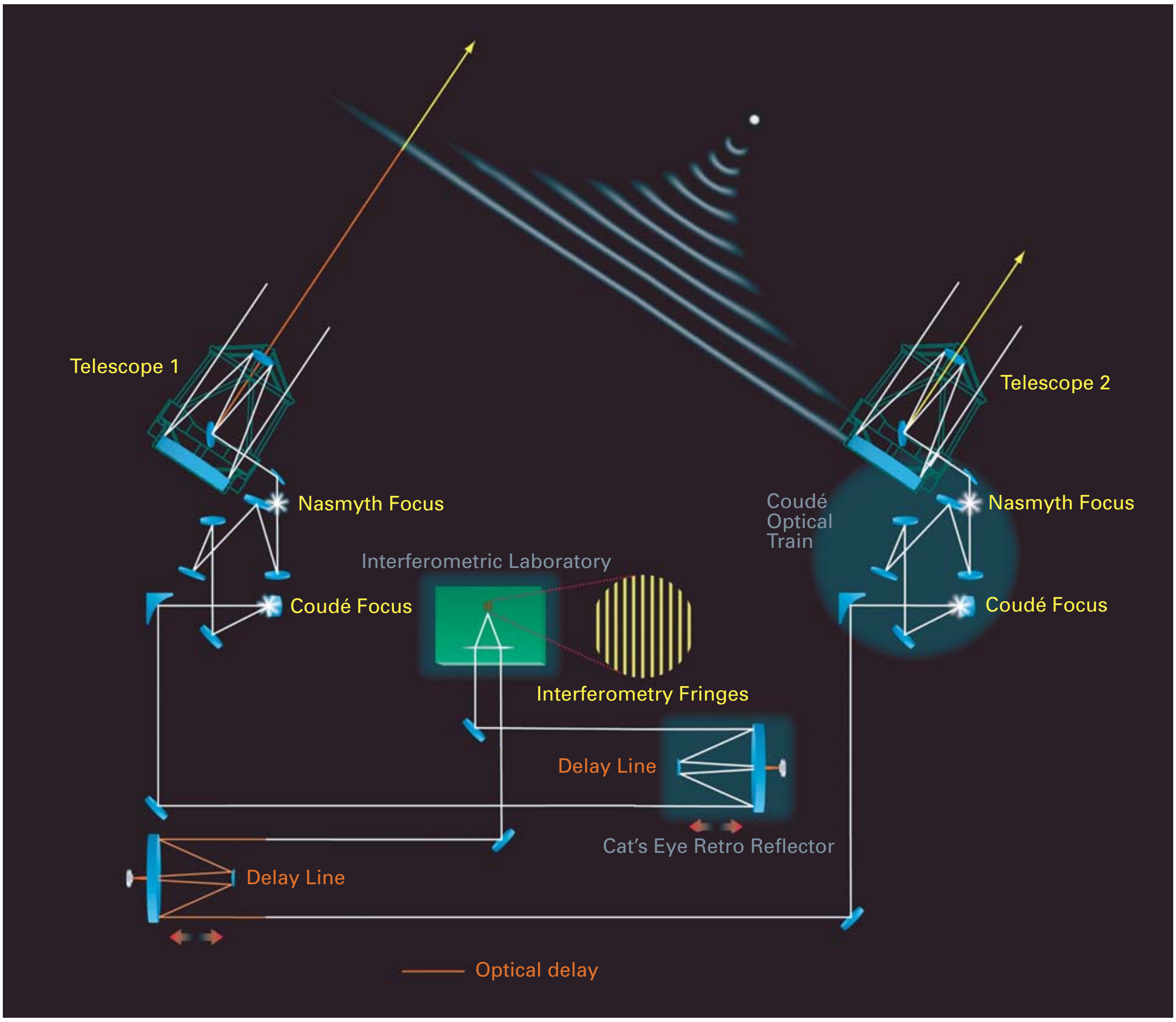


Fig. I.4: The Large Binocular Telescope on Mount Graham will be among the world's most powerful telescopes in a few years' time.

provide positions and colors of an estimated one hundred million celestial bodies as well as the redshifts of about one million galaxies and quasars. The observations are performed using a 2.5m telescope which was specially built for this purpose, located at Apache Point Observatory in New Mexico. The project is conducted by an international consortium of American, Japanese and German institutes. The German research institutes involved are MPIA at Heidelberg and MPI for Astrophysics in Garching. In exchange for material and financial contributions from the MPIA, a team of scientists at the Institute gets full access to the data as soon as they are obtained. After a testing phase of a little more than a year, the survey officially started in April 2000.

Satellite Astronomy

Since it was established, the MPIA has been engaged in extraterrestrial research. Associated with these activities was an early start in infrared astronomy which has been of great significance for the later development of the Institute as a whole. In the 1970's, two photometers were developed and built at MPIA which flew successfully on board the two solar probes **HELIOS 1** and **2**. At about the same time, the **THISBE** infrared telescope (Telescope of Heidelberg for Infrared Studies by Balloon-borne Experiments) was developed. It was carried by a high-altitude research balloon up to a height of 40 km where mid/far infrared observations are possible.

Today, the MPIA is participating significantly in the **ISO** project of the European Space Agency ESA: **ISOPHOT**, one of four scientific instruments on board of ISO, was built under the coordinating leadership of the Institute. For over two years, ISO provided excellent data. It was switched off on 8th April 1998, after its coolant supply had been exhausted. In the meantime, numerous papers concerning all areas of astronomy have been published, demonstrating the capability of this space telescope.

In summer 1998, the post-operative phase began which is due to last three years. During this phase, the data are carefully calibrated and archived. Here, a clearly arranged archive classified by objective criteria is of particular importance. To accomplish this task, ESA set up a central archive at its ground station at Villafranca, Spain, in 1998, while the institutes which had provided the instruments or were participating in another way in ISO built up data centers of their own.

Under an agreement with ESA the ISOPHOT Data Center at MPIA is one of the nodes in this international network of eight ISO data centers (see Annual Report 1998, p. 6). In cooperation with the ISO Science Operations Center, Madrid, the standard "PHT Interactive Analysis" software (PIA) has been developed at MPIA to analyze the raw data supplied by the satellite. Apart from pure archiving and recalibration, the Heidelberg Data Center acts as a service facility for astronomers. In the year under report, assistance was provided for about 30 visitors.

On the scientific side, there was a series of very successful studies, including the observation of the background radiation of young galaxies and the confirmation of the unified scheme for quasars and radio galaxies (both in Chapter IV.2) as well as the extensive study of ultra-luminous infrared galaxies (Chapter II).

The experience gained with ISOPHOT was decisive for the MPIA's significant participation in the construction of the **Pacs infrared camera**. This instrument will operate on board the European HERSCHEL infrared observatory (formerly the Far Infrared and Submillimeter Telescope, FIRST, Chapter III). The launch of this 3.5 m space telescope is planned for 2007.

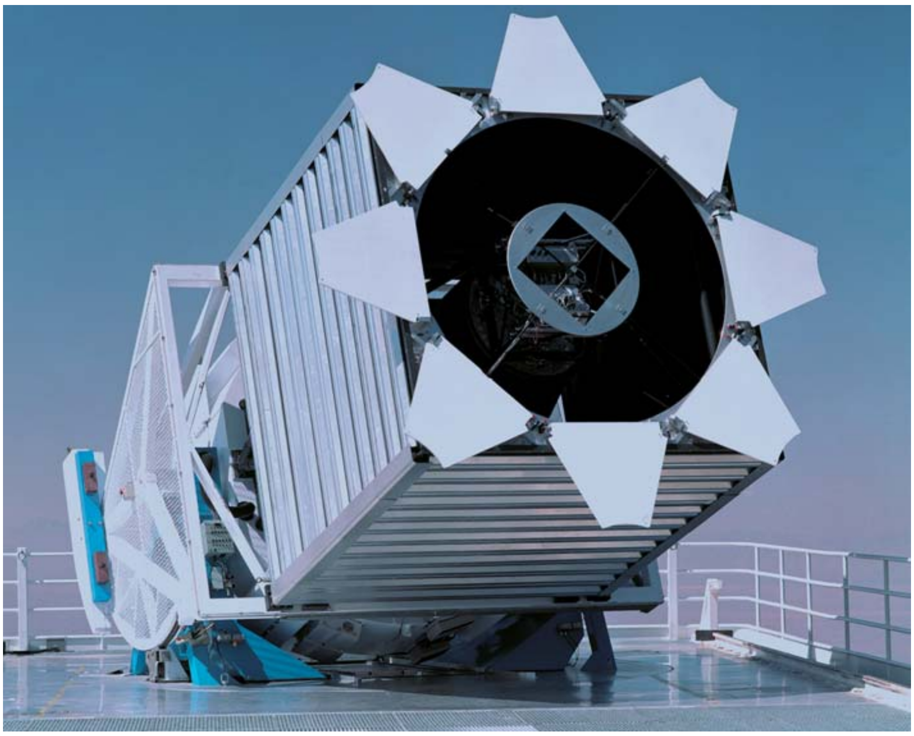


Fig. I.5: The 2.5 m telescope of the Sloan Digital Sky Survey (image: SDSS)

The Institute is participating in a satellite experiment proposed to NASA by Johns Hopkins University, Baltimore. This telescope, known as **PRIME** (Primordial Explorer), is intended to map a large part of the sky down to a magnitude of 24.5 in the wavelength range between 0.9 and 3.4 µm. PRIME would be a predecessor of NGST (New Generation Space Telescope), the planned successor to the HUBBLE Space Telescope. It would comprise a 75 cm telescope moving around Earth in a polar orbit at 650 km altitude. The telescope's focal plane is split by three mirrors into four wavelength channels equipped with newly developed infrared arrays.

In a series of individual 150 sec exposures, PRIME could scan a quarter of the entire sky within three years with an unprecedented accuracy, providing new findings in virtually every field of modern astronomy. For example, the telescope could detect at least 1000 supernovae of type Ia in the redshift range $1 < z < 5$ and measure their light curves, as well as finding hundreds of brown dwarfs at distances up to 1000 parsecs, extrasolar planets the size of Jupiter at distances up to 50 parsecs, quasars with redshifts up to $z = 25$ and protogalaxies up to $z = 20$.

A phase A industry study of the telescope was prepared in 2000. MPIA is to provide the telescope.

Teaching and Public Relations Work

The Institute's tasks also include teaching and informing the general public about results of astronomical research. Members of the Institute give lectures and seminars at Heidelberg University as well as at schools, adult educations centers and planetaria. They also appear at press conferences or on radio and televisions programs, in particular on the occasion of astronomical events which attract major public attention. Numerous groups of visitors come to the MPIA on the Königstuhl and to the Calar Alto Observatory. Since 1976, a regular one-week teacher training course is held in autumn at MPIA which is very popular among teachers of physics and mathematics in Baden-Württemberg. Finally, the monthly journal *Sterne und Weltraum* (*Stars and Space*), co-founded by Hans Elsässer in 1962, is published at MPIA. This journal is intended for the general public but also offers a lively forum both for professional astronomers and for the large community of amateurs in this field.

I.2 Scientific Questions

The central issue of all cosmological and astronomical research deals with the formation and evolution of the universe as a whole as well as of stars and galaxies, the Sun and its planets. The MPIA's research program is oriented to these questions.

In the field of galactic research, the Institute concentrates on star formation in huge interstellar clouds of gas and dust. In the field of extragalactic astronomy, the focus is on large-scale structure of the universe, the search for primordial galaxies and the investigation of active galaxies and quasars (remote stellar systems with enormous luminosities). The observational research is supported by a group of theoreticians who use computer simulations to reconstruct processes in the universe extending over tens of thousands or millions of years. Thus, a fertile synthesis of observation and theory is achieved at MPIA.

Galactic Research

A central field of galactic research at MPIA is star formation. The first stages of this process take place in the interiors of dust clouds, and hence remain hidden from our view in visible light. Infrared radiation, however, can penetrate the dust, which is why the early stages of star formation are being studied preferentially in this wavelength range.

Using ISOPHOT, it was possible to detect very cold and dense regions within large dust clouds for the first time. These are protostellar cores, which are on the verge of collapse or already contracting (Chapter IV.1). Attracting much attention was the observation of planetary objects which are not in orbit around a star (Chapter II). As these objects are still very young and hot, they are detectable in the infrared range. Because of their low mass at least some of them would be classified as planets. "Free floating" planets, however, had never been observed before. The question how these objects formed is still unsettled to a large extent, starting a debate on the very definition of a planet. Mass is only one of several conceivable criteria.

The Institute's theory group has also dealt with different aspects of star formation in the year under report. Some scientists investigated the influence of turbulence within dense clouds of gas and dust on star formation. One result is that although turbulent supersonic gas flows can prevent the collapse of a large cloud as a whole, they do not hinder local regions from condensing and contracting further until stars are forming inside (Chapter IV.1).

The further course of stellar evolution is also of interest. Towards the end of the collapse phase, a disk of gas and dust is forming around the star due to the cloud's rotation. In this process the star accumulates matter from the disk, thereby increasing its angular momentum: the stars rotates ever faster. Eventually, the angular momentum and thus the centrifugal force would become too large for the protostar to continue contraction. Therefore, young stars have to be slowed down, that is, they must get rid of angular momentum. This is achieved in different ways in different evolutionary stages. Measuring the rotation velocities of young stars, astronomers from the USA and MPIA came across a relation between stellar rotation and the development of a surrounding disk, reinforcing the significance of a disk for the evolution of angular momentum in young stars. These observations were made possible mainly by the Wide Field Camera built at the Institute.

Extragalactic Research

Extragalactic research is dealing with galaxies and clusters of galaxies. In this field, one of the major tasks is to reconstruct galactic evolution. What was the star formation rate in the early universe? Did galaxies merge, thereby reducing their total number in the course of billions of years? These are only two of the crucial questions.

Like in the years before, the ISOPHOT instrument built under the leadership of MPIA provided valuable results in extragalactic astronomy in the year under report, too. It is known from nearby galaxies that intense star formation causes large masses of dust to be heated which then radiate in the mid- and far-infrared range. As spectra of galaxies in the early universe are redshifted, these objects should be observable mainly in the far-infrared and the adjacent millimeter range. With the ISO satellite observatory it was possible to observe this extragalactic background radiation in greater detail for the first time. Several extended projects were devoted to this subject which are now yielding first results. The data clearly show that the young galaxies have experienced violent evolutionary stages with burstlike star formation (Chapter IV.2).

A current central research topic of global interest is the nature of supermassive black holes in the centers of galaxies. Formation of massive black holes seems to be an integral part of the evolution of galaxies. Apparently this is true not only for galaxies with active galactic nuclei but also for normal galaxies like our Milky Way galaxy. Astronomers at MPIA together with colleagues in the USA were able to detect black holes of some tens to hundreds of millions solar masses in five weakly active spiral galaxies (Chapter II.3). The new measurements show even more clearly than before that the mass of the black hole is related to the larger properties of its several million times bigger host galaxy. This correlation is probably a result of galactic evolution. The reason for it, however, is not clear yet.

Massive black holes are the source of core activity in numerous galaxies. Meanwhile, about a dozen different types of active galaxies can be distinguished due to their observational characteristics. Since the late 1980's, however, more and more astrophysicists are convinced that these different types are in principle all constructed uniformly but that – as they are not spherically symmetric – their appearance varies with the angle at which they are seen. A crucial role in this picture is attached to a thick dusty torus surrounding the central black hole of the galaxies and obscuring it if viewed edge-on. Astronomers at MPIA together with colleagues from the University of Bochum were able to detect such tori in the infrared spectral range for the first time, confirming the highly debated unification of radio-loud quasars and radio galaxies. This study is based on highly sensitive ISOPHOT data.

II Highlights

II.1 Free Floating Planetary Objects

At the end of 1995, Swiss astronomers for the first time detected a planet orbiting another star than the Sun. Further detections followed, and by now more than 60 so-called extrasolar planets are known. All of them have been found only indirectly due to the gravitational effects they exert on their central star. It is not yet possible to observe them directly because they are so close to their central star to be completely outshined by it. Recently, astronomers from Spain, the USA and the MPIA surprisingly found objects in a star formation region in Orion with masses on the order of 10 Jupiter masses. As these bodies do not orbit around a star they are called "isolated" or "free floating planets". Moreover, several brown dwarfs were found in the same area. On the basis of these observations the frequency of these faint objects can be determined. At the same time it is interesting to ask how they are related with planets bound to stars.

Already in 1998, astronomers at the MPIA had used the 3.5 m telescope at the Calar Alto observatory to take near-infrared images of a small star cluster around the star Sigma Orionis, which is at a distance of 1150 light years. The field covers 847 square arcminutes, a little more than the full moon. Soon afterwards, Spanish colleagues at the Astrophysical Institute of the Canary Islands on Tenerife obtained pictures of the same field in the optical spectral range (Fig. II.1). Comparing these pictures, several objects attracted attention because of their unusual red color. To clarify their nature, further observations were made, using among others the 2.2 m telescope at Calar Alto, the UKIRT and one of the two Keck telescopes on Hawaii.

Photometric images of 64 objects were taken through a series of filters, while spectra of 14 objects could be obtained – not an easy undertaking at magnitude levels of 16.5 to 22.8 mag in the near-infrared (at a wavelength of about 0.9 µm).

The spectra showed clear evidence of atmospheres containing exotic molecules, such as titanium- and vanadiumoxide, but also water vapor. Thereby and because of their low ages of 1 – 5 million years these cluster members could be identified as brown dwarfs of spectral types between M6 and L4. Their temperatures range from 1700 to 2200 Kelvin.

Frequency of brown dwarfs and "free floating planets"

Brown dwarfs are objects ranking between stars and planets. If the mass of a celestial body is below ~ 0.07 solar masses (corresponding to 75 Jupiter masses), temperature and pressure in its central region do not get high enough to start nuclear hydrogen fusion. Only the fusion of deuterium and tritium can be ignited for a short period of time, but is turned off again soon after. Then the body cools down. Such an object is called a brown dwarf. If its mass is smaller than about 13 Jupiter masses, even the deuterium-tritium burning is no longer possible. Today, such a celestial body is called a planet by many astrophysicists, whereas according to the classical notion, only bodies which formed in a disk around a star are regarded as planets. Defining a planet only by its mass and not by its formation process is easier for the moment, as the formation process for objects of planetary masses, like those detected recently, is not known at all.

To identify the objects within the Sigma Orionis cluster, astronomers had to determine their masses. In this case, this was only feasible with the help of a model, which describes how quickly brown dwarfs and planets cool down after their formation. Given that all objects of the cluster have formed at about the same time, the smallest bodies should be the coolest. Such a model also relates the color of a celestial body to its mass: The smaller the body, the cooler and thereby the redder it is.

As is known from other studies, the star cluster in Orion is between one and five million years old. So three models, each assuming a different age, were calculated and the results compared with the observed data. The best fitting one was for an age of five million years (Fig. II.2). In this model the objects lined up along a mass sequence that ranges from extremely faint stars of at most 200 Jupiter masses through the range of brown dwarfs down to planets. The smallest ones only have about 5 Jupiter masses.

A central quantity of stellar astronomy is the mass function, which gives the number of stars per mass interval. Generally, this fraction increases inversely with mass so that there are many more smaller stars than bigger ones. Now, an important question is: Does this behaviour, which applies for a wide range of stellar

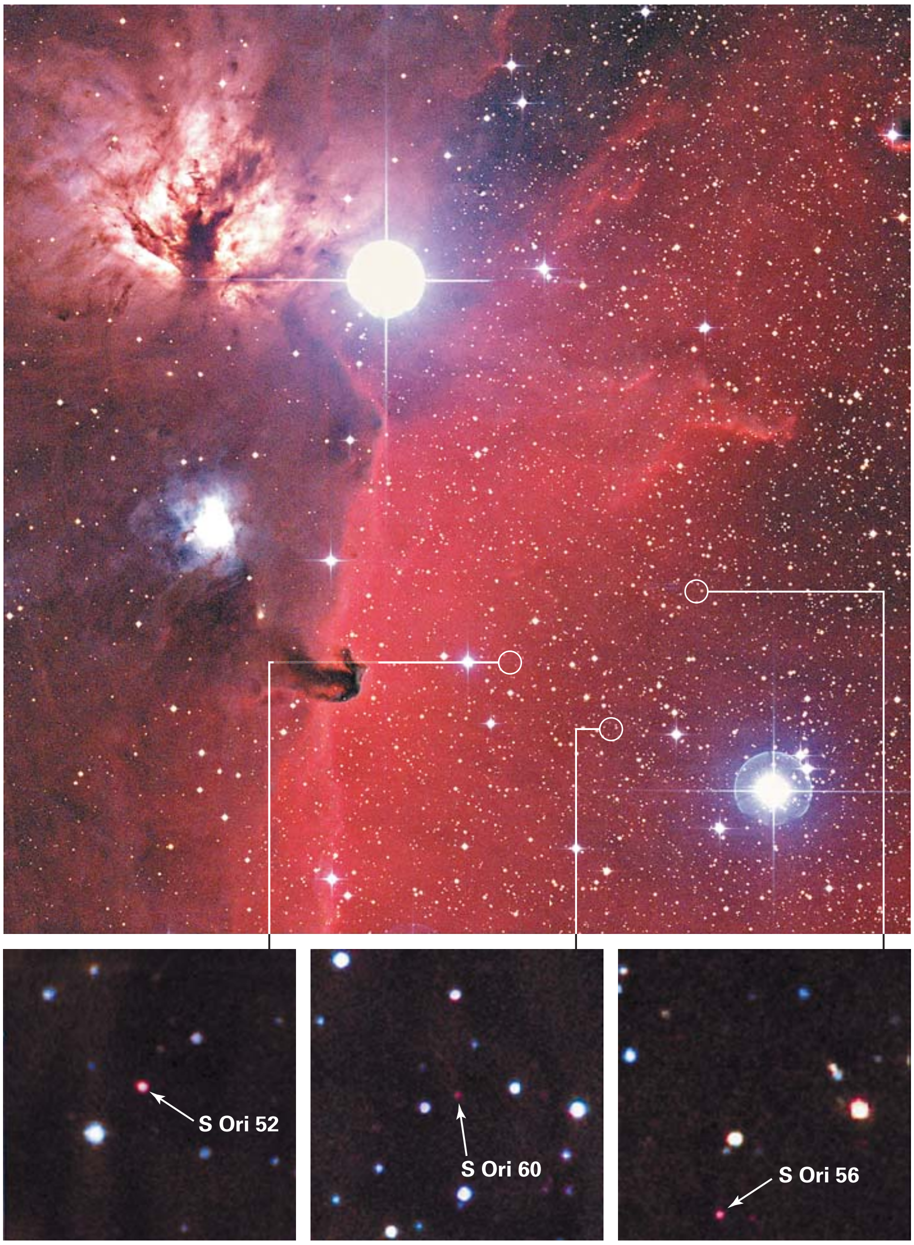


Fig. II.1: Near the Horsehead Nebula in Orion, astronomers detected for the first time "free" brown dwarfs und planets. (Photo: AAO, Zapatero Osorio)

masses, extend down to the lowest-mass objects? An answer to this question is very difficult, because star counts get incomplete when reaching the range of the lowest-mass and therefore faintest stars.

Last year, astronomers at the MPIA had discovered in the course of the CADIS project that this inverse proportion holds down to about 0.2 solar masses (see Annual Report 1999, p. 60). According to the recent observations of the Sigma Orionis cluster the relation seems to extend even into the range of brown dwarfs. The distribution reaches a maximum at an absolute near-infrared magnitude of 9 mag (corresponding to brown dwarfs of 0.05 to 0.08 solar masses). Then it decreases and remains constant over a wide range (Fig. II.3).

Using a stellar evolution model, the mass function can be calculated from the luminosity function, yielding the number of objects per mass interval at the time of their formation. As the exact age of the cluster is not known, this conversion is somewhat uncertain. Nevertheless, even under the assumption of different ages, the results suggest that the number of objects in the brown dwarf range increases further with decreasing mass. (Fig. II.4)

Extrapolation of the mass function confirmed for stars into the range of planets leads to the surprising result, that there are as many free floating planets of masses between 1 and 12 Jupiter masses as brown

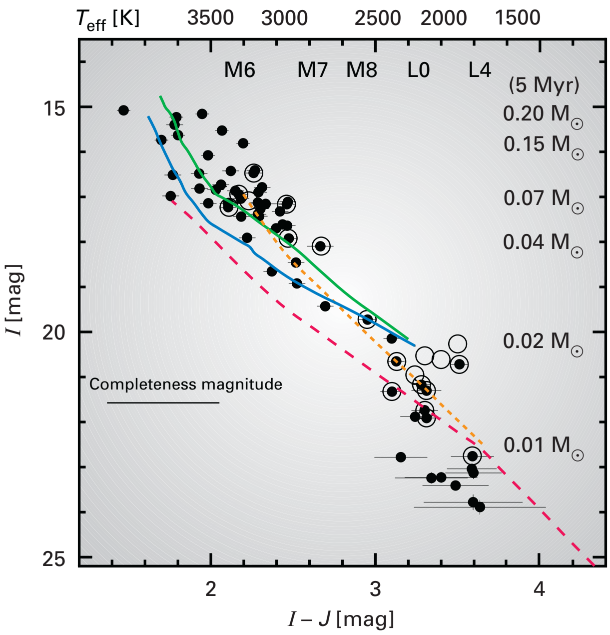


Fig. II.2: Color-magnitude diagram of the Sigma Orionis star cluster. The curves represent different models. The derived masses (right-hand scale) are for a cluster with an age of five million years.

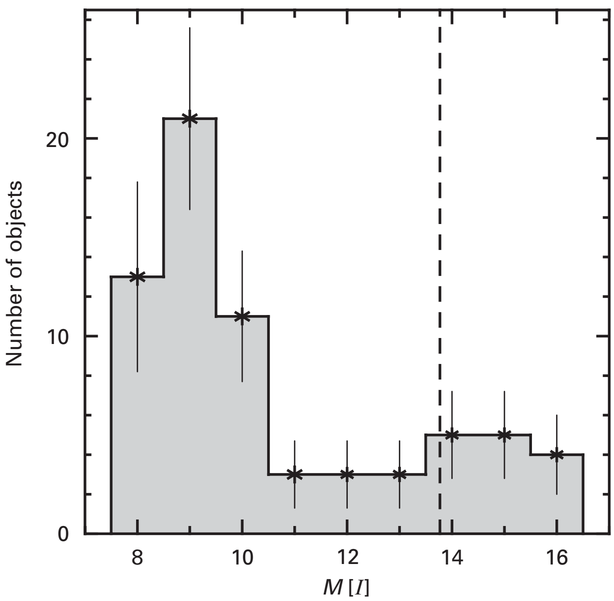


Fig. II.3: Luminosity function of the cluster members. The dashed line marks the completeness limit of the observations.

dwarfs. However, because of their low masses their overall contribution to the total stellar mass would amount only to about ten percent. Consequently, there should be 100 to 200 brown dwarfs and as many free floating planets within a radius of about 30 light years around the Sun.

As these objects are just at the detection limit of current large telescopes, the possibility to find them depends decisively on their age: The older they are, the cooler and fainter they become. Planets of 1 to 12 Jupiter masses with the same age as the Sun would have temperatures between 100 and 300 K and absolute near-infrared magnitudes at 1.2 µm of 20 to 25 mag. They could not be detected even in a few light years distance.

Why do “free floating planets” exist?

A good deal of the new observations comes as a surprise – the number of the detected low-mass bodies and, above all, the fact that there are isolated objects with planetary masses. Their isolation, however, is just the reason why these tiny dots are observable at all – planets orbiting a star are outshined by the star’s millionfold brightness. Moreover, at five million years the isolated planets are still very young and therefore hot enough to emit especially strong infrared radiation. But why do free planets exist in the first place?

According to our fundamentally confirmed notion, planets form within disks of gas and dust surrounding their young central parent stars. Although current models suggest that it is rather unlikely for a low-mass isolated planet to form from a collapsing interstellar cloud of at least one solar mass (corresponding to 1000 Jupiter masses), it is not completely excluded. It also seems possible, that the detected “planets” are impeded stars or brown dwarfs – bodies, whose growth was suddenly brought to an end by an unknown process. This could have been caused by a strong particle wind from the nearby bright star

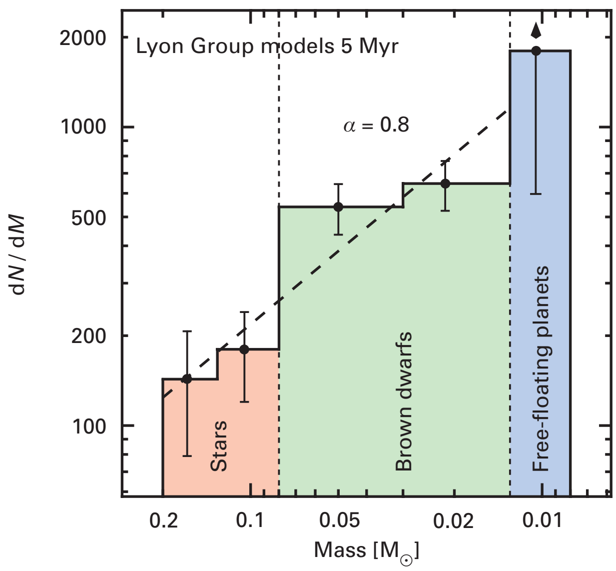


Fig. II.4: The original mass function for the members of the Sigma Orionis cluster, calculated for an age of five million years. The inclined dashed line represents the best model.

Sigma Orionis or a supernova explosion in close proximity, destroying the neighboring circumstellar disks from which newly forming stars were accumulating matter during their growing stage.

Another possible formation process for isolated planetary objects has been indicated by computer simulations, performed also by the theory group at MPIA (see Annual Report 1997, p. 58). If newly forming planetary systems move around in space and get sufficiently near to one another, they can snatch protoplanets from each other by gravitational interaction and expel them into interstellar space. Eventually, this could lead to chaotic planetary orbits within a young system, so that some members are catapulted out of the system by the gravitation of the others. So the newly discovered loners might be planets that were torn off from their "home star".

But there are some problems with this explanation. Free objects originating this way should have high velocities and rapidly leave the cluster in which they formed. Therefore the process just described should produce sporadical free bodies and not the large numbers that were found in the Sigma Orionis cluster.

This exciting discovery sheds new light on the formation of stars and planets, indicating processes not previously considered by astrophysicists. It also shows that the definition of celestial bodies like planets, brown dwarfs and stars has to be reconsidered.

II.2 Three Stages of Dust Heating in Ultra-Luminous Infrared Galaxies

Ultra-luminous infrared galaxies (ULIRGs for short) emit a large fraction of their luminosity in the far infrared spectral region due to warm dust. ULIRGs are colliding galaxy pairs, sometimes in an advanced state of merging. Possible sources of their ultra-high dust luminosities are large numbers of newly forming stars within both galaxies as well as quasars embedded within their centers. In the course of merging, the initially cold dust of the parent galaxies may be heated by different processes. To recognize such processes the dust emission has to be investigated over the complete infrared and sub-millimeter range. In the year under report, astronomers at MPIA together with colleagues from the University of Bochum have conducted the most extensive photometric study of ULIRGs so far. They succeeded in identifying three different stages of dust heating and their relations to central black holes, star formation, as well as cold cirrus-like dust.

Among the spectacular discoveries of the IRAS infrared satellite in the mid 1980's was the hitherto unknown class of ultra-luminous infrared galaxies. Unlike normal galaxies ULIRGs emit more than 90% of their energy in the far-infrared range between wavelengths of 60 µm and 100 µm in the form of dust emission. At the same time, these huge amounts of dust block any optical view of processes within. Sensitive, high-resolution images taken with the Hubble Space Telescope in the near-infrared revealed ULIRGs to be interacting galaxies, sometimes even in an advanced state of merging (Fig. II.5).

Such extremely close interacting systems show an increased rate of star formation. Here, a major contribution to a better understanding came from theoretical studies: As strong tidal forces overcome the angular momentum barrier, which normally keeps interstellar gas clouds on regular orbits around the center of mass, large amounts of gas plunge into the newly forming gravitational centers. Clouds colliding there condense into large numbers of dense cores, which develop into massive luminous stars. Galaxies displaying such a sudden burst-like increase of star formation are called starburst galaxies.

Moreover, the in-falling gas can “fuel” the accretion disk of an already existing central black hole. In fact, about 30 % of all ULIRGs show spectral lines indicating an active galactic nucleus similar to that in Seyfert galaxies and quasars. According to further theoretical considerations, the burnt-out super star clusters themselves could collapse into a new black hole, turning a starburst galaxy into an active galactic nucleus.

Dust is mixed with the interstellar gas at a ratio of approximately 1 : 100 by mass. The dust very effectively absorbs the short-wavelength radiation of hot stars and active galactic nuclei and re-radiates the absorbed energy at longer wavelengths in the infrared range. In interacting galaxies, the gas is, like the dust, concentrated in dense regions, thus obscuring the core at shorter wavelengths. To explore these hidden processes, it is practical to study the dust emission itself, which can only be done in the infrared.

Besides the controversial question of the dominating energy source of ULIRGs – starburst or quasar – it is interesting to know if ULIRGs in general, or at least in an early evolutionary state would harbor cold dust similar to the infrared cirrus in our own Milky Way. Studies across the entire infrared range from 1 to 1000 µm should provide important clues about the interactions of the different dust components and their heating sources. While in the near- and mid-infrared range new evidence for the presence of quasars is expected, the far-infrared and sub-millimeter emission should be dominated by starbursts and cool dust.

From 1996 to 1998, 41 of the nearest and brightest ULIRGs were observed photometrically at wavelengths between 10 and 200 µm using ISOPHOT. (As the objects are too distant and too compact to be imaged in detail at these wavelengths, their integrated flux is determined photometrically and the spectral energy distribution is analyzed over a large wavelength range.) In addition, about half of the sources were observed with the James-Clerk-Maxwell Telescope on Hawaii at 450 µm and 850 µm using the SCUBA instrument and with the ESO/SEST sub-millimeter telescope on La Silla at 1300 µm. Moreover, astronomers at the Institute were able to study the spectacular Antennae galaxy pair, a system which is probably just developing into an ULIRG. Finally, using the MAGIC camera at the 2.2 m telescope on Calar Alto, MPIA astronomers obtained also near-infrared images at 1.2 µm and 2.2 µm. These, too, show irregular structures and extended tails as a consequence of galaxy collisions (Fig. II.6). With these data, statistically-usable, consistent, infrared and sub-millimeter photometry of 22 ULIRGs is available for the first time.

Three stages: Hot, warm and cold dust

The spectral energy distributions (Fig. II.7) show four significant characteristics:

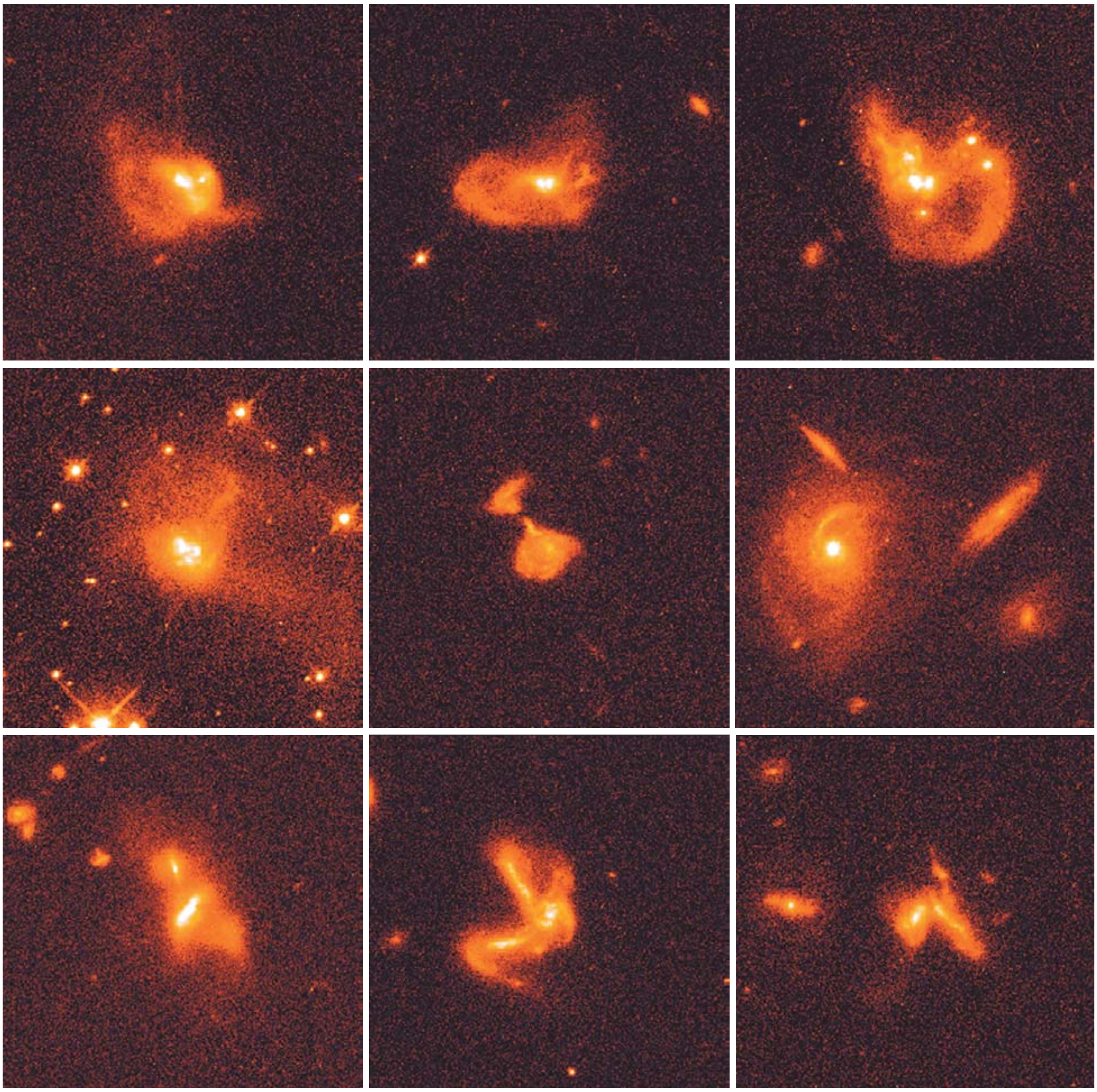
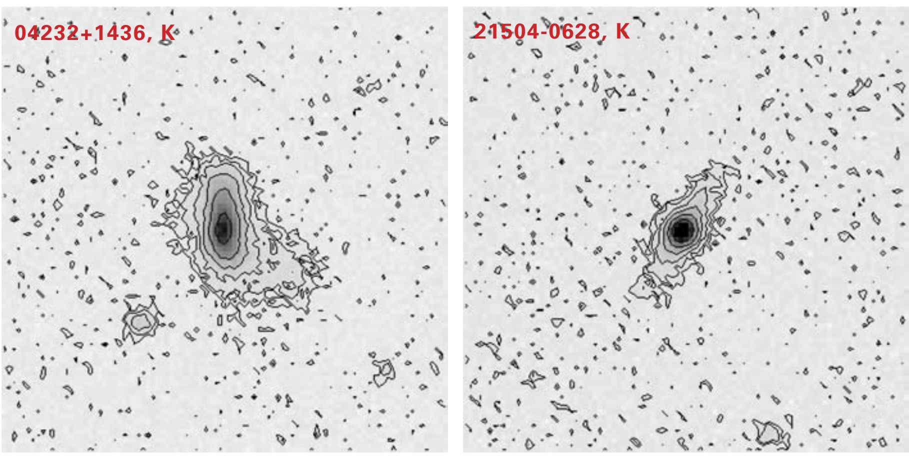
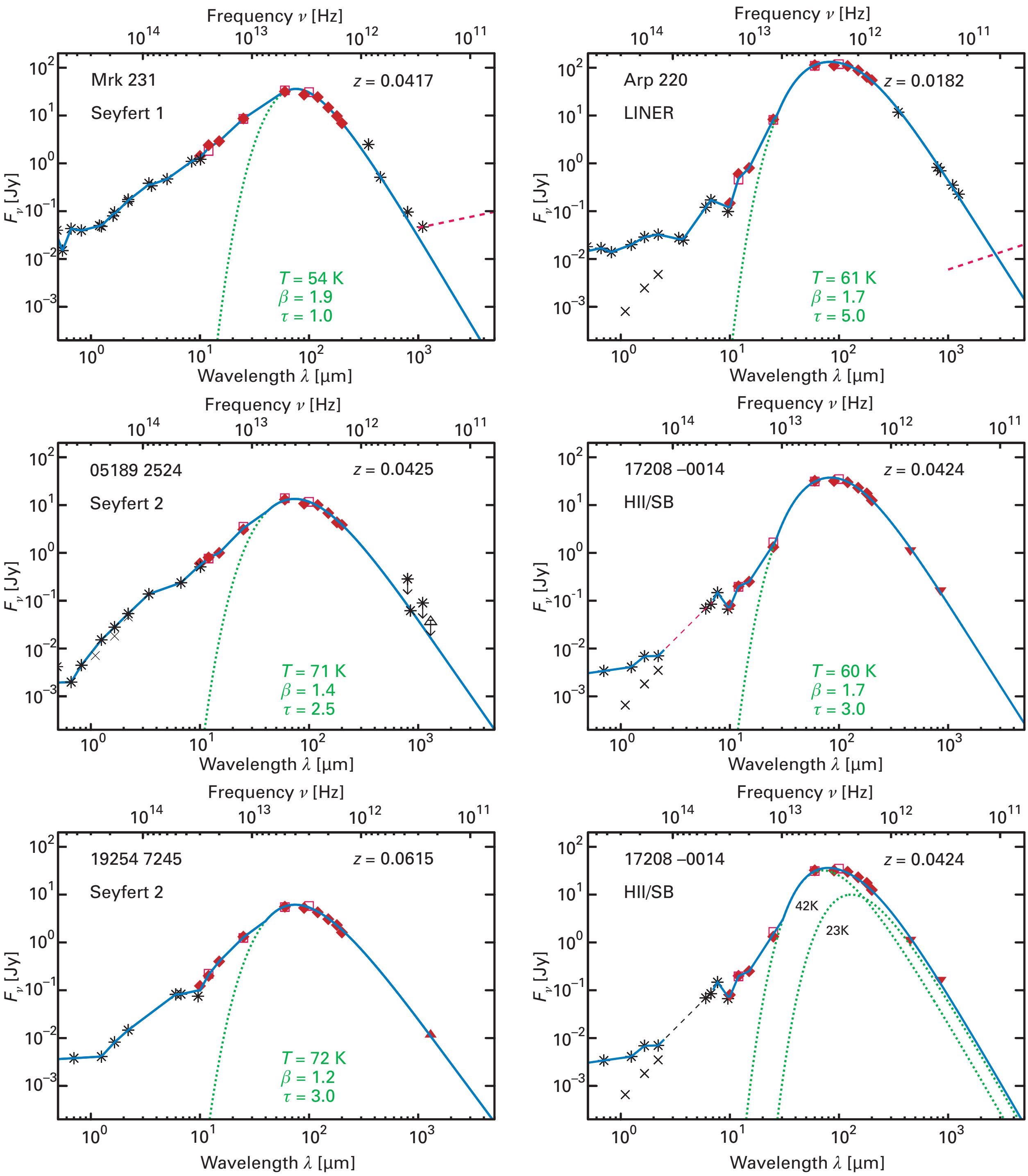


Fig. II.15: ULIRGs, imaged with the HUBBLE Space Telescope. (Photo: ESA/NASA).





▲ **Fig. II.7:** Spectral energy distributions of some ULIRGs. Left column: ULIRGs with steadily increasing intensity in the near- and mid-infrared range. Right column: ULIRGs with a plateau, followed by a steep increase. On the longer-wavelength side of the maximum the intensity decreases with differently steep gradients (left column, top: steep, bottom: flat). The parameter ß describes the emissivity of the radiating dust grains (see text). As illustrated by IRAS 17208-0014 with a mean value of β (β < 2), spectra can also be fitted instead with several Planck curves with β = 2.

◀ **Fig. II.6:** Two of the newly studied ULIRGs, imaged at 2.2 μm with the MAGIC camera at the 2.2 m telescope on Calar Alto.

1. The maximum of the measured intensity always lies in the far infrared between 60 µm and 100 µm, corresponding to a dust temperature of about 50 Kelvin. This is characteristic for all ULIRGs.

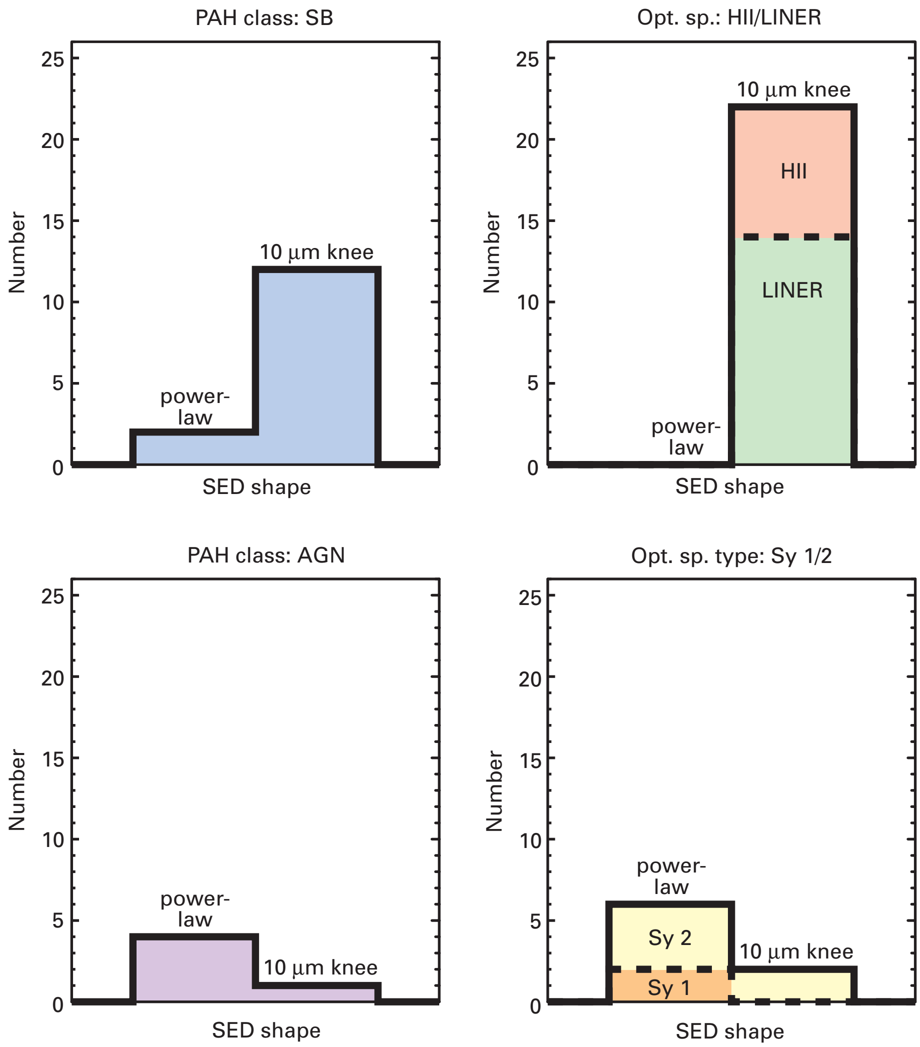
2. In the near and mid-infrared the spectra show two different basic shapes: The first is characterized by a steep but steady increase of the intensity with wavelength. The radiation originates from hot dust of temperatures between 100 K and 1000 K. The second shape exhibits a flat plateau between 1 µm and 10 µm followed by an abrupt increase between 10 µm and 40 µm. Maybe the radiation of the hot dust has experienced stronger extinction so that normal "blue" light coming from outer regions with smaller extinction is outshining the "reddened" fraction. While the first shape is only observed in ULIRGs with an active galactic nucleus, all ULIRGs which only exhibit evidence of starbursts are among the second type (Fig. II.8). But there are also mixed shapes and overlaps. These two spectral shapes offer a nice criterion – also applicable to faint sources – to track down quasars in ULIRGs using photometry in the near and mid-infrared.

3. At wavelengths longward of the intensity maximum, that is, in the extreme far-infrared and sub-millimeter range, ULIRGs dominated by active galactic nuclei cannot be distinguished from those dominated by starbursts (Fig. II.9). This suggests that the 50 Kelvin warm dust (and possibly other cooler components) is heated mainly by starbursts and not by the central black hole. The mass of warm and cooler dust is a hundred to a thousand times larger than that of hot dust.

4. Independent of the type of galaxy (AGN or Starburst), the intensity decrease with increasing wavelength in the extreme far-infrared and sub-millimeter range in some cases is flat, in others steep.

Such differences have been found in other galaxy types, too. Their interpretation is presently the subject

Fig. II.8: Comparison of different classes of ULIRGs. In Seyfert galaxies (bottom), the flux increase in the near- and mid-infrared range mostly follows a steep power law while it is flat in starburst galaxies (top), demonstrating the consistency with the spectral classification in the optical (left) and in the mid-infrared (right).



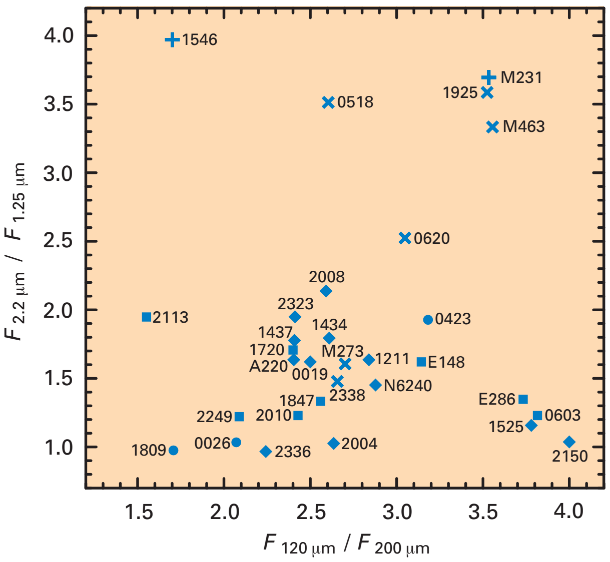


Fig. II.9: Color-Color diagram of ULIRGs. Crosses label Seyfert galaxies with central black holes; other symbols denote starburst galaxies. While most of the Seyfert galaxies can be clearly distinguished from other ULIRGs by their near-infrared colors (*y* axis), a black hole apparently has no influence on the distribution of the far-infrared colors (*x* axis).

of intensive investigation. The spectral energy distribution of the dust can be modeled by so-called modified Planck spectra, with the modification depending on the characteristics of the dust. Two competing explanations for the varying decrease of the long wavelength Rayleigh-Jeans tail are discussed:

The first explanation is that the steepness depends on the distribution of the size of the dust grains, described by the emissivity parameter β. (The emissivity gives the emission efficiency at a given wavelength relative to a perfect blackbody.) At long wavelengths, large grains can emit more easily than small ones. A dust cloud consisting mainly of large particles with diameters up to about 3 µm is expected to show a relatively flat spectrum and a value of β near 1. Typical dust clouds in our Milky Way by comparison have a steeper Rayleigh-Jeans tail with β near 2, thus containing mostly grains smaller than 1 µm.

Others argue that a flat Rayleigh-Jeans tail could also be caused by superposition of several (modified) Planck curves of different temperatures. This is also supported by spatially resolved observations of the Antennae galaxies (see below), which are thought to be a ULIRG in the making.

Based only on integrated spectra, this controversy cannot be resolved. The majority of normal spiral galaxies, as well as the so-called Markarian galaxies with an intense radiation field of a central accretion disk, have values of β near 2. So it is obvious to assume the average grain size of dust clouds in starburst galaxies to be small. If this value of β also applies for ULIRGs, those with a flat Rayleigh-Jeans tail should contain different dust components of different temperatures from warm to cold.

In view of the complex optical morphology it seems plausible that the description of the dust content by only one (modified) Planck curve with a single temperature is too simple. On the other hand conditions in ULIRGs are undoubtedly very peculiar, signaled by huge luminosities and very high extinctions. Thus, the dust may well show rather exotic characteristics with large particles prevailing. To put it into descriptive and somewhat exaggerated words: A cosmic pile of sand?

Indeed, in this case the dust clouds would be dense enough to prevent even the long-wavelength far-infrared radiation from escaping freely to the outside. Thus ULIRGs would be optically thick even at 100 µm. At present, this striking notion cannot easily be discarded.

An important step forward to resolve this question was taken by astronomers at MPIA, who compared the line strengths of polycyclic aromatic hydrocarbons with the strength of the sub-millimeter continuum. This comparison provides a strong argument against a single Planck curve hypothesis (see below).

Thus, the entire dust content detected can be used to confirm a complete model of ULIRGs, a model which which had been proposed in the late 1980's. It comprises three basic building blocks, the dust components and their temperatures being indicators of physical processes and evolutionary states:

1. Hot dust with temperatures between 100 and 1000 Kelvin. (The highest temperatures are close to the evaporation temperature.) The dust is heated by radiation from the accretion disk of the central black hole.

2. Warm dust at about 50 Kelvin. It is distributed in the large star formation regions of the galaxy and heated mainly by young massive stars.

3. Cold dust at about 20 Kelvin. It corresponds to the cirrus dust filaments of our own Milky Way, and is located outside the active regions. If such cold clouds are situated close to the active centers, they have to be denser than the thin Milky-Way cirrus to be sufficiently protected against the strong radiation field. These dense, cold dust complexes could serve as a not-yet-ignited reservoir of future starburst activity.

Although further confirmation of this three-stage dust model is still needed it already provides a framework for interpretation of further observational results.

Polycyclic aromatic hydrocarbons

Using the ISOPHOT-S spectrograph, MPIA astronomers reported new findings on the characteristics of polycyclic aromatic hydrocarbons (PAHs) in our Milky Way and other nearby galaxies (see Annual Report 1999, p. 24). In particular, the observations suggest PAHs being ubiquitous in the interstellar medium. Of special interest is the prominent PAH emission band at 7.7 µm. The strength of this spectral band relative to the mid- and far-infrared continuum has provided a widely-accepted criterion of the dominance of either active galactic nuclei or starbursts in ULIRGs.

The aforementioned new result is the following: The long wavelength part of the spectral energy distribution (> 60 µm) can be fitted with one single (modified) Planck curve with just one temperature. If the dust content of ULIRGs were modeled this way, the Planck fit to the detailed spectral energy distributions would automatically yield the optical depth τ. (τ is a measure of the dimming of light by dust at a given wavelength.) At 100 µm wavelength, values of 0.5 up to > 5 for the optical depth τ are derived, values > 1 being already remarkably high. In this case the dust clouds also have a strong obscuring effect in the mid-infrared range. As the PAHs obviously are mixed with the interstellar medium, the strength of their emission bands should also be affected significantly by extinction. Thus, ULIRGs with a high value of τ are expected to show a decreasing relative PAH strength. The data, however, do not show such a correlation (Fig. II.10). On the contrary, the observed relative PAH strength is independent of the modeled optical depth – thus the 1-component model is not appropriate to describe the dust content of ULIRGs.

Even more exciting is the following discovery: Apart from a few exceptions, the ratio of the PAH line

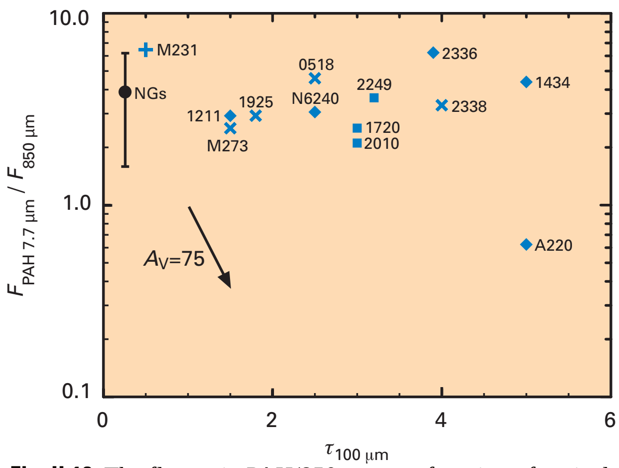


Fig. II.10: The flux ratio PAH/850 µm as a function of optical depth τ. Apart from one exception (Arp 220) the values for ULIRGs lie in a relatively small horizontal strip at 5 ± 2. For normal galaxies, they lie in the same region (vertical bar on the left). With increasing τ, the ULIRGs do not show a decrease parallel to the orientation of the arrow. This is another argument against the description of the spectral energy distribution by a single Planck curve.

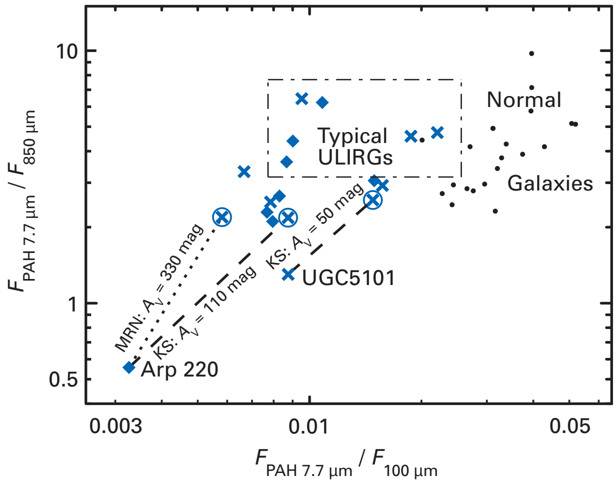


Fig. II.11: Color-Color diagram of ULIRGs and normal galaxies. The dashed rectangle indicates the region populated by ULIRGs (apart from Arp 220 and UGC 5101) after correction with known extinction values. Arp 220 and UGC 5101 show significantly smaller values of the 7.7 µm / 850 µm flux ratio than the other ULIRGs, Arp 220 even has a markedly smaller 7.7 µm /100 µm flux ratio. The dotted and the dashed lines represent the shifts caused by extinction for two different dust models. The encircled crosses indicate the possible location without extinction near typical ULIRGs.

strengths and the continuum at 850 µm is not only independent of the modeled optical depth but also populates a range of values with surprisingly small scatter, actually like a "material constant" of the interstellar dust (Fig. II.11). To confirm this finding, astronomers at MPIA searched the ISO and SCUBA archives for PAH and 850 µm data of other, mostly normal galaxies. Indeed, the PAH strength normalized to the sub-millimeter flux turned out to lie in a well-defined narrow range for almost all galaxies observed so far.

For the ratios of PAH line strength to the continuum at 100 µm, however, differences show up: ULIRGs have smaller values than normal galaxies (Fig II.11). This can be explained by ULIRGs having higher dust temperatures than normal galaxies and radiating more intensely at 100 µm. This behavior also suggests that PAHs are not so much associated with the warm dust heated by starbursts, but rather with the cold dust of the cirrus (or in dense molecular clouds), which is radiating intensely in the sub-millimeter range.

In Fig. II.11 two exceptions attract attention by particularly small relative PAH strengths. These are caused by high extinction even in the mid-infrared range. The extinction in both ULIRGs, UGC 5101 and especially Arp 220, is enormous.

This is an impressive demonstration that the intensity ratio of the PAH bands to the continuum in the sub-millimeter range can be used as a new method to study high extinctions: While PAH emission is sensitive against extinction in the mid-infrared range the radiation at 850 µm is always optically thin.

Measuring the latter therefore allows normalization with the content of the entire dust column. This feature in particular represents an advantage of the new approach compared to previously known methods, in which the extinction was determined exclusively at significantly shorter wavelengths, thus possibly only "scratching" the surface of the dust column.

A hidden quasar in Arp 220?

Arp 220, located at a distance of about 200 million light years, is the nearest and probably best-studied ULIRG. Invisible at optical wavelengths, two galactic core regions with a projected separation of 0.″8 (corresponding to 800 light years) show up on near-infrared images. Although a broad spectral line typical of active galactic nuclei was measured in the 1980's using near-infrared spectroscopy, it was so faint that in numerous subsequent observations starbursts were favored more and more as the dominating energy source of this classical ULIRG.

Now, an extinction of 150 magnitudes in the optical range (corresponding to a dimming by a factor of 1060) is shedding quite another light on Arp 220. Taking into account this enormous extinction is the clue to the interpretation, providing the de-reddened true spectral energy distribution. In their analysis scientists at MPIA show the mid-infrared luminosity as well as the ratio of mid- to far-infrared luminosity after de-reddening taking on values as they so far are only observed in quasars and active galactic nuclei (Fig. II.12).

These results are in agreement with current CHANDRA X-ray satellite measurements, which astronomers in Great Britain and the US interpret as convincing evidence for a quasar being present in one or even both of the nuclei in Arp 220. These new findings, obtained by two independent methods, support each other and revive the debate on hidden quasars. They demonstrate how our fundamental view of cosmic phenomena can be affected by dust absorption.

The Antennae – a ULIRG in the making

At a distance of 70 million light years, NGC 4038 and NGC 4039 form the pair of colliding galaxies which is closest to us. Because of the shape of its spectacular tidal arms, it is also called the Antennae (Fig. II.13). While stars can be expelled from the disk by elastic collisions during the merger, thereby forming the tidal arms, the interstellar matter experiences inelastic collisions and concentrates mainly in the joint central region. There, it is compressed, and as a consequence millions of new stars are forming within

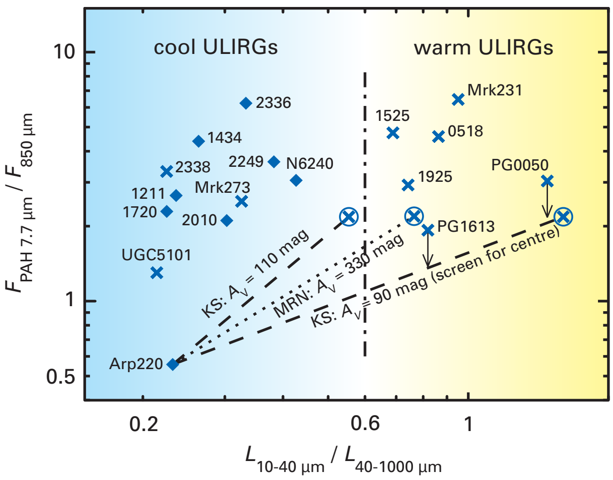


Fig. II.12: Color diagram of ULIRGs. After de-reddening Arp 220 shows PAH/850 values similar to a typical ULIRG. Depending on the assumed model for the dust grains (MRN, KS, screen), Arp 220 lies in the region of so-called warm ULIRGs with highly active galactic nuclei or of quasars.

in the region of most violent interaction in both galaxies. As many of these star formation regions still are deeply embedded within dust they are not visible in optical light but only at mid-infrared wavelengths, where the dust becomes transparent. From the color and luminosity of the dust emission in the far-infrared and sub-millimeter range, conclusions can be drawn about hidden star formation processes.

Some years ago, astronomers at MPIA using ISOPHOT had determined the system's infrared luminosity in a range between 10 and 200 µm to be 6.4×10^{10} solar luminosities, which is lower than the 10^{12} solar luminosities normally found in ULIRGs. However, it seems reasonable to expect the Antennae to develop into a ULIRG in the course of its further merging. Because of its proximity it is an excellent laboratory for detailed studies of this galaxy type.

Astronomers at the Institute together with colleagues in Great Britain and the US were able to observe this colliding galaxy pair with unprecedented resolution using ISOPHOT at 60 and 100 µm as well as SCUBA at the James-Clerk-Maxwell Telescope at 450 and 850 µm.

Because of the larger telescope aperture relative to the observed wavelength more details are seen in the sub-millimeter images than in the infrared images (Fig. II.14). Most remarkable are the condensations K1 and K2, located exactly within the collision zone of both galaxies. They are about 6500 light years apart and contain ~10^7 solar masses of dust each. This amount of dust, corresponding to about 20 % of the dust content of a normal galaxy, is squeezed into a relatively small volume about 2000 light years across. The nuclei of both galaxies have been detected, too, but they are less prominent.

Fig. II.13: The Antennae in the optical range. The HST image on the right-hand side (detail) clearly shows colliding dust clouds and numerous nests of young blue stars. (image: NASA/ESA)

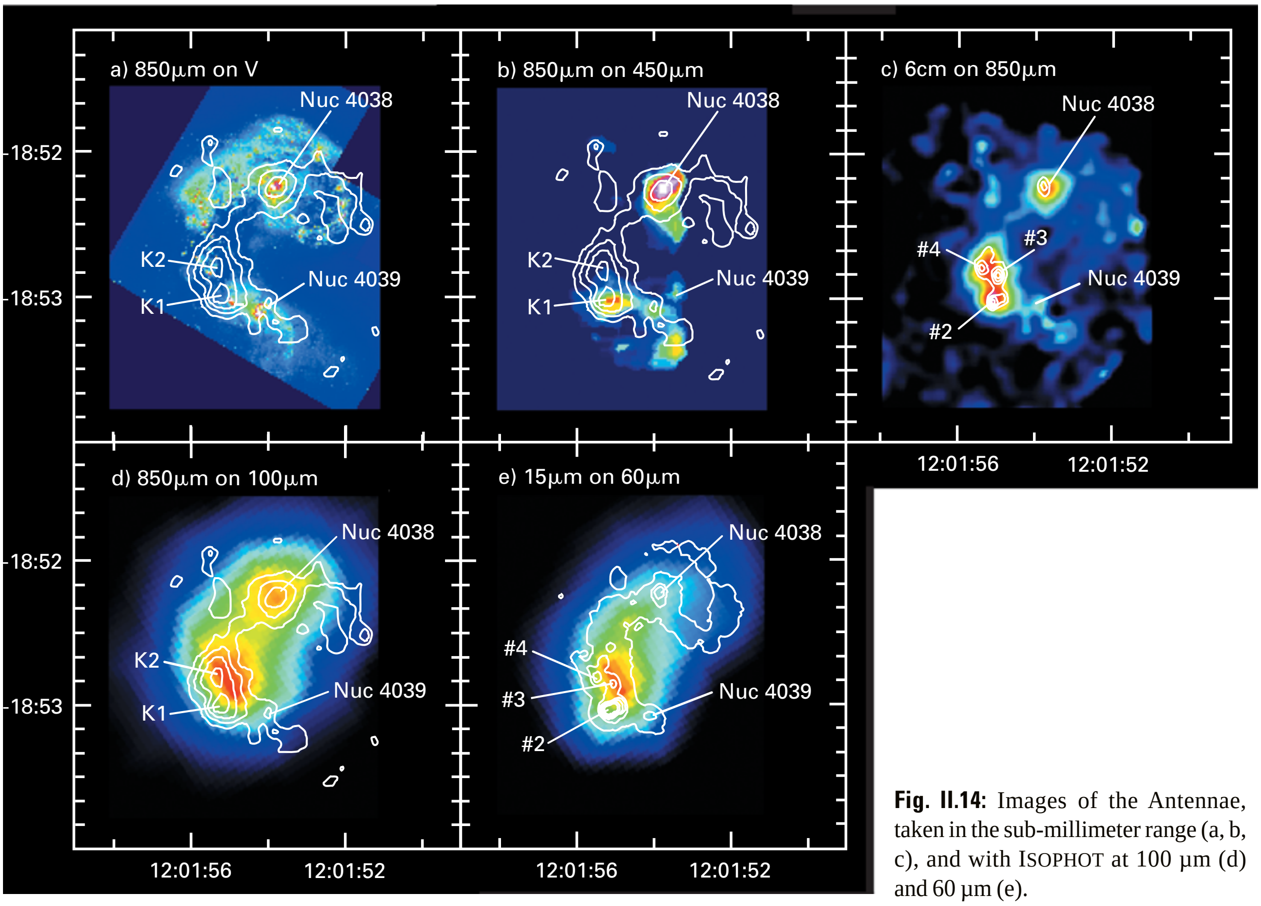


Fig. II.14: Images of the Antennae, taken in the sub-millimeter range (a, b, c), and with ISOPHOT at 100 µm (d) and 60 µm (e).

The biggest surprise has been the difference between the two condensations K1 and K2: While being equally bright at 850 µm, the northern knot K2 is significantly fainter at 450 µm, and thus is likely much cooler than the southern knot K1. It is thus suggested that most of the dust in region K1 has already been heated by starbursts, but not so in K2.

Comparison with observations in other wavelength ranges shows both knots being detected in the mid-infrared at 15 µm and in the light of the CO molecule, as well as in the radio range at wavelengths of 6 and 20 cm. The cold knot exhibits significantly fainter signs of violent starbursts than the warm knot K1.

These studies show that in addition to starburst regions, in which dust has already been heated, there are cold regions in a proto-starburst stage, which will soon develop into breeding grounds for a large number of new stars, thereby increasing the total infrared luminosity considerably and turning the Antennae into a ULIRG.

II.3 Black Holes in Galactic Centers

Formation of massive black holes in the centers of galaxies seems to be an integral part of the evolution of such stellar systems. Apparently, this is true not only for galaxies with active galactic nuclei, but also for normal galaxies like our Milky Way system. Astronomers at MPIA together with colleagues in the US were able to detect black holes of some tens to hundreds of millions solar masses in five weakly-active spiral galaxies. The new measurements show even more clearly than before that the mass of the black hole is related to the larger properties of its several million times larger host galaxy. This correlation has to be a result of galactic evolution. The reason for it, however, is not yet clear.

Black holes in galactic centers have masses roughly between one million and one billion solar masses. They are found in elliptical as well as in spiral galaxies, but only in those spirals showing a central bulge. The bulge is an almost spherical region containing mostly old stars. It resembles in shape and color a small elliptical galaxy. In 1995, astronomers from the US noticed that the mass of a central black hole is increasing with the absolute luminosity of the surrounding bulge. As luminosity is a measure of the amount of matter existing in the form of stars the mass of a black hole apparently increases with that of the bulge. As it turned out, black holes always contain about 0.2% of the mass of the surrounding central region (Fig. II.15a). This correlation, however, shows a large scatter: At a given luminosity the masses of the black holes can differ by a factor of thousand.

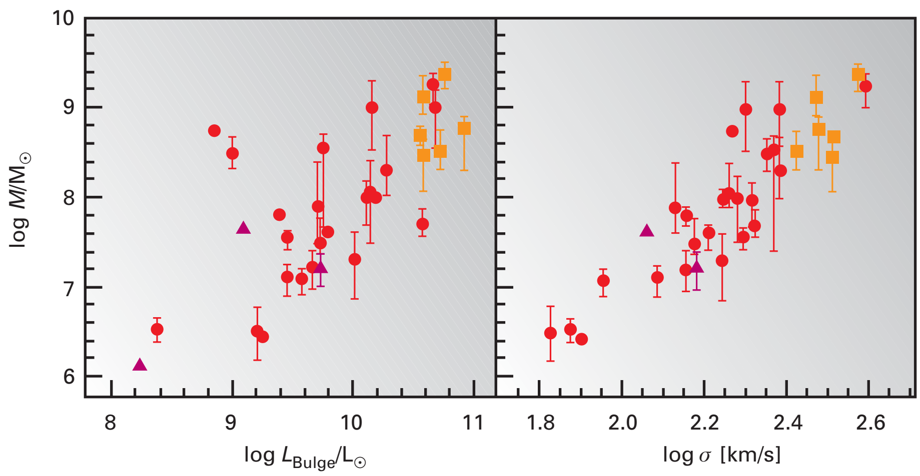
Studying 30 galaxies, another team of astronomers recently found a much tighter correlation between the masses of central black holes and the velocity dispersion of the bulge stars: The more massive the black hole, the faster the bulge stars move (Fig. II.15b).

Although at first sight these relations appear to be plausible, they turn out to be a big surprise on closer inspection: If a central black hole only has 0.2% of the total bulge mass accordingly its gravity is much lower than that of all bulge stars together. Consequently, it is not able at all to affect the motions of the large majority of stars in the central region: Most stars do not feel its influence at all. Thus the recently found correlation between black hole mass and the velocity dispersion in the bulge is by no means conclusive. It has to be related causally to the evolution or even the formation of galaxies.

Black holes in four weakly active spiral galaxies

To confirm these new results and to broaden the database, astronomers at the Institute together with colleagues in the US initiated the "Survey of Nearby Nuclei" using the Hubble Space Telescope. The goal was to study spectroscopically many spiral galaxies which are classified as weakly-active, and to determine the masses of putative black holes in their centers. The observations were performed using the STIS spectrograph on the Hubble telescope. Its long narrow slit was placed across the center of the galaxy so that the velocity of the interstellar gas relative to the center could be obtained from the Doppler shift of the spectral lines at increasing distances. The velocity in

Fig. II.15: Fig. II.15: The recently found correlations between central black hole masses and luminosity (a) as well as between central black hole masses and velocity dispersion of surrounding bulge stars (b).



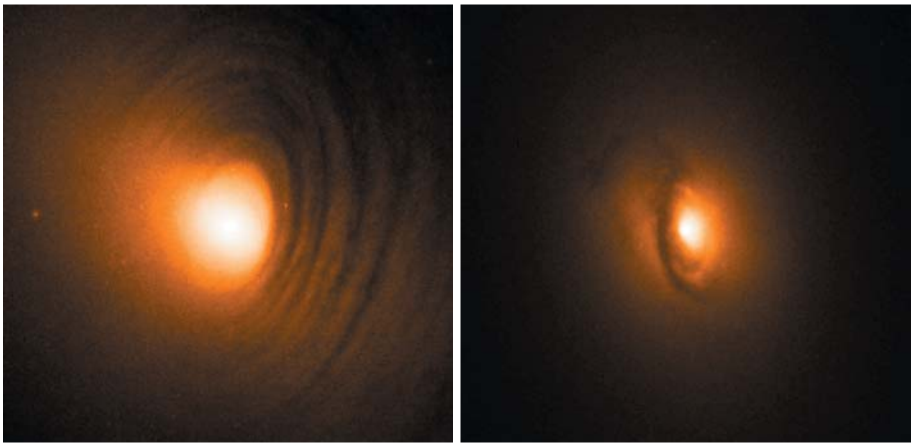


Fig. II.16: Images of the central regions of galaxies NGC 2787 and NGC 3245 taken with the Hubble Space Telescope. Thin dust lanes are seen, probably indicating the inclination of the inner gas disks.

turn yields the galactic mass within the respective radii. A prerequisite for this method to work is that the gas be moving in the gravitational field free of outer perturbations.

In twelve objects, emission lines of sufficient intensity were detected. However, eight objects were excluded from the study because of strong asymmetries of the lines with respect to the center, indicating the gas is disturbed and not moving on circular orbits.

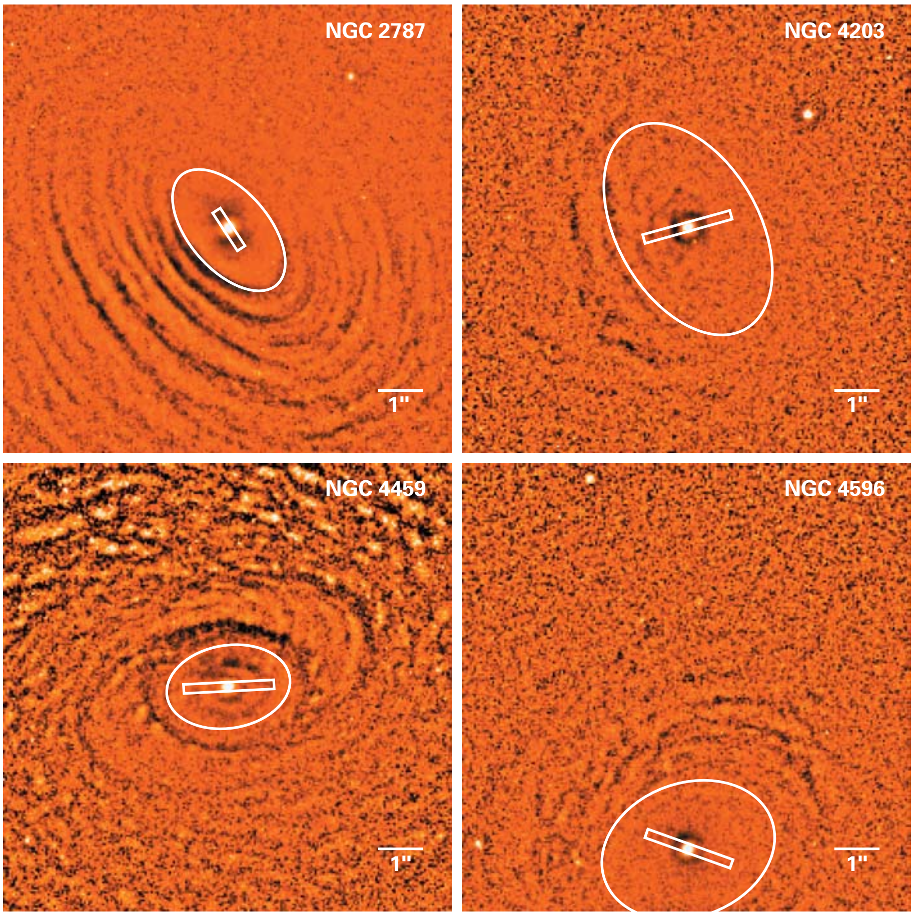


Fig. II.17: The four galaxies observed. The elliptical disks derived from the models and the positions of the slit of the spectrograph are shown.

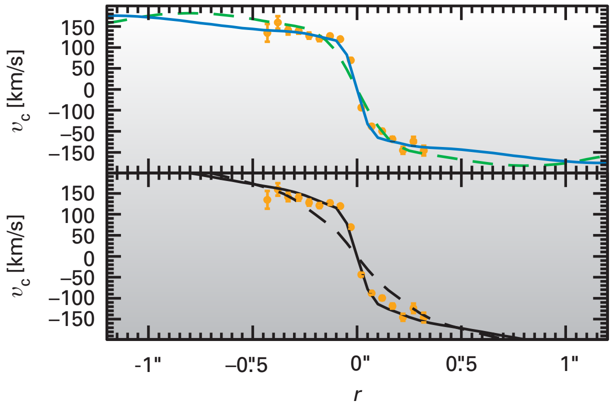


Fig. II.18: Rotation curve of the gaseous disk in NGC 2787. Shown is the model with an unconstrained inclination of the disk (above) and that with a disk inclination derived from the shape of the dust ring (below).

Four galaxies were left: NGC 2787 (at a distance of 42 million light years, Fig. II.16a), NGC 4203 (at 32 million light years), and NGC 4459 and NGC 4596 (both at 55 million light years). At these distances, the spatial resolution of the spectrograph corresponds to 8 to 14 light years.

To begin, radial velocities of the gas were determined from the spectral shifts of the emission lines. Then a model of the gas moving in a disk in the combined gravitational field of the bulge stars and of the black hole was calculated. This was achieved by first deriving the mass distribution of the stars from the luminosity distribution, assuming a constant mass-to-light ratio. The mass distribution was found to show a point-like cusp in the center, probably caused by a small gaseous accretion disk around the black hole emitting non-thermal radiation. As it does not contribute to the general stellar gravitational field, this cusp was removed from further calculations.

In order to determine the central mass from the velocity field of the gas in the disk the inclination of the disk to the line of sight has to be known. However, in the central region, which is of special interest, the inclination cannot easily be recognized. Images with the Hubble Space Telescope, though, show thin elliptical dust lanes (Fig. II.17), wich are assumed to have the same orientation as the gaseous disk.

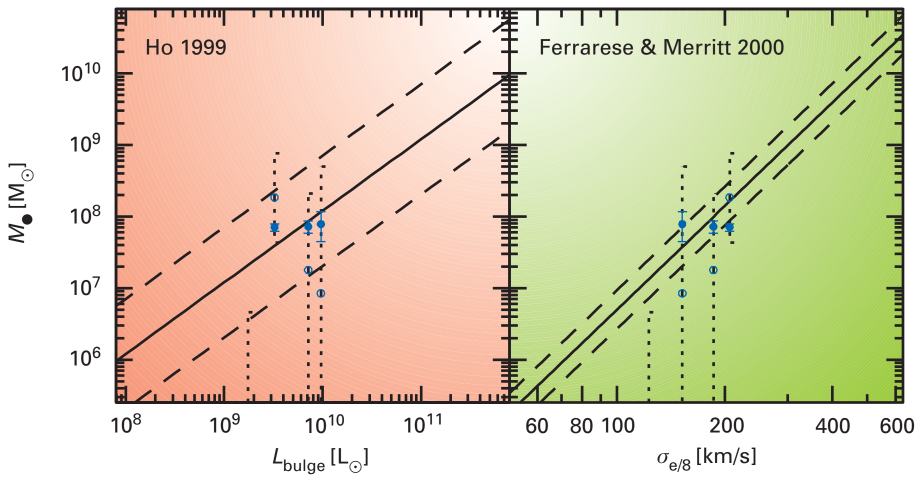
An example of the velocity profiles of the disk derived from two models is illustrated by NGC 2787 in Fig. II.18. Obviously, the model defined by the dust lane (bottom) is in better agreement with the observations than that with unconstrained inclination (top). The masses of the putative black holes derived from the models are about 5×10^7 solar masses for NGC 4203 and 7×10^7 solar masses for each of the other three galaxies. The value for NGC 4203 is uncertain.

These values have been used to test the recently-found correlations between the masses of black holes and the total bulge mass or the velocity distribution, respectively, confirming them within the uncertainty limit (Fig. II.19). This is of special interest, as the correlations had been studied so far almost exclusively in elliptical galaxies. The fact that they also hold in three spiral galaxies is important in the light of theories of galactic evolution. Moreover, the scatter of the measurements is shown to be lower than previously assumed by a factor of two.

Fig. II.19: Masses of black holes as a function of the total mass and the velocity distribution of the bulge, respectively. The linear correlation is confirmed within the 1-sigma range (dashed lines).

The Black Hole in the S0 Galaxy NGC 3245

The S0 galaxy NGC 3245 (Fig. II.16), located at a distance of 65 million light years, has been studied in particular detail, showing mild activity and an unresolved radio source in its central region. In addition, spectroscopic observations had suggested high rotati-



on velocities near the center. MPIA astronomers obtained Hubble Space Telescope images through different filters, as well as several spectra (Fig. II.20). The central disk has a size of only $1''.1 \times 0''.4$, corresponding to a radius of 360 light years.

In order to determine the contribution of the invisible putative black hole to the gravitational field, the mass of the stars and the disk in the central region must first be measured. For the disk, a mass of 2.4×10^6 solar masses was obtained – low enough to be ignored in modeling the dynamics.

Fig. II.21 shows the spectra containing emission lines of hydrogen and nitrogen. After subtracting the starlight from these spectra, the lines were fitted by a model. Varying model parameters, like the mass-to-light ratio, the density profile of the gas in the disk and the disk's inclination, yielded the best fit with the observed lines and velocities. Instrumental effects, like broadening of the emission lines or superposition of light from different disk regions lying within the slit, have been meticulously taken into account.

The lines were shown to broaden considerably with decreasing distance to the center. This could be caused by gaseous clouds being either strongly turbulent, or moving on elliptical orbits around the center. Without really knowing the cause for the line broadening, two models were calculated, one of which allowed for the effect while the other did not. With these models it was possible to determine the rotation curve of the gas disk and the mass within the central spatially unresolved region (Fig. II.22). A mean value of 2.1×10^8 solar masses was obtained from all simulations, with an uncertainty of about 25%. As it turned out, the meticulous care in calculating the models was necessary in order to determine the mass this precisely.

Although these observations cannot prove that the central mass really is a single black hole, there seems to be no physically-sensible alternative. Models with a dense central cluster of dark bodies have rotation curves with shallower central slopes. Statistically, models without a central massive object can be ruled out at the 99.99 % confidence level.

The velocity dispersion in the inner region of NGC 3245 is 230 km/s. For this value, the correlation

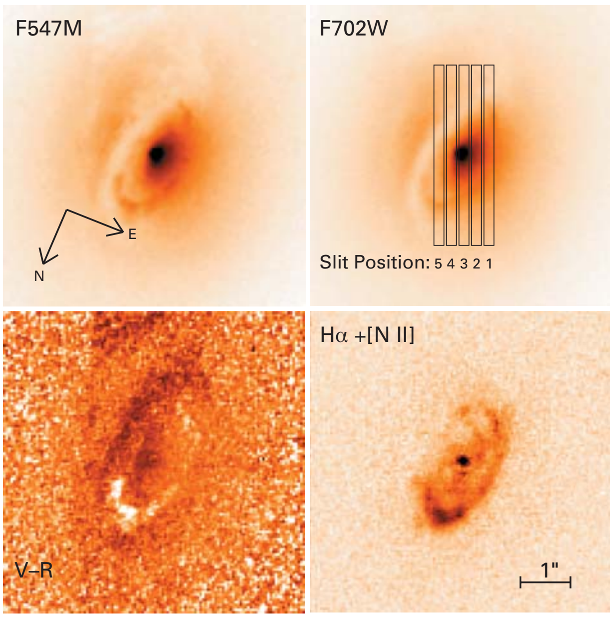


Fig. II.20: NGC 3245 in blue and red light (top) as well as in the light of hydrogen and nitrogen emission lines (bottom, at right). The difference between visible and red light (bottom, left) indicates regions of different extinction. In the upper right, slit positions of the spectrograph are shown.

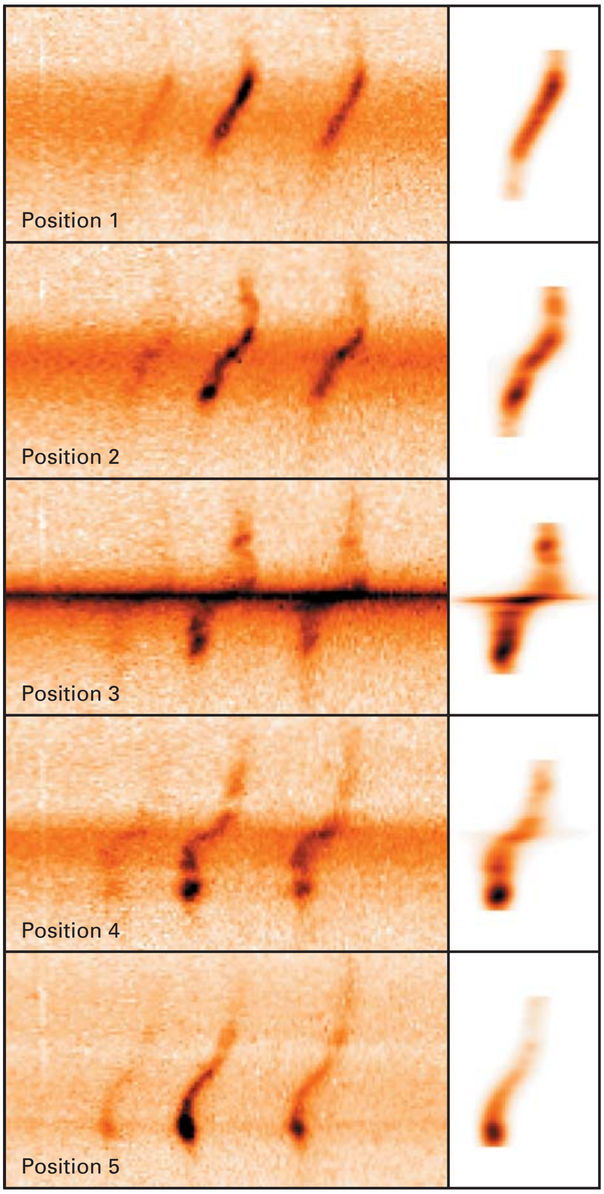


Fig. II.21: Spectra showing hydrogen and nitrogen emission lines. At right, a best-fit model of the lines.

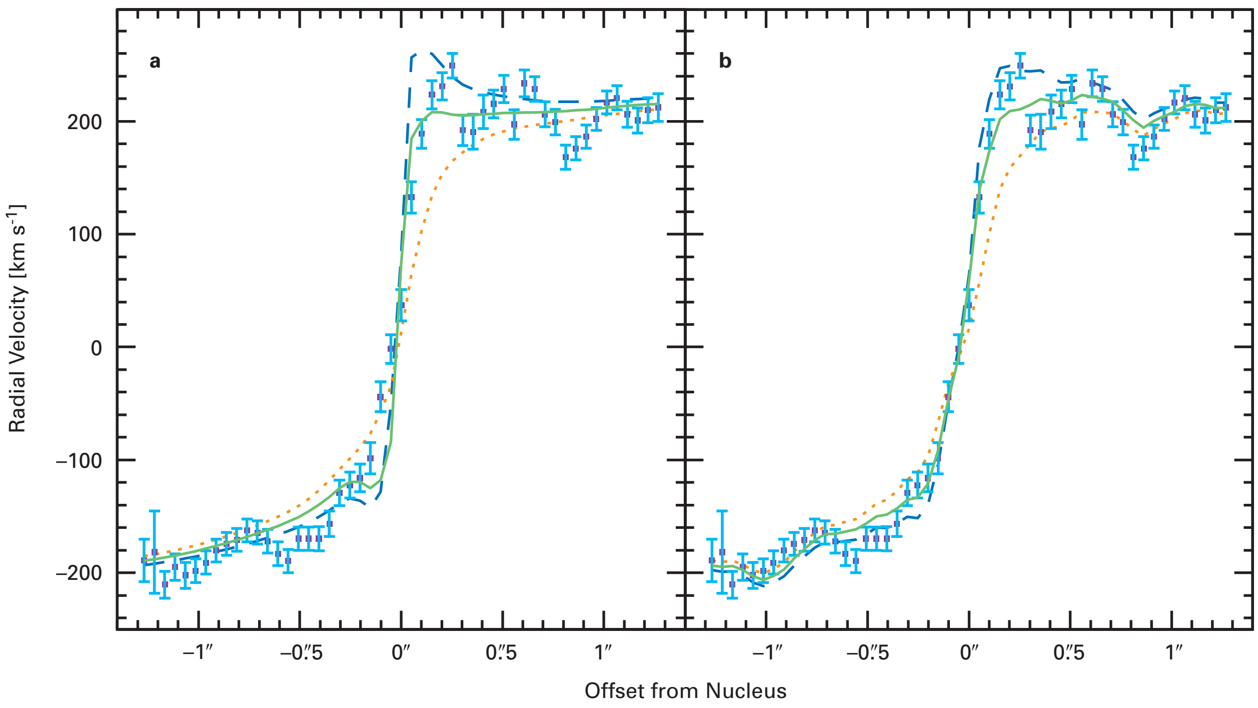


Fig. II.22: Data and rotation curves for two simulations. Dotted line: without black hole; solid line: black hole with 2×10^8 solar masses; dashed line: black hole with 4×10^8 solar masses.

described above (Fig. II.19) predicts a black hole mass of $(2.0 - 2.5) \times 10^8$ solar masses, which is in very good agreement with the value determined in this study. Thus, the correlation between the mass of the black hole and the velocity dispersion also holds for NGC 3245.

It is yet unclear what causes the correlation between the mass of a central black hole and the properties of the surrounding bulge. According to theoreticians at the MPI for Astrophysics at Garching, it confirms the model of hierarchical galaxy evolution, which suggests that currently-observable large galaxies have formed by merging of small galaxies in the early universe. These “building-block galaxies” already contained lower-mass black holes which combined to form a single supermassive black hole. Computer simulations indeed predict a correlation of the black hole mass and the velocity distribution in the bulge for this hypothesis. The same, however, holds for models assuming simultaneous formation of bulge and central black hole from an initial vast cloud. Further observations are needed to clarify these fundamental processes of the formation and evolution of galaxies.

III Instrument Development

The performance of a telescope depends critically on the quality and efficiency of the instrument mounted in the focal plane. Cameras produce images as sharp as possible of celestial bodies, and spectrographs disperse light as finely as possible into its spectral components. Last year, a series of instruments has been developed and built at MPIA to significantly increase the telescope's efficiency and to considerably broaden their range of application. Presently, several instruments are under construction which will be used at the Calar Alto observatory, at the ESO Very Large Telescope, and at the HERSCHEL infrared space telescope currently being built by ESA.

The instruments are built in the workshops at MPIA, frequently in cooperation with small and large companies. The requirements set by the scientists often present these firms with completely new tasks, the know-how gained this way strengthening their competitive capacity in the global market. Of particular importance are Charge Coupled Devices (CCDs) – light-sensitive semiconductors with quantum efficiencies of 60 to almost 100%, depending on the wavelength range. Normal commercial CCDs cannot be used on a telescope, only chips of the highest technical standards are suited to astronomy. They are produced by companies, but their performance has to be tested meticulously at the MPIA's laboratories before they are used at a telescope.

Here is a summary of the MPIA's more recent instruments and of the actual state in the year under report.

ALFA – Adaptive optics for Calar Alto

In theory, the angular resolving power of a telescope, that is, its capability to produce separate images of two objects, increases with the diameter of the primary mirror. Practically, however, the turbulence of the atmosphere blurs longer-exposure images to such a degree that the resolution is only a half to one arcsecond at its best. Thus, large telescopes will not achieve a better resolution than those with apertures of 15 to 30 centimeters.

Astronomers and engineers at MPIA, together with colleagues at the MPI of Extra-Terrestrial Physics (MPE) in Garching, have built a so-called adaptive optics system for the near-infrared range. This system, called ALFA, corrects image fluctuations during the exposure (cf. Annual Report 1997, p. 11). This is accomplished by two central optical elements: 1) a wave front sensor which analyzes the stellar light and determines the distortion of the wave front; 2) a very thin flexible mirror which reflects the incoming light into the camera. On the rear of this mirror, there are a little less than a hundred small actuators deforming its surface constantly. The optimal actual form of the mirror is calculated by a computer using the data of the wavefront sensor. The form of the mirror is adjusted in such a way that the wave trains distorted by atmospheric turbulences are "smooth" again after being reflected by the mirror. Only then, the light reaches the camera, which produces an image at almost the theoretical resolution. In the wavelength range of 1 to 2.5 μm, in which ALFA is used for observations, a correction frequency of at least 100 Hz is required.

To operate the wave front sensor fast enough, a star with a certain minimum brightness is needed. This minimum brightness was reduced in the year under report from 13.5 to 14.2 mag, making ALFA one of the most sensitive systems of this kind.

Moreover, another experiment was installed to optimize observations using adaptive optics systems on a long-term basis: SCIDAR (Scintillation Detection and Ranging).

Adaptive optics systems can only partially compensate image distortions due to atmospheric turbulence. This affects mostly objects outside the central correction axis of the adaptive optics. The strength of this so-called anisoplanasy effect mainly depends on the vertical structure of the atmospheric turbulence. If there are several bright stars in the field of view during an exposure with adaptive optics, the strengths of the effect can be estimated to yield good photometric and astrometric measurements. Unfortunally, such rich star fields are rare, and the estimates are highly uncertain. This is where SCIDAR will be put into action.

SCIDAR produces a blurred image of a binary star (actually it is an image in the pupil plane). The verti-

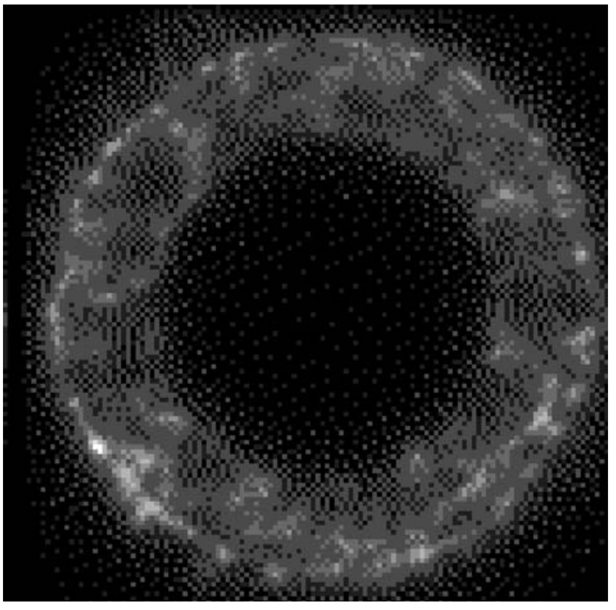


Fig. III.1: Pupil image of the 1.23 m telescope with SCIDAR. Intensity variations caused by diffraction effects within turbulent layers are seen (exposure time 1.3 ms).

cal structure of the atmospheric turbulence can be determined up to ~20 km hight by measuring the intensities of the pupil images of both stars. While measurements of the phase distortions above the pupil cannot yield information on the vertical structure of the turbulence, the strength of the scintillation depends on the hight of a turbulence layer above of the observer. Thus, they contain information on the vertical distribution of the turbulence.

At the end of 2000, the SCIDAR instrument of the Imperial College in London was used for the first time at the 1.23 meter telescope on Calar Alto synchronously with ALFA observations at the 3.5 meter telescope. Basically, it is a camera with a light intensifier and a sensitive detector. The real work, however, begins with the data analysis. The first test (Fig. III.1) has been successful. In summer 2001, more observations will follow. If the SCIDAR technique shows its merits it could be employed later at the adaptive optics system of the Very Large Telescope, for instance. Here, the instrument could be used at one of the smaller telescopes as a kind of "extended weather station", while the adaptive optics is operating at the large telescopes.

ALFA – Astronomical performance

Astronomers at the Institute together with colleagues from other research institutions have performed a number of highly successful observations. In collaboration with astronomers at MPE, they were able, for example, to take near-infrared spectra of the star T Tauri with a spatial resolution of about 0.15 arcseconds.

A whole class of young stars of about one solar mass and a maximum age of one million years has been named after T Tauri. During the last 20 years, this stellar prototype has turned out to be much more complex than expected. Today it is known to comprise at least three, perhaps even four stars. Only the main component to the north (T Tau N) is visible in the optical spectral range. The star T Tau S located 0.7 arcseconds south of it is only detectable in the infrared range. As late as 1998, a companion of T Tau S has been found, also in the infrared, at a distance of only 0.05 arcseconds.

The T-Tauri system displays diverse physical phenomena. A fast gaseous flow in the eastern direction had been detected already in the 1980's by astronomers at MPIA. In 1997, scientists at the Institute were able to show for the first time that magnetic fields are playing an important role in this flow (see Annual Report 1997, p. 48).

For their recent observations, the astronomers used an instrument built at MPE, which allows spectroscopy of a complete two-dimensional 1-arcsecond-square field, the 3D-spectrograph. The T-Tauri system was studied at wavelengths around 1.65 and 2.2 μm using the 3.5 m telescope at Calar Alto (Fig. III.2).

The spectra (Fig. III.3) show T Tau S surrounded by hot, dense dust. At the same time hydrogen lines can be recognized in T Tau S and N. They probably are formed in a dusty wind from both stars. Due to the high resolution of the images, it was possible to show that the wind sets in within a few tens of astronomical units from the star. Moreover, the recent

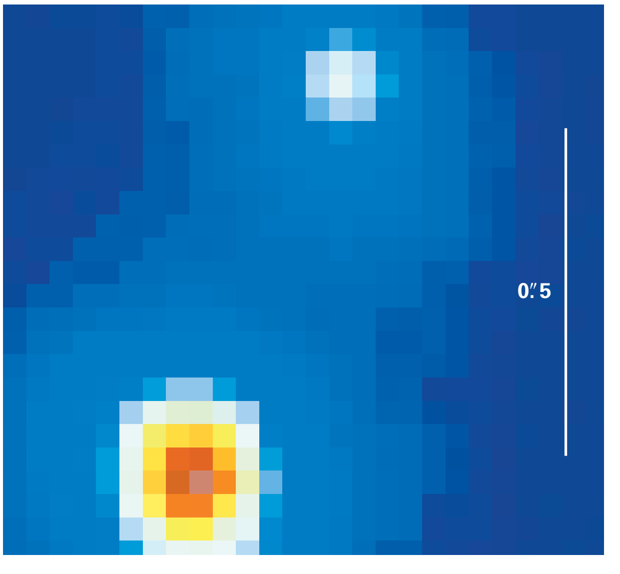


Fig. III.2: False-color view of the T-Tauri system on the 3D-detector. Each pixel of this image contains a complete spectrum in the K-band (around 2.2 μm). The separation of both components is 0.69 arcseconds.

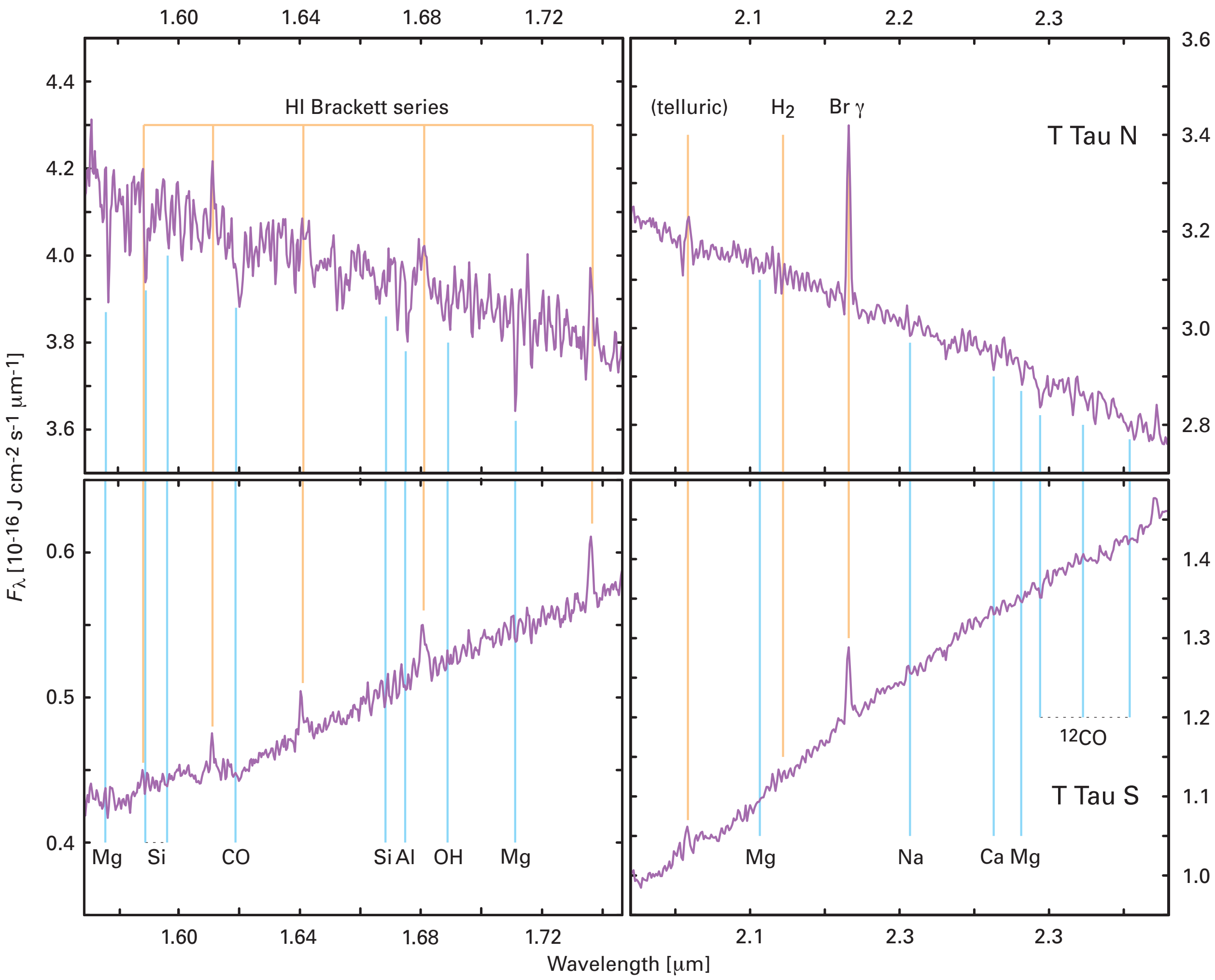


Fig. III.3: H- and K-band spectra (1.65 and 2.2 μm) of T Tau N and S. The spectra have been extracted from the central 2 x 2 pixels of the stellar cores (see Fig. III.1). The different spectral indices of both components are clearly discernible as well as the total absence of photospheric absorption lines in the spectra of T Tau S, which suggests the red color is caused by thermal emission of hot dust.

observations further support a model of T Tau S and its close companion in which each star is surrounded by a dense dusty disk seen edge-on. Although the optical light of both stars is absorbed by these disks, it can escape from the poles and is observed there – if not spatially resolved.

In collaboration with colleagues at the observatories in Jena and Tautenburg, two star formation regions were successfully observed in the near infrared for the first time using ALFA. These observations were part of an extensive observational program in the course of which both regions have additionally been studied polarimetrically in the infrared and at a wavelength of 1.3 mm on La Silla. The results of the ALFA observations will be outlined here.

The two objects called G11.11-040 (G11 for short) and G341.21-0.21 (G341) are so-called ultra-compact HII regions. In such regions, massive stars are forming, ionizing the surrounding gas by their intense hot radiation. At a distance of 17,000 and 12,000 light years, respectively, both objects are about ten times farther away than the star formation region within the Orion Nebula, for instance, and are much more difficult to observe. As they are so small, both objects cannot be resolved with usual methods. Now, G11 was successfully resolved using ALFA.

Five objects were photometrically observed within G11 (Fig. III.4). These objects are hot young stars, each surrounded by an ultra-compact HII region. One turned out to be an O5-, two others to be B1 main-sequence stars, meaning that they already have reached hydrostatic equilibrium. The remaining two objects obviously are still too young to have arrived at the main sequence.

Using the adaptive optics system ADONIS on La Silla, nine stars could be identified within G341, two of them being O- and several others being B main-sequence stars. These objects are 20 times as massive

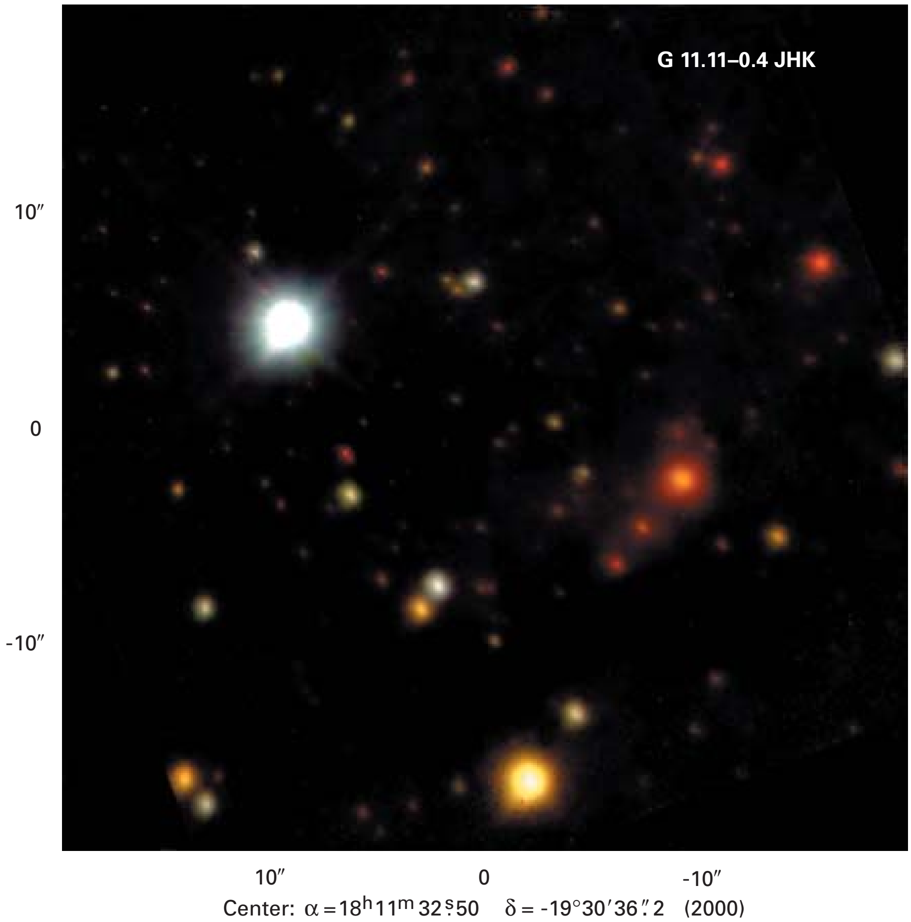


Fig. III.4: The star-forming region G11.11-040, imaged with ALFA. Three images at 1.25, 1.65 and 2.2 μm were superimposed to yield an infrared ”color” image.

as the Sun. Comparison of their masses with the total mass of the G11-complex of ~10,000 solar masses shows, that about half a percent of the interstellar matter has been turned into stars.

This is impressive evidence that very massive stars, too, can form in compact groups rather than as isolated objects. In the future, high-resolution spectra will be taken of these hot stars. The adaptive optics system presently built for the ESO Very Large Telescope or the future European HERSCHEL infrared space telescope will be suitable for this task.

ALFA with a laser guide star

If all objects in the field of view are too faint for the wave front sensor, astronomers have to create an “artificial star”. This is done by shooting a laser beam parallel to the telescope’s line of sight towards the sky. At an altitude of about 90 kilometers, the beam hits an atmospheric layer enriched with sodium atoms. The wavelength of the laser is set to excite the sodium atoms, which subsequently glow. Thus, a spot of light is created above the telescope which ideally resembles a star of 10th magnitude. It is used by adaptive optics as the bright reference star for image correction.

Such a system was built for Calar Alto, thoroughly tested and optimized (see Annual Report 1999, p.31). It was shown that observations using ALFA with a laser guide star are practicable in principle. The efficiency of the laser guide star, however, depends, among other things, on the meteorological conditions. Unfortunately, a sensible application at Calar Alto would be possible only with too high an effort.

The experiences gained at Calar Alto, though, are not lost: They will be of great value in building an adaptive optics system for the ESO Very Large Telescope. MPIA and MPE together are going to install a sodium laser there, called PARSEC, at one of the 8 meter telescopes. It will produce a continuous beam with a power of 10 to 15 watts. From 2003 on, the laser guide star together with the CONICA camera, also built at the Institute, and the NAOS adaptive optics are meant to increase the efficiency and power of this telescope. For the more distant future, there are plans to use up to five guide stars simultaneously at one telescope. This way, the corrected field of view could be significantly extended.

LAICA – the wide field camera for Calar Alto

In the future, major findings are expected from research programs searching for faint objects in large fields. This new development is increasingly taken into account by the Institute. First, a wide field camera was built in collaboration with ESO for the 2.2 m telescope at La Silla (see Annual Report 1998, p. 33). In the year under report, it was decided to build a new wide field infrared camera for Calar Alto, named Omega 2000 (see below).

The Large Area Imager for Calar Alto, LAICA for short, will be commissioned in 2001. This camera will work in the prime focus of the 3.5 m telescope, yielding aberration-free images over a field of $44' \times 44'$ (corresponding to 115 mm). In its focal plane, a mosaic of four CCDs is mounted, each having 4096×4096 pixels. The imaging scale will be 0.″225 per pixel (see Annual Report 1999, p. 33).

For production reasons, the CCDs cannot be connected without gaps. They are therefore located about 20 mm apart (a little less than the size of a CCD), leaving a broad cross-shaped region in between. Thus it is not possible to image a contiguous area of the sky in one single shot. But this can be compensated without major effort by taking three more shots at different positions, thereby filling the gaps. A set of four images covers a contiguous field of one square degree, corresponding to about five times the area of the full moon.

In addition, two smaller CCDs are integrated in the focal plane for guiding purposes. With their help, image rotations, which may occur in longer observations, can also be corrected. In summer, this guiding system was successfully tested at the telescope.

For the time being, two filter sets are planned. The magazine contains 20 filters which are taken out by a robot arm and put into the light path.

Construction of LAICA started in early 1999. In the year under report, the mechanics was completed and cold-tests were successful. Commissioning, however, was delayed because the CCDs had not been delivered on time by the manufacturer, and one CCD was broken. At the end of the year, the total equipment was finally shipped to Calar Alto, and on May 20th, 2001, LAICA saw first light (Fig. III.5). After further optimizations, the camera will be regularly at the telescope from Fall of 2001 on.

OMEGA 2000 – a wide field infrared camera for Calar Alto

The Institute is strongly engaged in infrared astronomy as evidenced by the recent MAGIC, MAX, OMEGA-Prime and OMEGA-Cass instruments. The

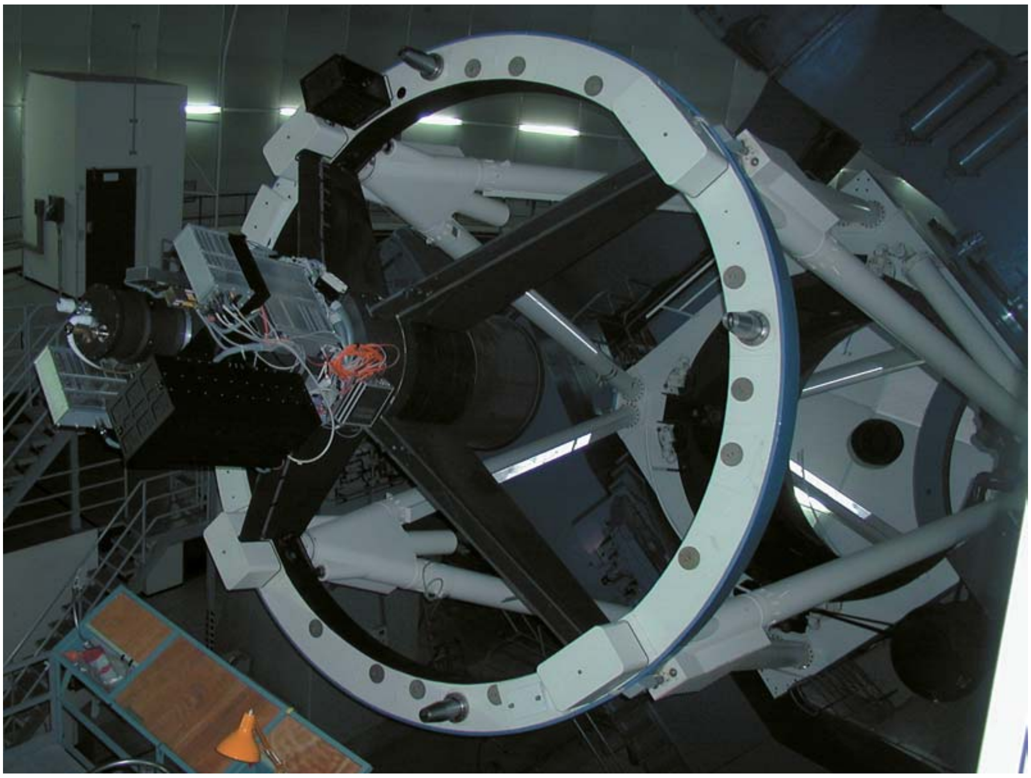


Fig. III.5: LAICA during tests in the prime focus of the 3.5 m telescope on Calar Alto.

development of new cameras depends critically on the availability of infrared detectors. Only recently have arrays with 2048 × 2048 pixels been obtainable. They are sensitive up to a wavelength of 2.4 µm and their quantum efficiency between 0.8 and 2.4 µm is about 60 %.

To keep Calar Alto at the forefront of infrared astronomy, MPIA has decided to develop and build a new near-infrared camera. It will be similar to OMEGA-Prime, but its field of view will be five times larger with a size of 15′ × 15′, corresponding to a quarter of the area of the full moon (Fig. III.6). The instrument will be used in the prime focus of the 3.5 m telescope, where it will have an image scale of 0.″45 per pixel at a focal ratio of *f*/2.35.

Because of the large field of view and the fast read out required for the infrared detectors a high data rate of about 100 Gbytes per night is expected. Handling these data will push the Calar Alto computer network to its limits and require the latest input-output technology as well as a significantly larger storage area than before.

According to the plans, OMEGA 2000 will be put in regular operation in 2002 and then replace the previous workhorse OMEGA-Prime.

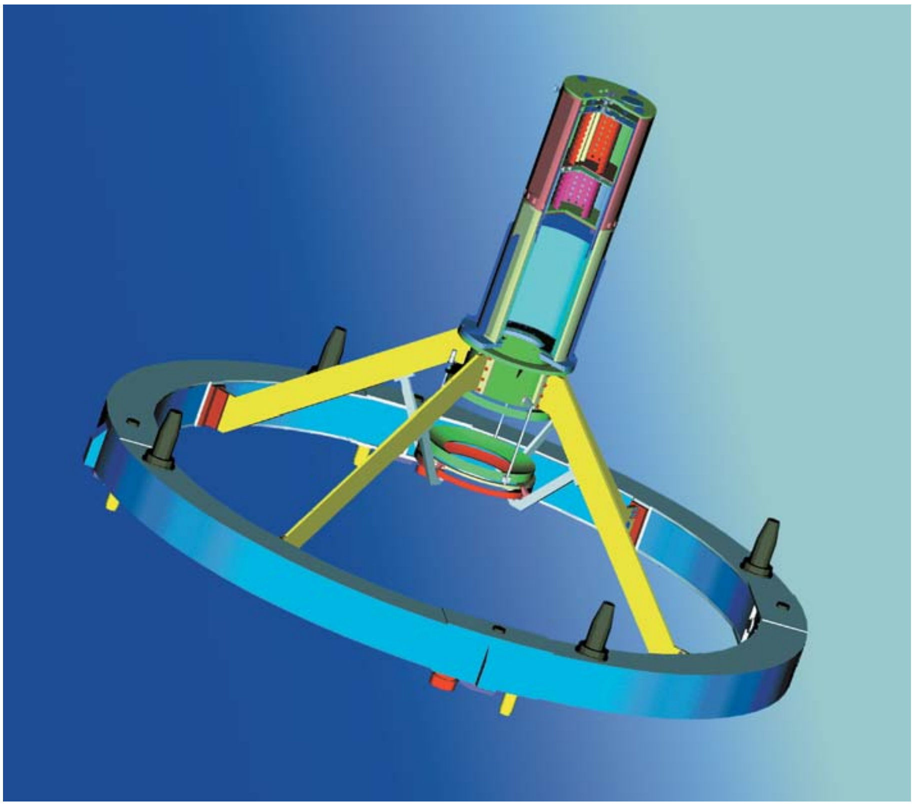
Fig. III.6: Setup of OMEGA 2000 at the front ring of the 3.5 m telescope.

CONICA – a high resolution infrared camera for the VLT

CONICA is a high-resolution camera for the 1–5 µm infrared range. It is currently being built under the leadership of MPIA in collaboration with MPE. It will be used in the Nasmyth focus of the third out of the four telescopes of the ESO Very Large Telescope. Together with the adaptive optics system NAOS, CONICA is expected to yield diffraction-limited images in the near infrared between 1 and 5 µm with a resolution as high as 0.026 arcseconds.

An infrared array with 1024 x 1024 pixels is used as the detector. The image scale can be selected between 0.014 and 0.11 arcseconds per pixel. For each of these scales two camera systems are available working in the wavelength ranges from 1 to 2.5 µm and from 2 to 5 µm. Depending on the selected configuration, the image field has a size of between 14″ × 14″ and 56″ × 56″, and a diameter of 73″ at the lowest resolution.

CONICA is a multi-purpose instrument with a Fabry-Pérot interferometer (wavelength range: 2 to 2.5 µm), a set of 20 standard filters and 15 narrow-band filters, as well as Wollaston prisms and polarisation filters to measure the linear polarisation of extended objects. In addition, four grisms allow two-dimensional spectroscopy at medium spectral resolution. Thus the instrument is suited for all current fields of research.



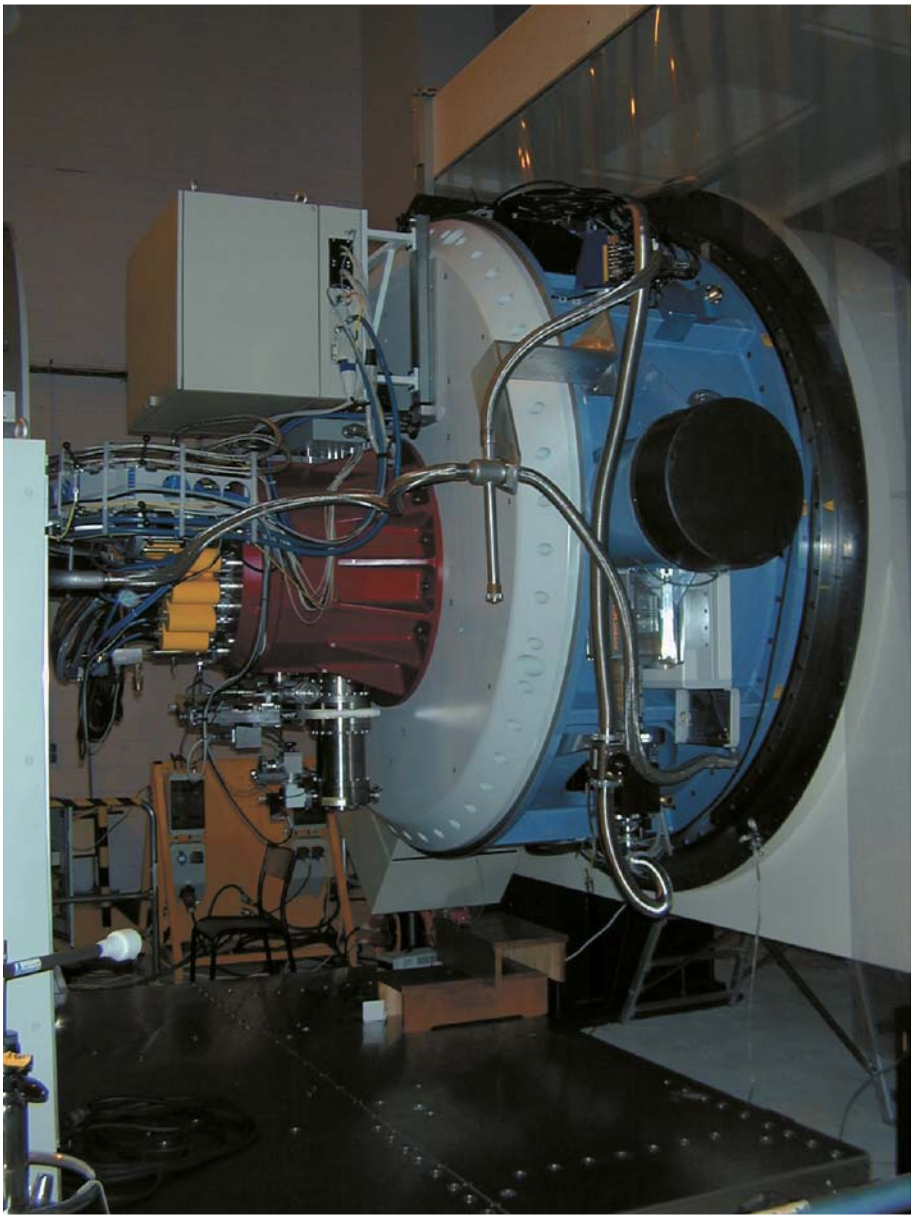


Fig. III.7: CONICA during tests in Meudon.

In the year under report, the infrared camera was completed at the Institute's laboratories. ESO was able to check the entire instrument during summer. For weeks, it was tested painstakingly and, after some optimizations, sent to a large laboratory at Meudon near Paris where the entire platform of the VLT's Nasmyth focus is duplicated. There, CONICA will be tested together with the adaptive optics system NAOS (Fig. III.7). If all tests are passed, CONICA will be shipped to Chile in summer 2001.

CONICA will be used mainly to study star formation regions and protoplanetary disks as well as the Galactic center. In the extragalactic field, observations of the central cores of active galaxies and the examination of distant infrared galaxies will be given high priority. As a compensation for their effort, the astronomers of both MPIs will share 45 guaranteed observing nights with CONICA.

MIDI – an infrared interferometer for the VLT

In the near future, the VLT will also operate as an interferometer. For this purpose, the light paths of two or more telescopes will be combined and coherently superimposed on a common image plane (Fig. III.8). An interferometer of this kind has the spatial resolution of one single telescope with a mirror as wide as the separation of the interferometrically coupled telescopes. Two of the VLT's telescopes, being 130 m apart, will achieve a resolution of a few thousandths of an arcsecond in the near-infrared range.

One of three planned interferometers, named MIDI, is being developed and built under the leadership of MPIA. Also involved are colleagues from the Netherlands and France, as well as from the Kiepenheuer Institute of Solar Physics in Freiburg and the Thuringian State Observatory, Tautenburg. MIDI is intended to enable interferometry with two telescopes at wavelengths between 8 and 13 µm and will signify a huge step forward as far as spatial resolution is concerned. MIDI is expected to achieve a resolution of about 0.″02 within a image field about 2″ across. The detector consists of an array with 320 by 240 pixels, with one pixel having a size of 50 µm × 50 µm. Observations at different wavelength ranges are made possible by ten filters.

Interferometry at these wavelengths puts heavy demands on technology. Two problems of central importance are: light waves arriving from both telescopes have to be combined in the instrument with a phase coincidence as precise as about 1 µm. Because of the intense thermal background radiation, large parts of the instrument have to be cooled. The detector will be the coldest part with a temperature of 4 to 8 Kelvin; the cold section of the optics will be around 40 Kelvin, and the outer radiation shielding for the cooling system about 77 Kelvin.

The difference in path lengths of the collimated beams arriving from the two telescopes is mainly due to geometry, and will already have been compensated for the most part before the beams enter the instrument. In addition, the path difference changes during the observation due to the turning of the celestial sphere. This problem is resolved by an optical system moving on a cart in a tunnel below the telescopes (called a delay line). The light beams arriving from the telescopes are reflected by the system, their different path lengths being compensated by shifting the system. In the year under report, the delay line was tested successfully for the first time on Cerro Paranal in Chile (Fig. III.8). Inside MIDI, the remaining difference in path lengths is compensated by means of movable piezoelectrically driven mirrors. A beam splitter combines the beams to create the interference image.

MIDI's final design review took place at ESO in February 2000. Thereafter, almost all hardware could be manufactured during the year under report. For example, the dewar of the instrument (weighing 500 kg) was assembled and the read-out electronics of the detector was tested (Fig. III.9). The conception of the control electronics was completed, too. Colleagues from the Kiepenheuer Institute of Solar Physics also delivered the "warm optics", which compensates the path difference of the two light beams. This system was calibrated and thoroughly tested at the Institute. ESO delivered the optical table which will also be used later on Cerro Paranal. As the optical bench must be extremely stable and shock-absorbent it measures 2.1 by 1.5 meters and is 61 cm thick. In November, the integration of the MIDI instrument on the optical bench was started. First tests of the cooled optics will be made in spring 2001 after the Dutch partner institute ASTRON will have sent this system to MPIA.

Fig. III.8: The delay line of the interferometer below the VLT's telescopes. ESO)

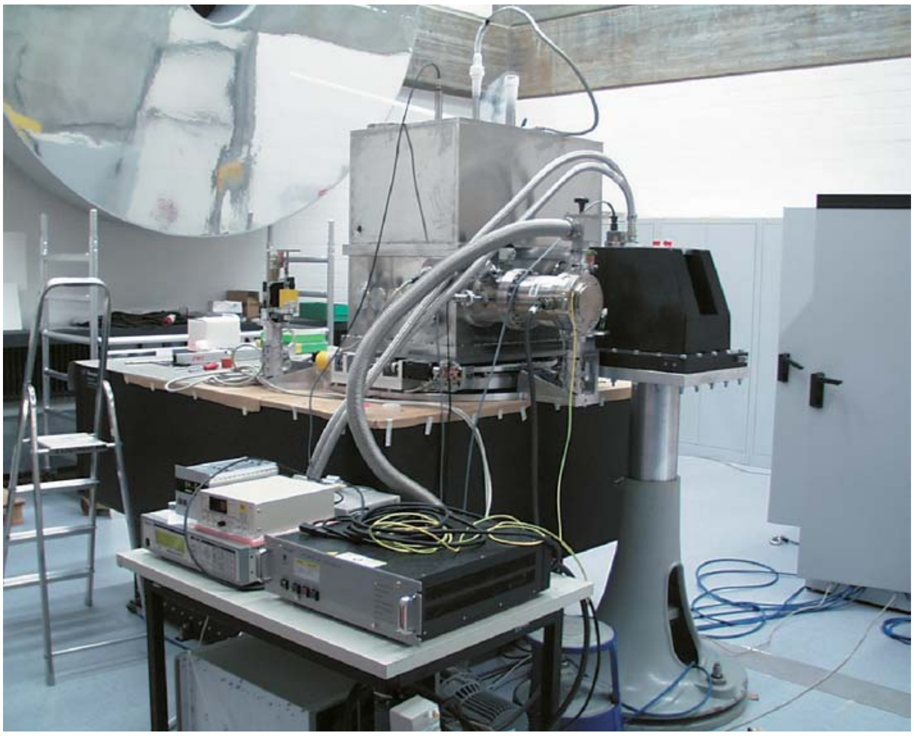


Fig. III.9: The cooling unit of MIDI during tests at the Institute.

First interferometric observations with two of the 8 m telescopes of the VLT are planned to start in the second half of 2002. The team will be granted a total of 30 observing nights on the 8 m unit telescopes, distributed over several years, and about three times as many nights at the 1.8 m "auxiliary" telescopes.

At the moment, MIDI observations are planned to focus on active galactic nuclei (black holes), young stars, extrasolar planets, circumstellar dust envelopes, protostellar and protoplanetary disks as well as binary stars.

PACS – the infrared camera for HERSCHEL (formerly FIRST)

In 2007, the European Space Agency (ESA) plans to launch the HERSCHEL far-infrared telescope (formerly called Far-Infrared and Submillimeter Space Telescope, FIRST) as its fourth major "cornerstone" mission. HERSCHEL will be provided with a 3.5 m mirror and three scientific instruments covering the wavelength range from 60 to 700 µm. These are being designed and built by international science consortia. One central issue of the research program will be the observation of protostellar dust clouds and protoplanetary disks. The submillimeter emission of very distant young galaxies will be detectable, too. MPIA will participate in the construction of one of the instruments, named PACS (Photoconductor Array Camera and Spectrometer). The MPE leads the PACS consortium.

PACS is being designed for photometric and spectrometric studies in the wavelength range between 60 and 210 µm. MPIA will make major contributions to the development of the cameras and pre-amplifiers, as well as to the focal plane chopper and the data center. Based on experience with ISO, the Institute will participate in the detailed planning of the structure of the HERSCHEL ground segment and in particular of the control center for PACS. The Institute will also be responsible for all aspects of the calibration of PACS during the flight.

After a prototype of the chopper was built and tested at the Institute in 1999 (Fig. III.10), Carl Zeiss / Oberkochen was appointed to manufacture the flight model. A chopper is used for the following purpose: during infrared observations, a more or less confusing background signal occurs, for example due to thermal emission of the telescope. To be able to take this signal into account, the object examined and a neighboring "empty" sky section are measured alternately. The empty section gives the background which is subtracted later from the signal produced by the actual object plus background. The alternating observation of two sky sections is achieved by putting a mirror into the light path which tips ("chops") to and fro at high frequency.

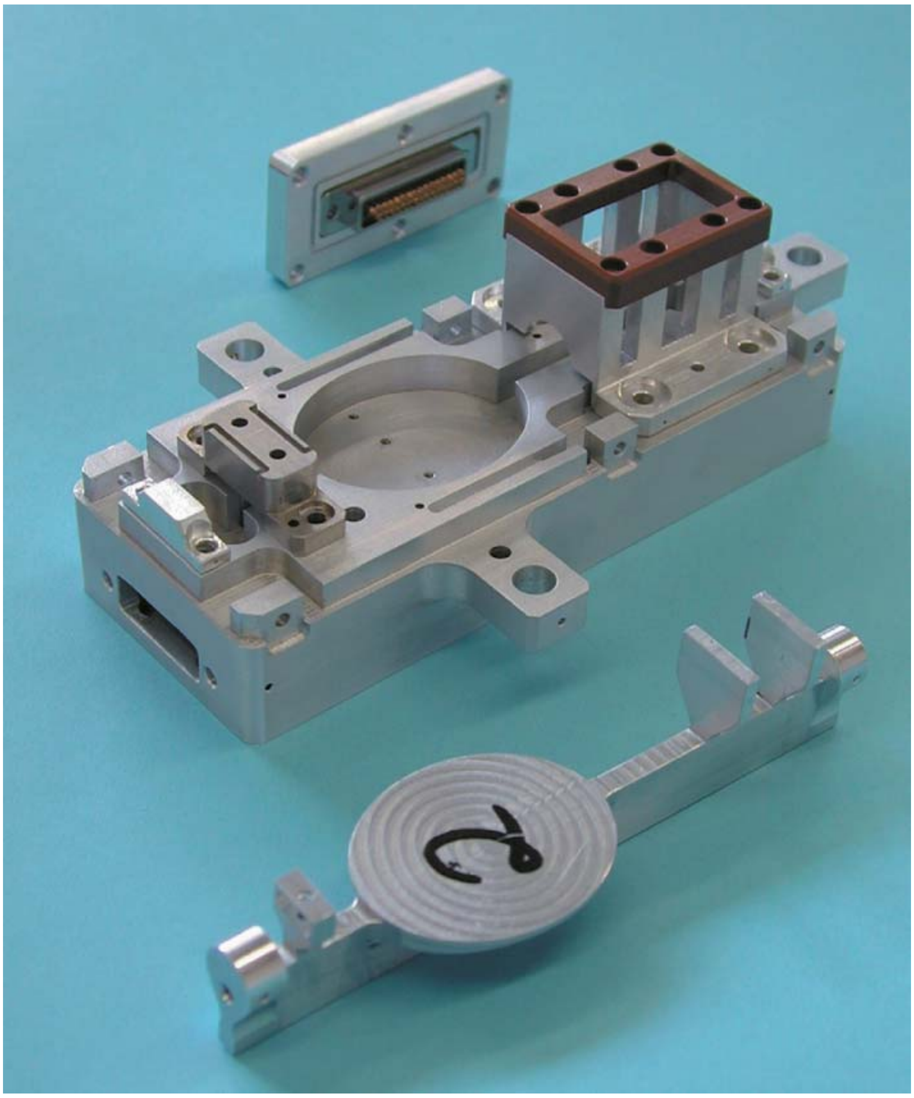


Fig. III.10: The PACS chopper in the Institute's laboratory.

LUCIFER and LINC – Two Innovative Instruments for the LBT

As mentioned in chapter I, Germany will have a 25 % share in the Large Binocular Telescope (LBT), led by the MPIA under the auspices of the "LBT Beteiligungsgesellschaft," together with the MPI für extraterresstrische Physik in Garching, the MPI für Radioastronomie in Bonn, the Astrophysikalisches Institut Potsdam, and the Landessternwarte Heidelberg. Unlike all previously-built telescopes, the LBT will be equipped with two mirrors on a single mount. Each mirror has a diameter of 8.4 meters. Commissioning of the telescope with the first mirror will take place early in 2004. After the commissioning of the second mirror one year later, interferometry will be possible.

Under the direction of the Landessternwarte Heidelberg, the German partners are building a pair of near-infrared spectrographs for the LBT, called LUCIFER (Fig. III.11). The MPIA will supply the entire detector package and will develop the overall design of the cooling system. Integration and tests of the instrument will also be carried out in the laboratories of the MPIA. In addition to the MPIA and LSW, the MPI für extraterrestrische Physik, the Universität Bochum and the Fachhochschule für Technik und Gestaltung in Mannheim are involved in the development and construction of LUCIFER.

In early 2004, the first LUCIFER unit will begin operations using the first big mirror. The second LUCIFER will be installed after the commissioning of the second mirror 13 months later. With LUCIFER, both direct imaging and long-slit spectroscopy in the wavelength range 0.85–2.45 microns will be possible. In order to reduce thermal background radiation of the instrument, LUCIFER will be cooled by mechani-

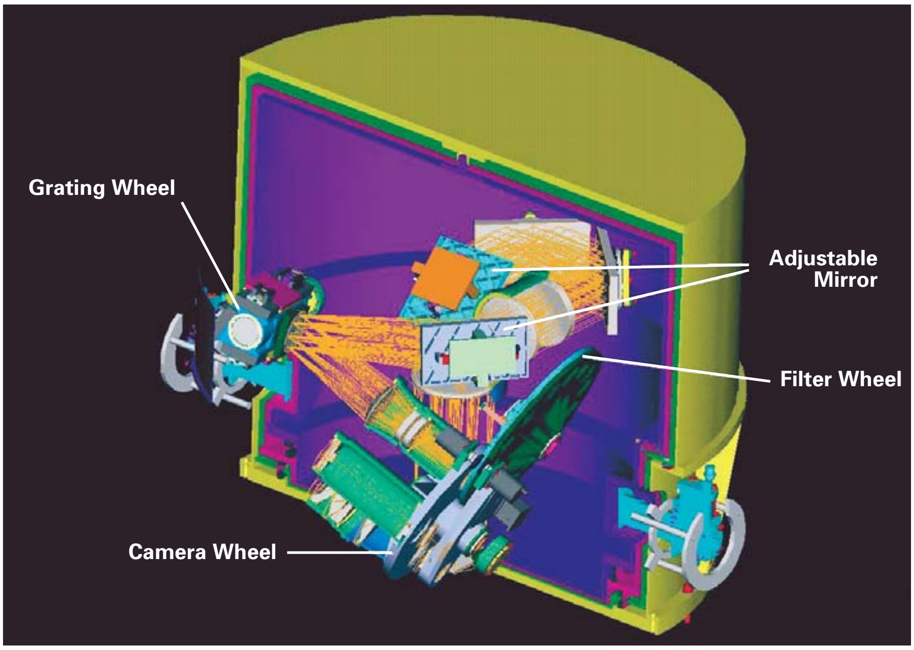


Fig. III.11: The oprtical and mechanical design of LUCIFER.

cal refrigerators to approximately –200° C. A total of six observing modes are planned:

Seeing-Limited:
– direct imaging with a field of view 4'
– long-slit spectroscopy with a slit length of 4'
– multi-object spectroscopy

Diffraction-Limited:
– direct imaging with a field of view of 0.5'
– long-slit spectroscopy
– integral field spectroscopy

For diffraction-limited imaging, the LBT yields excellent spatial resolution varying from 0.″031 at 1.23 microns to 0.″056 at 2.2 microns. The cameras need to be exchanged, in order to obtain the highest image quality for all seeing-limited imaging modes. A total of three cameras are planned with a resolution of 0.″015, 0.″12 and 0.″25 per pixel. The detector consists of an infrared array with 2048 × 2048 pixels.

LUCIFER's science program will focus on faint objects in the near infrared, including young, highly-redshifted galaxies. In addition, astronomers look forward to important progress in the field of faint red stars and brown dwarfs. Dust disks around young stars and in the centres of active galaxies are an additional observational priority.

One of the most ambitious instruments on the LBT will be the near-infrared and visible wavelength beam combiner, LINC. This instrument combines the radiation of the two primary mirrors, allowing unprecedented spatial resolution. Due to the enormous collecting area, the LBT operating in beam-combined mode will be the most powerful telescope in the world. Beam combiners like LINC have not yet been built, however, and there are a number of technical challenges to be addressed.

The MPIA is the lead institute in the LINC collaboration, and is currently developing the extremely demanding optical design (Fig. III.12). Other members of the collaboration include the Osservatorio Astrofisico di Arcetri (Firenze) and the Universität zu Köln.

With LINC, interferometry at wavelengths between 0.6–2.4 microns will be possible. For visible light, a CCD with pixels between 9 and 12 microns will be used, and for the near-infrared channel, operating between 1 and 2.4 microns, an infrared array with 2048 × 2048 pixels of 18 microns each will be implemented.

The interferometer works closely with the adapti ve optics (AO) system. Depending on the wavelength, the AO system will deliver a field between 5 and 20 arcseconds. The ultimate resolution of LINC also depends on the wavelength, and is 0.″006 at 0.7 microns and 0.″02 at 2.2 microns.

Science observations with LINC will focus on all areas of astronomy, ranging from supernova cosmology to the structure of protostellar disks and the search for extrasolar planets.

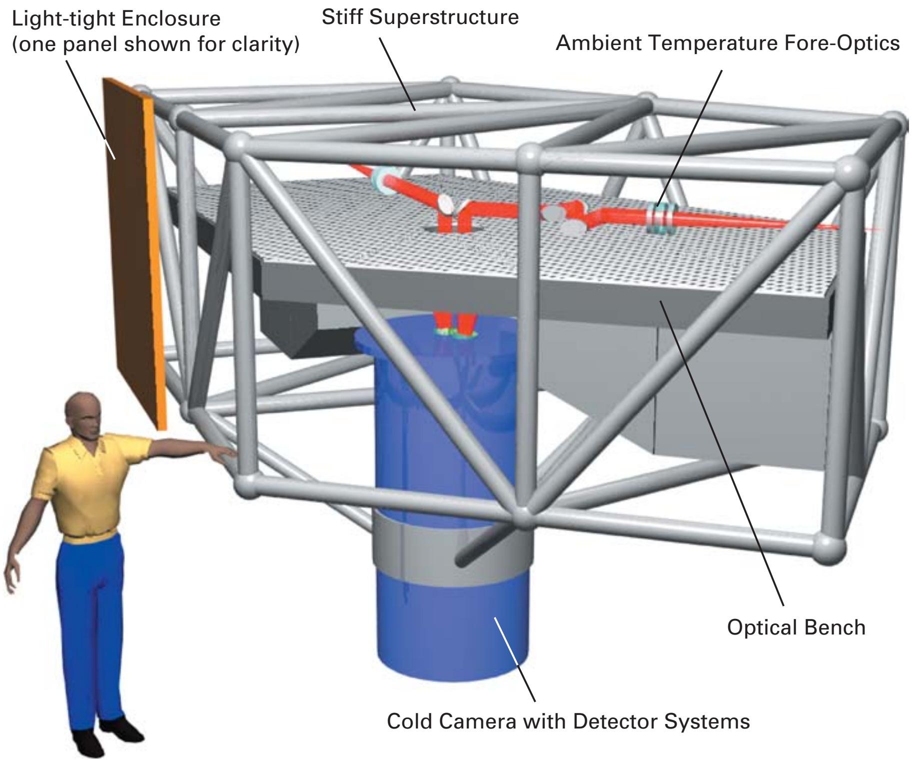


Fig. III.12: The basic design of LINC.

ISOPHOT: measuring scattered light during a solar eclipse

As reported in Chapter I, the Institute has a major part in the scientific success of the European ISO infrared observatory. The ISOPHOT instrument was built under the coordinating leadership of MPIA, and with the ISOPHOT data center the Institute has taken on an essential task in the post-operational phase. Since the construction of the telescope, astronomers at the Institute have been concerned with the problem of suppressing scattered light within the instrument. Only now this disturbing factor could be analyzed quantitatively in all its facets.

Scattered light can reach detectors in different ways and thus distort the measurements. Therefore, during every observation one has to make sure to prevent scattered light of bright objects like the Earth or the Sun from entering the telescope. The telescope had been encased by a helium-cooled, long baffle

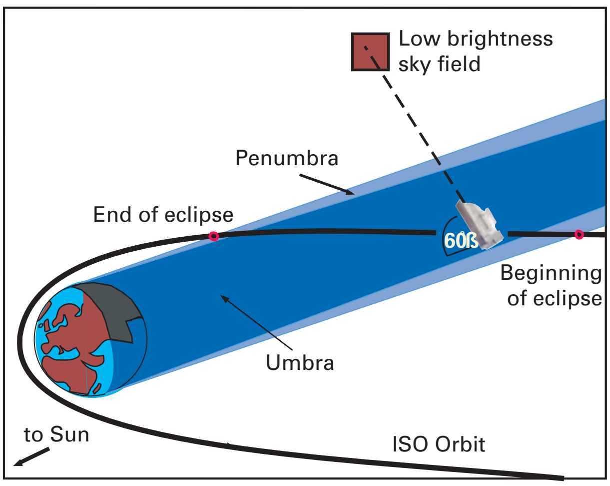


Fig. III.13a: In September 1997, ISO crossed the shadow of the Earth. During this phase, measurements of scattered solar light were taken.

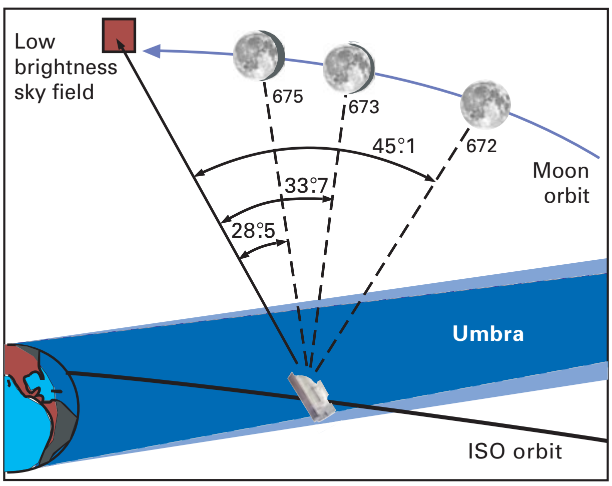


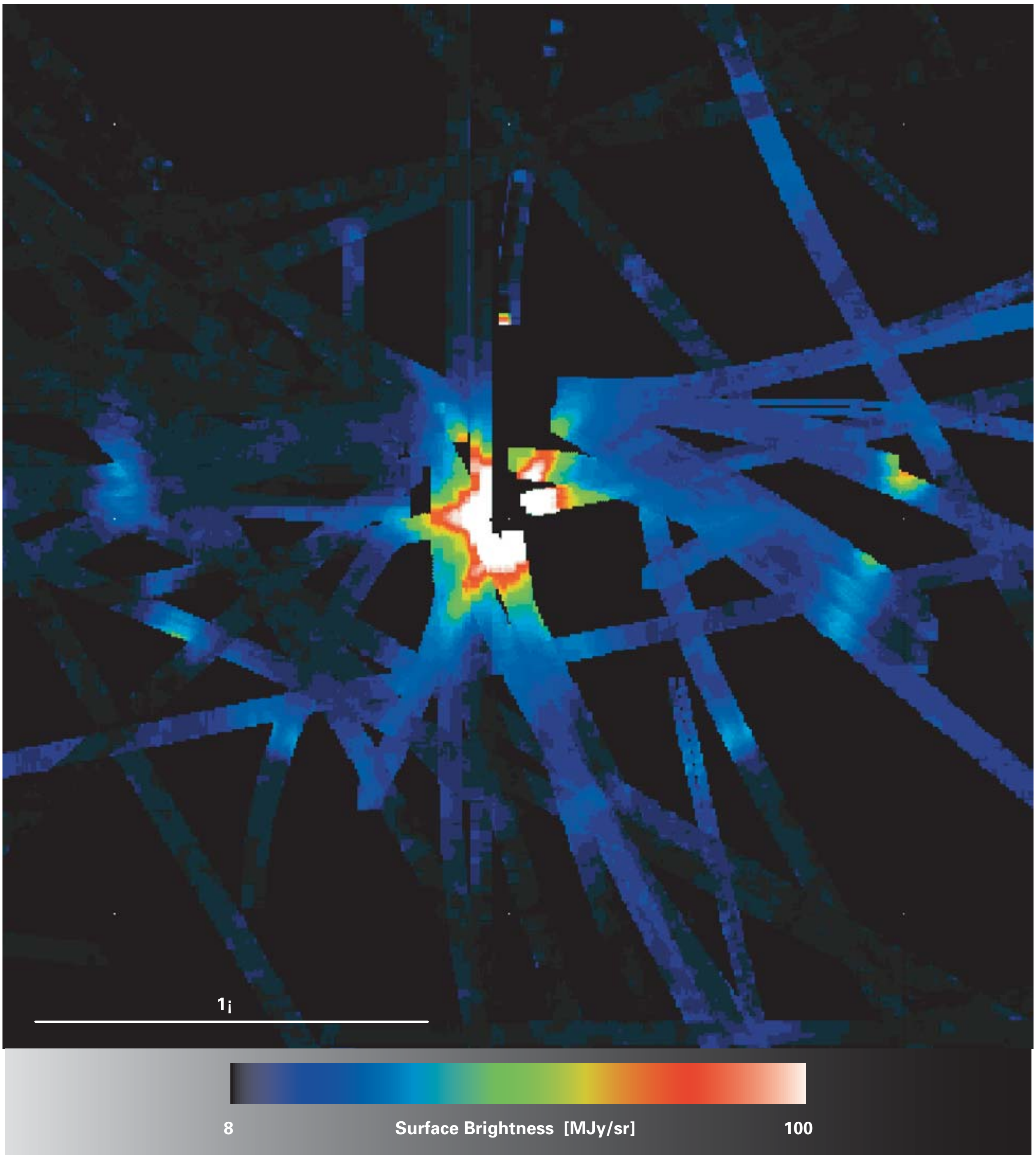
Fig. III.13b: While ISO flew through the Earth's shadow three times the Moon was approaching the telescope's field of view. Thus measurements of scattered lunar light could also be taken.

system with a passively cooled solar screen at its front. Additionally, astronomers had laid down in advance that appropriate minimum distances had to be kept to the line of sight to the following objects: Sun 60 degrees, Earth 73 to 87 degrees, Moon 24 degrees and Jupiter 5 degrees.

To avoid intrinsic thermal emission, the telescope and instruments were cooled to 4 Kelvin. Moreover, all inner parts were covered with a paint which appears "black" in the infrared. During the entire construction phase advice from the Institute's infrared astronomers was repeatedly taken into account in the construction.

In addition to these precautions, attempts were made during the construction phase to theoretically quantify the remaining scattered light using computer simulations. Special attention was paid to emission

Fig. III.14: Saturn at 170 µm wavelength. The diffraction structure of the secondary mirror support is seen as well as a faint ghost image at a distance of about one degree.



from the Earth and Moon at 25 µm and to the intrinsic thermal emission of the telescope at 170 µm which seemed to be especially critical. The simulations predicted the scattered light remaining in any case below 10% of the natural brightness of the night sky.

As ISO functioned for a longer period of time than initially expected, in September and October 1997, the unique situation arose that the telescope was flying through the Earth's shadow during photometrical observations. So, from ISO's point of view a solar eclipse occurred (Fig III.13a). This situation allowed a unique experiment to be performed to measure the scattered light from the Sun. For this purpose, a sky section 60 degrees away from the Sun was observed shortly before, during, and after the eclipse. A significant fraction of scattered light from the Sun should then appear as an increased infrared background before and after the eclipse. A special advantage of this method is to be able to turn on and off a very bright source, so to say, without changing the settings of the telescope, which can continue its measurements uninterrupted. In a detailed analysis of the measured data, no detectable signal of scattered light from the Sun was found within the sensitivity limits.

For the duration of the eclipse, no commands could be send to the satellite. Nevertheless, the measurements could also be used to estimate possibly scattered light from the Moon. ISO crossed the Earth's shadow during three successive orbits. In this period of time, the Moon moved across the sky towards ISO's field of view, its distance decreasing per orbit from 45 to 33 and then to 28 degrees (Fig. III.13.b). Therefore, an alleged fraction of scattered light from the Moon would have to increase from orbit to orbit. But this effect, too, could not be detected at the achieved accuracy level. The same result was obtained for measurements of scattered light from Earth, which had been most feared by astronomers.

However, astronomers had a small surprise when analyzing the influence of a very bright point-like source on the measurements. Direct observations of bright objects already had shown that no scattered light was detectable within a radius of 15” from the source. By chance then, astronomers at the Institute came across an unexpected phenomenon. In some cases, the telescope accidentally had passed the planet Saturn quite closely during slews from one object to another. From these data an image of the planet which glows very brightly in the infrared range was obtained (Fig. III.14). It had a rayed shape which was ascribed to diffraction at the secondary mirror support. Additionally, the planetary image is surrounded by a faint ring at about one degree distance. The intensity of the ring is about one percent of that of the central image.

The cause for this “ghost image” is not definitively clear yet. Astronomers presume, though, that it is produced by light falling under a shallow angle onto a cap above the secondary mirror and being reflected there towards the detector. Such an effect could be minimized or even be avoided in future telescopes by building smaller secondary mirror supports.

On the whole, the studies yielded the reassuring result that in 99 % of all data no corrections for scattered light have to be done. Only with fainter extended objects a more detailed analysis might be necessary. The results on scattered light described above, particularly with respect to the secondary mirror support, will be included in the construction of future infrared space telescopes, such as HERSCHEL for instance.

IV Scientific Work

IV.1 Galactic Astronomy

Rotation of Young Stars

Stars are forming by gravitational collapse in the densest regions of molecular clouds. At the end of the collapse phase, a disk of gas and dust forms around the star due to the cloud's rotation. During this process, the star accumulates matter from the disk, thus gaining more and more angular momentum: The star rotates increasingly faster. Without the effect of a braking mechanism, the angular momentum and thus the centrifugal force would eventually become too large for the protostar to continue to gather matter from its surroundings and to contract. Therefore, young stars have to be slowed down during the accretion phase. This is achieved in different ways in different evolutionary stages. Measuring the rotation velocities of young stars, astronomers from the US and MPIA came across a relation between stellar rotation and the development of a surrounding disk, reinforcing the significance of a disk for the evolution of angular momentum in young stars. These observations were made possible mainly by the wide filed camera built at the Institute.

Fig. IV.1: The young star cluster in the Orion Nebula, imaged with the wide field camera.

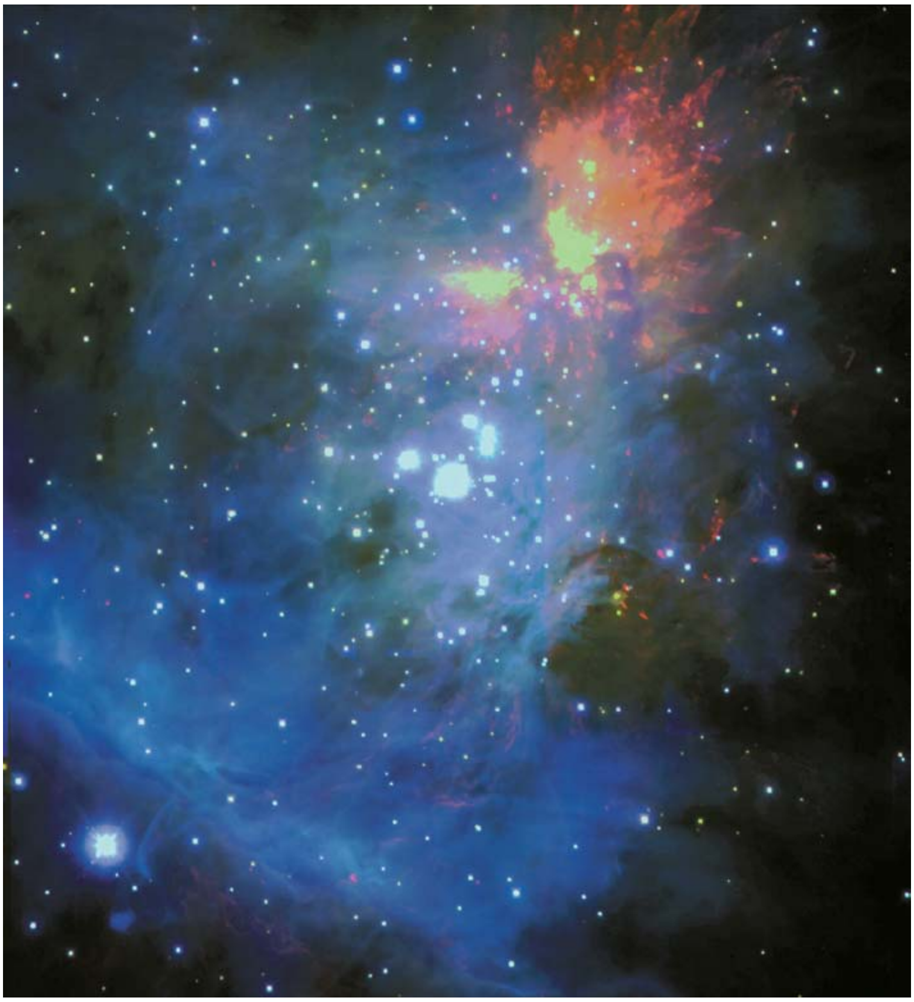


Fig. IV.2: The young star cluster IC 348, imaged in the near-infrared range (2MASS, Univ. Massachusetts)

Stars of about one solar mass and an age of up to one million years are named after the prototype T Tauri. Today, two types are distinguished on the base of emission lines in their spectra: one type has strong lines, the other one weak ones. But both types vary in brightness. While classical T-Tauri stars have strong emission lines and typically show irregular brightness variations over very long time scales from hours up to years, T-Tauri stars with weak lines mostly vary regularly with periods of several days.

Today, astronomers assume classical T-Tauri stars are still surrounded by dense disks from which they accumulate matter. In this process, disturbances arise in the disk, causing large blobs of matter to plunge down onto the star, which in turn causes the observed irregular brightness variations.

T-Tauri stars with weak lines, however, are a little more advanced in their evolution. They have lost their disk earlier or it has thinned out rapidly. This can be caused by a close companion, for example. The periodic brightness variations of weak-line T-Tauri stars presumably are due to large darker spots on their surface. The brightness decreases every time the spot is moved by rotation to the star's near side, as seen from Earth. If such a spot remains stable over several rotation periods, the period of the brightness variation exactly corresponds to the rotation period – thus offering the opportunity to study the rotation of young stars and possibly find out when and how they lose excess angular momentum.

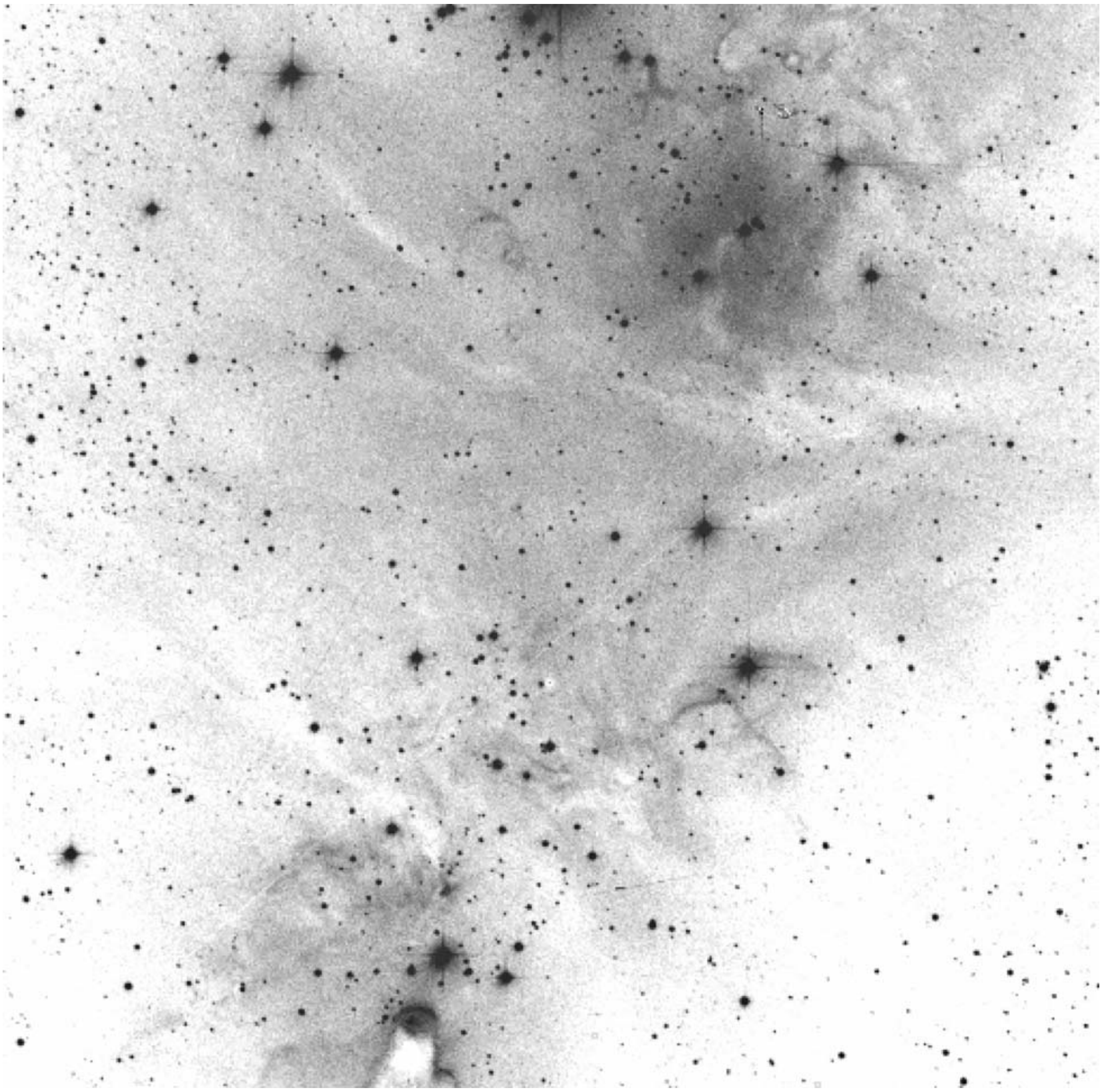
Although brightness variations of young stars have been known for a long time, their study was limited to single objects so far. One reason for this is that many star formation regions are very extended and cannot be imaged as a whole on the usually small fields of view of the telescopes. This shortcoming has been eliminated at the end of 1998 by means of the wide field camera built by astronomers at MPIA and ESO (see Annual Report 1998, p. 33). It has an unusually large image size of 33′ × 33′, corresponding to about the apparent diameter of the full moon. The camera operates at the 2.2 m telescope on La Silla, Chile. For the study described here, a smaller telescope in the US was used also.

In collaboration with US colleagues, three star clusters of different ages were investigated: the Orion-Nebula cluster (Fig. IV.1) at a distance of 1500 light years and an age of about one million years; IC 348 (Fig. IV.2), 850 light years away and around 1.3 million years old; and NGC 2264 (Fig IV.3), about 2400 light years away and 2-3 million years old.

During an observation campaign around the turn of the year 1998/1999, the astronomers were able to observe the Orion-Nebula cluster from La Silla for more than 50 nights. This cluster is well suited for such a study since about 2300 young stars are observable there within a relatively small region. When permitted by other research programs conducted at this telescope, the star field was imaged several times each night. Subsequently, the stellar light curves were derived. A total of 400 stars were shown to vary periodically in brightness (Fig. IV.4). This series of observations alone has almost tripled the data set available so far. As this star cluster had been studied frequently before by other astronomers, masses were already known for 335 of the variable stars. Thus, this cluster was of central significance for the subsequent analysis.

In a second step, it was interesting to compare the rotation periods of stars of different ages. For this purpose, stars of the Orion cluster and of IC 348,

Fig. IV.3: The Open Cluster NGC 2264.



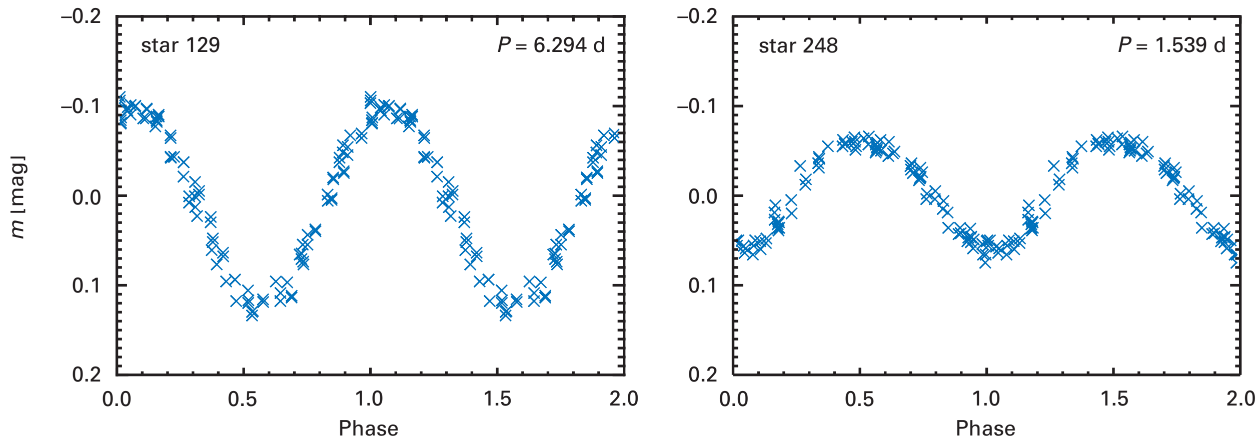


Fig. IV.4: Two examples of light curves for periodically variable members of the Orion-Nebula cluster.

which are only one million years old, were compared to those of NGC 2264, which are three times older. Only stars heavier than 0.25 solar masses were considered. (The reason for this lower limit is explained below.) As can be seen from Fig. IV.5, both groups behave differently. The rotation periods of the younger stars in Orion and IC 348 show a distribution with two maxima. There is one group with rotation periods around two days and another group with periods of about eight days. The older stars of NGC 2264 apparently do not show such a bimodal distribution. Although the number of stars in NGC 2264 is not very high and therefore statistics are not very good, the majority of stars there rotate with periods between two and five days. More observations of this cluster using the wide field camera are planned.

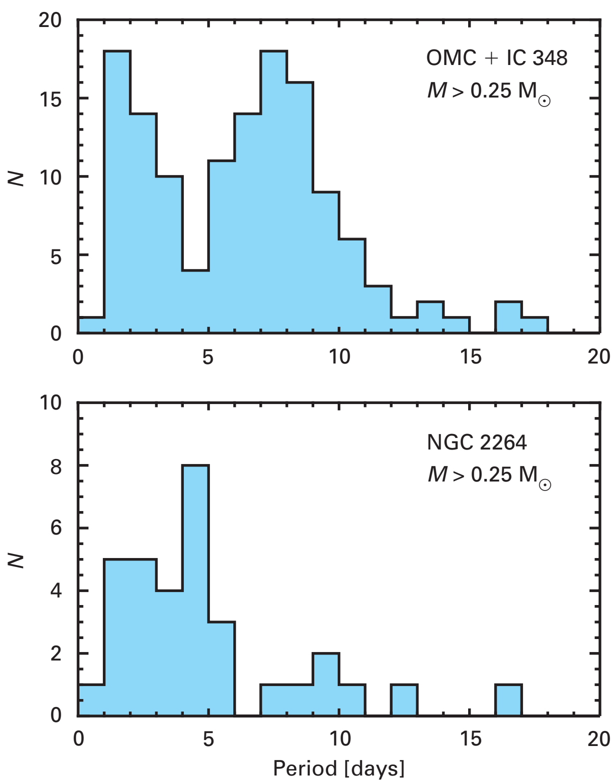


Fig. IV.5: Distribution of rotation periods for stars more massive than 0.25 solar masses. Top: the young stars of the Orion cluster and IC 348; bottom: the older stars of NGC 2264.

Circumstellar disk causes loss of angular momentum

This observational result can be explained to a large extent by a theory involving circumstellar disks. In this theory, the young stars are assumed to have magnetic fields. This assumption is supported by numerous observations, and in the end, the spots which are thought to be responsible for the brightness variations are also caused by magnetic fields. The field extends far into space and interacts with charged particles of the disk surrounding the star. The magnetic field is stirring the disk like a mixer in the dough. The disk is slowed down in this process, and the slowing is transferred to the star's rotation. Computer simulations show this so-called "disk locking" to be able to decelerate a young star to half its rotation velocity within one million years.

The recent observational data can be explained by this theory as follows: In the younger clusters, in Orion and IC 348, a larger portion of the stars still has pronounced disks so that disk locking is very important for this group.

Some of the stars already are slowed down by disk locking. The slowly rotating stars are still surrounded by disks, and the faster ones have lost their disks. As the stars contract, they rotate increasingly faster.

This does not explain the difference between both groups, however. The difference might be due to different stellar masses which were not taken into account except for the lower mass limit of 0.25 solar masses. Observations in the infrared range suggest that the slowly rotating stars belong to the class of weak-line T-Tauri stars. Presumably, they are no longer surrounded by a disk. In the older cluster NGC 2264, most of the stars seem to rotate faster, possibly indicating the portion of young stars with disks being smaller for a longer period time. The disk locking is not working any longer and the stars get faster again as they are contracting.

This would mean that a majority of the circumstellar disks around T-Tauri stars are dissipated after one to two million years, either because the star has accumulated almost all the material or has dispersed it by means of its intensive particle wind. The same time scales are obtained by other observations, too. The absence of intense infrared emission from dust ("infrared excesses") in young stars, for example, indicates a somewhat older age of the cluster. One or two million years is a relatively short period of time, contradicting several theories according to which large planets like Jupiter take at least ten million years to form.

In addition, the study revealed another interesting aspect. Considering only the stars of the Orion Nebula, a distinction with respect to the masses is found (Fig. IV.6): Only stars heavier than 0.25 solar masses show the bimodal distribution of rotation periods. Lower-mass stars within this cluster behave differently, having a broader distribution of rotation periods with a maximum at two to three days. Thus, lower-mass stars rotate faster on the average than the more massive ones.

This result can be explained by stellar evolution theory. Stars above 0.25 solar masses start deuterium (heavy hydrogen) fusion in their centers after about one million years. As a result, the star's temperature rises, counteracting contraction. Thus, contraction is slowed and the star's rotation velocity does not increase any further. Stars below 0.25 solar masses take a longer time to reach the temperature and density needed for deuterium burning. They contract unhindered, rotating faster and faster.

This is only the beginning of an explanation of the connection between the rotation velocity of young T-Tauri stars and their surrounding disks of gas and dust. To follow up this important phenomenon of star formation, detailed observations in the infrared range as well as spectroscopic studies are required, yielding more information on the properties of the disks.

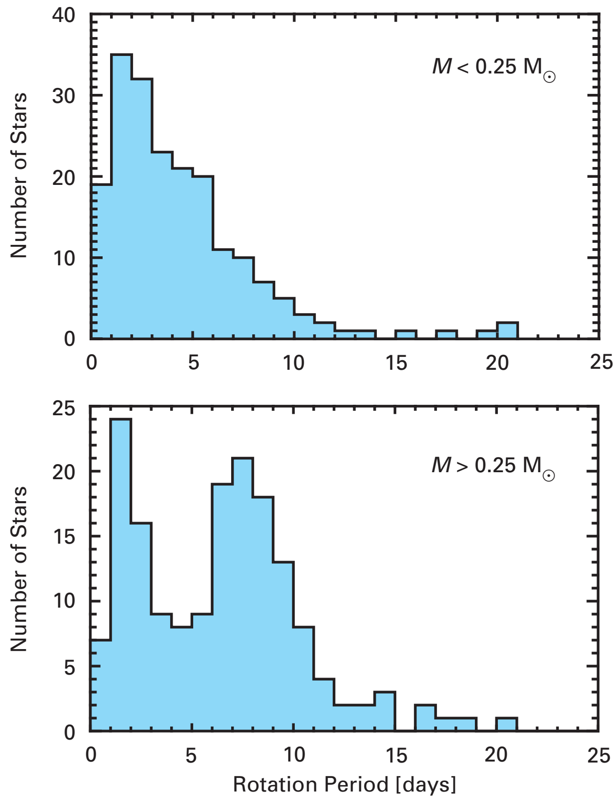


Fig. IV.6: Distribution of rotation periods of stars in the Orion cluster above and below 0.25 solar masses.

Orbital Periods and Masses of Young Binaries

The mass of a star determines its inner structure and evolution. For young stars, however, this important quantity can be determined directly only in a few cases. It is mainly derived from observed magnitudes and colors by comparison with a stellar evolution model. A more direct method is to calculate the total mass of two stars in a binary system from their observed orbital period. In the year under report, a team of astronomers in Tautenburg, California and at MPIA succeeded in measuring the distances and motions of a greater number of T Tauri stars within binary systems. The data already allow a statistical statement on the masses of the individual components of the stellar pairs. The determination of exact orbital parameters, though, has to await future observations.

T Tauri stars are in a pre-main-sequence stage, meaning they have not yet reached hydrostatic equilibrium, in contrast to, for example, our Sun, who reached it about 4.6 billion years ago. A lot of T Tauri stars are known. Characteristic properties of T Tauri stars include that they may be surrounded by large quantities of dust, eject narrow particle beams (jets) into space, or show strong X-ray activity. One goal of astronomy is to understand how these phenomena are correlated with different evolutionary stages and different masses of stars. Although there is a handful of young stars whose masses have been determined through radial velocity measurements, in the majority of cases mass estimates are obtained from theoretical calculations of mass-dependent evolutionary tracks and their comparison to the observed colors and luminosities of stars. In this way, the ages and masses of the stars can be derived from observational quantities. The values, however, depend on the model whose quality is difficult to assess.

Therefore it would be extremely desirable to determine the masses of a sufficient number of young stars independently of a model. One method is to measure the orbital periods and distances within binary stars. Newton's law then gives the mass of the system, that is, the sum of the masses of both components. In 1995, a team of American astronomers for the first time published a mean value of 1.7 solar masses for 20 T Tauri binary systems.

Similar observations were performed by astronomers at the Institute and their colleagues, based on a larger number of objects observed for a longer period of time in the near-infrared at wavelengths of 1.25, 1.65 and 2.2 µm. Using the 3.5 m telescope at Calar Alto and the ESO New Technology Telescope in Chile, they applied the technique of Speckle interferometry. The Speckle technique, which has a long tradition at MPIA, allows to circumvent the atmospherical seeing which impedes the separation of very close stellar pairs. This technique is absolutely necessary for the following reason. During the relatively short observation period of a few years only orbital motions of relatively close binaries can be detected. The components of the observed stars, lying in distances of 450 to 620 light years, are separated by not more than 0.5 arcseconds. While on long exposures the individual members cannot be resolved, this is very well possible with Speckle interferometry. Here many short exposures (only about a tenth of a second long) are obtained and later added up in a computer. So the physically best possible spatial resolution (diffraction limit) can be achieved.

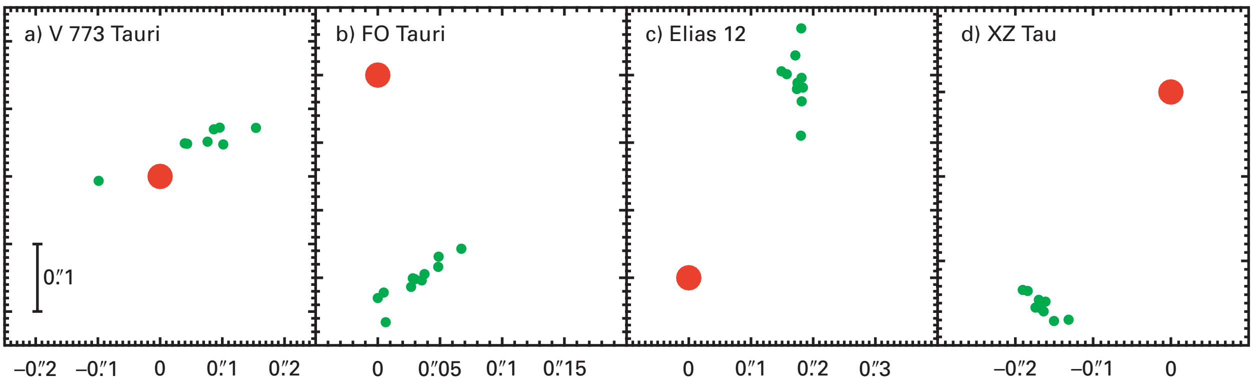
In the data analysis, the newly observed stellar positions of 34 systems have been compared with already existing data. These comprise partly the T Tauri stars studied in 1995 by the American colleagues and partly systems observed by the HUBBLE Space Telescope, but for the most part own data from previous observations. The time base was maximally ten years. Distances were obtained through observations of the relevant star clusters with the HIPPARCOS astrometric satellite.

Comparison of the older images with the new ones yielded the velocities of the companion stars relatively to their respective primaries (Fig. IV.7). In principle, two stars lying along the same line of sight could in fact be at vastly different distances from us and not at all physically bound. One such case was identified with high probability and excluded from the data. Furthermore, it was found that companions within close systems (maximum separation of 25 astronomical units) on average had higher velocities than those in wide ones, as is expected from Kepler's law (Fig. IV.8) – a fact that suggested all cases are real binaries.

The data material, however, was not yet sufficient to determine the orbital period. On the one hand, the time intervals between the first and the last measurement were too short, and on the other hand astronomers could only measure the velocity component within the celestial plane. But it was possible to calculate statistically an average mass value for all systems. This procedure involves Kepler's third law and takes into account that the inclinations of the orbits against the celestial plane and the eccentricities of the elliptical orbits are not known.

In computer simulations, ten million binary systems with observed separations between 10 and 70 AU, a wide range of eccentricities, and total masses

Fig. IV.7: Observed motions of companions (green) relative to their respective primary (red): **a)** V 773 (motion counterclockwise, from right to left), **b)** FO Tau (clockwise, from left to right), **c)** Elias 12 (clockwise, top-down), and **d)** XZ Tau (clockwise).



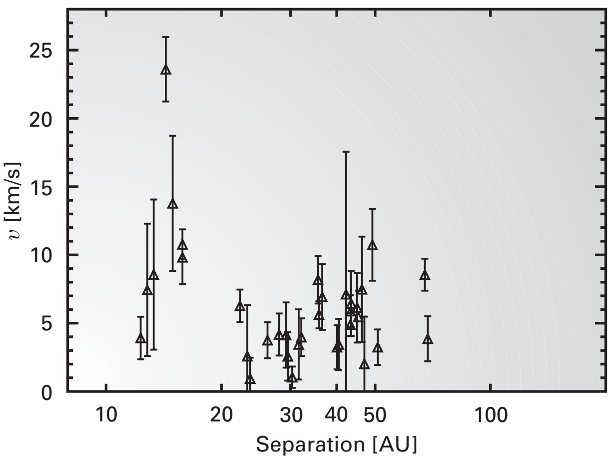


Fig. IV.8: Relative velocities of the components as a function of their mutual distance.

of 0.5 to 2.5 solar masses have been distributed in space with arbitrary inclinations. Comparison with the observed data yields an average mass for all systems of 2–0.7 solar masses. Of course, this value is just a rough idea as it assumes an equal mass for both coponents of the binary systems. Nevertheless, it allows a first comparison with results based on stellar mass determinations using stellar evolution models. With these, theoreticians had obtained masses between 0.9 and 1.3 solar masses for individual stars within the Taurus-Auriga and Scorpius-Taurus star formation regions. For this subgroup, astronomers at the MPIA and their colleagues derived masses of 1.2–0.5 solar masses.

So there is already a rather good agreement between the empirically obtained values and the theoretical ones, with several models being especially promising. Further observations, yielding more measured points and a larger time base, will enable astronomers to determine the masses of several systems individually.

ISOPHOT Observes Star Formation within Dark Clouds

Stars form deeply hidden within dense interstellar clouds of gas and dust. Therefore the first stages of star formation are not observable in optical light. Infrared radiation, however, can penetrate the dust. The ISOPHOT camera, built at MPIA and flown on the ISO infrared satellite, made it possible for the first time to detect those extremely cold condensations at wavelengths up to 240 µm in the interior of such clouds, from which new stars will form.

Mature stars reach temperatures of many million degrees within their inner cores. At the beginning of their formation, though, stars are the coldest places in the universe. The reason for this is the following: The outer regions of interstellar dust clouds are heated by the surrounding general star light, especially by its ultraviolet and blue portion. This radiation, however, cannot penetrate deeply into the cloud. Therefore the innermost regions are protected against the heating through stellar radiation and cool down considerably.

If the density in some part of a cloud exceeds a critical value, this region contracts under the influence of its own gravity. Only when this stage is attained the matter starts to heat slowly because of contraction and the induced increase of pressure. Eventually, the temperature in the center of the condensation reaches several million degrees and nuclear fusion ignites – a star is born. In this phase, the stars frequently have already dissolved their surrounding dust clouds and are visible now in optical light.

To a large extent the process of star formation can be studied observationally. Until recently, however, the very first stages, in which the condensations are still very cold, had mostly been hidden from view. Only in the radio spectral range molecules could be detected within presumed pre-stellar cloud cores. Now, with ISOPHOT, an excellently suited instrument is available to identify these first condensations in the interior of dust clouds.

ISOPHOT was one out of four scientific instruments onboard the European space telescope ISO which observed selected celestial objects for about 29 months, till April 1998. ISOPHOT, built under the direction of MPIA, worked as a photopolarimeter, camera, and spectrophotometer in the wavelength range from 2.5 µm to 240 µm. Thus ISOPHOT could detect thermal emission of dust at temperatures as low as about 11 Kelvin.

Star formation within the Chamaeleon complex

The constellation Chamaeleon in the southern sky harbors an extended region of dense molecular clouds. Three distinct condensations are called Cha I, Cha II, and Cha III. Radio observations already had indicated star formation processes within this dark cloud complex. As it is only about 500 light years away, there was a chance to spatially resolve pre-stellar cores in its interior, which are some 0.7 light years across, corresponding to about 5 arcminutes on the celestial sphere.

In the year under report, Finnish and Hungarian astronomers, together with colleagues at MPIA, published two papers on their detailed studies of the Chamaeleon complex.

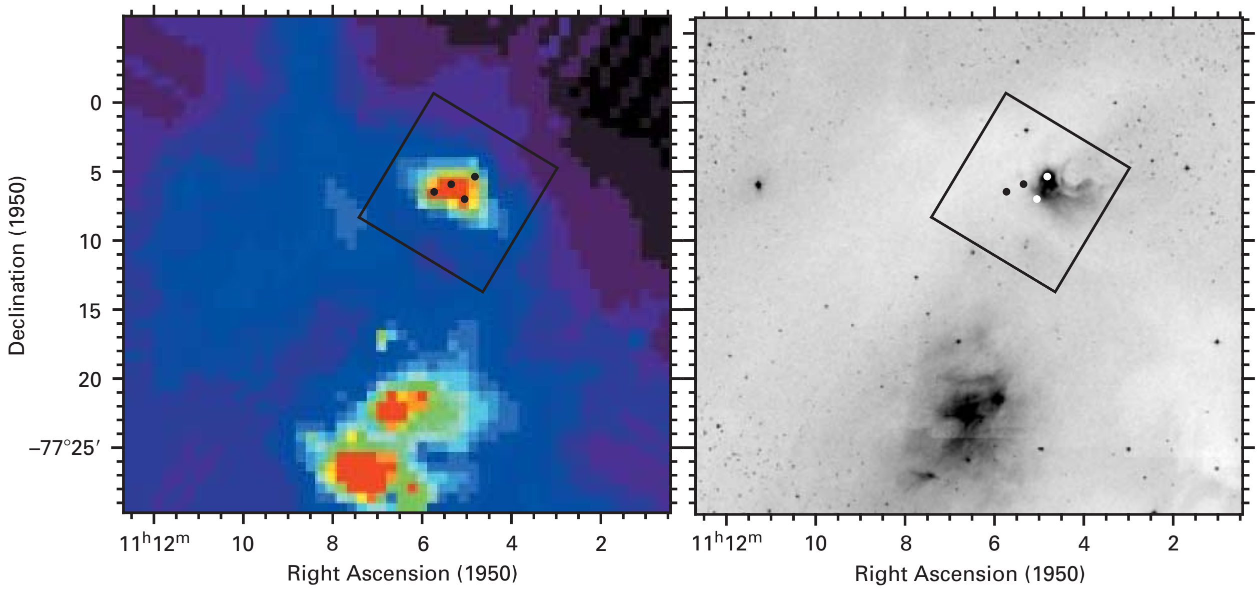
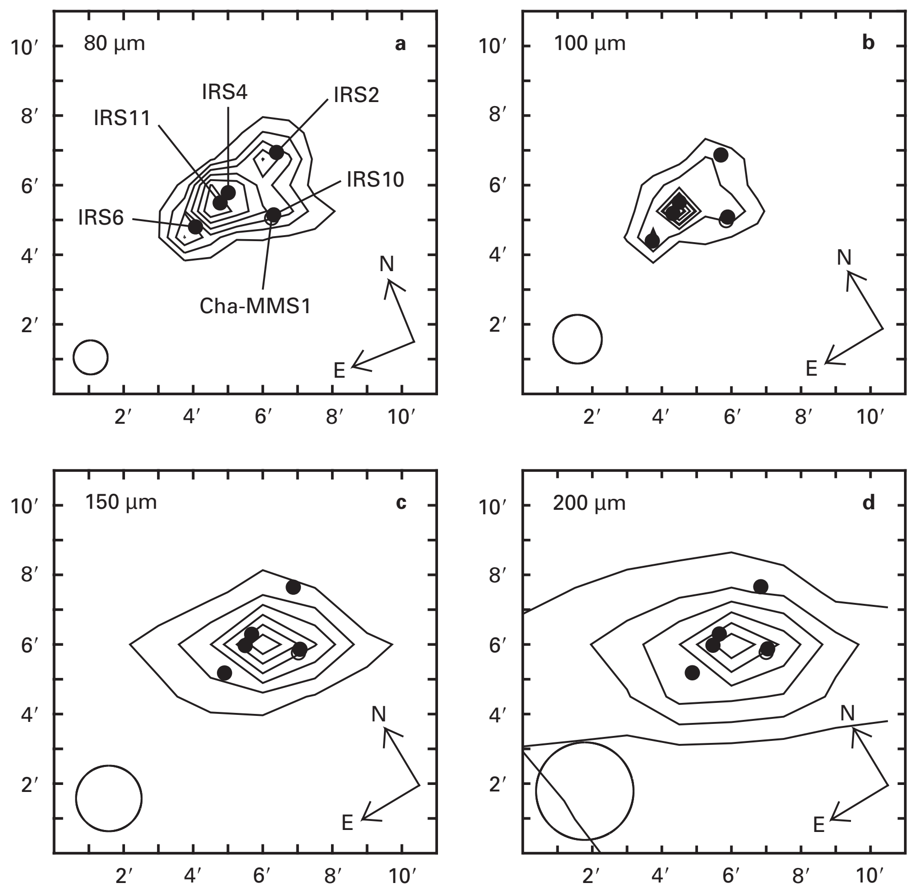


Fig. IV.9: The Chamaeleon I region, imaged at 100 µm wavelength by ISOPHOT (left), and in the optical (right).

Fig. IV.10: The infrared sources in Cederblad 110, imaged by ISOPHOT at four wavelengths.



One paper exclusively dealt with the subcomplex Cha I. It is characterized by three reflection nebulae named after the astronomer Cederblad, who found them as early as 1946. One of them, Cederblad 110, is illuminated by a T Tauri star (Fig. IV.9). Like our Sun, it is of spectral type G, but only about one million years old. In the 1980ies, the infrared satellite IRAS had already detected three sources in Cederblad 110, which were called IRS 2, IRS 4 and IRS 6. IRS 2 turned out to be the illuminating T Tauri star while IRS 4 and IRS 6 were only detectable in the infrared. As the maximum of their emission lies beyond the IRAS detection limit of 100 µm, only conjectures on the evolutionary stage of these objects were possible. Moreover, radio observations showed an object south of IRS 2 and IRS 4, called Cha-MMS 1, from which a molecular outflow seems to emanate – a phenomenon frequently observed in young stars.

With ISOPHOT, it was possible to detect IRS 2, 4 and 6 at wavelengths longer than 80 µm although the camera's spatial resolution at 200 µm was not sufficient to separate the sources. At 80 µm and 100 µm Cha-MMS 1 could also be detected. This source got the additional designation IRS 10 (Fig. IV.10).

The four sources mentioned above lie within an extended region of infrared radiation. After subtracting this extended emission as well as the four point sources from the image a faint source located between IRS 4 and IRS 6 showed up which was named IRS 11. It could be detected only at 80 µm, however, as the spatial resolution was no longer sufficient at longer wavelengths. But a different team of astronomers had observed the Cha 1 region, too, using the ISOCAM infrared camera on ISO. They found a source at wavelengths of 7 µm and 14 µm, which lies almost exactly at the position of IRS 11. Most likely, it is one and the same object.

Thus a total of five sources is presently known in Cederblad 110: IRS 2, 4, 6, 10 and 11. Now it would be interesting to know their evolutionary stages. Decisive clues come from their spectral energy distributions, which could be measured completely by ISOPHOT for the first time because the emission maxima of the sources lie at wavelengths longer than 100 µm (Fig. IV.11). As shown in the figure, the far-infrared emission can be fitted quite well with blackbody functions which yield dust temperatures of 20 to 25 Kelvin. The total luminosities of the sources can be derived from their overall spectrum. They differ strongly, lying between 0.4 and 3.4 solar luminosities. Thus the sources also have to be at different temperatures. The stronger the energy distribution in Fig. IV.11 increases towards shorter wavelengths, the higher is the temperature of the object. Model calculations yielded temperatures of 2700, 260, 72 and 19 Kelvin for the sources IRS 2, 6, 4, and 10, respectively.

Obviously the objects are of different age. Maybe they have formed in two episodes. First, the source IRS 2, which is now illuminating the reflecting nebula Cederblad 110, formed one million years ago. The other four sources, however, are much younger, 100 000 years at most. It is possible that IRS 2 has triggered the formation of these younger objects.

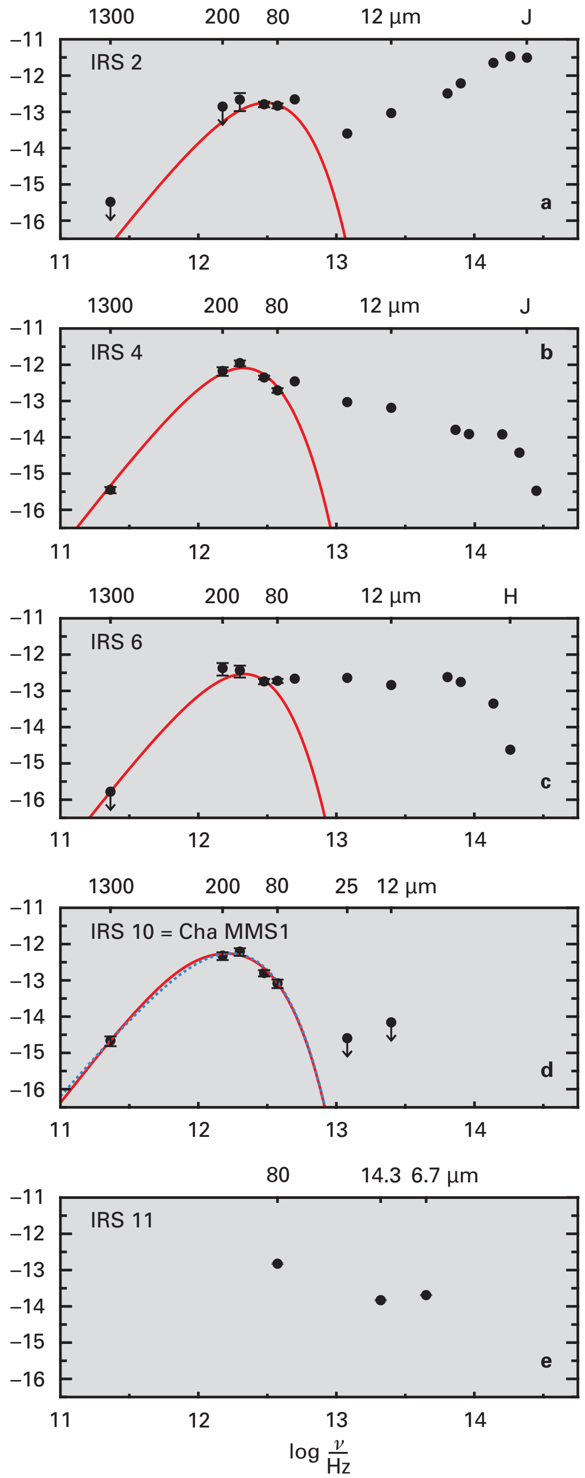


Fig. IV.11: The spectral energy distribution of the infrared sources in Cederblad 110.

The coolest object IRS 10 occupies a special position. Most probably it is one of the very few known real protostars. These objects are already in the contracting phase while still gathering matter from their surroundings, but have not yet ignited nuclear fusion in their centers. Their typical signs are:

- detectability only at wavelengths longer than about 10 µm
- temperatures of about 15 to 30 Kelvin
- activity like molecular outflows, observed mainly in the CO emission line
- at least 2 % of the total emission at wavelengths longer than 350 µm.

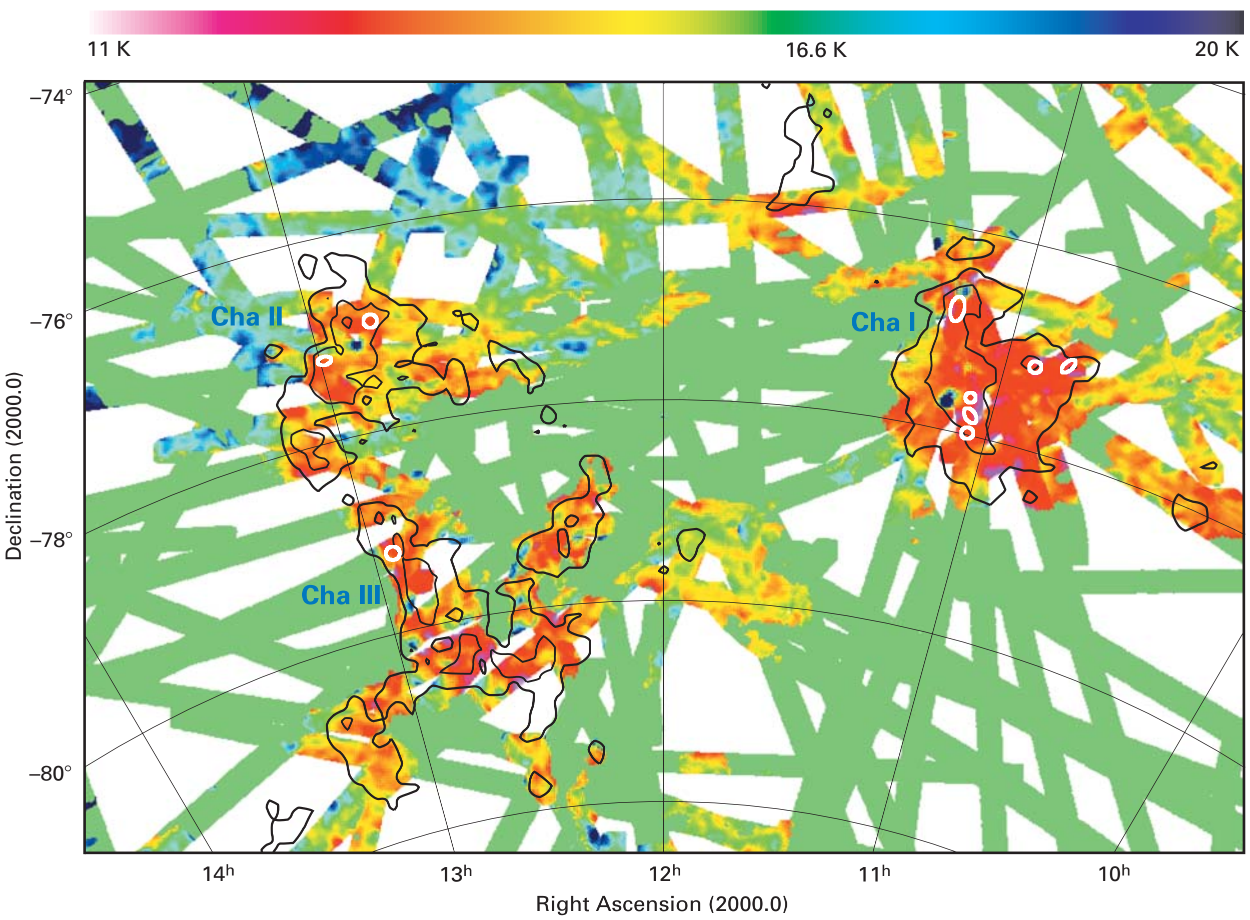
IRS 10 meets all these criteria. Obviously it is a small protostar of about half a solar mass.

Observations in the far infrared with ISOPHOT and in the submillimeter region also allowed the mass of the stars and the clouds to be estimated. The mass of the entire cloud Cederblad 110 amounts to 15 to 19 solar masses. The stars have a total mass of 3 to 4 solar masses. From that it follows that 16 to 21 % of the initial cloud material has been transformed into stars. This value is considerably higher than that of 2 to 9 % that was obtained for Taurus-Auriga, a huge star formation region in the northern sky. But it is comparable to that of the Rho-Ophiuchi cloud. The cause for these differences is not clear. Presumably they are related to highly differing values of the star density, which is about 1500 times higher in Cederblad 110 than in the Taurus-Auriga region.

The Chamaeleon complex in the ISOPHOT Serendipity Survey

A second possibility to observe the Chamaeleon star formation region was offered by the ISOPHOT Serendipity Survey. This survey was a by-product of the ISO mission. As the satellite normally was pointed to selected objects it had to be slewed between the pointed observations from one position on the sky to the next. In order not to waste this slewing time the camera C200 in ISOPHOT was kept turned on during the slew. This way, one-dimensional scans across the whole sky in the far-infrared band around 200 µm were obtained – a spectral region still unexplored until the

Fig. IV.12: Color-temperature map of the Chamaeleon region from the Serendipity Survey.



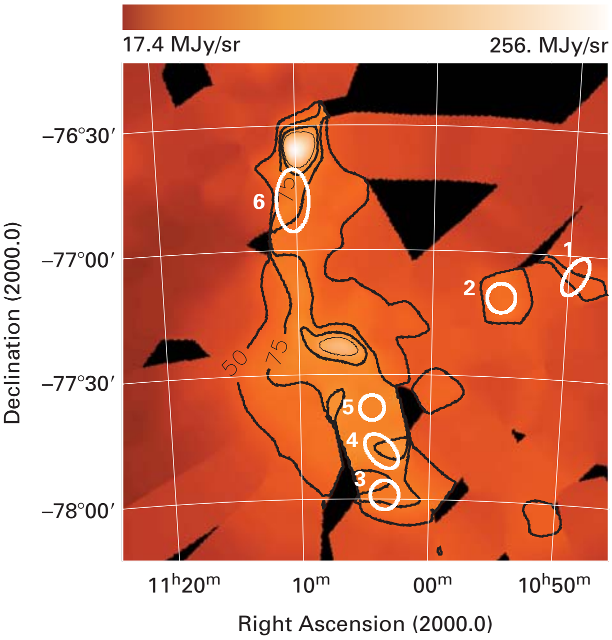


Fig. IV.13: Chamaeleon I at 170 µm. The small white ellipses indicate the "cold knots".

ISO mission. In this manner, an additional 15 % of the entire sky could be scanned in 3 arcminute wide strips.

A field with a total size of 20° × 20° in the constellations of Chamaeleon and Musca has been crossed very frequently by the "slewing beam", so all in all about a quarter of the molecular cloud complex in Chamaeleon has been mapped. These data obtained at 170 µm were compared to the 100 µm IRAS data. The interesting cool regions stand out due to their large intensity ratio *I*(170 µm)/*I*(100 µm).

The comparison results in a color-temperature map of the three main complexes Chamaeleon I, II, and III (Fig. IV.12). It shows mostly cold regions with temperatures below 15 Kelvin. Only a few "warm" regions up to 20 Kelvin occur in the north-eastern part. The diffuse material between the main clouds has temperatures around 16 Kelvin, which is in agreement with the temperatures expected for dust heated from outside by the diffuse radiation of surrounding stars.

In addition, very cold spots with temperatures as low as 12 Kelvin are seen, all of them small structures within the clouds. A total of nine such cold regions has been found, six of them in Chamaeleon I (Fig. IV.13). Two of them correspond to the cold clouds described in the previous section. The temperatures of 13.7 Kelvin determined in both studies are also similar, within the uncertainty limit of 0.5 Kelvin, demonstrating the efficiency of the search for cold sources by the ISOPHOT Serendipity Survey.

To learn more about these interesting features the astronomers compared their results with those of other authors. As it turned out, the cold knots correspond to regions with particularly strong dust absorption (extinction) in the visible light. A linear dependence between the intensity of the far-infrared emission at 170 µm (cold dust) and the extinction could be established – a clear indication for the emission at 170 µm coming from larger dust grains, which are also responsible for the optical extinction. Apparently the far-infrared maps always reflect the density distribution of the dust within the clouds. In addition, the cold regions are associated with high concentration of CO gas found by Japanese astronomers in 1998.

From all this it can be concluded that the cold regions are condensations within the Chamaeleon clouds. The observationally derived gas density is about 10^4 hydrogen molecules per cubic centimeter in knots about 0.7 light years across. The evolutionary stage of these cores (pre-stellar clouds on the verge of collapse or in an early collapse phase) has to be determined by further observations, in the sub-millimeter region for instance, which are already underway.

Isolated star formation in Barnard 217

Three of the ISO slews have also crossed the dark cloud Barnard 217 (B 217, see Fig. IV.14), allowing this small cloud to be observed in the far infrared for the first time. B 217 is located at the end of a large dust filament within the Taurus molecular cloud complex. At a distance of about 450 light years, the dark cloud is rather small with a size of 2 × 1.3 light years (corresponding to 15 arcminutes × 10 arcminutes on the sky). In the interior of such clouds single stars could be forming, which is why this cloud repeatedly has been the target of astronomical observations. These observations showed, that B 217 indeed consists of two approximately equally sized clumps. Corresponding to their location they are denoted as B 217 SW (southwest) and B 217 NE (northeast). IRAS had found an infrared source between these two condensations – a young star illuminating a reflection nebula. This nebula is aligned perpendicularly to the axis connecting B 217 SW and B 217 NE and has a cometary shape, as it is often found in young stars.

Although this showed B 217 to be a region of active star formation, the physical state of the two clumps remained unclear. From ISOPHOT measurements at 170 µm and existing IRAS data dust temperatures of 12 Kelvin and 11 Kelvin were derived for the two cloud parts. These unusually low temperatures again indicated very dense cloud cores. Surprisingly the ISO data showed another source about 3 arcminutes northwest of B 217 SW. With 13.3 Kelvin, this region, called B 217 NW (northwest), is slightly warmer than the other two condensations. From the intensities at 170 µm masses of 1.5, 2.6 and 3.8 solar masses have been derived for the three cores, respectively.

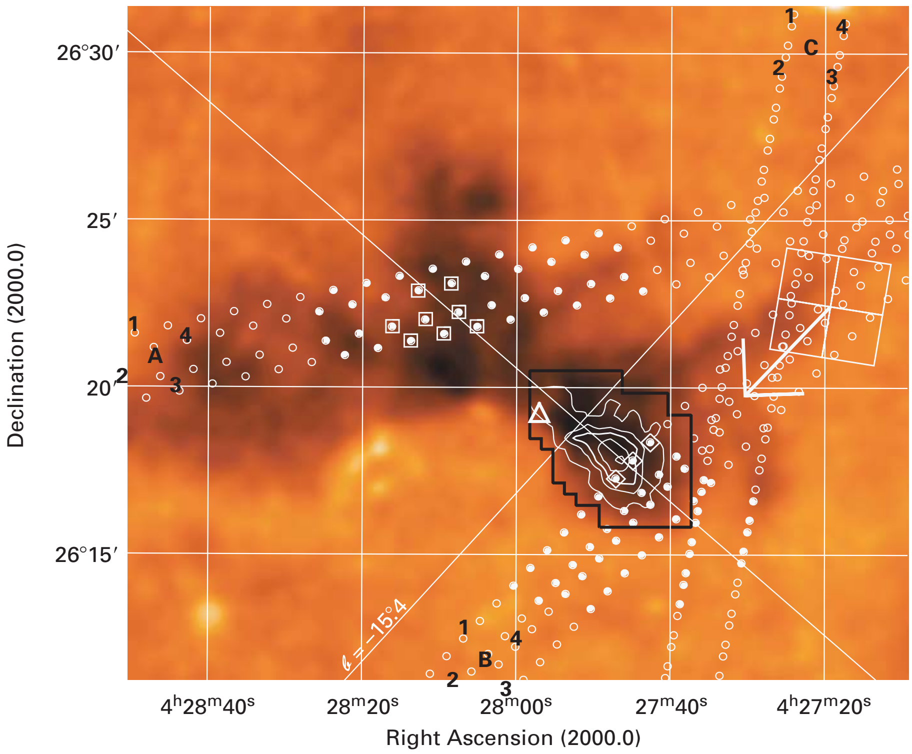


Fig. IV.14: In optical photos B 217 appears as a dark patch. The region has been crossed three times by serendipitous ISO slews (A, B, C).

To get more information about the gas in B 217 astronomers at MPIA together with a colleague from Italy also performed radio observations of the core B 217 SW, using the 100 m radio telescope of the MPI for Radio Astronomy at Effelsberg. The ammonia molecule (NH_3) was detected, which is a good density indicator. After NH_3 had already been found earlier in B 217, the MPIA team and their colleagues could now detect this molecule clearly enough in the cold region to determine temperature and density. Even a density profile within the knot could be derived. According to this, the (converted) number density of H_2 decreases exponentially from at least 3×10^5 cm^{-3} at the center to 6×10^3 cm^{-3} at the edge (Fig. IV.15). The kinetic temperature, describing the thermal motion of the gas, increases linearly from about 9 Kelvin at the center to 12 Kelvin at the edge (gas and dust do not have the same temperature). From this, the potential energy and thermal energy of the gas can be estimated. The result, showing the potential energy being about twice the thermal energy, suggests that this region is close to hydrostatic equilibrium. Thus the collapse could start any time. The same seems to apply to the second cold knot in B 217 NE.

The new observations show the small dark cloud 217 to be in a very dynamical state. While a star is just forming in it (the T Tauri star) there are two or three dense dusty cores, which are about or have just begun to contract to form new stars in the near future. As in Cederblad 110 there are two episodes of star formation in B 217, which obviously do not interfere with one another. Remarkably, both dominant dust clumps in B 217 lie perpendicularly to the longitudinal axis of the cometary nebula, illuminated by the young star. Normally, such a reflection nebula is associated with a bipolar gas flow in the direction of the longitudinal axis, which probably coincides with the star's rotational axis.

These studies demonstrate the great potential of the ISOPHOT Serendipity Survey: After finding cold dust in other galaxies with this method, astronomers at MPIA now detected cold cores within molecular

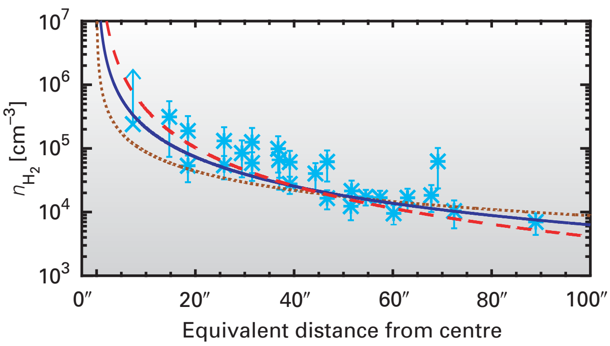


Fig. IV.15: Radial density distribution in B 217. The dotted, solid and dashed curves represent exponential declines with exponents of -1, -1.5, and -2, respectively.

clouds in our own Milky Way. Up to one hundred of these young star-forming regions are expected to be found in our Galaxy. Further observations, as have already begun in the sub-millimeter and millimeter range, as well as far-infrared observations with future space telescopes, will be based on them.

Palomar 5 – a Dissolving Globular Cluster

Presently, about 150 globular clusters are known in our Milky Way system. They move around the galactic center at different distances and on different orbits, passing through the galactic plane again and again. During every passage they loose some of their members, i.e., they are slowly dissolving. The strength of this effect should depend on the mass and compactness of a global cluster as well as on its distance from the galactic center. The observational confirmation of this dissolution effect is difficult, since normally only few cluster members leave the cluster, and in order to detect them a large area has to be surveyed. A team of astronomers at MPIA and in the US recently succeeded in detecting this effect directly for the first time in the globular cluster Palomar 5. This system shows two distinct "tails" of stars which have been ripped from their community.

Globular clusters contain between ten thousand and several million stars and are 40 to 400 light years across. The stellar density generally increases strongly towards the center where it can be up to ten thousand times higher than in the solar neighborhood.

The Galactic globular clusters are generally found in an extended halo more than 300 000 light years across and move around the Galactic center on elliptical orbits. They are thought to have formed when a huge primordial gas cloud started to contract gravitationally, giving birth to our rotating Galaxy. Because of its angular momentum the remaining gas cloud later flattened into a disk. Within this disk additional stellar populations formed, which also include our Sun.

During the last twelve billion years the globular clusters were affected by a number of processes, which were induced mainly by the Galactic gravitational field. As globular clusters move around the Galactic center on highly inclined elliptical orbits with orbital periods of several hundred million years, they experience strongly variable tidal forces. These tidal forces supply energy to the cluster stars, thereby changing the stellar orbits within the cluster. As a result, some stars can leave the immediate gravitational field of the cluster and move towards its outskirts, where the Galactic gravitational field dominates. This process eventually leads to the formation of symmetric tails, consisting of stars that are no longer bound to the cluster but still follow its orbit.

Computer simulations predict that half of the present-day globular clusters will be dissolved this way within the next ten billion years. Accordingly, clusters in the stage of advanced dissolution should already be observable, making themselves conspicuous by tidal tails stretching along their orbits. As searches for such structures require a large field of view photographic images were used in the first studies. However, because of sensitivity inhomogeneities and a relatively poor angular resolution of the photographic plates the detection of tidal tails remained uncertain.

The ongoing "Sloan Digital Sky Survey" (SDSS) offered an opportunity to use data of unprecenently high quality for searches for tidal tails to the scientists at the MPIA. The SDSS is the most ambitious sky survey going on so far, imaging about a quarter of the entire sky in five wavelength ranges with a mosaic CCD camera. The final catalogue will provide positions and colors of an estimated one hundred million celestial bodies as well as the redshifts of about one million galaxies and quasars. The observations are performed using a 2.5 m telescope built especially for this purpose at Apache Point Observatory in New Mexico. The project is conducted by an international consortium of US, Japanese, and German institutes. The German research institutes involved are MPIA at Heidelberg and MPI for Astrophysics at Garching. In exchange for financial and other contributions by MPIA a limited number of scientists at the Institute gets full access to the data. After a testing phase of a little more than a year the survey started officially in April 2000.

During the commissioning phase of the SDSS a region was imaged containing the globular cluster Palomar 5, some 75 000 light years away. Its peculiar characteristics render this cluster an especially interesting research object. With a mass of only 13 000 solar masses and a comparatively large core radius of 65 light years it is one of the lowest-mass Galactic globular clusters and shows a very low central concentration (Fig. IV.16). This makes it a candidate for a cluster in the state of dissolution.

Using the data of the Sloan Survey, an area of 6° × 3° around the cluster was studied. It contains cluster stars as well as large numbers of field stars in the Milky Way that are not associated with Palomar 5. In addition this region is studded with background galaxies. In order to recognize the complete spatial distribution of the cluster stars a method had to be found to separate Galactic field stars from cluster members. This was done by taking advantage of the five-filter photometry of the SDSS.

First, all stars lying near the cluster center (as seen from Earth) and which therefore most likely belong to the cluster, were plotted in a color-magnitude diagram. The same was done for stars at a greater distance to the cluster the majority of which should be field stars. Galaxies were excluded by their extended structure or by their colors, which differ from cluster stars. A statistical comparison of the resulting distributions in the color-magnitude diagram then showed the region which is suited best for the selection of cluster stars.

This is illustrated by Figure IV.17. The two diagrams to the left show the colors (in the color indices c_1 and c_2 especially adjusted to the cluster stars) and magnitudes of all stars within 3 arcminutes around the cluster core. The thin lines mark the expected distribution of the cluster stars taking into account uncertainties in the photometric measurements. The thick lines give the range of colors and magnitudes that is most favorable for finding members of Palomar 5.

The two diagrams to the right of Fig. IV.17 show stars from two regions outside the cluster. While on the panel labeled "field" (far right) there are only a few stars within the selection region marked by the thick line, another field (labeled "tail", second panel from right) exhibits a significant overdensity of stars. Apparently these are former members of Palomar 5 which have left the cluster.

After applying this method to the entire area observed, the spatial distribution of the stars can be traced. Stars matching the cluster photometrically are especially numerous within two elongated regions outside of Palomar 5 (Fig. IV.18). These tails stretch out symmetrically from the center towards the north and the south for about 0.2 degrees (corresponding to 260

Fig. IV.16: Multicolor composite image of Palomar 5 from the Sloan Digital Sky Survey. The loosely distributed stars of this cluster appear yellowish and blue. They are mainly subgiants and main-sequence stars.

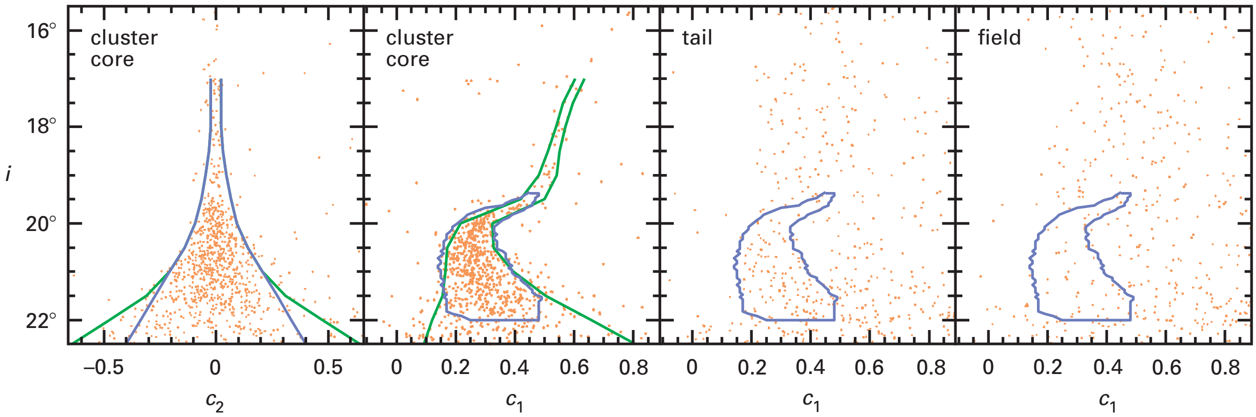


Fig. IV.17: Color-magnitude diagram for stars within ("cluster core") and around ("field") Palomar 5. Cluster stars mainly lie within a region marked by a purple line. This is also where the stars of the tail appear (second diagram from right).

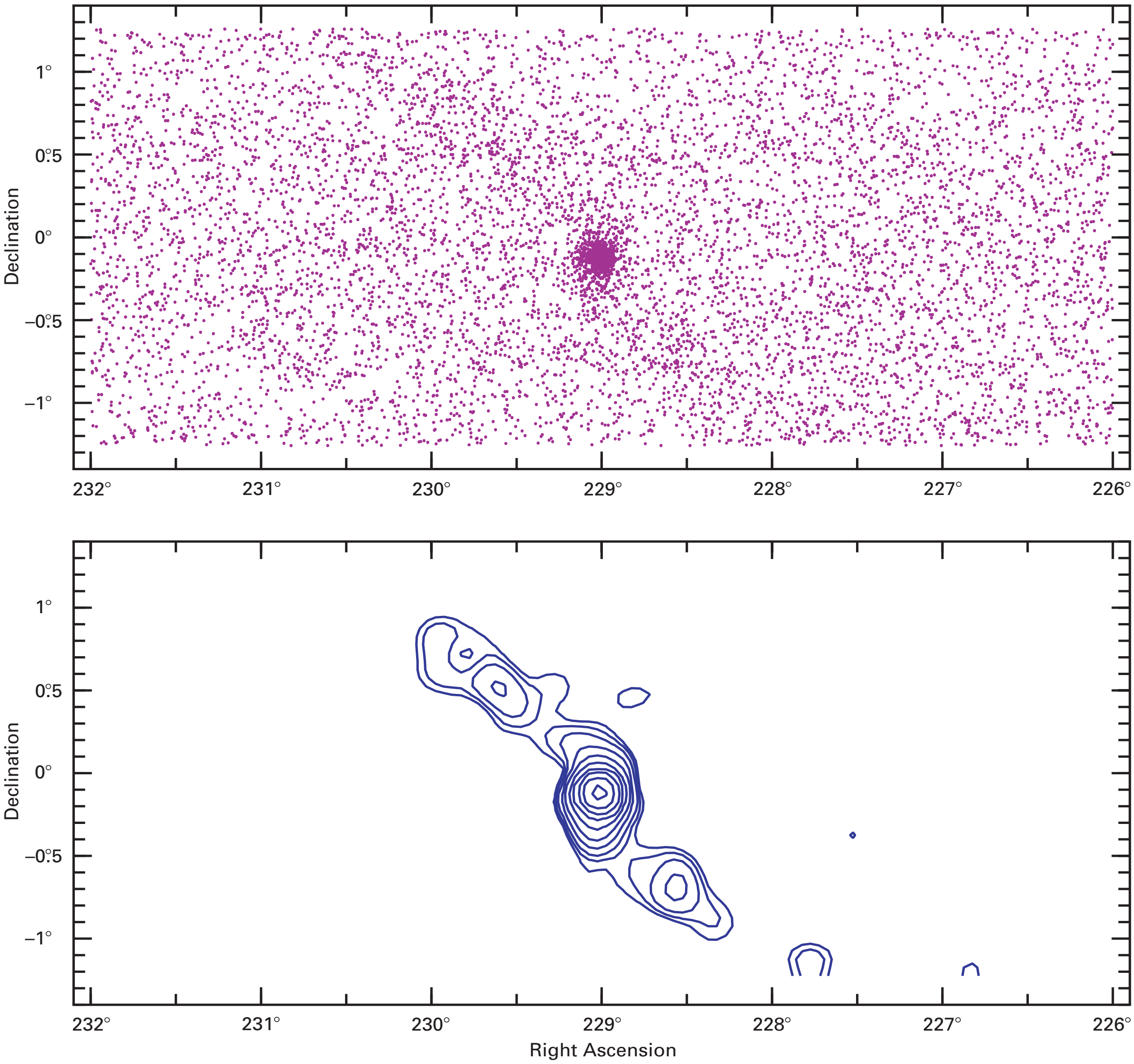


Fig. IV.18: Spatial distribution of field stars photometrically matching the cluster and of true members of Palomar 5 (above). The contour plot (below) shows the corresponding lines of equal surface densities of the stars.

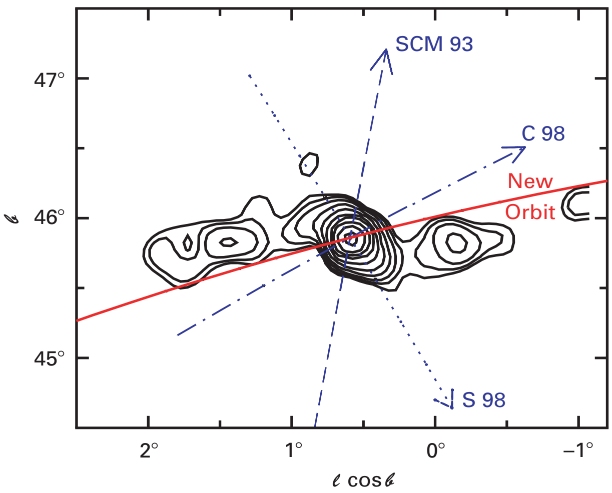


Fig. IV.19: Contour plot of Palomar 5 (black) and directions of its motion in space, as measured previously (blue). The red line shows the new estimate of the cluster's orbital path based on the geometry of the tails.

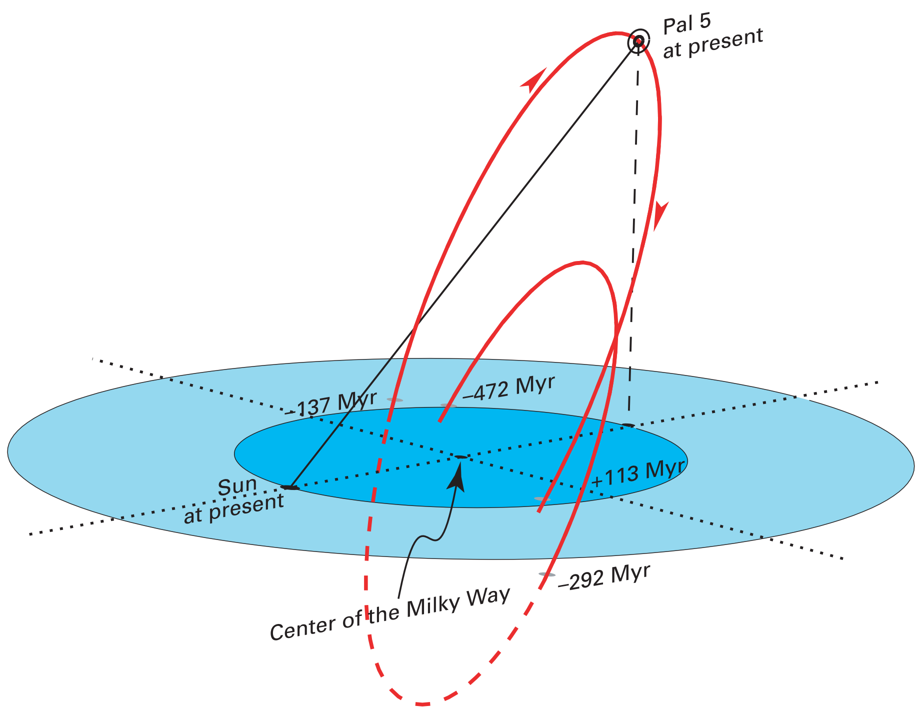
light years) and then turn over to the southwest and northeast, respectively. Stars belonging to the tails can be detected in both directions up to about 0.8 degrees (1000 light years) from the cluster center. All in all, the tails contain about half as many stars as the cluster itself, demonstrating the substantial mass loss thatPalomar 5 has suffered.

The shape of the two tails agrees with the results of computer simulations. Accelerated by gravitational pertubations induced by the Galactic gravitational field some cluster stars move outwards and leave the cluster in the direction of the Galactic center and in the opposite direction. Due to the Galaxy's differential rotation (the orbital velocity decreases with increasing distance to the Galactic center) the trajectories of the "runaways" bend around and eventually follow their own orbits around the galactic center, which are quite similar to that of the cluster.

The geometry of the stellar distribution in the tails allows one to determine the cluster's motion in space by means of the orientation of the tails. During the last years there have been several attempts to measure the motion of Palomar 5 directly using astrometrical methods – with contradictory results. As seen in Fig. IV.19 only the last measurement from 1998 (C98) is approximately in agreement with the orientation of the tails.

The new study made it possible to determine the tangential component of the motion much more precisely, showing that Palomar 5 is moving on an elliptical orbit around the Galactic center, with the smallest and the largest distances being 23,000 and 62,000 light years, respectively (Fig. IV.20). It was calculated from these orbital elements that during the past 500 million years the cluster has passed three times through the Galactic plane. The tails presently observed probably result from these events. 113 million years from now Palomar 5 will again pass through the Galactic plane. As this passage will coincide with its

Abb. IV.20: Three-dimensional view of the Galactic orbit of Palomar 5, from the past 500 million years until the next passage through the Galactic disk. The passages are marked by little circles in the plane and designated with the passage times. Presently, Palomar 5 is on the far side of the Galaxy and almost at its largest distance to the Galactic center.



closest approach to the galactic center it will be accompanied by especially strong disturbances that may eventually dissolve the cluster completely.

The observation of the tails of Palomar 5 supports the theory of globular clusters being in a permanent process of dissolution. In a next step astronomers plan to measure spectroscopically the radial velocities of stars in both tails. These data will allow an even better determination of the cluster's Galactic orbit and its inner dynamical state. Moreover, the team at MPIA will study other globular clusters with the same method, as soon as the Sloan Survey will have covered sufficiently large areas around these objects.

Turbulence in Star Formation

Stars form deep within large clouds of gas and dust. Radio observations have shown that the cloud medium is highly turbulent, its components moving with supersonic speeds. Shock waves run through the cloud, keeping it from collapsing. However, it has been known for a long time that matter can locally condense, forming new stars. The role of turbulence in this process is currently unclear, since a satisfying theoretical description of turbulence still has to be found. Scientists at the Institute have been dealing with this issue for years. During the year under report, two new papers were written, which take into account self-gravity of matter for the first time and therefore can explain observations much better than before.

Turbulent gas motions in the interior of large molecular clouds represent an unresolved problem in different respects. According to model calculations the turbulent gas looses its kinetic energy rapidly in the form of heat. Shock fronts occurring in this process are damped very quickly and decay. This is in contrast to the observations, however, which show the gas being turbulent in almost all clouds. Thus, there are processes at work that keep up turbulence.

For some time, it was assumed that magnetic fields could trigger so-called magneto-hydrodynamic turbulence, which gives off its energy more slowly. The theory group at MPIA was able to reconstruct the three-dimensional behavior of magneto-hydrodynamic waves in a molecular cloud in a computer simulation with unprecedented accuracy (see Annual Report 1997, p. 57). These calculations also clearly showed that magnetic fields are not able to maintain turbulence.

A conceivable way out of this problem is offered by the assumption that stellar winds and jets or the energetic emission of young hot stars are continuously supplying kinetic energy to the gas. However, it does not seem plausible any longer that these processes can keep up turbulence. On the whole, the turbulence of large clouds remains a secret. The questions of its origin and effects on star formation will be a future central issue of research at the Institute.

But even without a detailed understanding of exactly how turbulence is maintained, it can be taken into account in model simulations of large clouds. Until now, however, self-gravity was never included in the calculations. This was done for the first time by the Institute's theory group. The gas was assumed to be compressible and isothermal, meaning that it does not change its temperature.

Simulations with turbulence and self-gravity

The evolution of the model cloud was calculated at high resolution. Its total mass was chosen to be 200 Jeans-masses. The Jeans-mass represents a critical mass limit above which a cloud starts to collapse due to self-gravity. Depending on temperature, it is typically between one and five solar masses. Thus, the model corresponded to a real cloud of 200 to 1000 solar masses. The molecular cloud was represented by an ensemble of pseudo gas particles which was put into turbulent motion by imposing a certain velocity field (Gaussian velocity distribution) upon it. This field evolved independently, with the turbulence driven by a constant energy supply yielding an average gas velocity of six times the velocity of sound.

Figure IV.21 shows the further evolution of the cloud. Although turbulence keeps the cloud as a whole from gravitational collapse, local condensations form after a while. If the masses of such condensations exceed a certain value (the Jeans-mass), these protostellar cores continue to contract under the influence of their own gravity. They are forming mainly at the intersections of denser gas filaments. The plots b) to d) show the state of the cloud after 20%, 40% and 60% of the total gas mass, respectively, have accumulated within the dense cores. They cover a period of just under 500 000 years. Comparison with a simulation without constantly driven turbulence (Fig. IV.22) clearly shows the difference: Turbulence causes the dense cores to form more slowly. Moreover, the forming star cluster is not as strongly concentrated in the turbulent scenario as in the other one.

To compare the theoretical simulations with observations, so-called probability distribution functions were calculated. These are based on the following considerations: If a cloud is observed at radio wavelenghts, one looks right through it and any physical quantity is measured at any point only in projection onto the celestial plane. The spatial distribution can only be obtained using model assumptions.

In the simulations, this was taken into account by determining radial velocities and densities at any point of the model cloud "in projection" as well. Fig. IV.23 shows the derived probability distribution functions for the stages depicted in Fig. IV.21. They were obtained by determining the physical quantities (density and radial velocities) at about 4000 points in the cloud and plotting them as statistical distributions.

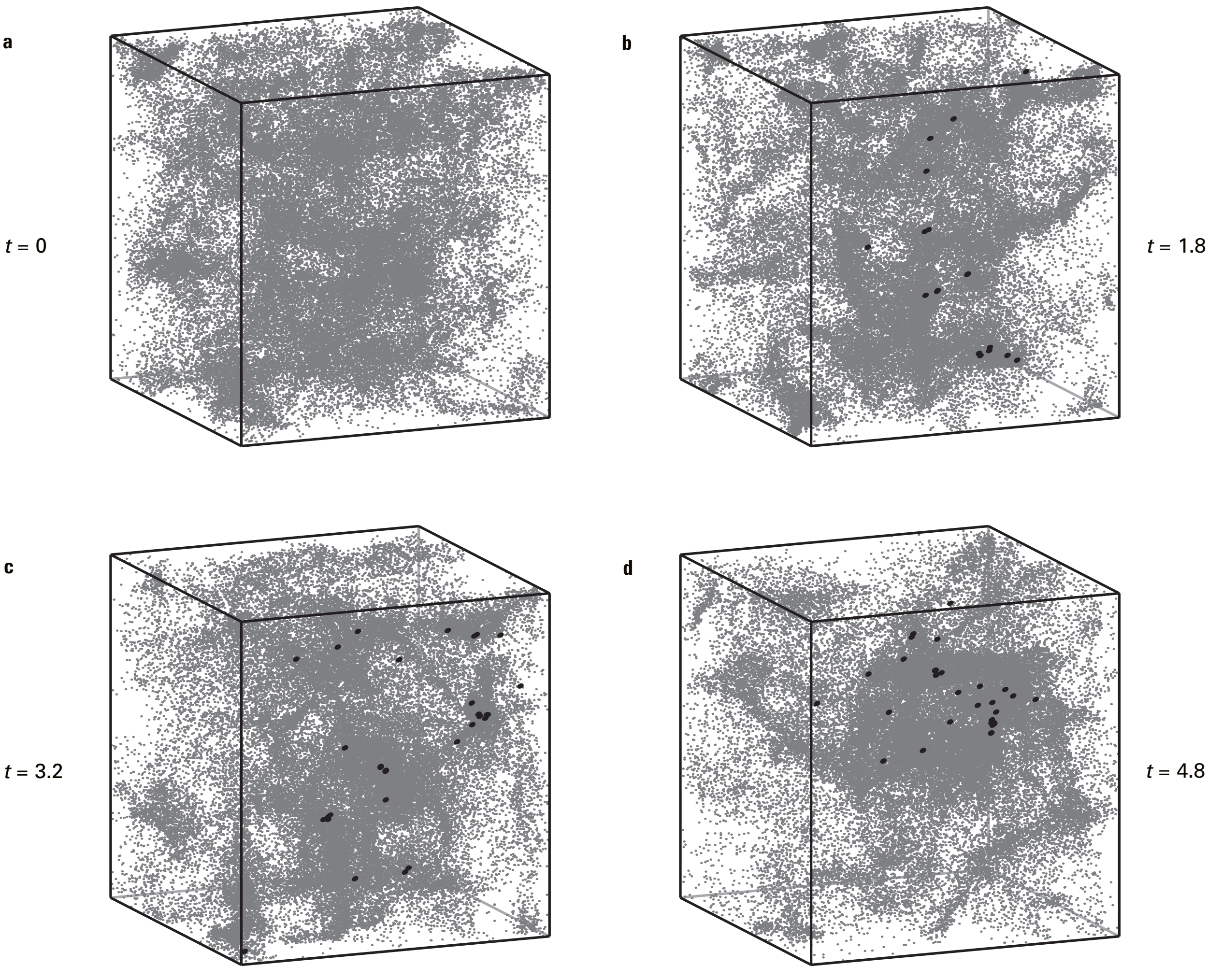
At the beginning, the density distribution is of almost Gaussian shape. In the course of time, it gets broader and broader and deviates further from the normal distribution. This is caused by the constant turbulence. Such broad density distributions are actually observed in interstellar clouds. From phase b) on to the right dense protostellar cores appear. In contrast, the velocity distribution approximately maintains its Gaussian distribution and broadens only slightly.

Fig. IV.21: Evolution of the gas cloud under the influence of self-gravity with constantly driven turbulence. Time is given in units of the free-fall time which is 100,000 years in this case.

Comparison with observations, as they are available for the star forming regions near Rho Ophiuchi or in Orion, for example, shows that models with constantly-driven turbulence and self-gravity are in much better agreement with reality than models without these properties. Thus, these simulations seem to be good descriptions of the processes in the interior of interstellar clouds with ongoing star formation. In the future, it would be interesting to test if it is possible to infer the physical causes of the turbulence from the shape of the probability distributions. One has to bear in mind, though, that, among other things, these distribution shapes depend on the accidental line of sight.

Rotation of turbulent clouds

On smaller scales of about half a light year, condensed cores are found in the interior of the clouds. With masses of about one solar mass, they are the direct progenitors of stars. Since they form in a turbulent medium, they are turbulent themselves. Radio astronomers have measured velocity fields (more exactly, velocity gradients) within many of these



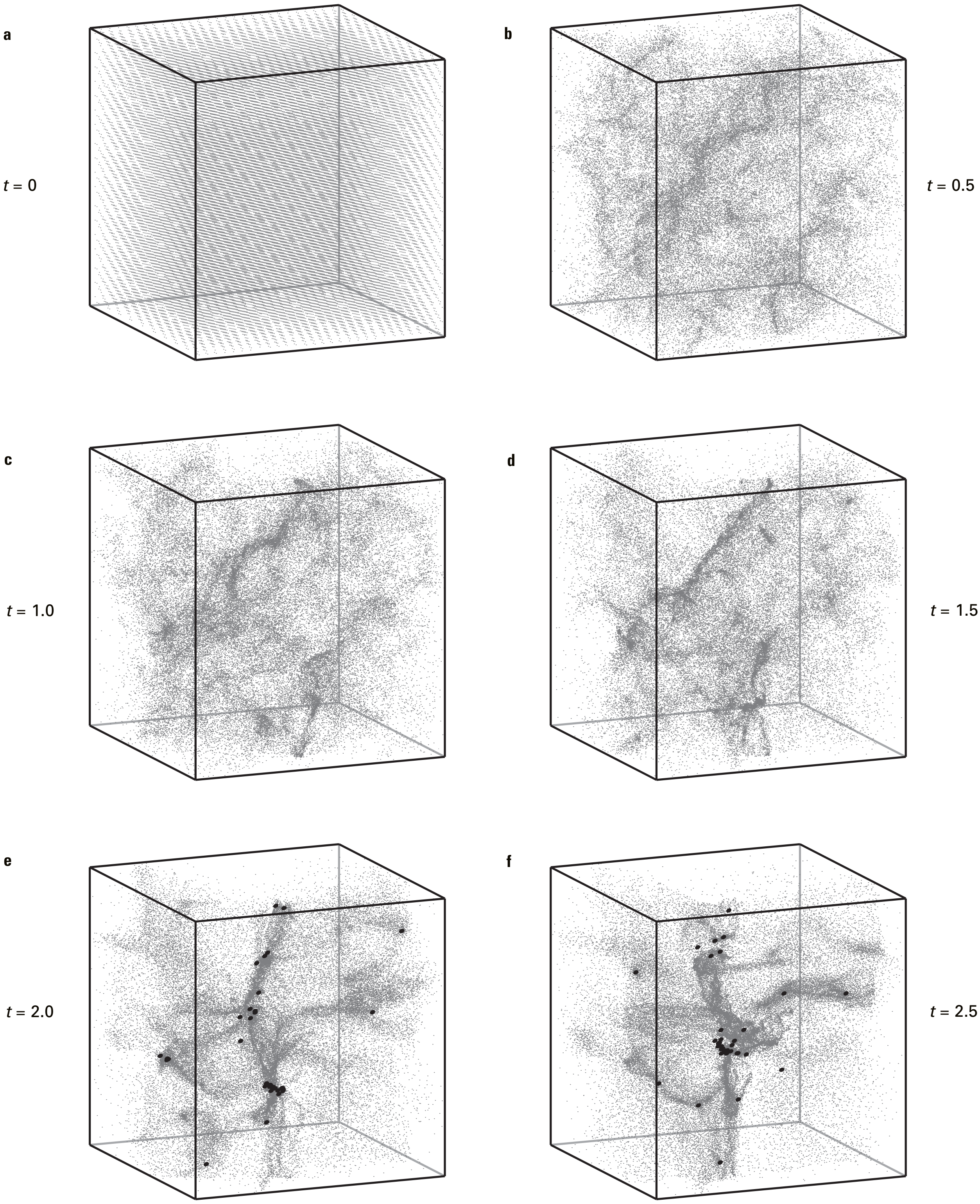


Fig. IV.22: Evolution of the gas cloud under the influence of self-gravity without constantly driven turbulence. As in Fig. IV.21, time is given in units of the free-fall time.

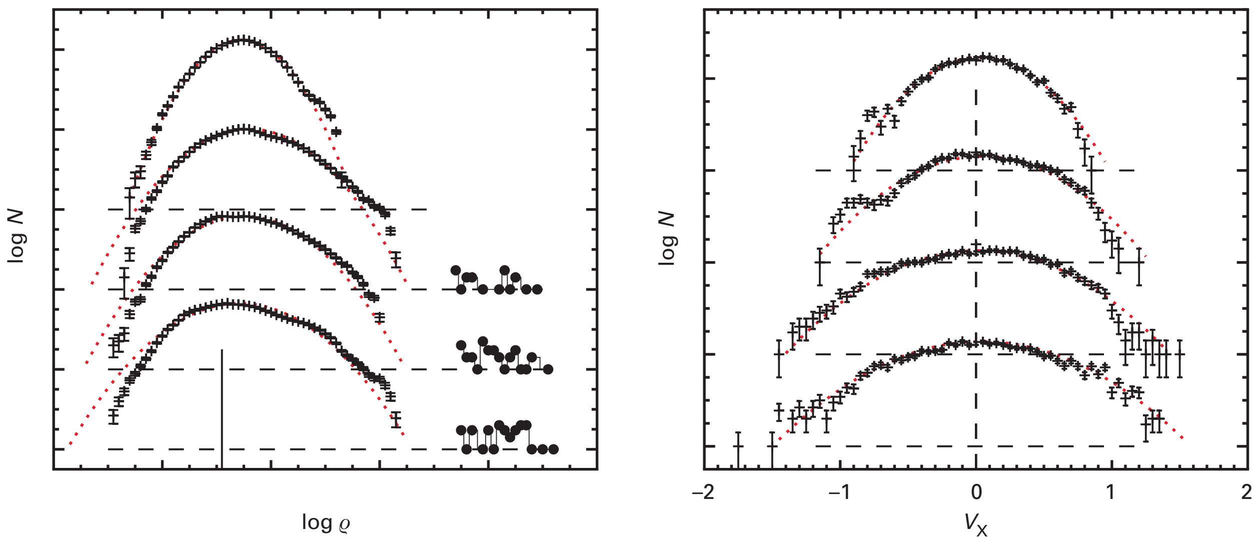


Fig. IV.23: Probability distributions of the density (left) and radial velocity (right). In the density distribution the formation of protostellar cores (dots) is discernible from phase b) on.

cloud cores. While one side of the cloud is approaching us, the other is receding. So far, this was interpreted as rotation of the clouds. In principle, the clouds could obtain their angular momentum from the Galaxy's differential rotation. This means that the velocity of an object decreases with increasing distance to the Galactic center. An extended object like a cloud – for which this applies, too – is set into rotation.

Angular momentum should have significant influence on star formation, as it causes the protostellar cores to rotate and flatten into disks. Within the disks, then, binary and multiple stellar systems as well as planetary systems form. The strength of the angular momentum determines the stellar separations in these systems and also the properties of the planetary systems.

However, questions have been raised repeatedly whether the rotation of the clouds can be detected at al, since it should rather be masked completely by the violent turbulence. In principle, there is only one reason why the angular momentum of a cloud is so difficult to determine: because the radial velocities can be measured – as described above – only in projection onto the celestial plane, summed over the entire line of sight.

Theoreticians at MPIA together with colleagues in the US investigated the connection between turbulence and rotation and compared their results with observations. In their calculations, they simulated a cloud with a diameter of about 0.7 light years and a total mass of 5 solar masses, the density increasing from outside to inside according to a power law. A turbulent velocity field was imposed upon this system and its subsequent evolution was followed. Then the "movie" was stopped to determine the velocity field. As it turned out, the individual angular momenta of the small-scale turbulence fields do not compensate each other completely on average, but in most cases leave a random net angular momentum, which appears to the observer as a large-scale rotation of the cloud.

The fact that the turbulence velocity increases with the size of the turbulence cells has an additional effect. Thus, the velocity picture is dominated by the biggest cells which extend across the entire cloud. As a result, a velocity gradient is measured within the cloud, which, however, does not originate from rotation but from inner turbulence.

This means that the angular momentum of a cloud cannot be calculated from the measured velocity gradient. The rate of this net angular momentum depends on the random projection of the cloud onto the sky, that is, on the line of sight. Correspondingly, the angular momenta calculated from 4000 simulated cases show a broad distribution (Fig. IV.24), lying in a range of (0.5–2.5) $\times$ 10^{21} cm^2/s. This is in very good agreement with a value of 1.2 $\times$ 10^{21} cm^2/s which was obtained from observations of clouds about 0.6 light years across. The broad distribution also matches the fact that the separations of the components in binary stars are widely scattered: A small angular momentum results in a close system, a large one in a wide system.

Using simple estimates, the result found numerically can be extrapolated to larger clouds of diameters up to 4 light years. Here, too, the observations are in good agreement with the calculations (Fig. IV.25).

Thus, turbulence has proven to be the source of the net angular momentum. It is also the reason for the formation of binary stars. In future studies, scientists at the Institute plan to include additional physical effects to make their simulations even more realistic. One of these effects, for example, is the velocity field influencing the density distribution and vice versa.

Planet Formation in Binary Stars

Theory and observations alike have confirmed that stars are forming mainly in binary and multiple systems. If both stellar components are separated by a large distance, each is surrounded during its formation phase by a gas and dust disk of its own; if they are close together, a common disk is developing around them. Within these disks planets can form. So far, theoreticians have dealt almost exclusively with the formation of planets in single stars and thus have ignored the majority of young stars. The theory group at MPIA has now tackled the question in which way a companion star is influencing planet formation. The first studies already show that in certain binary systems planet formation is severely disturbed or even prevented.

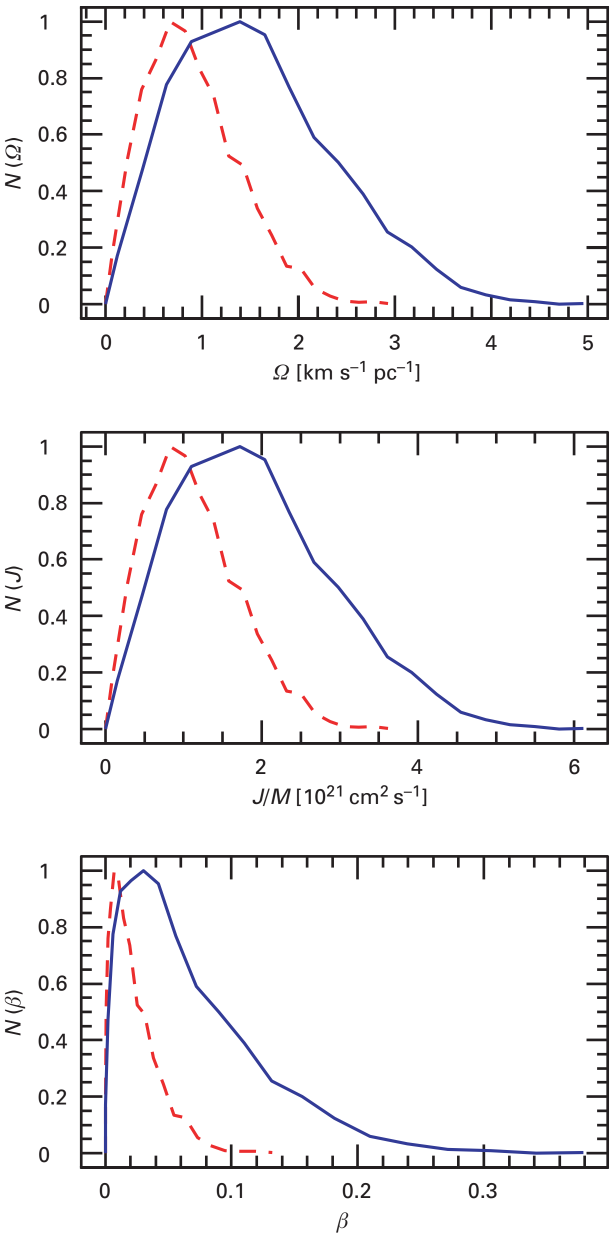


Fig. IV.24: Distribution of the net angular momenta caused by turbulence. Two distributions originating from different turbulence fields are shown.

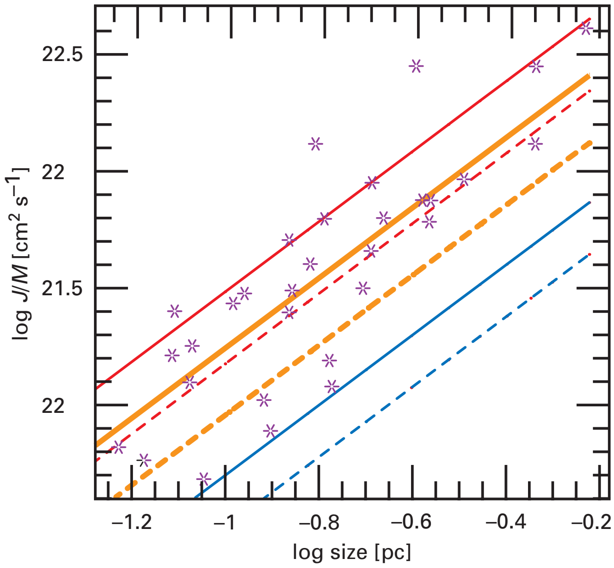


Fig. IV.25: Observationally derived angular momenta (stars) and results of simulations with different turbulence fields. Values should lie between the lower dashed line and the upper solid line.

Observations in the sub-millimeter range, which show the thermal radiation of dust, suggest that close binaries with relative separations up to one astronomical unit (AU) develop a common (circumbinary) disk. In wide pairs, separated by more than 100 AU, each component is surrounded by its own (circumstellar) disk. What happens in the intermediate range is largely unclear and depends among other things on the masses of the stars, the eccentricities of their orbits and the angular momentum of the disks (see Annual Report 1997, p. 59). Only few results have been obtained so far by observations: Both components of the binary GG Tau, being 45 AU apart, are surrounded by a common disk, while the star Z CMa consists of two components, which are separated by 100 AU and have circumstellar disks of their own, as astronomers at MPIA had found in 1998 (see Annual Report 1998, p. 16). Can planets form in such systems?

Three cases are known, in which extrasolar planets do exist in binary systems: 16 Cyg B, 55 Cnc, and Tau Boo. With relative separations of 700, 1150 and 240 AU, respectively, the stars are very far apart while in each system one planet is orbiting one of the components on a very close orbit (orbital radii: 1.7, 0.1, and 0.05 AU, respectively). Thus the companion star is several hundred to ten thousand times farther away from the primary star than the planet, making its gravitational perturbation small.

Using computer simulations, members of the MPIA theory group have now investigated if and how planets can form in binary systems. Due to the enormous computing effort involved, the scientists concentrated on a special case corresponding to a well studied real binary star. The star in question is L 1551 IRS 5 (Fig. IV.26), a young object at a distance of 450 light years, which has been intensively studied for years by astronomers at MPIA.

Computer simulations of a real case

L 1551 IRS 5 is a young binary about 500,000 years old, whose components are separated by about 50 AU. Each component is surrounded by its own disk of about 20 AU diameter and 0.05 solar masses. On a larger scale, the star is embedded in an extended nebula with a size of 2400 AU × 1100 AU. Also characteristic of a young binary star are two narrow particle beams, so-called jets, which are ejected in opposite directions into space.

Theoreticians have used this object as a model for their computer simulations. Two identical stars with 0.5 solar masses each have been assumed, which are both surrounded by identical disks of 30 AU diameter and 0.05 solar masses each. In the simulation, each disk comprised 60 000 particles, which initially orbited the star on circular trajectories. Density and temperature of the disk decrease from the star outwards following power laws of $r^{-3/2}$ and $r^{-1/2}$, respectively. In addition, it was assumed that both stars are orbiting one another on elliptical paths (eccentricity of 0.3) with an orbital period of about 340 years.

The material of the disks was assumed to be viscous, so shock waves and turbulence could occur. These processes will heat the disks and are of great significance for the evolution of the system. Furthermore, it was taken into account that in these processes the dust is radiating thermally depending on its temperature.

The behavior of the disks was followed over a period of eight orbits, or 2700 years. Fig. IV.27 shows the systems shortly before (above) and after (below) passing the point of nearest approach (periapsis). It can be seen that the gravitation of both systems pro-

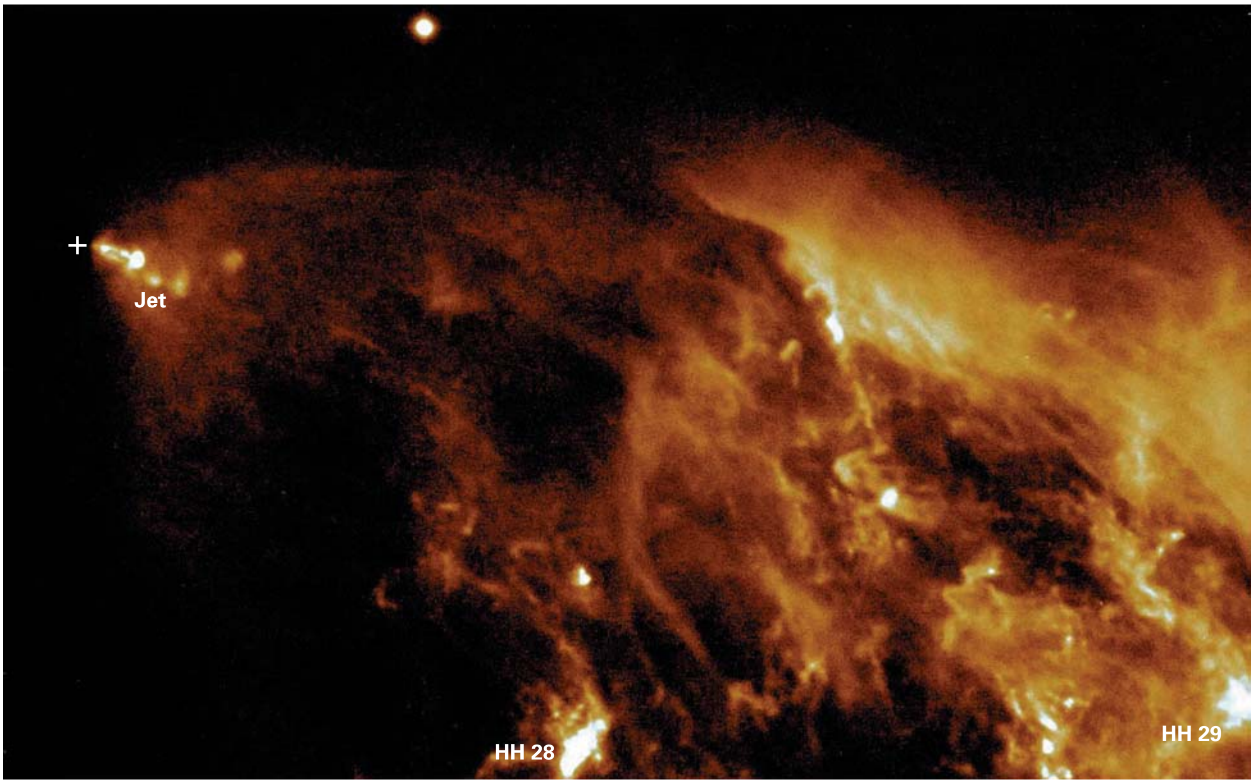


Fig. IV.26: L 1551, photographed in visible light at Calar Alto Observatory. The cross marks the position of the young star IRS 5, which is hidden behind dust and therefore only visible in the infrared. The jet emanating from IRS 5 and the extended cometary reflection nebula can be recognized as well.

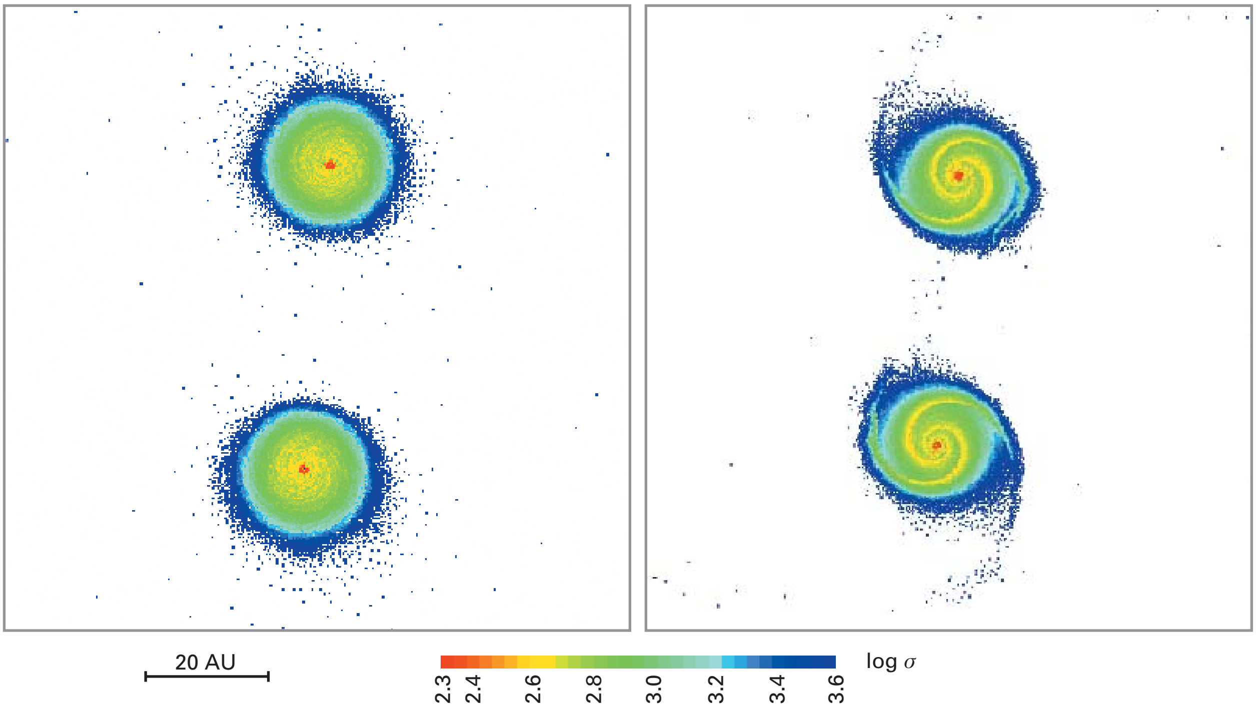


Fig. IV.27: The two disks of the simulated binary system before periapsis (left) and shortly after (right). The stars orbit each other counterclockwise; they reach periapsis when both are 35 AU apart. In the diagram at right both stars have interchanged their positions compared to the diagram at left.

duces spiral waves within the disks at periapsis. These waves, however, dissolve rapidly when the stars are receding again from one another on their elliptical orbits. During every orbit, this process of cyclic shock wave formation is repeated in almost unaltered form, so presumably it will continue for a longer period of time. The rapid dissolution of the spiral structure is the result of heating by the shock waves: High temperatures stabilize the disk.

This cyclic heating of the dust presumably prevents the formation of planets. Theoreticians believe that planets form when spiral arms, representing condensations of dust, fragment into smaller pieces which then further condensate. But obviously this process is impeded by the heating of the disk.

Moreover, due to the high temperatures already existing dust grains evaporate and therefore can not accumulate into larger bodies. This is especially true for particles made of water ice, which comprise an estimated 40% of the first ice grains. Within the spiral structures, temperatures reach values between 200 and 1100 Kelvin while the water ice grains already begin to evaporate around 150 Kelvin (Fig. IV.28). The spiral arms rotate independently of the dust grains with the orbital period of the binary star. Thus the entire matter of the disk is traveling several times through the arms and heats up before the arms dissolve again. As it takes a dust particle about two years to cross an arm there is ample time for it to evaporate. Only thermoresistant materials like iron-rich silicates or organic compounds can survive in the disk and possibly grow, especially in the cooler outskirts.

Comparing the emission of the model disks with the observations has been of interest as well. Fig. IV.29 shows the combined values of both components (dots) as well as the values of the single components (crosses). Despite some uncertainties in the measure-

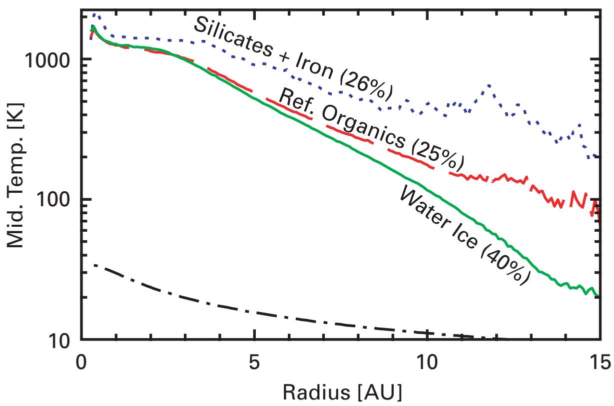


Fig. IV.28: Temperatures within the disk before periapsis (solid line), after periapsis (dashed line), and within the undisturbed disk (dash-dotted line). The dotted line represents the maximum temperatures within the spiral arms. To the right, evaporation temperatures of different particle types are given.

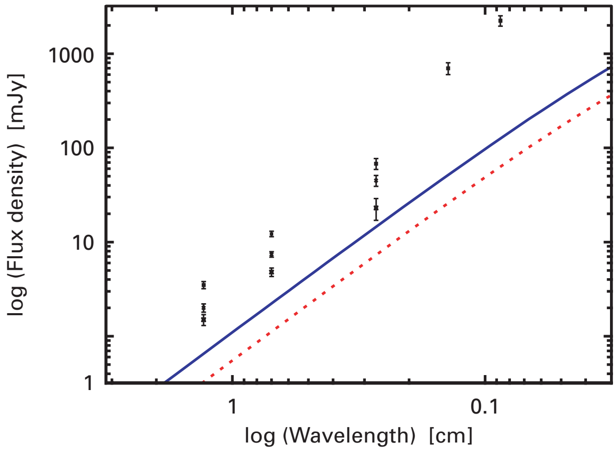


Fig. IV.29: Radiation intensities at L 1551 IRS 5 (orange and blue) compared to simulation (dotted line for one of the binary components, solid line for both components together).

ments, the results of the simulation are significantly lower than the measured values, suggesting the disk temperatures being even higher in reality than in the models. This in turn would speak even more strongly against the possibility of planets forming there.

On the whole, it is shown that planet formation is not possible at all in such binary systems or at least is severely impeded. The simulations shown are only the beginning of much more extensive studies which will calculate, for example, heating and cooling of the disk in more detail and consider disks of different masses. A comparison of binary stars of different masses and a wide range of relative separations would be of special interest. In addition, three-dimensional simulations would be highly desirable.

IV.2 Extragalactic Astronomy

Lopsided Spiral Galaxies

Galaxies lead an eventful life, approaching each other, colliding or merging. Recently, astronomers have discovered more and more new forms of these cosmic interactions, which have a significant influence on the evolution of the stellar systems. Scientists at MPIA together with colleagues at Steward Observatory, Arizona, have studied spiral galaxies, which show an asymmetric distribution of stars on opposite sides of the galactic center. They found out, an increased rate of star formation is associated with this "optical lopsidedness". The reason for this is not yet clear. But most likely lopsidedness and increased star formation are caused by close passages of smaller galaxies.

Today, it is unquestioned that interactions with neighboring objects play an important role in the evolution of galaxies. The cosmological scenario of hierarchical structure formation predicts that major galaxies formed in the early universe by merging of several smaller galaxies (see "Far Infrared Extragalactic Background Radiation" in this Annual Report, p. 23). But even in the present-day universe spectacular examples of colliding galaxies can be observed, producing a firework of star formation (see "Cold Dust in the Antennae" in this Annual Report, p. 71). At the same time, an increased amount of matter may be funneled into the galactic central regions to be swallowed there by a giant black hole. Even if two galaxies just get close to each other, strong tidal forces will cause their interstellar matter to be stirred up, thereby enhancing star formation. Moreover, there is growing evidence that elliptical galaxies have formed by mergers of spirals (see Annual Report 1999, p.67).

But not always are the effects of interactions between galaxies that spectacular. Weaker gravitational forces can have significant consequences as well. They occur, for instance, when two big galaxies pass each other at great distance or when structure and kinematics in the interior of a major galaxy are influenced by the gravitational field of a small one. It seems plausible that star formation, too, is triggered by such events.

It became apparent already in the early 1980ies that roughly 50% of all spiral galaxies have asymmetric rotation curves and also slightly asymmetric distributions of atomic hydrogen. To study this phenomenon more thoroughly, asymmetric mass distributions in spiral galaxies have been examined systematically since the mid-1990ies, using the stellar light as an indicator. In principle, asymmetries of the surface brightness can be caused also by extended dust complexes, covering greater parts of the star fields. But in 1998, this effect could convincingly be excluded.

If the disks of so many spiral galaxies show large-scale asymmetries in the stellar distribution, the most likely explanation is an external effect, namely a perturbation by a nearby galaxy. Simple estimates and computer simulations suggest that the perturbation of the gravitational potential and the resulting asymmetric mass distribution should be smoothed out again after about one billion years. So, on cosmic time scales, it is a rather transient perturbation. But as many spiral galaxies show this "optical lopsidedness" it has to be rather common.

In a new, systematic study, astronomers at MPIA together with a colleague at Steward Observatory, Arizona, observed 40 spiral galaxies. The selected sample comprised relatively nearby objects (with redshift $z < 0.03$) which are seen almost exactly face-on. In Fig. IV.30 some examples are shown. The surface brightness of a highly inclined galaxy is difficult to determine because of the considerable obscuration by dust.

For each of these galaxies, spectra of the entire surface were obtained by placing a long slit across the galaxy at a number of different positions. So it was possible to obtain the integrated flux of the galaxy in the light of particular spectral lines. The Balmer lines of hydrogen are of special interest because their intensities are an indicator of young hot stars. This way, at the same time the star formation rate could be determined.

In practice, this was done by first preparing two model spectra. One was that of a sun-like star (spectral type G), representing the "old" stellar population of a galaxy. The second one, a hot A star, stood for the young population. A comparison of the measured spectra with these templates then allowed to estimate the star formation rate in each of the galaxies. Subsequently, the strength of the star formation rate was compared to the degree of the galaxy's optical asymmetry, which was mathematically quantified as the deviation from a completely homogenous surface brightness.

Fig. IV.31 shows that the fraction of young A stars is increasing with the degree of the optical asymmetry. As A stars have a lifetime of only about 500 million years, the optical lopsidedness has to last at least as long after its onset. From the spectra it can be estimated that about one billion stars have formed during

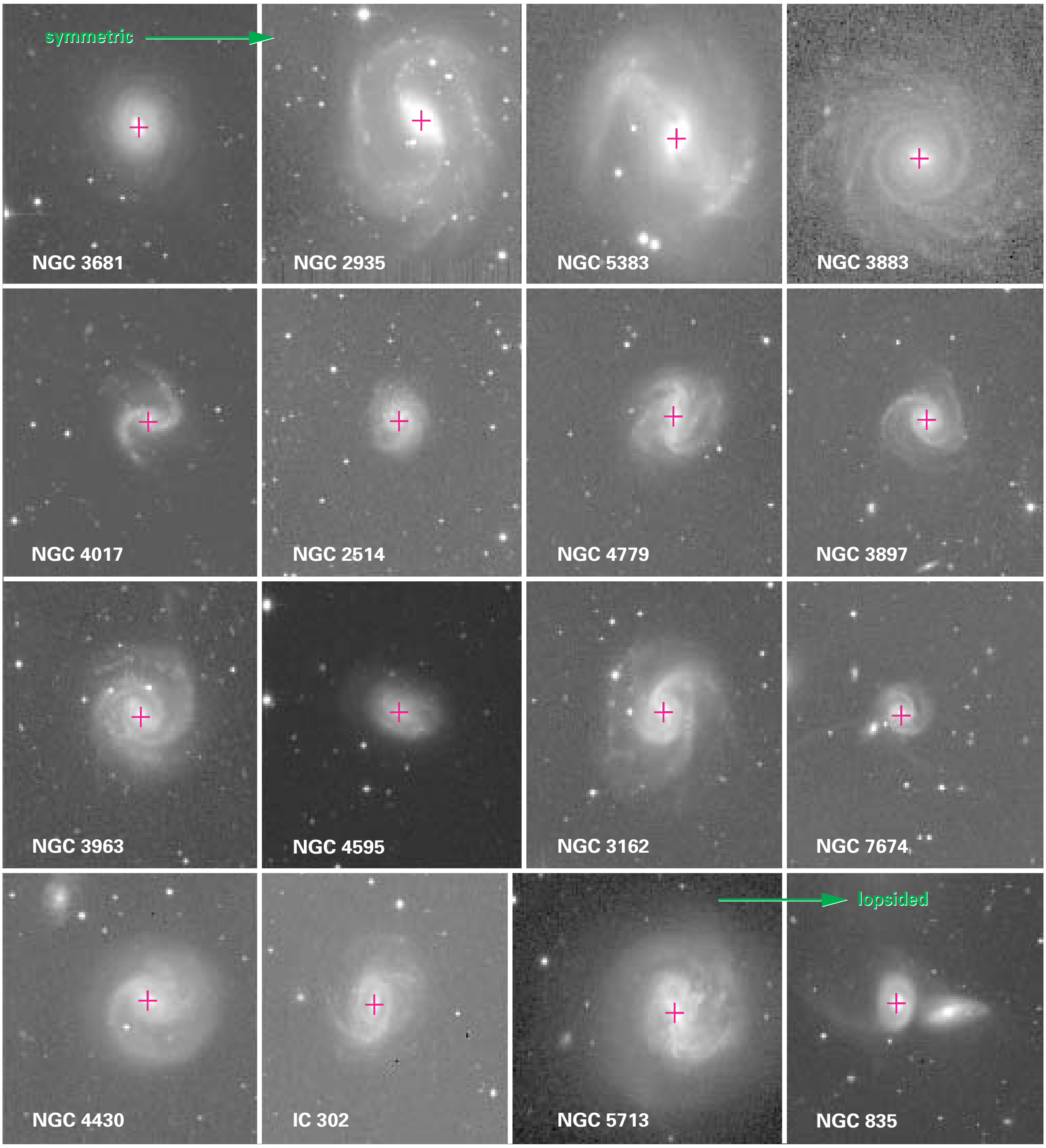


Fig. IV.30: Examples of some of the observed galaxies with and without pronounced optical lopsidedness. The asymmetry of the galaxies increases from upper left to lower right.

the past 500 million years in the asymmetric galaxies, corresponding to a star formation rate eight times higher than in normal spiral galaxies. During such an era approximately 10% of all stars of an average galaxy are forming.

Hence this is an important phase in the evolution of galaxies. About one fifth of all observed galaxies are asymmetric. Assuming such a perturbation to last about one billion years, it follows that each spiral galaxy has experienced such a phase about four times in its lifetime.

Obviously such events are of great significance for the evolution of galaxies. Studies of this topic, however, have only just begun. Subsequent observations are planned to clarify the origin of optical lopsidedness. Interaction with nearby small galaxies is a likely cause, but still has to be proven. Here, data of the Sloan Digital Sky Survey should be very useful. On the theoretical side, numerical simulations with

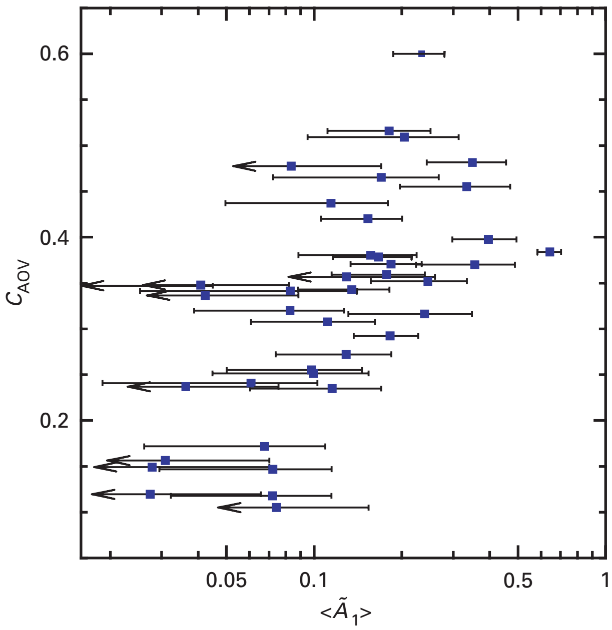


Fig. IV.31: Fraction of young A stars (C_{A0V}) as a function of optical asymmetry <A_1>.

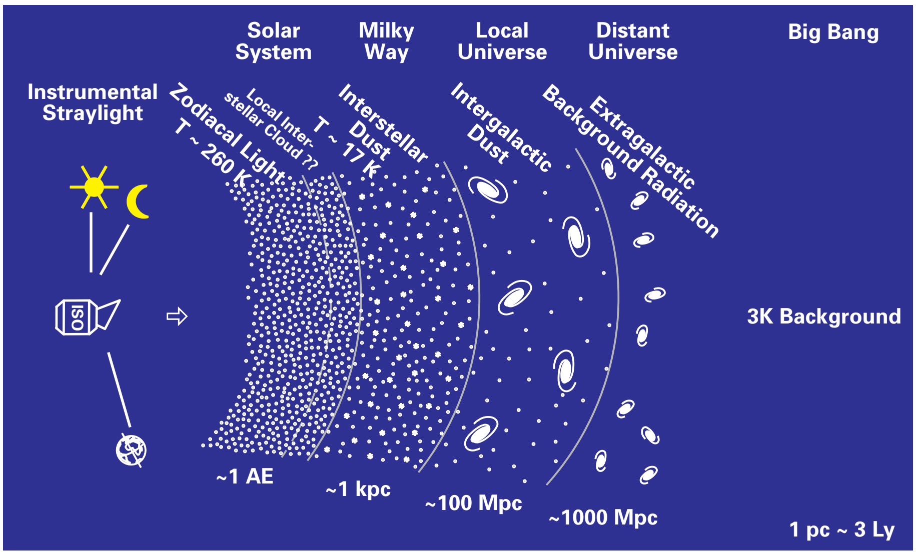
high spatial resolution need to be done to study the eff LINC ects of weak interactions between galaxies.

Far Infrared Extragalactic Background Radiation

A major goal of observational cosmology is to reconstruct the evolution of galaxies. What was the star formation rate in the early universe? Did galaxies merge, thus diminishing their total number over billions of years? These are only two of the basic questions. It is known from nearby galaxies that intense star formation causes large masses of dust to be heated which then radiate in the mid- and far-infrared range. As spectra of galaxies in the early universe are redshifted these objects should be observable mainly in the far infrared and the adjacent millimeter range. With the ISO satellite observatory it was possible for the first time to observe this extragalactic background radiation in greater detail. So several extended projects were devoted to this subject, which are now yielding first results. The data clearly show that the young galaxies have experienced evolutionary stages with burstlike star formation.

The sensitivity of the ISO instruments covered almost the entire infrared range up to ~200 µm. Thus they were able to detect every type of dust, even the coolest one. In fact, ISO has peered through several "curtains", located at quite different distances from Earth (Fig. IV.32). Within the solar system, this is the interplanetary dust. Under favorable conditions, sunlight, which has been reflected by it can be seen with the naked eye as zodiacal light. At a temperature of 270 Kelvin this dust is relatively warm, so its thermal radiation is the strongest noise source in front of the weak background radiation. At significantly larger distances of hundreds or thousands of light years, cool interstellar dust is spreading. Because of its wispy diffuse appearance it is also called cirrus. Until recently, very little was known about dust outside the Milky Way system. Observations with ISOPHOT, however, suggest that dust also exists in galaxy clu-

Fig. IV.32: Scheme of the different "infrared curtains" that ISO was able to peer through. The intensity of the foreground sources is factors of ten higher than that of the extragalactic background radiation, making the analysis of the latter very difficult.



sters. Studies of this subject are presently going on at MPIA (see Annual Report 1997, p. 26).

The extragalactic background radiation is known only since recently. It had first been studied in some detail by the American COBE satellite. But the instrument DIRBE onboard COBE had a low spatial resolution of only 42 arcminutes and was not able to detect single sources. Furthermore, the background signal had been very weak and consequently the measured intensity was very uncertain. But it is thought very likely that this radiation arises from young galaxies which are several billion light years away from us.

There is only one signal coming from an even larger distance, namely that of the cosmic background radiation. It has its maximum in the millimeter range, though, and originates from a very early stage, a few hundred thousand years after the big bang. In the early 1990's, this radiation had been measured by COBE with high accuracy over the entire sky.

For the observation of the extragalactic background of young galaxies celestial areas have to be chosen that are as free as possible of the other foreground sources mentioned above. There are several eligible regions highly above the galactic plane where interstellar dust is very sparse.

With the ISOPHOT instrument, built at MPIA, four major observational projects on the extragalactic background have been conducted, yielding first results in the year under report. They clearly indicate a violent galaxy evolution in the early universe.

The extragalactic background radiation

Only when in the mid-1990's far-infrared and submillimeter observations reached sufficient sensitivity, it became more and more apparent that the star formation rate in the early universe had been underestimated. Until then it had been derived mainly from observations in the optical and UV range, a spectral region normally dominated by hot young stars. Star formation regions, however, are surrounded by large amounts of dust, which effectively absorb stellar light. The dust is heated by this process and starts to radiate in the infrared. Nearby normal spiral galaxies are known to emit as much as 30 % of their total luminosity in the infrared. In systems with intense star formation (starburst galaxies) the infrared fraction of the total luminosity even can reach 95 %. It is thought that these galaxies are identical with the so-called Ultra Luminous Infrared Galaxies (ULIRGs; see chapter II.2 of this Annual Report). The intensity maximum usually lies at wavelengths between 50 and 100 µm. In young galaxies, this maximum is shifted by cosmological redshift even further into the far-infrared and submillimeter range. Most of these objects probably are not visible in the optical light because of strong dust absorption.

With ISOPHOT it was possible to study galaxies in the early universe in detail. The big advantage of ISOPHOT compared to COBE has been its significantly higher resolution of about two arcminutes at 170 µm and its ability to point at celestial areas where the confusing foreground emission of Galactic cirrus is relatively low. Therefore topics such as the flux level at long wavelengths and the numbers of detectable point sources could be addressed. Moreover, the new data will serve as a base for further submillimeter observations.

The ISOPHOT observational projects

In the course of the investigation of the extragalactic background radiation four major projects were conducted, two of which will be described here in more detail. First the observational results are presented, followed by the combined interpretation of the data.

1. The largest field has been observed in the course of the FIRBACK project (Far-Infrared Background), which is a collaboration of astronomers from France, Italy, Great Britain, Germany, and the US. During 150 hours of observing time a total area of four square degrees has been examined at 170 µm (Fig. IV.33). The individual fields were located far above the galactic plane and are as free of confusing cirrus as possible. Nevertheless, it was rather difficult to clearly identify the point sources and measure their intensities. Eventually 196 sources were found with intensities between 180 and 500 mJy.

2. The project ISOPHOT CIRB (Cosmic Infrared Background Radiation) was carried out by MPIA in collaboration with astronomers from Helsinki. Eight fields with a total area of about 1.5 square degrees have been mapped at wavelengths of 90, 150, and 180 µm (Fig.IV.34). The goal of the project was to determine the number of objects and their luminosities. Here, the fundamental problem of infrared cirrus confusing the detection of galaxies arises. Other observations, however, had shown that in the selected fields the cirrus is low enough as not to hamper the observations significantly. Furthermore, it is possible to separate the cirrus emission from that of the extragalactic background, because it has different radiation temperatures and thus different intensity distributions over the three measured wavelengths. In addition, data analysis later discriminated sources which show up only at one wavelength from those which appear on at least two maps. The differences were not serious, though, which strengthened the confidence in the applied analysis method. In total, 55 point sources were found. As they can not be

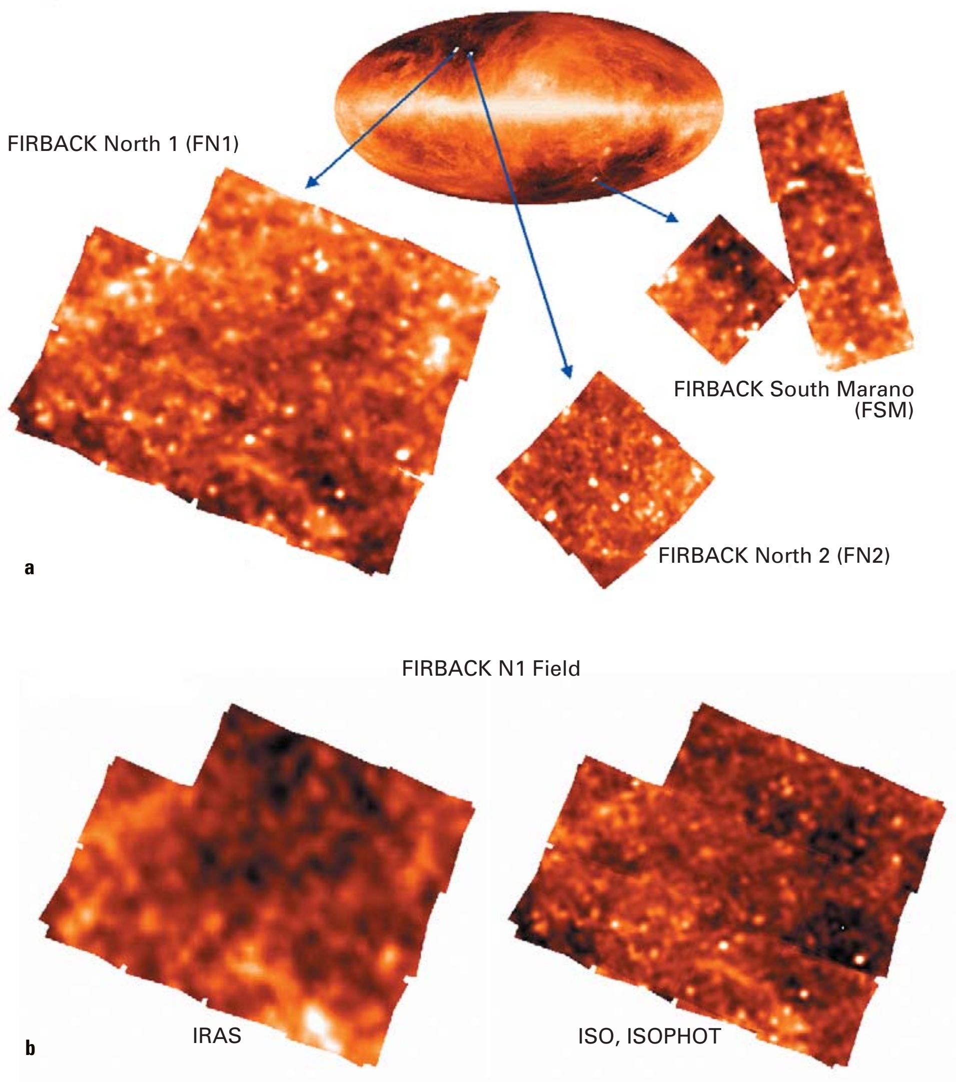


Fig. IV.33 a): Positions of the FIRBACK fields in the sky. They are all located at high galactic latitudes. **b)** One of the fields, imaged by IRAS (left panel) and imaged by ISOPHOT (right panel).

identified with known objects, probably all of them are distant galaxies.

At the same time the European Large Area ISO Survey (ELAIS) at 90 µm was performed as well as the survey at 60 and 90 µm in the region Selected Area 57. They will not be described here.

Hierarchical evolution of the universe

With the FIRBACK and ISOPHOT CIRB projects it was possible for the first time to resolve the background radiation into single sources and to measure the far-infrared radiation fluxes of distant point-like galaxies, as was shown above. A more detailed analysis showed that about 15% of the diffuse background radiation measured by COBE originates from young galaxies. In reality, the fraction is probably even higher, for even with ISOPHOT a significant rest of the far-infrared emission remained spatially unresolved. Where it comes from has to be investigated by future space missions. Here, even “exotic” processes like particle decay in the early universe can not be excluded.

The new data allowed to test different models of galaxy evolution. Two theory groups in Italy and France had recently developed such models, which could now be compared with the latest measurements. The simulations start with the gravitational collapse of vast gas clouds which later will form galaxies. Then smaller regions within the clouds condense into stars. The star formation rate of the models is assumed to be proportional to the remaining amount of gas. In each galaxy, stars form according to a sufficiently known mass function. Secondary effects like supernova explosion are also taken into account.

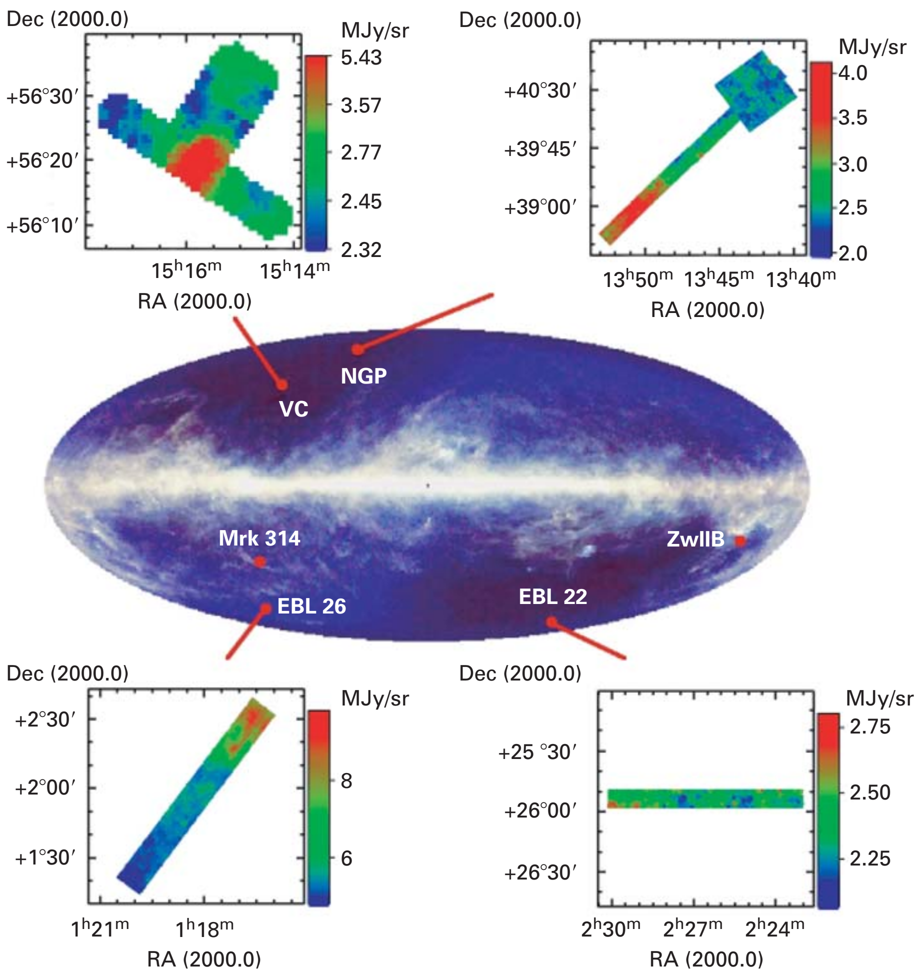


Fig. IV.34: Four CIRB fields in the sky.

From this, the combined radiation field of all stars within a galaxy can be derived, which partly will be absorbed by dust and be re-emitted in the infrared. Until this point the models are analytic. However, there are further aspects, which can not be derived from the simulations but have to be fed in "by hand" according to observational evidence. Among the most important of these aspects is the merging of galaxies and the resulting greatly enhanced star formation rate.

In recent years, it became more and more apparent that gravitational interactions and merging of galaxies have played a major role in the early universe. The galaxy evolution theory presently favored by many cosmologists is based on so-called hierarchical structure formation. Accordingly, there were more, but smaller galaxies in the early universe than today. Therefore the galaxy density at that time must have been much higher. Consequently, mergers occurred frequently, forming the large galaxies that are observed in the present-day universe. During the merging of two galaxies their interstellar matter is partly compressed, triggering violent star formation. As a result, many starburst galaxies are forming.

Although the theory of the hierarchical structure formation is supported by different observations it is not yet confirmed. A comparison of the new ISO data with the models provided another possibility to further clarify the issue. As it turned out, the predictions of the different theoretical models diverge with increasing wavelengths. The reason for this are the starburst galaxies, which emit most of their total luminosity in the far infrared, as will be shown below.

Fig. IV.35 shows the comparison of the galaxy density measured by ISOPHOT CIRB in three wavelength ranges with the predictions made by theoretical simulations. At 90 µm the measured results agree within the uncertainty limits with all the models. With increasing wavelengths, however, it becomes apparent that the model without galaxy mergers (dotted line) can be excluded. At 180 µm there are at least ten times as many infrared sources as predicted by this model.

In much better agreement with the data are two models which, in different ways, take into account the effects of starburst galaxies and ULIRGs, respectively. In one model (solid line), it is assumed that their

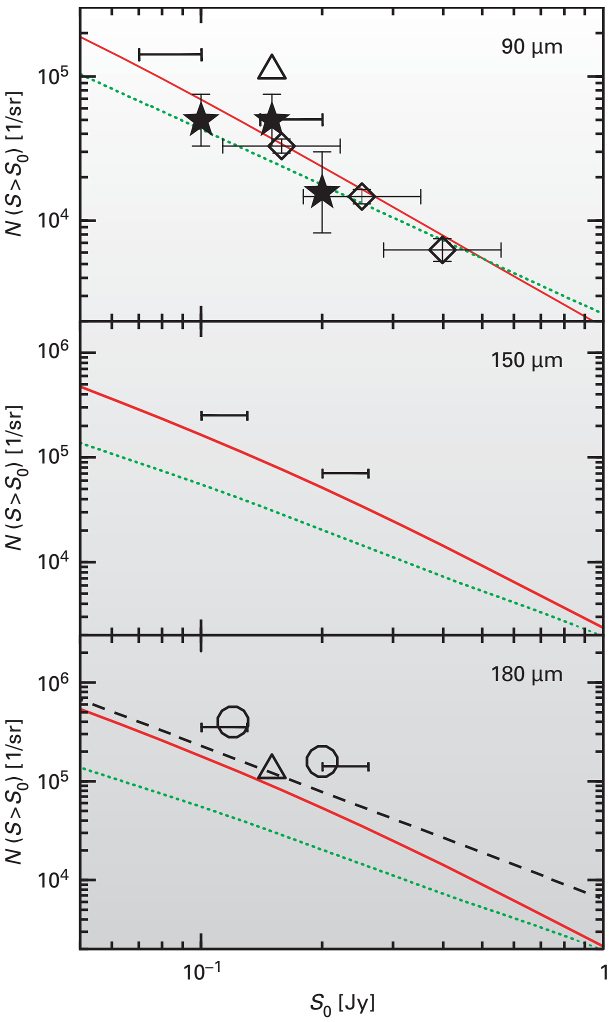


Fig. IV.35: Comparison of the galaxy density measured by CIRB in three wavelengths ranges with the predictions of the theoretical models.

numbers increase with increasing redshift, according to the hierarchical structure formation theory which predicts fewer merging galaxies and thus fewer ULIRGs as the universe gets older. In the second model (dashed line), dust rich galaxies with high star-formation rates at low redshifts have been assumed in addition.

The data strongly support the latter two models. Furthermore, the intensity distribution between 90 and 180 µm can easily be explained as the sum of the emissions of single infrared luminous galaxies with redshifts between z = 0.5 and z = 1, while normal elliptical and spiral galaxies can not account for the far-infrared data.

Fig. IV.36 shows the galaxy density at 170 µm as measured by FIRBACK compared with the different model scenarios. Here too, the measured number of galaxies is ten times higher than the predictions of the model without ULIRGs (dotted, below). Even if a ULIRG population growing with increasing redhift is added (solid line, middle), the measurements exceed the model by a factor of two. Only if the number of ULIRGs in the early universe is raised still further, the model is in agreement with the data (dashed, above).

With that, the issue of galaxy evolution in the universe is certainly not settled yet. It is entirely possible that different models will predict very similar intensity distributions of the extragalactic background radiation. Nevertheless, great progress has been made by excluding several scenarios at a high confidence level.

The new ISOPHOT data will serve as a catalogue for subsequent observations with different telescopes. At present, measurements in the sub-millimeter range are possible, for instance with SCUBA at the James-Clerk-Maxwell Telescope or with MAMBO at the German-French IRAM. For the future, astronomers place their hopes in the air-borne infrared telescope SOFIA and the European space telescope HERSCHEL, in which also astronomers at MPIA are involved (see Chapter III).

ISO Confirms Unification of Radio Galaxies and Radio-Loud Quasars

For several decades, astronomers have studied galaxies with active nuclei. Meanwhile at least a dozen different types are discernible on the basis of their observational characteristics. These include, for instance, Seyfert galaxies of type 1 and 2, BL Lac objects, radio-quiet and radio-loud quasars as well as radio galaxies. Since the late 1980ies, however, more and more astrophysicists are convinced that these different types are in principle all constructed uniformly and – as they are not spherically symmetric – their appearance varies with the angle of view under which they are seen. An essential structure element of this unified scheme is a thick dusty torus

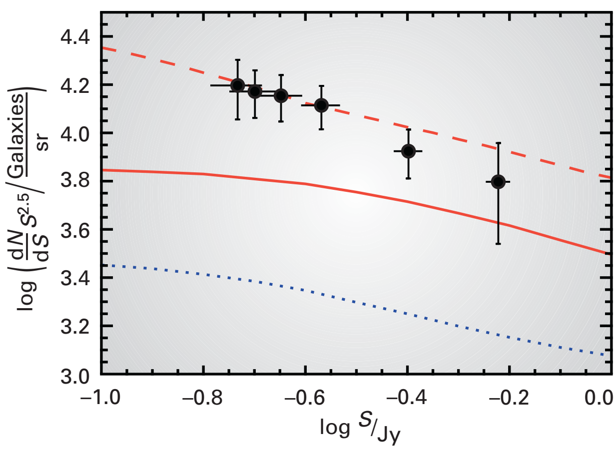


Fig. IV.36: Comparison of the galaxy density measured by FIRBACK at 170 µm with the predictions of different models.

surrounding the central black hole of the galaxies and obscuring it if viewed edge-on. Astronomers at MPIA together with colleagues from the University of Bochum were able to detect for the first time such tori in the infrared spectral range, confirming the highly debated unification of radio-loud quasars and radio galaxies. The study is based on highly sensitive data from the ISO archive, demonstrating the possibilities of the recently approved 5- till 6-year-long active archive phase of the ISOPHOT data center.

The unified scheme

The scheme for a unified description of active galaxies is based on a few fundamental components (Fig. IV.37, above): At the center of the galaxy a black hole of at least one million solar masses is located, attracting matter from its surroundings. Because of friction and other processes this matter loses kinetic energy and slowly spirals into the black hole. In doing so, the hot gas emits energetic radiation, mainly in the X-ray, UV- and optical spectral region.

Supported by strong magnetic fields, two gaseous jets can simultaneously be ejected perpendicularly to the disk plane in opposite directions with almost the speed of light. Due to interactions with gas, these jets often end far outside the galaxy within extended lobes that are very luminous at longer radio wavelengths. Inside the jets, electrons are moving close to the speed of light, spiraling outward from the black hole on helical trajectories centered on the magnetic field lines and emitting synchrotron radiation in the direction of their motion. This short-wavelength radio emission is characterized by its anisotropy, forming a cone, similar to a headlight, centered on the jet.

The unified scheme interprets the different appearance of active galaxies as a strictly geometric effect. Depending on the viewing angle under which such a radio-loud galaxy is seen, the observed radiation spectrum is dominated by different components of the complex system. If a jet is pointing directly towards Earth, the synchrotron radiation emitted by electrons prevails, making the short-wavelength radio spectrum very bright. This is observed, for example, in BL Lac objects. If the jet axis is viewed under a larger angle, the long-wavelength radiation of the radio lobes dominates, as seen in most of the radio-loud quasars and radio galaxies. Radio galaxies are believed to harbor a massive central black hole because it provides the only explanation for the jets. But only a fraction of radio galaxies exhibits the optical features observed in radio-loud quasars, like broad spectral lines and high luminosities. So the great challenge is to examine if radio galaxies – at least those with particularly bright radio lobes – actually are nothing else than radio-loud quasars whose cores are not visible in the optical.

To explain this fact within the framework of the unified scheme, a highly debated further component was postulated already in 1989: a thick dusty torus, 10 to 100 light years across, surrounding the black hole and the central active zone. Viewed edge-on, such a torus would obscure the black hole. But it would have to dim the light of the central core by about 50 magnitudes, corresponding to a factor of 10^{-20}. Only then the optical and UV radiation typical for quasars would no longer be detectable.

The unified scheme is thought to be very attractive since it describes the multitude of active galaxies by a common fundamental model. The unification of Seyfert galaxies of type 1 and 2, for example, is widely accepted, but it is not at all established for radio-loud quasars and radio galaxies. On the one hand, the central components are so small that they are indiscernible even with the highest resolution instruments. There is just indirect evidence for absorbing dust in the surroundings of the black hole. On the other hand, some astronomers consider the model too simplified. It does not take into account the evolutionary stage of the radio lobes nor the circumgalactic environment nor the possibility of the central engine being in different physical states. So the fueling rate of the black hole or the flow of matter within the jet may vary from object to object.

Infrared observations using ISOPHOT

The unified scheme can be tested very elegantly by infrared observations. Although the optical light of the central core is not visible if the torus is viewed edge-on, it heats the postulated dust which in turn emits isotropic infrared radiation, that is, a uniform radiation in all directions (Fig. IV.37, bottom). At wavelengths longer than about 20 μm even the dense dusty disk should become transparent, so quasars and radio galaxies with equal isotropic luminosities of the radio lobes are expected to show equal thermal radiation intensities in the mid- and especially in the far-infrared range, too.

Already in the early 1990’s, attempts had been made to verify the unified scheme using data from the IRAS infrared satellite. The results, however, remained inconclusive because of insufficient sensitivity and wavelength coverage. It was not possible to distinguish between a thermal component and synchrotron emission. Partly, the observations even contradicted by the unified scheme.

The new study with ISOPHOT covering wavelengths between 5 μm and 180 μm was performed in the course of the ISO European Central Quasar Programme. Ten quasars and ten matching radio gala-

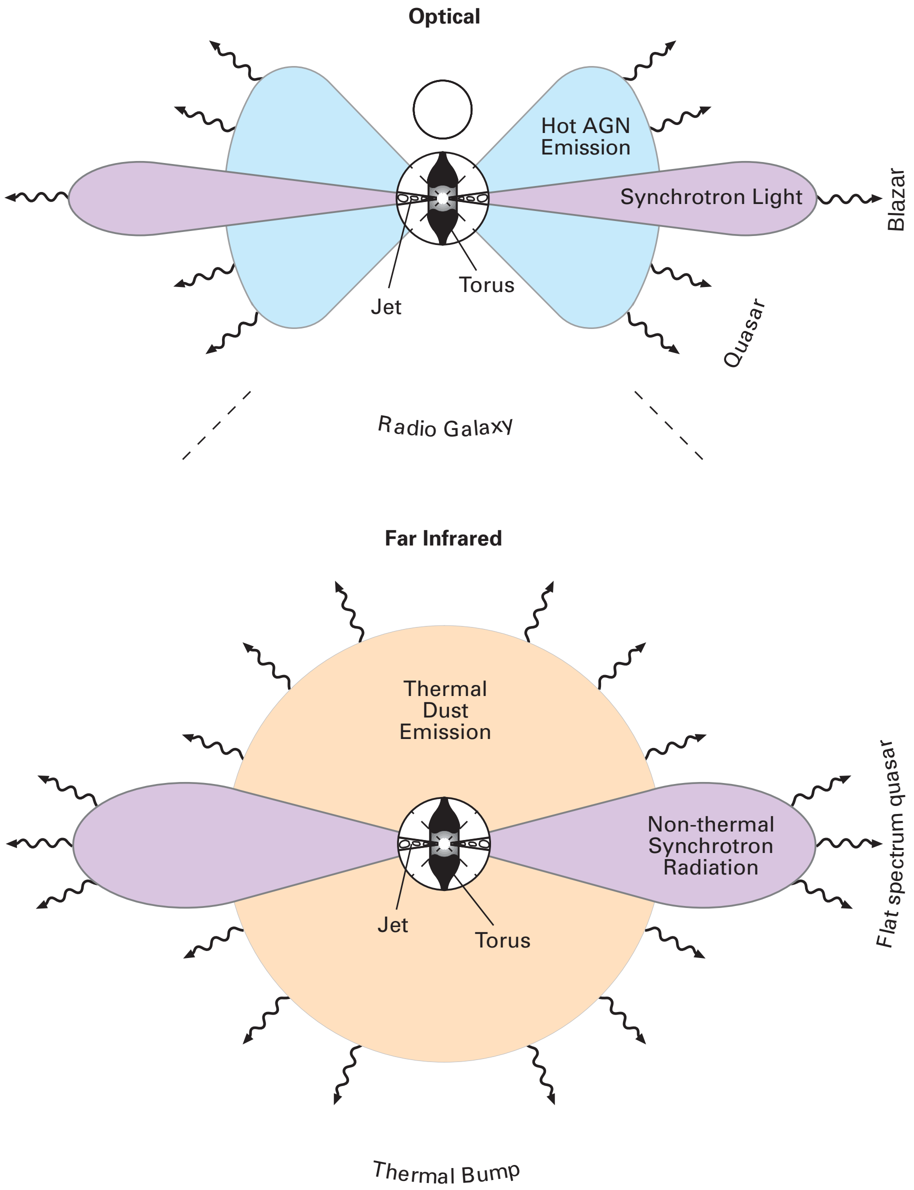


Fig. IV.37: The unified scheme for active galaxies. At optical wavelengths (top) the black hole and the surrounding hot disk cannot be seen when viewed edge-on, because thick dust is obscuring them. In the far infrared (bottom) the dust radiates isotropically. At these wavelengths therefore all systems look the same from every direction.

xies have been selected from the 3rd Cambridge Catalogue at 178 MHz, that is, at a wavelength where the isotropic radiation of the radio lobes is dominant (and not that of the jets). Quasar/radio-galaxy pairs with equal redshifts and equal luminosities at 178 MHz have been compared at a time to possibly exclude cosmic evolutionary effects. The pairs have redshifts between z = 0.05 and z = 2. Thus they are at quite different distances from us, that is, at different cosmic epochs.

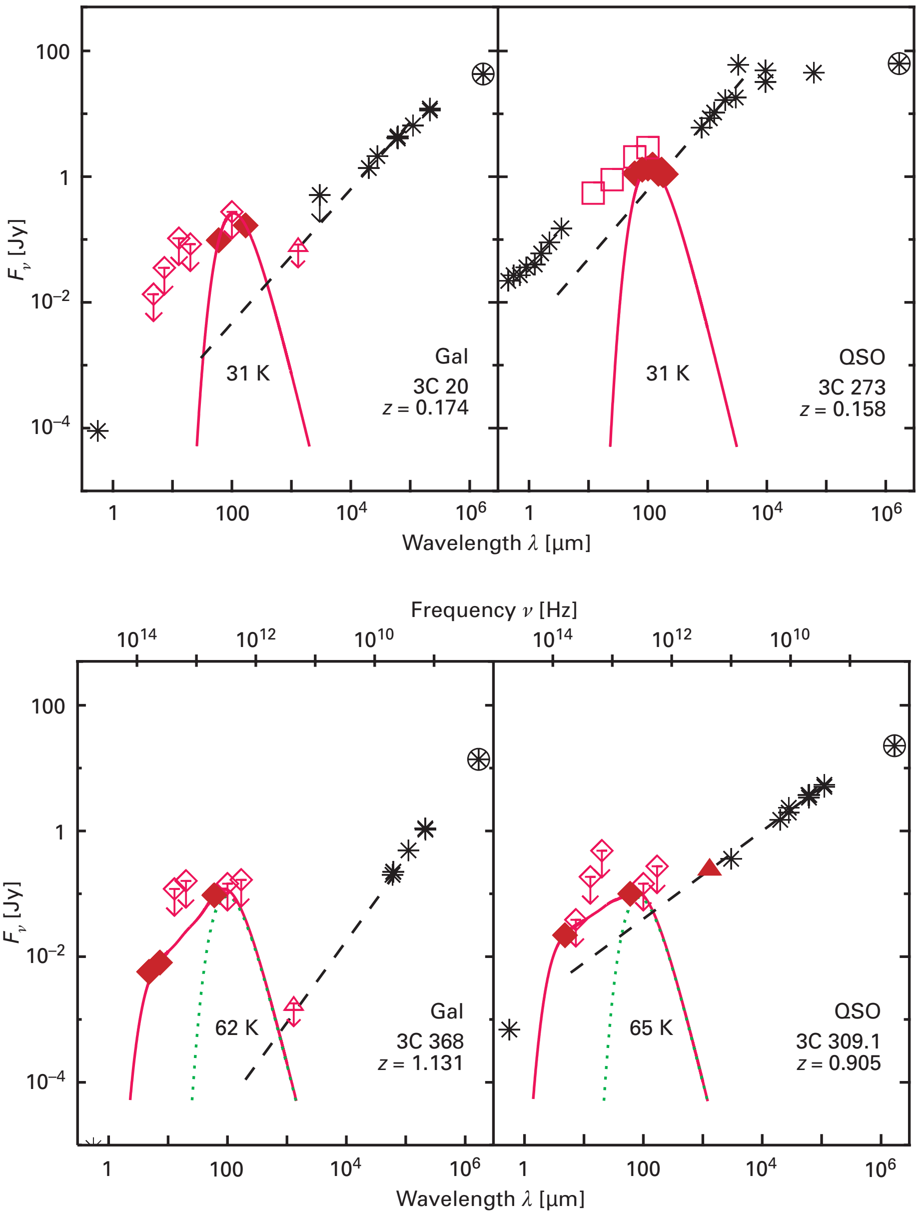
In addition, seven objects have been observed at a wavelenght of 1.3 mm using the French- German IRAM telescope at Pico Veleta. Together with optical and radio data measured previously, the spectral energy distribution could be determined over a large wavelength range. First results concerning some single objects had already been presented in the Annual Report 1998. But they did not allow a general unification of radio galaxies and radio-loud quasars. This has only now been accomplished for the first time:

The high detection sensitivity and the quality of the spectral energy distributions now allow us to distinguish the thermal dust component from the synchrotron part beyond doubt. This is demonstrated in Fig. IV.38 for an example of two pairs. Two different radiation sources can clearly be recognized: On the one hand, there is synchrotron emission with a steadily decreasing intensity from the radio to the far- and mid-infrared range. It originates from electrons accelerated in magnetic fields. Interestingly, the quasars show a flatter synchrotron spectrum than the radio galaxies. This is in perfect agreement with the predictions of the unified scheme, for in radio galaxies the forwardly directed emission of the jets is not pointed as directly towards the observer as in quasars and therefore is fainter.

On the other hand, in all radio galaxies and in at least four quasars a thermal component is detectable as a significant bump above the smooth synchrotron spectrum. This thermal component has its maximum in the mid- to far-infrared region and comes from dust at temperatures between 30 and several hundred Kelvin. Luminosities and their lower limits all are between 10^{11} and 10^{14} solar luminosities, which is typical also for radio-quiet quasars (see Annual Report 1999, p. 72). Even in the three cases in which the thermal component is not discernible as a significant bump above the synchrotron spectrum the lower limits still allow for the presence of a dust component with quasar-typical luminosity.

Statistically as well as in the pair comparison both object types – radio galaxies and radio-loud quasars – principally show the same characteristics in the infrared to millimeter range, exactly as predicted by the unified scheme.

Fig. IV.38: Spectral energy distribution of the two pairs 3C 20 / 3C 273 and 3C 368 / 3C 309.1.



Evolutionary effects

The unified scheme could be tested even further. If the relation between radio galaxies and radio-loud quasars is determined solely by the geometric unification and not in addition by cosmic evolution or the circumgalactic medium, the radiation intensity in the far infrared should be the same for quasars and radio galaxies with identical core activity. The latter cannot be measured directly, though. But it seems plausible to assume that with increasing activity near the black hole the jet activity is increasing, too. This activity in turn is mirrored by the radio emission of the lobes, which are supplied with energy by the jets. In a simple approximation, the intensity ratio of the far-infrared to the radio emission should be about the same for all sources. As shown in Fig. IV.39, with a few exceptions this ratio is constant to a factor of 2 or 3. The small scatter of the infrared/radio luminosity ratio also confirms the principally major role of geometric unification in describing the relation between radio galaxies and radio-loud quasars. In exceptional cases additional effects have to be considered – certainly not an unexpected issue in view of the complexity of the objects. The separation of different effects remains a challenging task for future explorations.

The most prominent example for an unusual case is 3C 405, better known as Cygnus A (Fig. IV.40). It is the first radio galaxy discovered, and with a redshift of z = 0.056 one of the nearest to us. Seen edge-on, this galaxy with its two huge radio emission lobes is the classical prototype of a radio galaxy. But already in 1998, astronomers at MPIA were able to demonstrate that Cygnus A, too, is a quasar whose central core is shrouded in dense clouds of dust (see Annual Report 1998, p. 22). Nevertheless, the jet energy seems to be converted very efficiently into a high radio luminosity of the lobes – caused by a relatively dense circumgalactic medium – so that the ratio of infrared luminosity to radio luminosity is extremely low (Fig. IV.39).

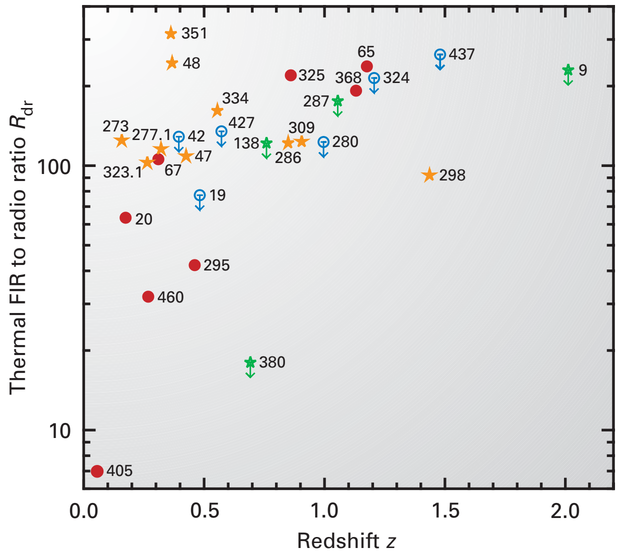
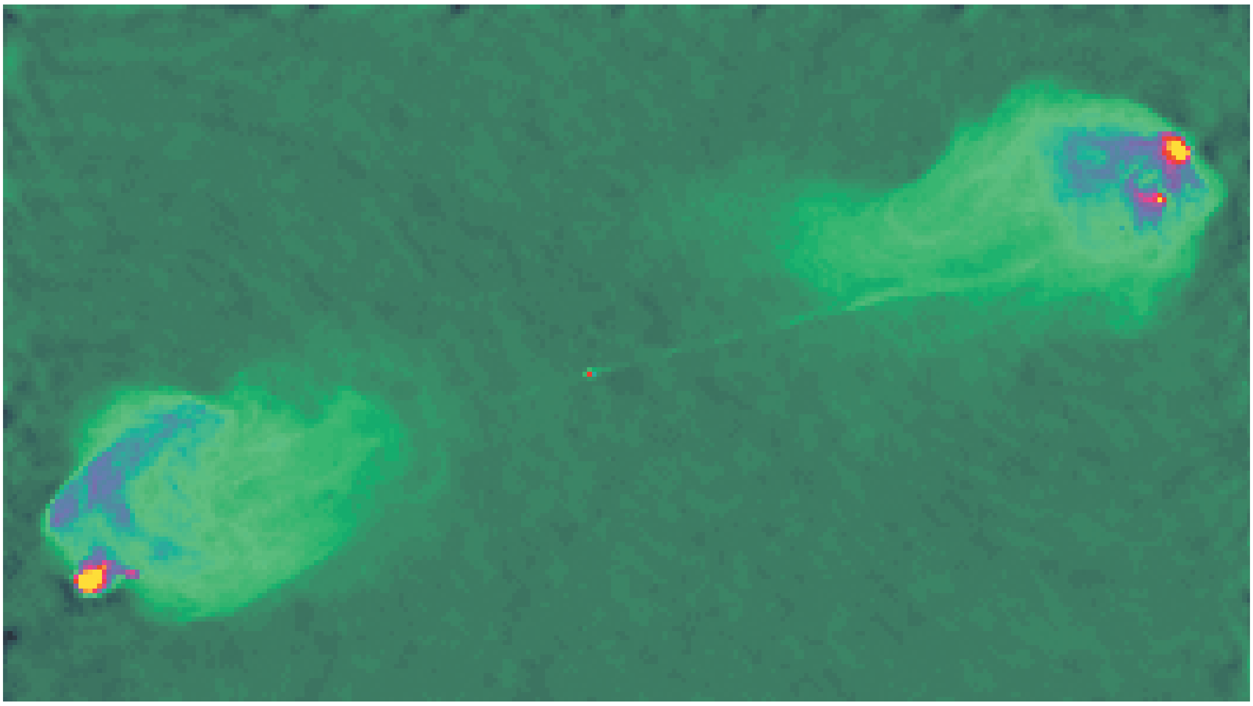


Fig. IV.39: Ratio of the luminosities in the far-infrared and radio range as a function of redshift *z*.

Fig. IV.40: Radio image of Cygnus A. (VLA)



In addition, Fig. IV.39 shows a slight trend: the ratio of the intensities of the thermal infrared emission and the radio emission increases with increasing redshift. Although the amount of data is yet too small to reveal whether this trend is significant it could indicate an evolutionary effect. In the early universe ($z > 1$) galaxies were closer together, experiencing frequently close encounters and collisions. Such events probably caused more matter being swirled into the galactic centers and swallowed there by the black holes. This increased the UV radiation of the core regions and thus the observable infrared intensity, too. But this process was not necessarily accompanied by an increased jet activity, which probably is influenced more strongly by the characteristics of the black hole, like its mass and angular momentum.

Therefore, quasars and radio galaxies in the early universe showed an increase of UV and infrared radiation, but not of radio emission. With increasing age the universe expanded and interactions between galaxies became rarer. Thus the "feeding rate" of the black holes dropped and so did the core activity in the surrounding disk. But it was still high enough to supply the radio jets with energetic particles and to light the radio lobes.

The concept of central galactic black holes suffering from "food shortage" when growing older is in agreement with other observations. In optical observations, American astronomers discovered that the quasar density peaked at a redshift around $z = 3$ (when the universe had about 10 % of its present age) and has been decreasing ever since.

In the near future, astronomers at MPIA plan to observe the dusty torus directly for the first time, using the new instruments of the Very Large Telescope. Here great hopes are placed in the infrared camera CONICA, built under the direction of MPIA and almost ready for service, and in the infrared interferometer MIDI which also has been developed and built in collaboration with scientists at the institute.

Staff

In Heidelberg

Directors: Appenzeller (temporary, until 31.7.), Beckwith (beurlaubt), Rix (Acting Director since 1.8.), Elsässer (em.), Münch (em.).

Scientists: Ábraham, Bailer-Jones, Beetz, Bianchi (until 30.6.), Birkle, Burkert, Dehnen, Feldt, Fried, Graser, Grebel (since 1.5.), Haas, Heraudeau, T. Herbst, Hippelein, Hofferbert, Ibata (until 30.9.), Kasper (15.8.–31.10.), Kiss (1.3.-31.8.), Klaas, Kley, Kümmel, Kroupa (17.7. until 31.10.), Leinert, Lemke, Lenzen, Ligori, Marien, Meisenheimer, Mundt, Neckel, Odenkirchen (since 1.5.), Röser, Slyz, Staude, Stickel, Wolf, Wilke.

Ph. D. Students: Dib (since 1.10.), Geyer, Harbeck (since 1.5.), Hartung, Heitsch, Hetznecker, Hotzel, Jesseit (since 1.5.), Jester, Khochfar (since 1.6.), Kasper (until 14.8.), Kleinheinrich, Kranz, Krause (since 1.5.), Krdzalic (since 18.9.), Kuhlmann (until 31.10.), Lamm (since 15.9.), Lang, Maier, Mühlbauer (since 1.7.), Naab, Phleps, Przygodda (since 1.11.), Rudnick, Sarzi (since 1.7.), Schuller, Stolte, Weiss.

Diploma Students: Bertschik, Helfert (until 30.4.), Krause (until 30.4.), Jesseit (until 31.1.), Khochfar (until 14.4.), Wackermann, Walcher (since 1.8.), Wetzstein, Ziegler (since 1.7.).

Scientific Services: Bizenberger, Fabian (until 31.5.), Grözinger, Hofferbert (since 1.8.), Laun, Mathar, Neumann (since 1.9.), Quetz.

Computers, Data Processing: Briegel, Helfert, Hiller, Hippler, Rauh, Storz, Tremmel, Zimmermann.

Elektronics: Alter (since 1.8.), Becker, Ehret, Grimm, Klein, Ridinger, Salm, Unser, Wagner, Werner (until 30.9.), Westermann, Wrhel.

Fine Mechanics: Böhm, Geuer (until 30.6.), Heitz, Meister, Meixner, Morr, Pihale, Sauer.

Drawing Office: Baumeister, Ebert (since 24.7.), Franke, Münch, Rohloff.

Design: Jung.

Photo Shop: Anders-Özçan.

Graphic Artwork: Meißner-Dorn, Weckauf.

Library: Behme.

Administration: Apfel (since 17.4.), Flock (freigestellt nach Altersteilzeitgesetz since 1.7.), Gieser, Kellermann, Hartmann, Heißler, Kellermann, Papousado, Schleich, Voss (since 1.6.), Zähringer.

Secretariate: Fé (until 31.3.), Goldberger, Heukäufer (until 6.12.), Janssen-Bennynck, Rushworth.

Technical Services: Behnke, Gatz, Götz, Herz, Lang, Nauss, B. Witzel, F. Witzel, Zergiebel.

Trainees: (Fine Mechanics) Fabianatz, Greiner, Haffner, Lares, Petri, Wesp.

Free Collaborator: Dr. Thomas Bührke.

Scholarship Holders: Cretton, Del Burgo (since 1.10.), Heraudeau (until 30.9.), W. Herbst (until 28.2.), Hozumi (until 7.4.), Kamath (1.6. until 31.10.), Kessel (DFG), Klessen (Otto Hahn Award), Kroupa (until 31.1.), Nelson, Pentericci, Popescu (Otto Hahn Award), Thiering (until 22.10.), Travaglio, Woitas (until 30.9.), Xu (until 15.5.).

Guests: Balsara, USA (October/November), Barrado-Navascués (June and November), Bodenheimer, Santa Cruz/USA (May), Ciecielag (July and September/October), Dye, Edingburgh/Schottland (January/February), Dodt, München, Hozumi, Kyoto/Japan (March/April), Majumdar, Bangalore/Indien (November), McIntosh, Tucson/USA (May and November), McKay, Michigan/USA (July), Mori, Tsukuba/Japan (October), S. Müller, Bochum (August), Patsis, Athen/Greece (September), Robberto, Tucson/USA (October), Shields, Ohio/USA (July), van der Marel, Leiden/Niederlande (July), Yonehara (Kyoto/Japan), Zaritski, Tucson/USA (July), Zabludoff, Tucson/USA (July).

Due to regular meetings of the ISOPHOT Co-investigators associated to other Research Institutes and industrial Firms in Germany and from abroad, numerous guests were at the MPIA for short times, who are not mentioned here individually.

Co-operative Students: Bach (15.2.–31.3.), Birkmann (28.2.–21.4.), Häring (16.8.-30.9), Link (since 1.9.), Lisker (1.8.–8.9.), Mayer (until 28.2.), Wieler (29.6.–31.7.), Mohammad (1.3.–31.8.), Müller, S. (until 28.2.), Schunck (21.8. until 30.9.), Tschamber (10.1.–31.3.), Weinmann (1.3.-31.8.).

Calar Alto/Almeria

Local Directors: Gredel, Vives.

Astronomy, Coordination: Thiele, Prada, Frahm.

Astronomy, Night Assistants: Aceituno, Aguirre, Alises, Hoyo, Montoya (until 30.11.), Pedraz.

Telescope Techniques: Capel, de Guindos, Garcia, Helmling, Henschke, L. Hernández, Raúl López, Morante, W. Müller, Nuñez, Parejo, Hernández Arabí (since 29.5.), Schachtebeck, Usero, Valverde, Wilhelmi.

Technical Services: A. Aguila, M. Aguila, Ariza, Barón, Carreño, Corral, Dominguez, Gómez, Góngora, Klee, Rosario López, Marquez, Martinez, F. Restoy, Romero, Sáez, Sanchez, Schulz (until 31.5.), Tapia.

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

Working Groops and Scientific Collaborations

Instrumental Projects

ALFA
Stefan Hippler, M. Kasper, M. Feldt, R. Weifl, R.-R. Rohloff, K.Wagner, P.Bizenberger and all technical Departments of MPIA and Calar Alto Observatory in collaboration with:
MPI für extraterrestrische Physik, Garching, University of Massachusetts, Amherst, USA.

CONICA
Rainer Lenzen, Becker, P. Bizenberger, A. Böhm, A. Hartung, W. Laun, N. Münch, R.-R. Rohloff, C. Storz, K. Wagner, in collaboration with: MPI für extraterrestrische Physik, Garching.

LAICA
Josef Fried, H. Baumeister, W. Benesch, F. Briegel, U. Graser, R.-R. Rohloff, B. Grimm, R. Klein, Unser, C. Marien, K. Zimmermann.

MIDI
Christoph Leinert, Uwe Graser, A. Böhm, B. Grimm, T. Herbst, St. Hippler, W. Laun, R. Lenzen, R. Ligori, R. Mathar, R. Mundt, U. Neumann, E. Pitz, F. Przygodda, R.-R. Rohloff, P. Schuller, C. Storz, K. Wagner, in collaboration with: Univ. Amsterdam, NL, Sterrewacht Leiden, NL, Observatoire Meudon, Meudon, France, Observatoire de Nice, France, Kiepenheuer-Institut Freiburg, Thüringische Landessternwarte Tautenburg.

PACS for HERSCHEL
Dietrich Lemke, O. Krause, U. Grözinger, R. Hofferbert, U. Klaas, O. Krause, M. Stickel, H. Baumeister, A. Böhm, coordination: MPI für extraterrestrische Physik, Garching, in collaboration with: DLR, Berlin, Universität Kaiserslautern.

OMEGA 2000
Coryn Bailer-Jones, H. Baumeister, P. Bizenberger, A. Böhm, B. Grimm, W. Laun, R.-R. Rohloff, C. Storz, Toews.

LBT with LUCIFER and LINC
Hans-Werner Rix, P.Bizenberger, B. Grimm, W. Laun, M. Olivier, R. Rohloff, in collaboration with: Landessternwarte Heidelberg.

ISO Data Center
Dietrich Lemke, ISOPHOT-PI and the ISO Group at MPIA: P. Abraham, S. Bianchi, del Burgo, M. Haas, P. Heraudeau, S. Hotzel, Kiss, U. Klaas, O. Krause, M. Stickel, K. Wilke.

Research Programmes

Free Floating Planetary Objects
Reinhard Mundt, Coryn Bailer-Jones, in collaboration with: Instituto de Astrofisica de Canarias, Caltech, Pasadena, USA, University of Hawaii, USA, Consejo Superior de Investigaciones Cientificas, Madrid, Ecole Normale Superieure, Lyon, France.

Three Stages of Dust Heating in ULIRGs
Ulrich Klaas, Martin Haas, H. Hippelein, K. Wilke, D. Lemke, in collaboration with: Ruhr-Universität Bochum, Joint Astronomy Centre, Hawaii, USA.

Black Holes in Galactic Centers
Hans-Werner Rix, Marc Sarzi, in collaboration with: Harvard Smithsonian Center for Astrophysics, Cambridge, USA, University of Arizona, Tucson, USA, Space Telescope Science Institute, Baltimore, USA, University of Padua, Italy, University of Ohio, Athens, USA, Carnegie Institutions of Washington, USA, University of California, Berkeley, USA, Caltech, Pasadena, USA.

Rotation of Young Stars
Reinhard Mundt, Coryn Bailer-Jones, in collaboration with: Wesleyan University, Middletown, USA, Yale University, Caltech, Pasadena, USA.

Orbital Periods and Masses of Young Binaries
Christoph Leinert, J. Woitas, R. Köhler, in collaboration with: Thüringer Landessternwarte, Tautenburg, University of California, San Diego, USA.

ISOPHOT Observes Star Formation within Dark Clouds
Dietrich Lemke, Stefan Hotzel, L.V. Toth, O. Krause, M. Stickel, in collaboration with: Universität Helsinki, Finnland, Astrophysikalisches Observatorium Arcetri, Italien, ESO, Chile, ISO Science Operations Centre, Villafranca, Spanien.

Palomar 5 – a Dissolving Globular Cluster
Michale Odenkirchen, Eva Grebel, W. Dehnen, R. Ibata, H.-W. Rix, A. Stolte, C. Wolf, in collaboration with: University of Chicago, USA, Fermi National Accelerator Laboratory, Batavia, USA, Princeton University, USA, Johns Hopkins University, Baltimore, USA, Naval Research Lab, Washington, USA, U.S. Naval Observatory, Flagstaff, USA.

Turbulence in Star Formation
Ralf Klessen, Andreas Burkert, in collaboration with: University of California, Santa Cruz, USA.

Planet Formation in Binary Stars
Andrew Nelson, Wilhelm Kley, Andreas Burkert.

Lopsided Spiral Galaxies
Gregory Rudnick, Hans-Walter Rix, in collaboration with: University of Arizona, Tucson, USA.

Far Infrared Extragalactic Background Radiation
Dietrich Lemke, M. Stickel, in collaboration with 14 Institutes in Europe und USA.

ISO Confirms Unification of radio Galaxies and Radio-Loud Quasars
Klaus Meisenheimer, Martin Haas, U. Klaas, D. Lemke, in collaboration with: Ruhr-Universität Bochum.

Projects not presented in this Report:

Emission Knots in the Helix Nebula
A. Burkert, in collaboration with: Rice University Houston, Texas, USA, Universität Mexiko.

Surface Characteristics of Extremely Cold Dwarfs
C. Bayler-Jones, R. Mundt.

Ice bands in the Spectrum of Haro 6-10
Ch. Leinert, S. Ligori, J. Woitas, in collaboration with: State University of Stony Brook, New York, USA, University of Wyoming, Laramie, USA.

Mass Determination for LHS 1070
Ch Leinert, J. Woitas, R. Köhler, in collaboration with: Astronomisches Recheninstitut Heidelberg, Wise Observatory, Tel Aviv, Israel, Universität Köln.

The Age of the Stars in the Solar Neighborhood
W. Dehnen, in collaboration with: University of Oxford, UK, University of Padua, Italy.

The Outflow of DG Tauri
R. Mundt, in collaboration with: Space Telescope Science Institute, Baltimore, USA, Dublin Institute of Advanced Studies, Dublin, Irland, Thüringer Landessternwarte Tautenburg, Landessternwarte Heidelberg.

The Formation of Star Clusters
R. Klessen, A. Burkert.

Ionizing Radiation in 3D-Simulations
O. Kessel-Deynet, A. Burkert.

Observations of the Andromeda Galaxy with ISOPHOT
L. Schmidtobreick, M. Haas, D. Lemke.

A Survey of Galaxies at the Northern Pole of the Ecliptic
M. W. Kümmel, in collaboration with: Landessternwarte Heidelberg.

The Distribution of Stellar Orbits in NGC 2320
H.-W. Rix, in collaboration with: Sternwarte Leiden, NL.

Axially symmetric Models of Galaxies
H.-W. Rix, in collaboration with: Sternwarte Leiden, NL, University of Arizona, Tucson, USA.

Observations of the Gravitational Lens Candidate RX J0921+4529
H.-W. Rix, in collaboration with: Harvard Smithsonian Center for Astrophysics, Cambridge, USA, University of Arizona, Tucson, USA, Space Telescope Science Institute, Baltimore, USA, University of Hawaii, USA, Astrophysical Institute of the Canary Islands, Spain.

Dark Matter Halos Around Galaxien
Andreas Burkert

The Mass Spectrum of Old Globular Clusters
A. Burkert, in collaboration with: University of California, Santa Cruz, USA.

Cooperation with Industrial Firms

Calar Alto Observatory
DSD Dillinger Stahlbau GmbH, Saarlouis
PEP Modular Computers GmbH, Kaufbeuren

LAICA
Filtrop AG, Balzers Liechtenstein
Präzisionsoptik Gera, Gera
Reichmann Feinoptik, Brokdorf

OMEGA 2000
Infrared Labs., Tucson USA
Rockwell, Thousend Oaks USA
Barr, Westford USA
GATIR, Archer USA
Kaufmann, Crailsheim

ALFA
AOA Inc., Cambridge, Massachusetts, USA
Cambridge Innovations, Framingham, Massachusetts, USA
Coherent GmbH, Dieburg
Fast ComTec, Oberhaching
Laser Components GmbH, Olching
Microgate S.r.l., Bolzano, Italy
MIT/Lincoln Laboratory, Lexington, Massachusetts, USA
OWIS GmbH, Staufen
Physik Instrumente, Waldbronn
Univ. Mannheim, Technische Informatik, Lehrstuhl Integrierte Optoelektonik, Mannheim
Xinetics Inc., Devens, Massachusetts, USA

MIDI
AMS, Martinsried
Baumer electric, Friedberg
Börsig, Neckarsulm
Faber Industrietechnik, Mannheim
Ferrofluidics, Nürtingen
Gerwah Präzisions GmbH, Grosswallstadt
Gutekunst, Metzingen
Hommel Werkzeuge, Viernheim
Infrared Labs, Tucson, USA
ISOLOC, Stuttgart
Melles-Griot, Bensheim
Newport, Darmstadt
OCLI, Santa Rosa, USA
Polytec, Waldbrunn
Präzisionsoptik Gera, Gera
RETEC Instrumnents, Idstein
Sky Blue, München
Taylor-Hobson, Wiesbaden
VSYSTEMS, München
Wiebusch, Volkmarsen

CONICA
Barr, Westford, Massachusetts, USA
Carl Zeiss, Jena
Janos, Townshend, Vermont, USA
Linos Photonics, Göttingen
Leybold, Hanau
Möller, Wedel
Omega, Vermont, USA
Pörschke, Höchst
Präzisionsoptik, Gera
Queensgate, Barkshire, GB
Richardson Grating, Rochester, USA
Vitron, Jena

PRIME
Kayser-Threde, Bremen

PACS
Agilent (formerly Hewlett-Packard) Böblingen
ANTEC, Kelkheim
API Portescap, Pforzheim
Buerklin, München
Comtronic GmbH, Heiligkreuzsteinach
Cunz, Frankfurt
GAF, Nussloch
GSF Forschungszentrum, Unterschleissheim
GVL Cryoengineering, Stolberg
Hopt GmbH, Schoemberg
Hoschar, Karlsruhe
Kayser-Threde. München
Keithley, München
Kugler, Salem
LeCroy, Heidelberg
MagnaC, Wendlingen
Meilhaus Elektronik, PuchheimKarte
Messer-Griesheim, Ludwigshafen
MKS Instruments, München
Novotek GmbH, Böblingen
Phytron-Elektronik, Gröbenzell
Polytec Gmbh, Waldbronn
Rutronik GmbH, Ispringen
Scientific Instruments Gilching
Tektronix, Köln
Vacuumschmelze, Hanau
Witte Geraetebau, Bleckede
Zeiss, Oberkochen

CCD Techology
Dataman, Pliezhausen
EEV Ltd., GB
Haefele, Schriesheim.
Heraeus, Hanau
Lockheed Martin Fairchild Syst., USA
Micro-Optronic-Messtechnik, Langebrück
New Focus, Santa Clara, USA
Philips, Eindhoven, Niederlande
Roth, Karlsruhe
SITe Corp., Beaverton, Oregon, USA
Steward Observatory, Tucson, Arizona, USA
Tafelmeier, Rosenheim

Computers
AKRO, Unterschleißheim
asknet, Karlsruhe
Additive, Friedrichsdorf
Bechtle, Heilbronn
Cancom, Frankfurt
Creaso, Gilching
Danes, Frankfurt
DELL, Langen
Edo, Hockenheim
Gordion, Troisdorf
h-soft, Stuttgart
INMAC, Mainz
ISP*D, Poing
LANTEC, Planegg
PROUT, Darmstadt
PTC, Mannheim
Rufenach, Heidelberg
Schulz, München
Scientific Computers, Aachen
Sun, Langen
Transtec, Tübingen

Workshops

ABB (ehem. Hartmann + Braun), Alzenau
Almet-AMB, Mannheim
Amphenol-Tuchel Electronics, Heilbronn
APE Elektronik, Kuppenheim
Astro- und Feinwerktechnik, Berlin
AVIMO, Somerset, U.K.
Best Power Technology, Erlangen
Binder Magnete, Villingen-Schwenningen
Börsig, Neckarsulm
Bubenzer Bremsen, Kirchen-Wehrbach
Bürklin, München
C&K Components, Neuried b. München
Cadillac-Plastic, Viernheim
Carl Roth, Karlsruhe
Cherry Mikroschalter, Auerbach
Com Pro, Stuttgart
Compumess Electronik, Unterschleissheim
Comtronic GmbH, Heiligkreuzsteinach
Conrad Electronic, Hirschau
Cryophysics, Darmstadt
Dalektron, Dreieich
Dannewitz, Linsengericht
Dürkes & Obermayer, Heidelberg
Dyna Systems NCH, Mörfelden-Walldorf
EBJ, Ladenburg
EBV-Electronik, Leonberg
EC Motion, Mönchengladbach
Edsyn Europa, Kreuzwertheim
Eldon, Büttelborn
Elna Transformatoren, Sandhausen
elspec, Geretsried
ELV Electronik, Leer
ERNI, Adelberg
eurodis Enatechnik, Quickborn
EWF, Eppingen
Faber, Mannheim
Farnell Electronic Components, Deisenhofen
Farnell Electronic Services, Möglingen
FCT Electronic, München
Fischer Elektronik, Lüdenscheid
Franke, Aalen
Fritz Faulhaber, Schönaich
Future Electronics Deutschland, Unterföhring
Gould Nicolet Messtechnik, Dietzenbach
Helukabel, Hemmingen
Herz, Leister Geräte, Neuwied
Hewlett-Packard Direkt, Böblingen
Holz Electronik, Kirchheim
Hommel-Hercules Werkzeughandel, Viernheim
Horst Göbel, Ludwigshafen
Horst Pfau, Mannheim
HOT Electronic, Taufkirchen
HTF Elektro, Mannheim
Huber + Suhner, Taufkirchen
IBF Mikroelektronik, Oldenburg
Infrared Labs, Tucson, USA
Inkos, Reute/Breisgau
iSystem, Dachau
ITE, Sandhausen
Jacobi Eloxal, Altlussheim
Jarmyn, Limburg
Kaufmann, Crailsheim
Kniel, Karlsruhe
Knürr, München
Lambda Electronics, Achern
Lemo Electronik, München
LPKF CAD/CAM Systeme, Garbsen
Macrotron, München
Matsuo Electronics Europe, Eschborn
Matsushita Automation, Holzkirchen
Maxim Ges. f. elektronische integrierte Bausteine, Planegg
Menges electronic, Dortmund
Metrofunkkabel-Union, Berlin
Mitsubishi-Electric, Weiterstadt
MSC Vertriebs-GmbH, Stutensee
MTI, Baden-Baden
Nanotec, Finsing
Nickel Schalt- und Messgeräte, Villingen-Schwenningen
Niebuhr Optoelectronik, Hamburg
Nies Electronic, Frankfurt
Nova Electronik, Pulheim
Otto Faber, Mannheim
OWIS GmbH, Staufen
Parametric Technology, Muenchen
pbe Electronic, Elmshorn
Physik Instrumente, Waldbronn
Phytec Messtechnik, Mainz
Plastipol, Runkel
PSI Tronix, Tulare, California, USA
Püschel Electronik, Mannheim
R.E.D. Regional-Electronic-Distribution, Rodgau-Jügesheim
Radiall, Rödermark
Rau-Messtechnik, Kelkheim
Reinhold Halbeck, Offenhausen
Retronic, Ronneburg
Riekert & Sprenger, Wertheim
Rittal-Werk, Herborn
Roland Häfele Leiterplattentechnik, Schriesheim
RS Components, Mörfelden-Walldorf
Rufenach Vertriebs-GmbH, Heidelberg
Rutronik, Ispringen
Sasco, Putzbrunn
Scantec, Planegg
Schaffner Elektronik, Karlsruhe
Schuricht, Fellbach-Schmiden
SCT Servo Control Technology, Taunusstein
SDRC, Neu-Isenburg
SE Spezial-Electronic, Bückeburg
Siemens IC-Center, Mannheim
Spindler & Hoyer, Göttingen
Spoerle Electronic, Dreieich
Steinbach, Bochum
Synatron, Hallbergmoos
Thorlabs, Grünberg
TMS Test- und Messsysteme, Herxheim/Hayna
Tower Electronic Components, Schriesheim
TreNew Electronic, Pforzheim
TS-Optoelectronic, München
TWK-Elektronik, Karlsruhe
Vacuumschmelze, Hanau
Vero Electronics, Bremen
W. & W. Schenk, Maulbronn
Wikotec, Bramsche
Wilhelm Gassert, Schriesheim
WS CAD Electronik, Berk Kirchen

Teaching Activities

Winter Term 1999/2000:

A. Burkert: Globular Clusters (Lecture);

J. Fried: Astronomical Trainig at the Frankfurt University;

M. Haas: Infrared Astronomy (Lecture);

Ch. Leinert, D. Lemke, R. Mundt, H.-J. Röser: Astronomy and Astrophysics III (Seminar).

Summer Term 2000

M. Haas: Far Infrared Astronomy (Lecture)

D. Lemke, R. Mundt, H. P. Gail: Astronomy and Astrophysics III (Seminar)

Ch. Leinert et al.: History of Astronomy (Seminar)

A. Burkert, H.W. Rix et al.: Stellar Dynamics (Seminar)

K. Meisenheimer, H.J. Röser: The Large Structure of the Universe (Seminar)

E. K. Grebel: Lecturer at the X. IAGUSP Advanced School on Astrophysics on Galaxy and Stellar Evolution, Mangaratiba, Brasil.

Winter Term 2000/2001

A. Burkert, H.-W. Rix: Elliptical Galaxies (Lecture)

D. Lemke, R. Mundt, H.J. Röser et al.: Astronomy and Astrophysics III (Seminar)

A. Burkert, H.W. Rix et al.: Structur, Kinematics and Dynamics of Stellar Systems (Seminar)

K. Meisenheimer et al.: Particle Acceleration and Radiative Processes in High-Redshift Radio Galaxies (Seminar).

Meetings, Invited Talks and Public Lectures

P. Ábrahám: AG-Tagung, Bremen, September (Splintermeeting ISO: talk); IAU Colloquium 181/COSPAR Colloquium 11, Canterbury, April (invited talk).

C. Bailer-Jones: AG-Tagung, Bremen, September (talk).

A. Burkert: Conference»Star Bursts«, Ringberg, October; invited talks: IAU-Symposium Nr. 200: »The birth and evolution of binary stars«, Potsdam, April; Workshop »Low Mass Star Formation«, Ringberg, June; Workshop »Molecular Clouds and Star Formation«, Heidelberg, July; Workshop »Dark Matter Halos«, Santa Cruz, USA, August; Conference»Modes of Star Formation«, Heidelberg, October; Conference »Evolution of the Cosmos«, Paris, France, November.

N. Cretton: Invited Seminar »Dynamical models for elliptical galaxies: black holes and dark halos«, Genf, February; Lectures on Galaxiendynamik an der Universität Padua, April; Conference»Galaxy Disks and Disk Galaxies«, Rom, June (invited talk).

J. Fried: public talk »Astrologie – Wissenschaft oder Aberglaube?«, FH Zweibrücken, December.

M. Geyer: AG-Tagung, Bremen, September (talk, poster); Conference»Galaxy Disks and Disk Galaxies«, Rom, June (poster).

U. Graser: SPIE ConferenceNr. 4006: »Interferometry in optical astronomy«, Garching, March (talk).

E. K. Grebel: Colloquium at ESO, Santiago, Chile, January (invited talk); Microlensing 2000: A New Era of Microlensing Astrophysics, Cape Town, Südafrika, February (invited talk); CTIO/ESO/LCO Workshop: »Stars, Gas, and Dust in Galaxies: Exploring the Links«, La Serena, Chile, March (talk); Kolloquium am STScI, Baltimore, USA, March (invited talk); Kolloquium in Caltech, Pasadena, USA, April (invited talk); Kolloquium am IGPP, LLNL, Livermore, USA, April (invited talk); Euroconference: »The Evolution of Galaxies, I. Observational Clues«, Granada, May (invited talk); Ringberg-Workshop: »Science with the LBT«, Rottach-Egern, June (talk); Star Formation Workshop, MPIA, Heidelberg, June (talk); Sloan Collaboration Meeting, Johns Hopkins University, Baltimore, September (talk); XIAGUSP Advanced School on Astrophysics: »Galaxy and Stellar Evolution«, Angra dos Reis, Brazil, September (Vorlesungen); AG-Tagung, Bremen, September (invited talk, poster); Joint Colloquium, MPE/MPA/ESO, Garching, October (invited talk); Internationaler Workshop »Modes of Star Formation and the Origin of Field Populations« am MPIA, October (Organisation); Physikalisches Kolloquium an der Universität Hamburg, November (invited talk); Kolloquium am Institut für Theoretische Physik und Astrophysik der Universität Kiel, November (invited talk); Kolloquium an der Sternwarte der Universität Göttingen, December (invited talk).

R. Gredel: Workshop on »The progress of the ISOGAL project«, Lorentz Center, Leiden, April; IAU Site 2000, Marrakech, November

M. Haas: Workshop FIRSED2000: »The Far-Infrared and Submillimeter Spectral Energy Distributions of Active and Starburst Galaxies« Groningen, April (invited talk); M 31 Workshop, Bad Honnef, May (talk); FIRST Science Conference, Toledo, December (talk).

D. Harbeck: AG-Tagung, Bremen, September (talk, 2 poster); Internationaler Workshop »Modes of Star Formation and the Origin of Field Populations« am MPIA, October (poster).

S. Hippler (poster): SPIE ConferenceNr. 4006: »Interferometry in optical astronomy«, Garching, March

S. Hotzel: Sternwarte Helsinki, May (invited talk); AG-Tagung, Bremen, September (Splinter meeting ISO: talk).

U. Klaas: Workshop FIRSED 2000: »The Far-Infrared and Submillimeter Spectral Energy Distributions of Active and Starburst Galaxies« Groningen, April

O. Krause (talk): SPIE: »Infrared Spacebourne Remote Sensing VIII«, San Diego, July (talk).

T. Kranz: Conference»Dark Matter in Astro and Particle Physics – Dark 2000«, Heidelberg, July

M. Kümmel: Euroconference: »The Evolution of Galaxies, I. Observational Clues«, Granada, May (poster); MPA/ESO/MPE Joint Astronomy Conference, Garching, August (talk); ESO/ECF/STScI Workshop on »Deep Fields«, Garching, October (poster).

B. von Kuhlmann: VC^3 – Victoria Computational Cosmology Conference, Victoria, Canada, August

S. Ligori: IAU-Symposium Nr. 200: »The birth and evolution of binary stars«, Potsdam, April (poster); Conference»Ionized Gaseous Nebulae«, Mexico City, November (poster).

Chr. Leinert: SPIE ConferenceNr. 4006: »Interferometry in optical astronomy«, Garching, March (talk); IAU-Symposium Nr. 200: »The birth and evolution of binary stars«, Potsdam, April (poster); NEVEC Inauguration Ceremony, Leiden, May (invited talk); Summer School on »Space and Ground Based Optical & Infrared Interferometry«, Leiden, September (invited talk).

D. Lemke: Univ. Wien, January (invited talk); Planetarium Wien, January (Öffentlicher talk); Deutsche Physikalische Gesellschaft, Bremen, March (invited talk); Budapest, May (invited vorträge); Trebur/Rüsselsheim, June (public talk); Conference »Infrared Thermography QIRT«, Reims, July (invited talk) COSPAR Space IR, Warschau, July (invited talk); IAU Symposium 204: »The Extragalactic Infrared Background and its Cosmological Implications«, Manchester, August (invited talk); (Splintermeeting ISO: Organisation): AG-Tagung, Bremen, September Nordenham, October (public talk).

R. Mundt: AG-Tagung, Bremen, September (talk); Conference»Emission Lines from Jet Flows«, Isla de Mujeres, Mexiko, November.

T. Naab: Conference»Galaxy Disks and Disk Galaxies«, Rom, June (2 poster); AG-Tagung, Bremen, September (talk).

M. Odenkirchen: Workshop on »Dynamics of Star Clusters and the Milky Way«, Heidelberg, March (talk); Sloan Collaboration Meeting, Johns Hopkins University, Baltimore, September (talk); Internationaler Workshop »Modes of Star Formation and the Origin of Field Populations« am MPIA, October (poster).

L. Pentericci: Dwingeloo Radio Observatory, The Netherlands, February (Invited colloquium); Leiden University, The Netherlands, February (Invited talk); Institute of Radioastronomy, Bologna, Italy, May (public colloquium); Conference on AGNs, Triest, May (talk); ESO/ECF/STScI Workshop on »Deep Fields«, Garching, October (poster).

A. M. Quetz: Schülertag Physik am MPIA, May; Rüsselsheim, September (public talk).

H.-W. Rix: Astronomisches Kolloqiuium »CASTLES«, Bonn, January; Gravitational Lenses as Cosmological Tools, Tel Aviv, March (talk); Sloan Digital Sky Survey, Seattle, March (talk); Structural Properties of Observed Ellipticals, University of California, Santa Barbara, March (talk); talkrunde Urknall, Berlin, April; MPIA, Heidelberg, May (invited talk); »Black Holes in Galaxies«, Max-Planck-Institut für Kernphysik, Heidelberg, May (invited talk); »The Growth of Density Fluctuations and Structure in an Expanding Universe«, Universität Heidelberg, May (invited talk); Schülertag Physik am MPIA, May; GAFOS-Meeting, Irvine, Kalifornien, June; Conference»Galaxy Disks and Disk Galaxies«, Rom, June (talk); Wissenschaftsshow, WDR, Köln, October; Sloan Digital Sky Survey, Volkssternwarte Bonn, November (talk).

H.-J. Röser: STScI Workshop: »A Decade of HST Science«, Baltimore, April (poster); NEON Sommerschule (Imaging and Photometry), Calar Alto, July (invited talk).

R.-R. Rohloff: SPIE ConferenceNr. 4006: »Interferometry in optical astronomy«, Garching, March (poster).

L. Schmidtobreick: M 31 Workshop, Bad Honnef, May (talk).

P. Schuller: Summer School on »Space and Ground Based Optical & Infrared Interferometry«, Leiden, September (poster).

A. Slyz: Workshop on »Numerical Methods in Astrophysics«, Tübingen, February; Workshop »Disk Galaxies and Galaxy Disks«, Rom, June; Workshop on »Star Formation«, Heidelberg, July; Brown Bag Cosmology Lunch Seminar: »Numerical Hydrodynamics«, Oxford, November; Kolloquium »Numerical Hydrodynamics from Gas-Kinetic Theory«, Leicester, November; Workshop on »Starbursts and the Structure and Evolution of Galaxies«, Puna, December (invited talk).

M. Stickel: IAU Symposium 204: »The Extragalactic Infrared Background and its Cosmological Implications«, Manchester, August (poster); AG-Tagung, Bremen, September (splinter meeting ISO: talk); ESO/ECF/STScI Workshop on »Deep Fields«, Garching, October (poster); FIRST Science Conference, Toledo, December (talk).

C. Travaglio: Euroconference: »The Evolution of Galaxies, I. Observational Clues«, Granada, May (poster); Workshop in Honour of Prof. G. J. Wasserburg, Turin, June (invited talk); Conference on »Nuclei in the Cosmos VI«, Aarhus, Denmark, July (talk und 3 poster).

M. Yan: IVth Tetons Summer Conference: »Galactic Structure, Stars, and the Interstellar Medium«, Jackson Hole, May (poster).

Service in Committees

A. Burkert: Senator of the Max Planck Society

J. Fried: Thesis Opponent at the Doctorate examination of T. Pursimo, Univ. of Turku, Finland.

E. K. Grebel: Referee for the National Fund for Science and Technology (FONDECYT), Chile; Referee for

La Palma and Teide Observatorien, Spanien; Referee for the Netherlands Research School for Astronomy (NOVA),

Niederlande; Member of the Core Science Team for a NIRMOS Microshutter Array for the Next Generation Space Telescope; Member of the PhD Advisory Council (PAC) at MPIA; Representant of the MPIA in the Collaboration Council of the Sloan Digital Sky Survey.

R. Gredel: Menber of the OPTICON working groop Future of medium-sized telescopes; member of the Evaluating Committee for the National Observatory of Athens; Member of the Calar Alto Program Committee

U. Klass: Member of the ISO Post Operations Coordination Committee.

Ch. Leinert: Member of the ESO working groop “Science Demonstration Time” for VLTI; member of the Finding Commission of the Jena University

D. Lemke: Referee for the Verbundforschung Astrophysik of the Federal Minisry of Sciuence and Technology; Member of the ISO Science Team of ESA.

R. Mundt: Member of the Calar Alto Program Committee.

H.-W. Rix: Member of the ESA Astronomy Working Group and of the ESO Visiting Committee

H.-J. Röser: Member of the Calar Alto Program Committee, Peer Review for Cycle 10 Hubble Space Telescope Proposals.

Publications

Ábrahám, P., L.G. Balázs and M. Kun: Morphology and Kinematics of the Cepheus Bubble. Astronomy & Astrophysics 354, 645-656 (2000).

Ábraham, P. and C. Leinert: ISO Observations of Binary T Tau Stars. In: Birth and Evolution of Binary Stars. (Eds) B. Reipurth, H. Zinnecker. IAU Poster Proceedings 200, Astrophysikalisches Institut Potsdam, Potsdam 2000, Proceedings of a Conference held at Astrophasikalisches Institut Potsdam, 10 - 15 April 2000, 34-35.

Ábrahám, P., C. Leinert, A. Burkert, T. Henning and D. Lemke: Far-infrared photometry and mapping of Herbig Ae/Be stars with ISO. Astronomy & Astrophysics 354, 965-982 (2000).

Acosta-Pulido, J.A., C. Gabriel and H.O. Castañeda: Transient Effects in ISOPHOT Data: Status of Modelling and Correction Procedures. Experimental Astronomy 10, 333-346 (2000).

Alton, P.B., E.M. Xilouris, S. Bianchi, J. Davies and N. Kylafis: Dust properties of external galaxies: NGC 891 revisited. Astronomy & Astrophysics 356, 795 (2000).

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Bacciotti, F., R. Mundt, T.P. Ray, J. Eislöffel, J. Solf and M. Camenzind: HST/STIS Spectroscopy of the Optical Outflow from DG Tau: Structure and Kinematics on Sub-arcsecond Scales. The Astrophysical Journal 537, L49-L53 (2000).

Bailer-Jones, C.A.L.: Stellar Parameters from very Low Resolution Spectra and Medium Band Filters. Teff_log g and [M/H] using neutral networks. Astronomy & Astrophysics 357, 197-205 (2000).

Bailer-Jones, C.A.L., P. Bizenberger and C. Storz: Achieving a wide field near infrared camera for the Calar Alto 3.5m telescope. In: Optical and IR Telescope Instrumentation and Detectors. (Eds) M. Iye, A.F.M. Moorwood. SPIE Proceedings 4008, SPIE, 2000, Proceedings of a Conference held at Munich, March 2000, 1305.

Bailer-Jones, C.A.L. and R. Mundt: A search for variability at and below the hydrogen burning limit. In: Stellar Clusters and Associations: Convection, Rotation, and Dynamos. (Eds) R. Pallavicini, G. Micela, S. Sciortinio. ASP Conference Series 198, Astronomical Society of the Pacific, San Francisco 2000, Proceedings of a Conference held at Sicily, May 1999, 341.

Barrado y Navascués, D., C.P. Deliyannis and J.R. Stauffer: WIYN Open Cluster Study : Litium in Cold Dwarfs of the M35 Open Cluster. In: Stellar Clusters and Associations: Convection, Rotation, and Dynamos. (Eds) R. Pallavicini, G. Micela, S. Sciortino. ASP Conference Proceedings 198, American Astronomical Society of the Pacific, San Francisco 2000, Proceedings of a Conference held at Sicily, May, 1999, 265-268.

Barrado y Navascues, D., J.R. Stauffer and B.M. Patten: A Lithium Age for the Young Cluster IC 2391. In: Stellar Clusters and Associations: Convection, Rotation, and Dynamos. (Eds) R. Pallavacini, G. Micela, S. Sciortinio. ASP Conference Series 198, Astronomical Society of the Pacific, San Francisco 2000, Proceedings of a Conference held at Mondello, Palermo, Italy, 25 - 28 May 1999, 269-272.

Bendo, G.J., R.D. Joseph, M. Wells, P. Gallais, M. Haas, A.M. Heras, U. Klaas, R.J. Laureijs, K. Leech, L. Metcalfe, M. Rowan-Robinson, B. Schulz and C. Telesco: Star Formation in a magnitude-limited sample of spiral galaxies. In: ISO beyond point sources: studies of extended infrared emission. (Eds) R.J. Laureijs, K. Leech, M. Kessler. Conference Series 445, ESA, Noordwijk 2000, Proceedings of a Conference held at Vilspa, September 1999, 143.

Bianchi, S., P.B. Alton and J.I. Davies: ISO observations of spiral galaxies: modelling the FIR emission. In: ISO beyond point sources: studies of extended infrared emission. (Eds) R.J. Laureijs, K. Leech, M. Kessler. Conference Series 445, ESA, Noordwijk 2000, Proceedings of a Conference held at Vilspa, September 1999, 149.

Bianchi, S., J.I. Davies and P.B. Alton: Monte Carlo predictions of Far-Infrared emission from spiral galaxies. Astronomy & Astrophysics 359, 65-81 (2000).

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Bianchi, S., A. Ferrara, L.J. Davies and P.B. Alton: Effects of Clumping on the Observed Properties of Dusty Galaxies. Monthly Notices of the Royal Astronomical Society 311, 601-610 (2000).

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Burkert, A.: The Structure and Evolution of Weakly Self-interacting Cold Dark Matter Halos. The Astrophysical Journal 534, L143-L146 (2000).

Burkert, A. and P. Bodenheimer: Turbulent Molecular Cloud Cores: Rotational Properties. The Astrophysical Journal 543, 822-830 (2000).

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Clemens, D.P., J. Bookbinder, A. Goodman, H. Kristen, P. Myers, P. Padoan, K. Wood, M.H. Heyer, C. Heiles, T.J. Jones, J. Dickey, E. Young, G. Rieke, K. Dow, C.D. Dowell, B. Draine, J. Greaves, U. Klaas, R.J. Laureijs, A. Lazarian, B. Schulz and E. Zweibel: The Milky Way Magnetic Field Mapping Mission: M4. American Astronomical Society Meeting 32, 5208 (2000).

Cretton, N., H.-W. Rix and P.T. de Zeeuw: The Distribution of Stellar Orbits in the Giant Elliptical Galaxcy NGC 2320. The Astrophysical Journal 536, 319-330 (2000).

Davies, R., A. Eckart, W. Hackenberg, T. Ott, A. Wirth, M. Kasper and A. Quirrenbach: The ALFA Laser Guide Star: Operation and Results. Experimental Astronomy 10, 103 (2000).

Davies, R.I., M.E. Kasper, N.A. Thatte, M. Tecza, L.E. Tacconi-Garman, S.W. Anders and T. Herbst: ALFA and 3D: integral field spectroscopy with adaptive optics. In: Adaptive Optical Systems Technology. (Ed.) P.L. Wizinowich. 4007, SPIE, Bellingham, WA. 2000, Proceedings of a Conference held at Munich, March 27 - 29, 2000, 952-961.

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Dehnen, W.: The Effect of the Outer Lindblad Resonance of the Galactic Bar on the Local Stellar Velocity Distribution. The Astronomical Journal 119, 800-812 (2000).

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Dennefeld, M., R. Gredel, A. Pizzella, P. Leisy, A. Budovicova, M. Markoulaki and I. Pascucci: Supernova 2000cw in MCG +5-56-007. IAU Conference Proceedings 7457, 4 (2000).

Dieball and E.K. Grebel: Studies of Binary Star Cluster Candidates in the Bar of the LMC. II. Astronomy & Astrophysics 358, 897-909 (2000).

Dieball, E.K. Grebel and C. Theis: Studies of Binary Star Cluster Candidates in the Bar of the LMC. I. SL 353 & SL 349. Astronomy & Astrophysics 358, 144-153 (2000).

Docobo, J.A., C. Alvarez, J.F. Lahulla, V. Lancharesi and A. Aguirre: CCD measurements of visual double stars from the German-Spanish Astronomical Center at Calar Alto. Astronomische Nachrichten 321, 53 (2000).

Dole, H., R. Gispert, G. Lagache, J.-L. Puget, H. Aussel, F.R. Bouchet, P. Ciliegi, D.L. Clements, C. Cesarsky, F.-X. Désert, D. Elbaz, A. Franceschini, B. Guiderdoni, M. Harwit, R.J. Laureijs, D. Lemke, R.G. McMahon, A.F.M. Moorwood, S. Oliver, W.T. Reach, M. Rowan-Robinson and M. Stickel: FIRBACK Source Counts and Cosmological Implications. In: ISO Surveys of a Dusty Universe. (Eds) D. Lemke, M. Stickel, K. Wilke. Lecture Notes in Physics 548, Springer, Heidelberg 2000, Proceedings of a Conference held at Ringberg Castle, November 1999, 54-61.

Eckart, A., S. Hippler, A. Glindemann, W. Hackenberg, A. Quirrenbach, P. Kalas, M. Kasper, R.I. Davies, T. Ott, S. Rabien, D. Butler, H.C. Holstenberg, D. Looze, R.-R. Rohloff, S.J. Wagner, N. Wilnhammer, D. Hamilton, S.V.W. Beckwith, I. Appenzeller and G. Genzel: ALFA: The MPIA/MPE Laser Guide Star AO System. Experimental Astronomy 10, 1-3 (2000).

Efstathiou, A., S. Oliver, M. Rowan-Robinson, C. Surace, T. Sumner, P. Héraudeau, M.J.D. Linden-VØrnle, D. Rigopoulou, S. Serjeant, R.G. Mann, C.J. Cesarsky, L. Danese, A. Franceschini, R. Genzel, A. Lawrence, D. Lemke, R.G. McMahon, G. Miley, J.-L. Puget and B. Rocca-Volmerange: The European Large Area ISO survey III: 90 µm extragalactic source counts. Monthly Notices of the Royal Astronomical Society 319, 1169-1177 (2000).

Eislöffel, J., R. Mundt, T.P. Ray and L.F. Rodriguez: Collimation and Propagation of Stellar Jets. In: Protostars and Planets IV. (Eds) V. Mannings, A.P. Boss, S. Russel. University of Arizona Press, Tuscon 2000, Proceedings of a Conference held at Santa Barbara, July, 1998, 815-840.

Elsässer, H.: Gefahren aus dem Weltall? Naturwissenschaftliche Rundschau 53, 61-68 (2000).

Evans, N., M. Wilkinson, P. Guhathakurta, E.K. Grebel and S.S. Vogt: Dynamical Mass Estimates for the Halo of M31 from Keck Spectroscopy. The Astrophysical Journal 540, L9-L12 (2000).

Feldt, M., T. Henning and B. Stecklum: Massereiche Sterne - Entstehung und Frühphasen. Sterne und Weltraum 39, 950-955 (2000).

Feldt, M., M.E. Kasper, F. Eisenhauer and S. Hippler: The Impact of Adaptive Optics on Star Formation research. In: SPIE Proceedings 4007. (Ed.) P.L. Wizinowich. Proceedings of a Conference held at Munich, 29-31 March 2000, 847-856 (2000).

Franx, M., A. Moorwood, H. Rix, K. Kuijken, H. Rottgering, P. van der Werf, P. van Dokkum, I. Labbe and G. Rudnick: FIRES at the VLT: the Faint InfraRed Extragalactic Survey. The Messenger 99, 20-22 (2000).

Fried, J.W., B. von Kuhlmann, K. Meisenheimer, H.-W. Rix, C. Wolf, H.H. Hippelein, M. Kümmel, S. Phleps, H.-J. Röser, I. Thierring and C. Maier: The Luminosity Function Of Field Galaxies And Its Evolution Since z=1. Astronomy & Astrophysics 367, 788-800 (2000).

Gabriel, C. and J.A. Acosta-Pulido: Deglitching Methods by the ISOPHOT Interactive Analysis. Experimental Astronomy 10, 319-331 (2000).

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