Max-Planck-Institut
für
Astrophysik

Annual Report 1999

Front cover: Numerical simulation of radiatively inefficient accretion ('ADAF') onto a black hole. Convective instabilities cause strong time-dependence, a possible cause for the variability seen in black hole X-ray sources (see contribution 'Comptonization, noise and reflection in black hole binaries' on p. 14). Colors scale: brightness indicates gas density, color shows entropy variations (blue=hotter, red=cooler). (P. Armitage)
back cover: Distribution of nickel, silicon and oxygen in an exploding massive star 1170 seconds after the neutron star has formed at the center. The region shown has a diameter of 4.4 million kilometers. Hydrodynamic instabilities have produced inhomogeneities in the expanding ejecta. Clumpy structures and long, extended filaments are rich in freshly created radioactive nickel (red and pink), silicon (green, light blue and whitish), and oxygen (deep blue) (Kifonidis, Plewa, Janka, Müller, see contribution 'Radioactive elements from supernovae' on p. 22).

Contents

1 General Information

1.1 A brief overview of the MPA

The Max-Planck-Institut für Astrophysik, usually called the MPA for short, is one of more than 70 autonomous research institutes within the Max-Planck Society. These institutes are primarily devoted to fundamental research. Most of them carry out work in several distinct areas, each led by a senior scientist who is a "Scientific Member" of the Max-Planck Society. The MPA was founded in 1958 under the direction of Ludwig Biermann. It was an offshoot of the MPI für Physik which at that time had just moved from Göttingen to Munich. In 1979 the headquarters of the European Southern Observatory (ESO) came to Munich from Geneva, and as part of the resulting reorganisation the MPA (then under its second director, Rudolf Kippenhahn) moved to a new site in Garching, just north of the Munich city limits. The new building lies in a research park barely 50 metres from ESO headquarters and is physically connected to the buildings which house the MPI für Extraterrestrische Physik (the "MPE"). This park also contains two other large research institutes, the MPI für Plasmaphysik and the MPI für Quantenoptik, as well as many of the scientific and engineering departments of the Technische Universität München (the "TUM"). In 1996 the institute's management structure was altered to replace the third director, Simon White, by a board of directors, currently Wolfgang Hillebrandt, Rashid Sunyaev and Simon White. Simon White acted as Managing Director until the end of 1999.

Research at MPA is devoted to a broad range of topics in theoretical astrophysics. Major concentrations of interest lie in the areas of stellar evolution, stellar atmospheres, nuclear astrophysics, supernova physics, astrophysical fluid dynamics, high energy astrophysics, radiative processes, structure, formation and evolution, gravitational lensing, the large-scale structure of galaxies of the Universe, particle astrophysics and cosmology. For many years the MPA had a strong group in General Relativity, but in mid-1995 most of this group moved to the newly founded MPI für Gravitationsphysik in Potsdam near Berlin.

Their departure allowed a consolidation of MPA activities in extragalactic astrophysics, as well as an expansion in a new area, high energy astrophysics.

Another new area for MPA is its involvement in ESA's Planck Surveyor project. The Planck satellite will be launched in early 2007 to produce highly sensitive, well resolved maps of the full microwave sky. MPA is contributing to Planck-related software development and will prepare all final data products of the mission for public release.

While most MPA research addresses theoretical issues, the neighbouring institutes provide complementary expertise and there are many collaborative projects with them. Major research programmes at MPE are concerned with instrumental and observational aspects of infrared, X-ray and gamma-ray astronomy, together with supporting theoretical work, while ESO carries out a broad range of instrumental and observational projects in the optical and infrared and is currently commissioning the VLT, the largest optical telescope in the world.

At any given time the MPA has about 30 scientists working on long-term positions at postdoctoral level and above, up to 10 foreign visitors brought in for periods of varying length under a vigorous visitor programme, and about 20 graduate students. The students are almost all enrolled for degrees in one of the two large universities in Munich, the TUM and the Ludwig-Maximilians-Universität (LMU). A number of the senior staff at MPA have teaching affiliations with one or other of these universities. Ties with the Institute of Astronomy and the Observatory of the LMU are particularly close because the observatory director (Rolf-Peter Kudritzki) is also a Scientific Member of the MPA.

Since 1996 the MPA is part of EARA, a European Association for Research in Astronomy which links it to the Institut d'Astrophysique de Paris, the Leiden Observatory, the Institute of Astronomy, Cambridge, and the Instituto Astrofisico de Canarias in a programme dedicated to fostering inter-European research collaborations. Such collaborations are also supported by membership in a number of EC-funded networks, two of which are coordinated from the MPA. Interaction with local institutions is enhanced by a Special Research Area funded by the German Research Foundation in the field of astroparticle physics. Other participants in this programme include the physics departments of the two universities, the observatory of the LMU, and the MPI für Physik.

1.2 Current MPA facilities

The MPA building itself is a major asset for its research activities. It was specially designed by the same architect as ESO headquarters, and the two buildings are generally considered as important and highly original examples of the architecture of their period. Although the unconventional geometry of the MPA can easily confuse first-time visitors, its open and centrally focussed plan is very effective at encouraging interaction between scientists and makes for a pleasant and stimulating research environment. Part of the ground floor and most of the basement of the building is currently occupied by the infrared group of the MPE, and this proximity significantly enhances the possibilities for interaction with this large and active observational/instrumental group.

The MPA and the MPE share a large and fully stocked astronomical library which is housed in the MPA building. It holds at present about 16000 books and conference proceedings and all major astronomical books and periodicals are available. The library staff can also provide access to a variety of on-line archives and are currently extending this capability. Further library material is available at ESO which in addition maintains a complete collection of optical sky maps and photographic sky surveys. Other large data analysis facilities are available at the MPE which is the European data centre for the ROSAT satellite and is providing a data centre for the ISO satellite mission.

The MPA has always placed considerable emphasis on computational astrophysics and has therefore ensured access to forefront computing facilities. The current in-house system is based on a central cluster of about 10 IBM RS6000 workstations, with additional Sun and SGI graphics workstations for data anlaysis and graphics applications. Users have free access to all workstations and are in general connected via large-screen X-window terminals or desktop workstations. For larger computing tasks MPA scientists use the facilities of the central computing centre of the Max-Planck Society (known as the RZG). This is part of the MPI für Plasmaphysik and is located a few hundred metres from the MPA. Current facilities at the RZG include a 784-processor CRAY T3E, an 18-processor IBM SP2, a 3-processor NEC SX-5, a large cluster of high-end workstations and a Terabyte mass storage system. MPA scientists have access to the RZG and are among the top users of the facilities there. An AFS file system ensures that the transfer of data among the MPA machines and from MPA to the RZG is now almost transparent to the user. Further computing power is available at a second Max-Planck Society computer centre which is operated jointly with the University of Göttingen, and provides additional access to large parallel machines.

1.3 1999 at the MPA

This year was one of consolidation and broadening of the initiatives started at MPA over the last few years. Work continued on MPA's contribution to the ESA Planck Surveyor mission. MPA's contribution to the software environment for the Planck project was developed further. The prototype software is being used to run an automated data-simulation pipeline, which was constructed and assembled under MPA coordination on dedicated MPA workstations. The next few years will see further expansion of these efforts, as well as the definition of MPA's specific responsibilities for science exploitation within the Planck Consortia.

As in every year since 1997, the MPA invited a world-class theoretical astrophysicist to give three talks over a one month period on a subject of his or her choice. This set of prize lectures, known as the Biermann Lectures, were given in 1999 by Robert Williams of the Space Telescope Science Institute. The subject of his lectures was "Galaxies in the Past; Nebulae for the Future" and touched the Hubble Deep Fields as well as the modeling of diffuse emission regions and the problems with abundance determinations in planetary nebulae. All lectures were very well attended and demonstrated the limitations of MPA's lecture theater once again. Needless to say, Bob stimulated lots of discussions which were ongoing even after he left the institute in August.

Several workshops and conferences were organized by MPA scientists in 1999, including a MPA/ESO Conference on "The First Stars" which took place in Garching in August, the second meeting of the German-American Academic Council Young Scholars Institute "Astroparticle Physics" at the Ringberg Castle and at Garching in September, a meeting of the TMR network on gravitational lensing in August, and a workshop on level-set methods in computational fluid dynamics in April, both hosted again in the MPA building.

MPA's national and international cooperations and collaborations flourished also in 1999. A major initiative designed to further enhance the visibility of astronomy in Garching/Munich and to increase collaboration between the different institutions is a proposal to create a Max-Planck International Research School in Astrophysics at the Ludwig-Maximilians-University in which the MPA will take an active part. A decision of the funding agencies is expected in May of 2000.

In January the Instituto Astrophysico de Canaris (IAC) signed a Memorandum of Understanding to join as the fifth member EARA, the European Association for Research in Astronomy, created in 1992 on the initiative by the French CNRS to set up Associated European Laboratories and to provide the formal structure which regulates international cooperation between institutions with compatible scientific programmes and complementary expertise. The other members are (besides MPA) the Institut d'Astrophysique de Paris (IAP), the Leiden Observatory, and the Institute of Astronomy in Cambridge (IoA).

Four new proposals involving MPA, submitted to the EC under the Fith Framework Plan, have been successful. Two of these are for scientific networks similar to the three TMR networks already in operation, but on different topics, namely "The Intergalactic Medium" and "The Cosmic Microwave Background". They will provide further doctoral and postdoctoral positions. A third new network will provide 72 months of support over a four year period to each EARA institute to act as a "training site" for doctoral students. This money will be used to support visits of up to one year by PhD students working in any (non-German) EU laboratory. The fourth network, OPTICON, creates a forum for discussion and strategic planning of the development of European resources in optical and infrared astronomy. The MPA and the MPI für Astronomie in Heidelberg are the German members of this grouping which involves major observatory operators such as ESO, PPARC, the CNRS, and the IAC in addition to purely research-oriented institutions.

In 1999, the idea to establish a Max-Planck Cosmology Group at the Shanghai Observatory in China was finally realised. The group leader will be Yipeng Jing who spent three years as a postdoc at MPA before taking up his current post in Tokyo. He will move to Shanghai in mid-2000 and has already begun recruiting other young researchers and graduate students. The final group will number 8 to 10 researchers. They will be visiting the MPA frequently in the future, and a number of MPA cosmologists will also be making extended visits to Shanghai to interact with them and with the rest of the observatory.

Demand for public relations work increased dramatically this year because of the solar eclipse. Garching was located only a few kilometers south of the center of totality. During the week of the eclipse, MPA was visited by groups from Denmark, the Netherlands and Germany, who were eager to learn about the institute and its research. On August 11, around the time of totality, a delegation of 20 U.S. Congress Members, Navy Escorts and staff aides, accompanied by the Acting Consul General, Mr. Ted Tanoue, arrived at MPA to join more than two hundred other guests in viewing this astronomical highlight of the year. A cocktail and lecture presentation was provided for the Congressional delegation. Unfortunately, heavy rainfall set in about 15 minutes before totality, and the dark clouds did not clear until five minutes thereafter. Nevertheless, our guests enjoyed impressive views of partial obscuration and the strange darkening at noon. Many of them bought T-

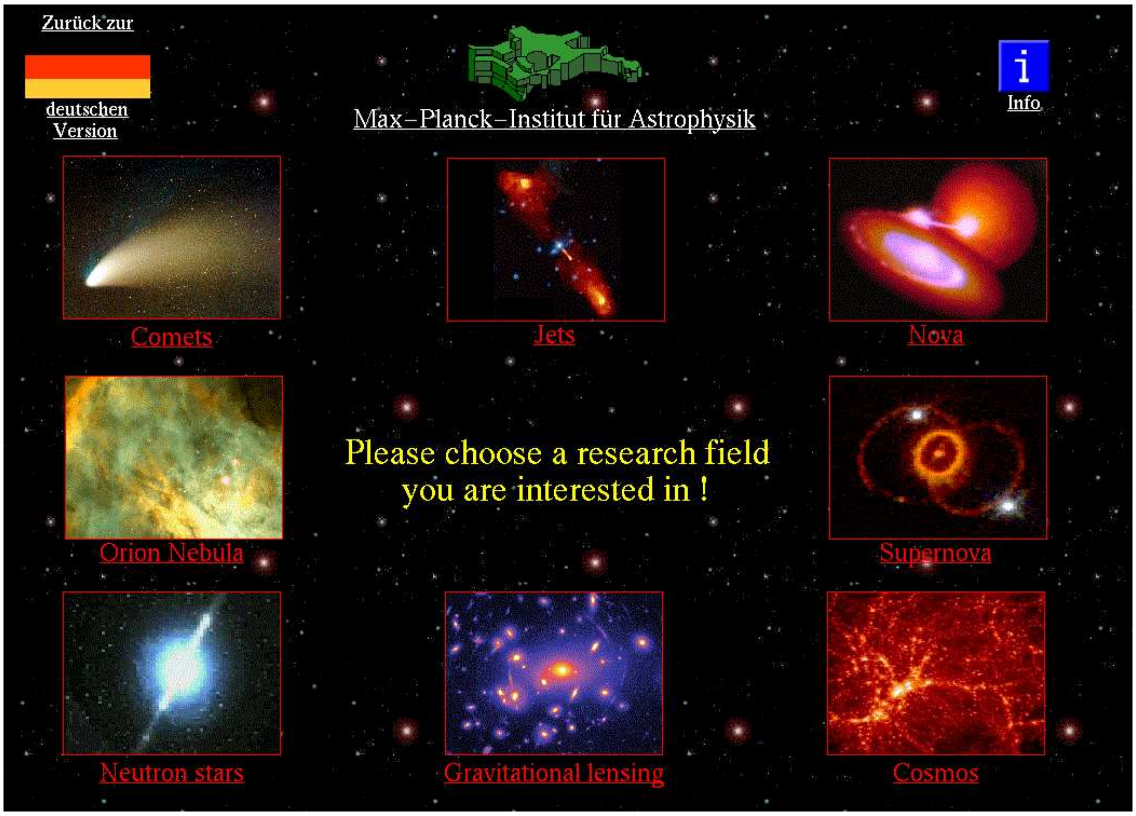

Figure 1.1: The surface page of the multi-media computer presentation of MPA research.

shirts with the MPA logo and a special eclipse design and stayed for the rest of the afternoon for beer and a barbecue.

An ambitious public relation project started this year was the development of a multi-media computer presentation of MPA research highlights.

This project was initiated as a result of a request by the Munich Deutsches Museum to local institutes for contributions to the astronomy exhibition. The MPA scientists wanted their presentation to be interactive and to be technologically advanced. It was therefore decided that computer visualization and animation would be key elements of the presentation. This appeared to be the ideal way of explaining exciting new observations from a new generation of ground and space-based observatories as well as presenting the most recent computer simulations carried out at the MPA.

The hurdles for starting up such a project were high. Not only did it mean an extra work load and investment of time, but because of lack of expertise and of professional guidance, the development of software tools proceeded initially by trial and error. With growing experience, however, the project gained more and more momentum. Following early successes, a larger number of people became motivated to join the effort. Eventually, a group of more than a dozen MPA scientists, post-docs, and PhD students, assisted by several undergraduate students, worked very hard and enthusiastically to realize the final product.

The presentation is now available in a preliminary final version. It includes input from eight science projects which are explained in audio-visual sequences of 3–6 minutes duration. Examples include how comets interact with the solar wind, how stars are born and die, how gravity bends light from distant galaxies and how tiny fluctuations in the infant Universe have grown into the galaxies and galaxy clusters we observe today. The movie allows viewers to choose between English and German dialogue. Information about the MPA is also provided (Fig. 1.1). The movies are supplemented with glossaries where important terms are explained and the spoken text is also provided in written form.

The presentation has been handed to the Deutsche Museum together with a computer workstation. It has been installed as a permanent exhibit in a prominent location in the astronomy section. The movies were also on display at MPA during the week of the solar eclipse and during the Open Day. Many visitors were delighted at the opportunity to "surf in the Universe". The presentation was also available at the Millenium Exhibition at the Technical University Munich in November 1999 and at a big astronomy exhibition in Berlin in January 2000. The latter is part of the "Jahr der Physik", proclaimed for the year 2000 by the German Ministry of Education and Research together with the German Physical Society. In addition, a memory-reduced version of the presentation is being made available to libraries, planetaria, school classes and interested individuals. Planning is underway to update and extend the material.

In August 2000 the new building of the MPI für extraterrestrische Physik will be completed. This will improve the office and laboratory situation of both institutes and allow MPA to adjust to its growing space needs, which result from the expanding activities we have witnessed during the last few years. In particular, the PLANCK project will be accommodated properly, and computer installations and the library will receive much-needed additional space. In-house constructions and moving will begin at the end of 2000 and extend into the following year and will include a completely new local computer network reaching from central switches into offices.

1.4 How to reach us

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  (initial + last name
  will reach most people,
  e.g. swhite for Simon White.)

  World Wide Web:
  http://www.mpa-garching.mpg.de

  anonymous ftp:
  ftp.mpa-garching.mpg.de

- MPA (reference) library:

  phone: +49-89-3299-3305/6
  FAX: +49-89-3299-3235
  email: lib@mpa-garching.mpg.de
  URL: http://www.mpa-garching.mpg.de/libris.html
  homepage: only local access

2 Scientific Highlights

2.1 Detection of a 'dark' mass clump

The deflection of light bundles from distant sources by the gravitational field of intervening mass inhomogeneities not only leads to a shift of the observed position of a source, but also distorts the shape of the images. This so-called shear transforms, to first order, a circular source into an elliptical image.

One can make use of the fact that the sky is densely covered with faint galaxies; deep optical images routinely yield a number density of galaxies of about 30 per square arc-minute. If these galaxies were intrinsically circular, then each image would allow us to estimate the local gravitational field of the deflecting mass distribution. However, since galaxies have an intrinsic ellipticity, one single image does not carry much information about the lensing potential. But if one assumes that the intrinsic orientations of galaxies are random, one can obtain an estimate of the shear by statistical methods.

As an example, consider a cluster of galaxies. The shear around this cluster leads to a preferential alignment of galaxy images in the direction tangent to the cluster center. The most extreme and beautiful example of this effect is the occurrence of giant luminous arcs, banana-shaped images of background galaxies. For larger distances from the center of the cluster image, the distortion becomes weaker and is less spectacular; nevertheless, by averaging over many galaxy images, this tangential alignment can be measured out to quite large distances. This weak lensing effect can be used to study the radial density profile of clusters, and has already been applied to about a dozen clusters.

The effect can also be turned around: Instead of measuring the shear around the positions of known clusters, one might try to search for points in the sky around which there is a statistically significant tangential alignment of distant background galaxy images. With this method, one would be able to define a sample of mass concentrations but without relying on the usual criteria for identifying clusters of galaxies, namely an over-density of galaxies or X-ray emission from a hot intra-cluster gas. The main interest in such a lensing-based cluster search is that the resulting cluster sample can be compared directly with cosmological models for the cluster abundance, without the need to predict the luminous properties of their member galaxies and/or the density and temperature of the intra-cluster gas, which are far more difficult to model. Since clusters provide one of the most important targets for observational cosmology, a light-independent search method for clusters would be of great value.

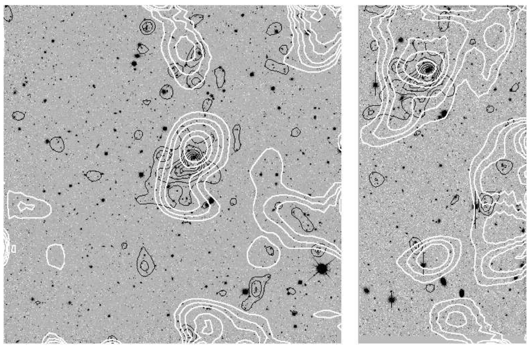

Figure 2.1: Reconstructed surface mass density contours, plotted on deep V-band (left panel, field size $14' \times 14'$) and I-band (right panel, field size $7.5' \times 15'$) image. The cluster Abell 1942 at redshift $z = 0.22$ is located in the center of the V-band, and close to the upper edge of the I-band image. About $7'$ to the South, a second mass concentration is seen, which, in various statistical tests, turns out to be about as significantly detected as the cluster itself. No over-density of galaxies is seen to be associated with this mass concentration.

In a project involving scientists at MPA and the IAP in Paris the mass distribution of the cluster Abell 1942 was studied. The weak lens-

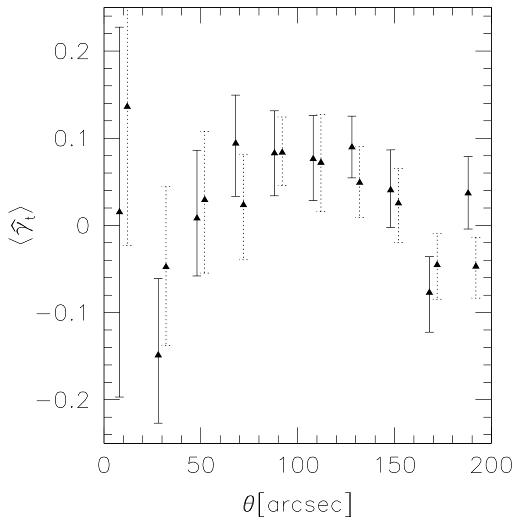

Figure 2.2: Binned in annuli of 20 arc-seconds width, the average tangential component of the image ellipticity is plotted as a function of angular separation from the clump center. The two different kinds of points and error bars correspond to the two independent data sets. One sees a smooth shear signal extending over a large range in angular separation, and the signals from both images are seen to be compatible.

ing effect of the cluster was detected as a very strong signal. In addition, about seven arcminutes to its South, another mass concentration showed up, with about the same statistical significance. However, no apparent over-density of galaxies signifying a cluster was seen there. For lack of a better name, we termed this a 'dark clump'. This finding needed to be verified by independent means, in particular since the dark clump was right on the edge of our data field. A second independent data set was obtained, using a different camera and a different wave-band for the observations. From both images, reconstructions of the projected mass density were obtained (Fig. 2.1). Not only is the cluster A1942 clearly detected in both images, but also the dark clump appears, and for the second image it is not near the boundary of the data field.

Using a specific measure for the tangential alignment of background galaxy images, we have quantified the statistical significance of the detection of the dark clump. This can be done by turning the orientations of all galaxies by a random angle and determining the tangential alignment from this randomized distribution. Repeating this process, one can determine how probable the occurrence of the measured alignment is from randomly oriented galaxy images. We found that one needs a million randomizations to find at least one case of alignment as strong as measured from the real data. For the second, independent data set, the probability for a random alignment was slightly larger. It was also checked whether this alignment signal was due to a few galaxy images for which the intrinsic orientation happens to conspire to generate a spurious alignment signal. This was done by plotting the tangential alignment as a function of separation from the center of the dark clump, as shown in Fig. 2.2. From this one sees that both data sets yield a tangential alignment which varies smoothly as a function of distance from the center. Therefore, we conclude to have found a mass concentration based solely on the lensing method.

The interpretation of the dark clump is not clear yet. Whereas a weak X-ray source has been identified close to it, its position differs from the clump position by more than the respective positional uncertainties, and it may therefore be an unrelated source. The dark clump may be a intermediate-redshift cluster with at normally high mass-to-light ratio, or a high-redshift cluster of very large mass. In order to distinguish between the various possibilities, further observations will be conducted. A deep infrared image of the clump should reveal an over-density of galaxies if it is a high-redshift cluster. Future, more sensitive X-ray images should reveal hot baryonic gas situated inside the potential well of the dark clump. If the nature of the dark clump can be determined, this finding would represent the first mass-selected cluster and thereby would open up a new census method for these cosmologically interesting objects. (Peter Schneider)

2.2 Debris from a shattered galaxy discovered in the Sun's backyard

Nearby relics of a long-dead galaxy have been unearthed by an MPA/Leiden Observatory collaboration using data from the European Space Agency's Hipparcos Satellite.

The comet debris which apparently killed off the dinosaurs survives as a thin layer of iridium-rich dust covering their fossilised bones. In the same way, debris from a dwarf galaxy destroyed by a collision with our own Galaxy can survive as relic streams of stars wrapping around the Milky Way. What should such streams look like and how can they be detected? Computer simulations of galaxy collisions offer some answers. Work by Amina Helmi (Leiden) and Simon White (MPA) showed that even galaxies destroyed during the Milky Way's infancy should still be detectable as ghostly sheets of stars moving on near-parallel orbits (see Figures 2.3 and 2.4). Encouraged by these results they began to search for real relic streams and found two in the Sun's vicinity which appear to be debris from a single dwarf galaxy torn to shreds by the Milky Way's gravity about 10 billion years ago.

Between 1989 and 1993 the European Space Agency's Hipparcos satellite measured the positions, distances and motions of hundreds of thousands of stars. The resulting catalogues, published in 1997, provide a unique opportunity to search for stellar streams. By sifting carefully through these catalogues it was possible to make a nearly complete census of weak-lined giant stars within a few thousand light years of the Sun. (For comparison, our Milky Way galaxy as a whole is about 50,000 light years across.) Earlier observations from the ground had shown that such giants typically contain less than a thirtieth as much iron and magnesium as the Sun, a sure sign that they are among the oldest stars in the Milky Way. These ground-based observations also measured how fast each star moves away from the Sun. Hipparcos, on the other hand, measured changes in the apparent direction of each star, thus establishing how fast it moves across the line-of-sight. Combining these data determines the direction of motion and the speed of a few hundred nearby old giants.

Analysing these observations, the Leiden-Garching team was struck by the fact that while most stars move in apparently random directions, two small sets of stars seem to be moving together. One set of nine stars pursues near-parallel orbits which cross the Milky Way's disk at high speed from North to South; a second set of three stars pursues orbits which cross the disk at the same speed and angle, but from South to North (see Figure 2.4). In both cases the direction and speed of the motion is well separated from those of the other nearby giants. Comparing with their published computer simulations, the team concluded that each set of stars is part of a debris stream, and that both streams come from a single dwarf galaxy which was torn apart by the Milky Way's gravity during or very soon after the Milky Way's own formation. The characteristics implied for this dwarf make it very similar to other small galaxies which still sur-

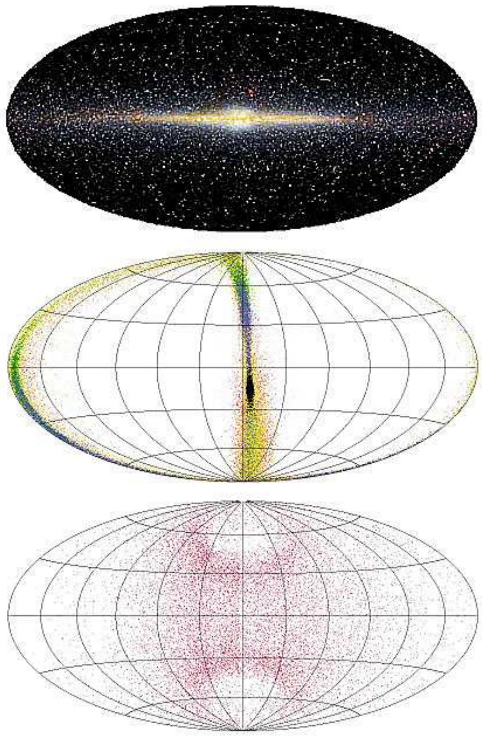

Figure 2.3: The top picture shows an image of the real sky made by the DIRBE instrument on NASA's Cosmic Background Explorer satellite COBE. At the wavelengths chosen to make this picture our own Galaxy, the Milky Way, shows up beautifully and looks very much like a distant galaxy seen edge-on. The middle picture shows the same map projection for a computer simulation of the disruption of a dwarf galaxy set up to resemble the recently discovered disrupting dwarf in Sagittarius. Stars from the dwarf galaxy are seen all around the sky but are confined to a narrow band near the galaxy's orbit. The black region shows the remaining body of the dwarf, while other colours differentiate debris streams torn off the dwarf during different passages near the Galactic Centre. Finally, the bottom picture shows a computer simulation of the debris from a dwarf that was destroyed during the Milky Way's infancy. This simulation was designed to produce streams similar to those discovered by the MPA-Leiden team. Stars are seen all over the sky with no remaining sharp features. The structure of the system only becomes clear when the motions and distances of the stars are measured. They all lie on sheets wrapped many times around the Milky Way, with the stars near any particular point on a sheet all moving on nearly parallel orbits.

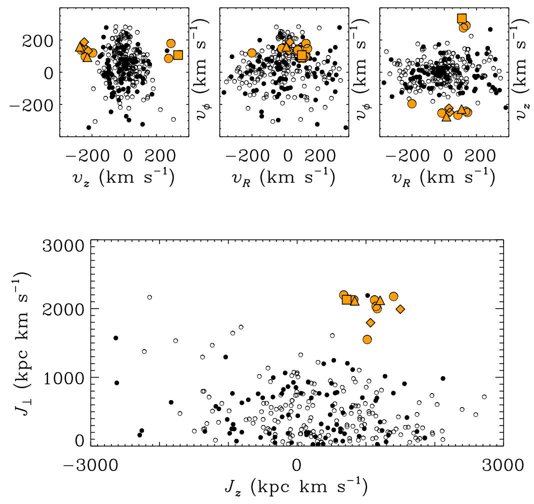

Figure 2.4: The velocity distribution of nearby halo giants with space motions measured by Hipparcos. Three orthogonal projections of velocity space are shown in the top plots, while the lower plot shows the distribution of stars in the space of their specific angular momentum about the Galactic rotation axis and orthogonal to this direction. The stars in the two debris streams are indicated by the larger grey symbols. Notice that the two streams superpose in angular momentum space, suggesting a common origin.

vive in the outskirts of the Milky Way system, as well as to the recently discovered Sagittarius Dwarf Galaxy which is just now being shredded by the Milky Way (Fig. 2.3). The stars in each set are distributed all over the sky, even though they move in parallel, showing that the Sun is actually sitting inside the two streams of debris.

The deeper significance of this discovery may lie in its implications for the Milky Way's formation. Our Galaxy has two major components. One is a highly flattened disk in which gas and stars circle the Galactic centre rather as the planets circle the Sun. The other is almost spherical and consists purely of old stars moving in near-random directions like bees in a swarm. The giants in the Hipparcos sample are nearby members of this second population. Most astronomers agree that the disk grew slowly as gas settled onto circular orbits and turned into stars. There is no consensus, however, about how the older component was assembled. Yesterday's wisdom, that it formed by the rapid collapse of a single massive gas cloud, is disputed by recent theories which suggest that it grew through the amalgamation of pre-existing smaller galaxies. In recent years galaxies have been discovered at such enormous distances that they are seen, not as they would be today, but as they were when they were young. These distant galaxies are indeed much smaller than older and nearer systems. They could, perhaps, be the building blocks of the near-spherical component of the Milky Way. The ghostly streams discovered by the MPA-Leiden team may be the first fossil evidence showing directly that our own Galaxy was put together from such pieces. (Simon White, Amina Helmi)

2.3 The thermal evolution of the intergalactic medium

Quasars are extremely luminous sources which can be seen out to the most distant regions of the universe. As the quasar light travels to us, it is partly absorbed by the gas along the line of sight. Thus every quasar spectrum is a one-dimensional map of the matter distribution along that line of sight. Most of the absorption occurs in regions close to the mean density, although occasionally the line of sight will intersect a forming galaxy, thereby locally producing stronger absorption. From a careful study of this absorption, we have deduced how the temperature of the universe has changed with time.

The absorption is produced by neutral hydrogen in the form of a very characteristic resonance absorption line, the $1 \rightarrow 2$ Lyman-α transition. The expansion of the universe has shifted the absorption wavelength $\lambda_0 = 1215.67$Å, as measured in the laboratory, to a longer wavelength $\lambda = \lambda_0\,(1+z)$, where the redshift $z > 0$ characterises the cosmological distance between us and the patch of neutral hydrogen. ($z = 0$ corresponds to the local universe, high values of z to regions far away.) All patches of neutral hydrogen combined then produce very many (several hundred) absorption lines in the quasar's spectrum. This part of the spectrum is usually referred to as the Lyman-α *forest*. (Because the many absorption lines make the spectrum look like the outline of trees in a forest.)

The properties of the absorption lines can be used to infer the temperature of the absorbing gas: if the gas is hotter, then the lines become wider. However, numerical simulations are needed to calibrate the relation between linewidth and gas temperature, because the expansion of the universe also broadens the lines. Therefore, an accurate temperature determination needs a careful comparison of quasar spectra computed from simulations of the intergalactic medium with observed quasar spectra.

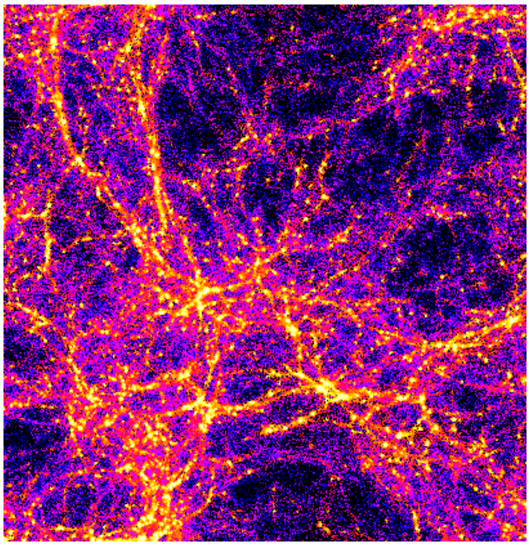

Figure 2.5: Density distribution in a box of size 1Mpc at a redshift of $z = 5$. Dark regions correspond to low densities, yellow to high densities. The distribution has a very filmentary appearance, with high density haloes, corresponding to forming galaxies, at the intersection of filaments.

We have performed several very high resolution simulations of the intergalactic medium (IGM). An example is shown in Fig. 2.5, which shows the density distribution in a periodic volume of space, colour coded according to gas density. The mass distribution has a very structured appearance, with filaments delineating almost spherical low-density 'voids' (dark in Fig. 2.5), and high density haloes (bright yellow) at the intersection of filaments. Though actual galaxy formation is not part of the simulations, in the real universe they presumably form at such intersections.

From these simulation results, we have computed mock quasar spectra, compared these with the best available observed spectra, and from this determined the temperature of the absorbing gas to an accuracy of ~ 10 per cent. The result is shown in Fig. 2.6. The temperature of the IGM decreases but then suddenly rises at a redshift ~ 3, after which it drops again.

The thermal evolution expected on theoretical grounds is shown as the solid line in Fig. 2.6. The temperature is expected to be a balance be-

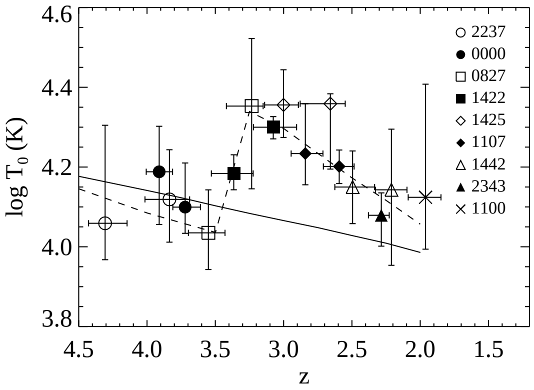

Figure 2.6: Evolution of the temperature of the intergalactic medium as a function of redshift, as determined from 9 high-resolution quasar spectra. Horizontal error bars indicate the redshift range spanned by the quasar's Lyman-α forest, vertical error bars are 1σ errors. Different symbols correspond to different quasars, labelled in the legend.

tween adiabatic cooling, due to the expansion of the universe, and photo-heating, due to sources (hot stars and quasars) of ultra-violet light. After an increase in temperature at high redshifts ~ 6, the temperature is expected to drop gradually due to adiabatic cooling. Clearly, there is a large discrepancy between this theoretical expectation and the measured evolution, which shows a large increase in T_0 at a redshift $z \sim 3$. The most straightforward interpretation is that Helium reionisation due to quasars is responsible for the temperature increase. This would fit in with other indications that the spectrum of ionising radiation changes around that redshift. At higher redshifts, $z \geq 4$, the temperature is still rather high, which may give us clues about when Hydrogen was reionised. (Tom Theuns)

2.4 A unified model for the evolution of galaxies and AGN

It has recently become clear that supermassive black holes weighing up to a billion solar masses are found in the central regions of almost all galaxies and have probably played a major role in their formation and evolution. When supermassive black holes accrete material, a substantial fraction of the binding energy of the infalling matter can be radiated away. The nucleus of the

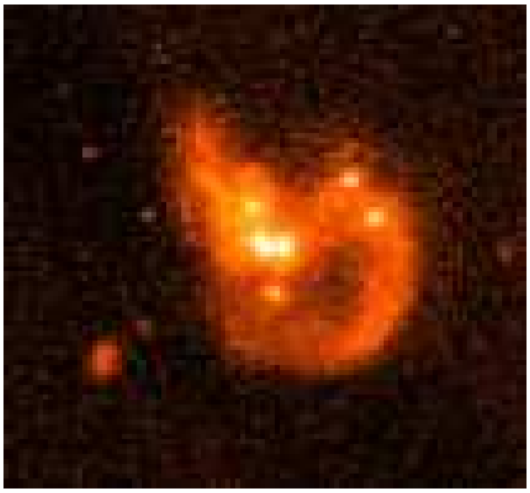

Figure 2.7: A spectacular multiple merger of galaxies observed with the NICMOS camera on board the Hubble space telescope by Borne et al.

galaxy increases enormously in luminosity and becomes visible as a so-called AGN, or active galactic nucleus.

Much of our knowledge about how supermassive black holes have evolved over cosmic timescales comes from studying the AGN population at different epochs (time since the formation of the universe). The space density of bright QSO's which are the dominant class of AGN, exhibits a rapid rise and fall with a conspicuous peak at a redshift of around 2, when the Universe was approximately a fifth of its present age. It is tantalizing that the peak of AGN activity coincides with the time at which most of the stars in the Universe were being formed in galaxies.

Another important piece of evidence linking the growth of supermassive black holes to the formation of galaxies is the discovery of a linear correlation between the masses of these black holes and the masses of the galactic bulges that harbour them. On average about 0.3 percent of the mass of the bulge is contained in the central black hole. This suggests that the formation of stars in bulges and the assembly of supermassive black holes at their centres are closely linked. So what is the physical mechanism responsible both for bulge formation and the growth of black holes? Many astronomers now believe that mergers between galaxies are the prime suspect.

According to the standard theoretical paradigm for the formation of structure in the Universe, small density inhomogeneities in the dark matter were generated shortly after the Big Bang by quantum fluctuations during a period of accelerated expansion, usually termed inflation. These early inhomogeneities were then gravitationally amplified as the Universe expanded. Eventually, material contained in initially overdense regions of the Universe stopped expanding and began to collapse. The smallest objects formed first in this way, and these later merged together to form larger and larger structures. Galaxies formed in regions where the overdensity of matter was high enough to allow gas to cool, condense and form stars.

This scenario is often referred to as the "bottom-up" or hierarchical model of structure formation. Detailed numerical simulations of the merger of two spiral galaxies of equal mass show that the remnant galaxy left after the merger is completed is structurally very similar to observed galactic bulges. During the merging process, tidal forces drive most of the gas in the galaxies to the centre of the remnant, where it is compressed and able to form stars and possibly even fuel a central supermassive black hole. Figure 2.7 shows a spectacular multiple merger in the real Universe, imaged by the NICMOS instrument on board the Hubble space telescope. Many such merging galaxies have star formation rates of a few hundred solar masses per year and some show evidence of an active galactic nucleus, suggesting that the merger has triggered

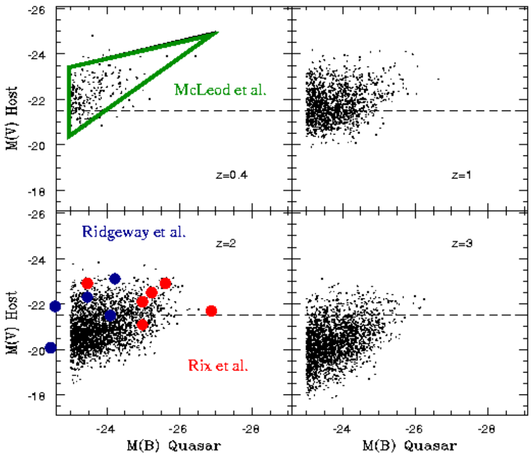

Figure 2.8: The brightness of galaxies harbouring AGN against the brightness of the AGN predicted by the models at four different redshifts. Some recent observational results are shown in colour.

the accretion of new material onto the central black hole.

This year MPA scientists developed a "unified" model for galaxy and AGN evolution that synthesized many of the ideas outlined above. These models track the formation and evolution of structure in the dark matter component of the Universe from standard cosmological initial conditions, as well as the formation and merging of galaxies within the potential wells defined by the dark matter. These models have already met with substantial success in explaining many of the observed properties of galaxies both at the present day and at high redshifts.

The main new ingredient was the hypothesis that supermassive black holes grew in mass during the same major merging events that produced galactic bulges. The MPA researchers demonstrated that the new unified models could not only explain many aspects of galaxy evolution, such as the evolution of the total star formation in galaxies as a function of cosmic epoch, but also the strong rise and fall in the space density of AGN.

Perhaps most interestingly, the models made a number of new and observationally testable predictions for the relation between the masses of supermassive black holes and the properties of their galactic hosts, as well as the relation between AGN luminosity and bulge luminosity at different cosmic epochs. Because massive galaxies assemble relatively late in hierarchical cosmogonies, quasars of fixed luminosity were predicted to reside in less massive host galaxies at higher redshifts. In addition, younger galaxies were predicted to contain lower mass black holes in their centres than older galaxies. The first prediction has already been confirmed by a number of recent observations (see Fig. 2.8). There has also been some suggestive evidence that black hole mass may indeed correlate with the age of the host galaxy. Future studies will no doubt shed further light on this issue. (Guinevere Kauffmann, Martin Haehnelt)

2.5 Comptonization, noise and reflection in black hole binaries

Black holes, when accreting matter from a companion star, are among the most luminous X–ray objects in our Galaxy. Due to the high angular momentum of the accreting matter it does not fall directly onto the black hole, but rather forms an accretion disk. Most of the gravitation energy is released close to the black hole before the accreting matter finally plunges into it. Sometimes the X–ray spectra of black holes are very soft, with most of the luminosity coming from photons with energy ~ 1 keV, while on other occasions the same source may produce very hard spectra, with luminosities peaking at photon energies of $\sim$100 keV. This bimodality is believed to be related to very different regimes of the accretion flow in the vicinity of the black hole. In one regime the accreting matter is very dense and cools efficiently by radiation, down to temperatures below $\sim$1 keV. In the other regime the matter is so rarefied that radiative cooling is not efficient, and the matter heats up to temperatures of tens to hundreds of keV. Low frequency photons in such a hot and rarefied medium can efficiently gain energy due to multiple scatterings on the hot electrons. This process is known as Comptonization. A generic prediction of the Comptonization theory is an approximate power law shape of the X-ray spectrum with an exponential cut-off at high energies. Such spectra are indeed observed from many black hole binaries. There are, however, subtle departures from a simple power law. These departures suggest that a fraction of the hard X–ray radiation is intercepted and reflected by nearby dense and relatively cold matter. Another remarkable feature of the X–ray emission from black holes is its strong and chaotic variability on time scales from milliseconds up to hundreds and thousands of seconds. It is likely that this aperiodic variability is due to instabilities in the accretion flow, which modulate the X–ray flux seen by the observer. (For a numerical simulation of such an accretion flow see the front cover.)

The whole picture is rather complex and raises many questions for which there are good guesses but no real answers. In particular it is not clear what is the source of the low energy photons for Comptonization or what is the nature of the dense and cold matter which intercepts and reflects the hard X–rays. The unprecedented effective area and timing capabilities of the Rossi X–Ray Timing Explorer satellite (RXTE) can be used to address these questions. In particular one can look for a correlation between various observable characteristics of the X–ray emission from black hole candidates, in order to establish physical connections

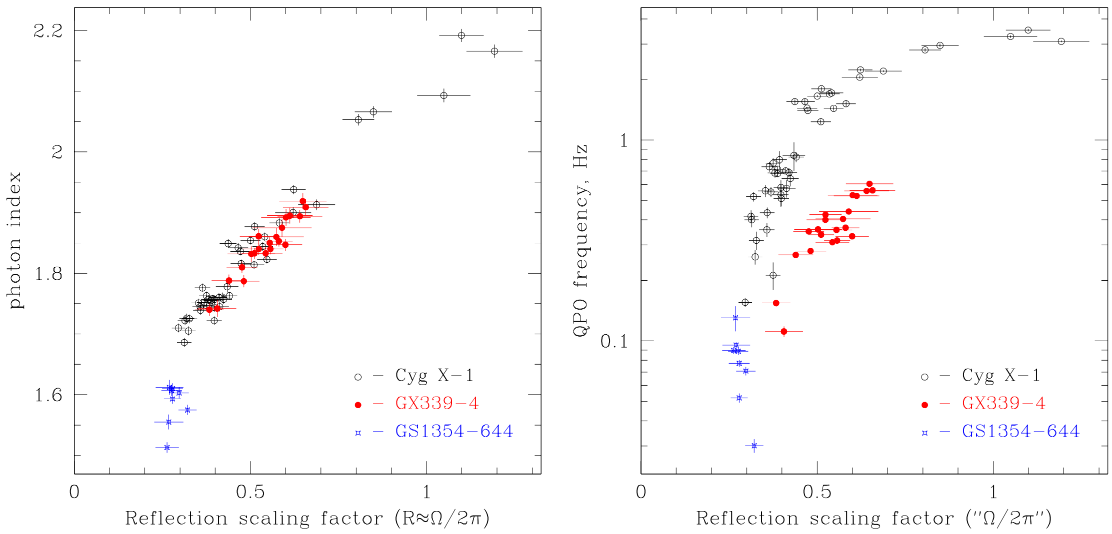

Figure 2.9: Dependence of the slope of the Comptonized radiation (*left*) and the QPO frequency (*right*) upon the amplitude of the reflection for three black hole candidates Cyg X-1, GX339-4 and GS1354-644 in the low spectral state. Public RXTE data from 1996–1998.

between processes taking place in the vicinity of the black hole. This has been done for several black hole candidates – Cygnus X–1, GX 339-4 and GS1354-644. Comparing the X–ray spectra observed at different times, it was found that the slope of the spectra is correlated with the fraction of the radiation intercepted and reflected by the dense and cold matter – the steeper the spectrum is, the larger is the fraction of the reflection. This is shown in Fig. 2.9 (left panel). Comptonization theory predicts that an increase of the influx of low energy seed photons to the Comptonization region will cool the electrons, hence cause the Comptonized spectrum to steepen. An increase of the flux of seed photons may mean that the source of the low energy photons gets closer to the Comptonization region. At the same time, moving dense and cold matter closer to the Comptonization region will increase the fraction of the reflected flux. Thus the observed correlation between the spectral slope and the amount of reflection suggests that the source of the low energy photons and the reflecting medium may actually be the same object.

This suggestion is strengthened when one looks at the variability of the X–ray flux. Often, there is a quasi-periodic oscillation (QPO) in the variability, whose frequency drifts up and down in time. From Fig. 2.9 one can see that both the slope of the X-ray spectrum and the QPO frequency correlate with the amount of relecting material deduced from the spectra.

The simplest (phenomenological) explanation of the above correlation is to assume that the accretion flow drastically changes its properties at some distance from the black hole. At large distances the accreting matter is dense, optically thick and relatively cold. This matter serves as the source of low energy photons and simultaneously as the reflection site. Closer to the black hole on the other hand the accreting matter is optically thin and it is responsible for the hard Comptonized radiation. The position of the boundary where the matter switches from dense to rarefied flow plays a major role in shaping the observable properties of X–ray radiation. The closer this boundary is to the black hole, the larger is the influx of soft photons into the Comptonization region (and therefore the steeper the spectrum), and the larger is the amount of hard flux intercepted and reflected. Simultaneously, the characteristic frequencies of variability are also increasing, because all hydrodynamic time scales become shorter as one approaches the black hole. This behavior would then provide an explanation for the correlation between spectral parameters (slope of the power law and amount of reflection) and the noise frequencies shown in Fig. 2.9 (right panel).

On the basis of this phenomenological model one can make specific predictions about the character of the variability of different spectral components, and predict observable details in the shape of the spectral features associated with reflection from the cold matter. Verification of these predictions will help to understand the geometry and dynamics of the accretion flow onto the black holes. Some of these predictions can be verified now with RXTE and XMM, while others will have to await for new generation of high energy resolution telescopes like Constellation-X and XEUS (Eugene Churazov, Marat Gilfanov).

2.6 Planet formation in massive protoplanetary disks

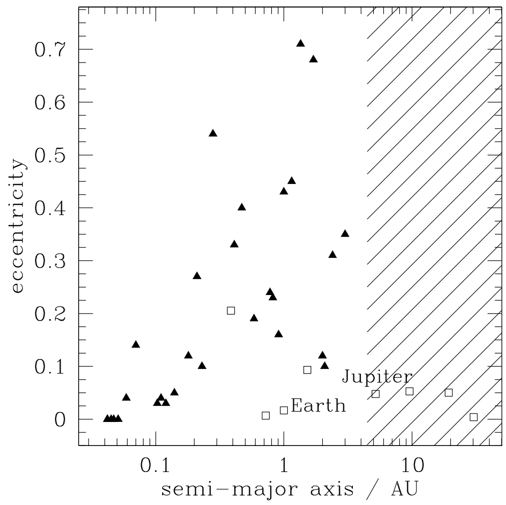

Figure 2.10: The orbital eccentricity and semi-major axis of extrasolar planets, as of early 2000. The orbits of planets in the Solar System are shown for comparison as open squares. Current searches have little sensitivity to planets in the shaded region at large orbital radii.

Planets form from the disks of gas and dust that are ubiquitous around young, solar type stars. Many such disks have now been directly imaged in nearby star-forming regions. Until five years ago, however, only one example of a formed planetary system was known – our own Solar System. As a result, much of the theory of how planetary systems form and evolve has been developed to explain a single extremely closely observed – but perhaps atypical – example.

Exquisitely accurate monitoring of the radial velocity of nearby stars for the periodic motion caused by orbiting bodies has now led to the discovery of around 30 extrasolar planets (see Fig. 2.10). Strikingly, planets have been found at extremely small orbital radii, much closer than the orbit of Mercury is to the Sun. They also occur further out, but then their orbits are significantly more eccentric than those of the giant planets (Jupiter, Saturn) in our own system. Among the discoveries, one planet has been seen in transit across the face of the parent star – thereby confirming that it is a giant, gaseous planet – and one system, Upsilon Andromedae, is known to harbour multiple planets. Observational limitations mean that these are all massive planets, of the order of a Jupiter mass, though three lower mass planets are known to orbit the pulsar PSR B1257+12. Since the formation mechanism for pulsar planets remains unclear, their existence serves mainly to emphasize the high probability of further surprises.

Forming planets in these unusual orbits is unlikely, so the most conservative interpretation is that planet *formation* in these extrasolar systems proceeded much as in our own Solar System, but that substantial orbital *evolution* has occurred subsequently to leave the planets where they are observed today. Plausible agents for such evolution include interactions between planets and the gaseous disk, between a massive planet and a disk of lower mass planetesimals, and amongst several massive planets.

Recent work by MPA researchers has studied the planet-disk interaction in a new regime, in which the protoplanetary disk itself is relatively massive. How common such initial conditions are is not known, but they are likely to be appropriate if planet formation occurs at an early epoch,when the central star itself is still growing rapidly. They may also apply at later times if angular momentum transport in the cool outer regions of the disk is inefficient. The importance of the disk mass is that for masses of around a tenth of the stellar mass, or higher, spiral arms form in the disk and act to transport angular momentum. Such a *self-gravitating* disk tends to evolve towards increased stability, and will not normally spontaneously fragment into planets. However, it can be driven to collapse by perturbations such as the gravitational forces due to (proto-) planets, provided that these occur more rapidly than the disk evolution timescale.

Figure 2.11 shows results from a hydrodynamic simulation of a Jupiter mass planet embedded in a self-gravitating protoplanetary disk.

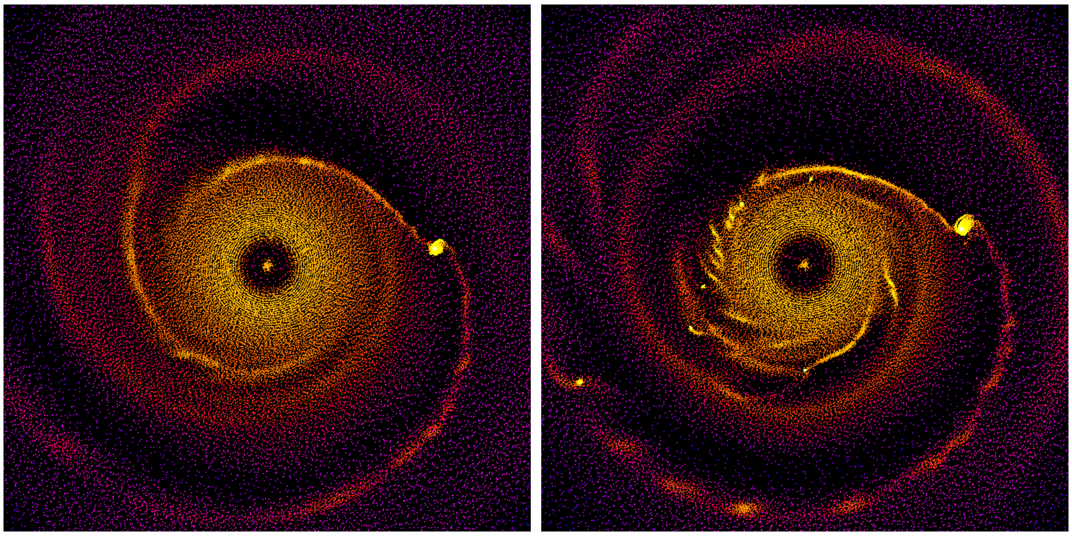

Figure 2.11: Interaction between a massive planet and a self-gravitating protoplanetary disk. The colours denote the logarithm of the the gas density. The planet clears a gap in the disk gas (left panel), but continues to accrete mass. Eventually, the growing gravitational perturbation drives fragmentation of the disk into additional planetary mass objects (right panel).

The gravitational influence of the planet first acts to clear a gap in the disk. This process also occurs in low mass disks (where the self-gravity of the disk is unimportant). Similar gaps have already been observed directly around young binary stars that are still surrounded by a circumbinary disk. Gaps produced by planets may be resolved in protoplanetary disks by future observations with millimeter-wavelength arrays. In this case, the presence of a gap does not prevent ongoing accretion along spiral arms onto the planet, which therefore grows in mass. When the mass of the planet (plus its circumplanetary disk) reaches around 5-10 M_{Jupiter}, the disk becomes unstable at the inner and outer edges of the gap. Rapid fragmentation into numerous planetary mass bodies ensues, and these start clearing their own smaller gaps in the disk gas. Similar results are obtained if the simulations are started with a lower mass planet. Higher resolution simulations than currently possible, however, will be needed to achieve the important goal of directly modelling the growth of a giant planet from such a small seed.

The existence of such a propagating mode of planet formation has several implications. It suggests that there is an upper limit to the growth of planets within disks. This is consistent with the observational indication that planets and brown dwarfs do not share a single mass function. It provides a possible mechanism explaining the rapid, early dissipation of protoplanetary disks, and shows a route to the formation of multiple massive planets. Such systems are often unstable over long periods, so these would be favourable initial conditions for the eventual formation of planetary systems comprising a few massive planets in eccentric orbits.

In the next few years, continuing radial velocity searches will be joined by a host of new planet detection techniques based on gravitational microlensing, stellar transits, high precision astrometry, and optical interferometry. The number of detections is likely to rise rapidly, along with the region of the mass-orbital radius parameter space (see Fig. 2.10) that is observationally accessible. Theoretical questions that will then become testable include attempts to understand the statistical distributions of planetary properties, and how the abundance and nature of planetary systems varies with the star formation environment. (Phil Armitage)

2.7 Continuous jets in microquasars

Jets, that is beamed outflows of fast-moving gas, have been known for a long time in connection with extragalactic radio sources. In these so-called Active Galaxies, the source of the outflows is believed to be a massive black hole (or its immediate environment) at the center of the galaxy.

Many of the X-ray binaries in our own galaxy are also thought to harbor black holes, though smaller by 6-10 orders of magnitude than the holes at the centers of galaxies. In these binaries, mass is transferred to the holes from their companion stars. Dissipation of the gravitational energy of the gas makes them visible as X-ray sources, in much the same way as happens in the Active Galactic Nuclei (AGN). It is therefore not surprising that these binaries also appear to produce fast outflows, even though direct evidence for this has been obtained only in recent years.

In some of these objects the velocity at which the material seems to flow exceeds the speed of light. Although this apparent violation of physical laws is only caused by a projection effect, the observation still implies that whatever is observed to move travels at 90% to 99% percent of the speed of light. In most of the systems with observed relativistic outflows the degenerate partner is thought to be a black hole. The presence of a relativistic outflow launched from the accretion disk around a black hole makes these systems very similar to the AGN in radio-loud quasars, except for the difference in scale. Hence the name 'microquasars'.

Whenever the outflows in microquasars can be resolved at radio frequencies, they show a knotty morphology. Discrete 'blobs' of material radiating radio waves via the synchrotron mechanism seem to move outwards from the source center at relativistic speeds. During their journey outwards the emission slowly fades; they become undetectable after a few tens of days. During this time their radio spectrum is observed to gradually steepen. These observations were interpreted in the past as discrete ejections of clouds of magnetised plasma, or plasmoids, which are much denser than the gas in the surroundings of the binary system and therefore move ballistically, like bullets. The decrease in their luminosity would be caused by the adiabatic expansion of the clouds, combined with the radiative energy losses of the relativistic electrons responsible for the synchrotron emission.

Several problems arise from this 'classical' picture. The radio luminosity is observed to decay so slowly that some form of confinement of the plasmoids has to be invoked. This contradicts the assumption of an essentially ballistic motion. Furthermore, the radiative energy losses of the relativistic electrons should lead to a sharp cut-off in the observed radio spectrum rather than a gradual steepening. Finally, the required rate at which energy is converted by the accretion disk into kinetic energy of the cloud immediately prior to the ejection is enormous. Even conservative estimates in some cases exceed the maximum luminosity (Eddington limit) of a black hole of ten solar masses.

At the MPA we have developed an alternative explanation for the relativistic outflows from microquasars to address these problems.

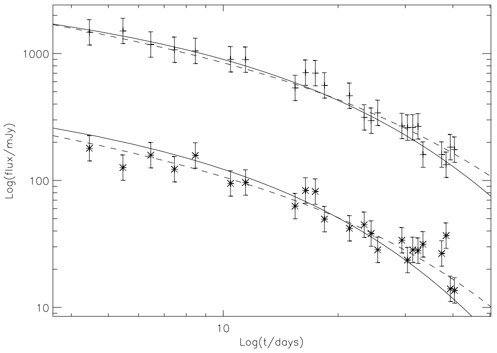

Figure 2.12: Comparison of the continuous jet model with observations of GRS 1915+105 at 1.4 GHz (crosses) and 3.3 GHz (stars, divided by a factor 5 for clarity). The two lines for each frequency show two different ways of constraining the model with the available observations.

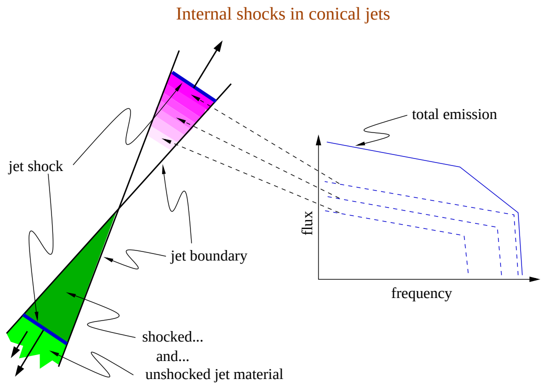

Figure 2.13: The effect of the radiative energy losses of the relativistic electrons accelerated by a shock traveling along a jet. The left panel shows the two-sided conical jet and the shocks traveling along it. The integrated spectrum resulting from the contributions of the jet regions with different high energy cut-offs are shown on the right.

We suggest that the outflows consist of a quasi-permanent jet flow, instead of episodic and discrete plasmoid ejections. The blobs seen in radio observations are then identified as shock fronts moving along the continuous plasma flow. These shock fronts could be caused by the interaction of fast moving parts of the jet material colliding with previously ejected slower material. This is analogous to the internal shock model for the afterglows of gamma-ray bursts.

The shocks traveling along the jet flow act as particle accelerators by first order Fermi acceleration. This means that electrons are scattered by irregularities in the magnetic field inside the jet, in front and behind the shock front, in such a way that they traverse the shock many times. During each crossing they gain energy and replenish the population of relativistic particles in the jet as the shock passes. If the jet has a conical geometry, the magnetic field strength inside the jet material decreases outwards along the jet. This will lead to a decreasing luminosity as the shock travels outwards. However, the continuous injection of relativistic particles by the shock counteracts this process, and the result is a considerably flatter lightcurve than in the plasmoid picture. Figure 2.12 shows the model predictions compared to the observations of an outflow in the microquasar GRS 1915+105.

The accelerated relativistic electrons are 'left behind' by the advancing shock, and continue to radiate for some time. Since the region of the jet emitting synchrotron emission at any given time is small, it is not resolved in present radio observations. Only the integrated emission of the entire region will be observed. Each population of electrons accelerated by the shock develops a high energy cut-off due to the radiative energy losses. The integrated spectrum is flat at low frequencies, since most electrons in the post-shock material contribute to low-frequency emission. At higher frequencies larger and larger fractions of the shocked jet material 'drop out' as time progresses, because of the decreasing high energy cut-off of the radiating electrons. As a result, the integrated spectrum steepens, (see Fig. 2.13). Because the magnetic field strength decreases outwards as well, the edge of the steeper spectrum shifts to lower frequencies. This sequence of events is consistent with the observed spectral steepening of the outflow components of microquasars.

Most of the observed emission is produced in the wake of the shock as it travels along the jet. Therefore in the resolved radio observations the velocity of the shock is measured, not the bulk velocity of the jet material which is overtaken by the shock. Together with the possibility that a large fraction of the energy converted to radiation is 'stored' in the jet material, this reduces the rate at which energy needs to be supplied to the outflow by the accretion disk.

The continuous jet model for microquasars is in excellent agreement with present observations. Work at the MPA continues to investigate to what extent these objects can be used as nearby analogues of their large-scale cousins, the extragalactic radio-loud quasars. (Christian Kaiser).

2.8 Relativistic jets from collapsars and gamma–ray bursts

Gamma–ray bursts (or GRB for short) are short lived sources of gamma radiation (photons of energy around 1 MeV) lasting from a fraction of a second to many hundreds of seconds. They are detected at random positions in the sky at a rate of about 1 per day. Although GRBs have been known since more than 30 years, their distance remained unknown until 1997, when the first afterglow of a GRB was discovered consisting of electro-magnetic radiation in the X-ray, optical and radio regime. The detection of GRB afterglows has become possible due to faster and better localization of the position on the sky of the gamma–ray bursts. Observation of the afterglows (meanwhile about two dozens have been detected) allows one to determine the distances of GRBs by measuring the redshift of their host galaxies. These measurements show that GRBs are located at cosmological distances roughly halfway between us and the edge of the observable universe.

From the amount of observed gamma radiation and the distance of the source one can infer a gamma-ray energy output that in extreme cases can be as large as 10^{54} erg assuming that the energy is emitted isotropically, i.e. with equal intensity in all directions. If the energy is preferentially radiated in some particular direction, e.g. if it is beamed into in a cone with a small opening angle (like the light beam from a light house), the required energy output of the source is considerably reduced.

The enormous energy output makes GRBs the most powerful phenomena in the whole universe, the brightest ones being brighter than all stars in the universe for the duration of the burst. The energy released corresponds to the complete conversion into energy of a mass of the order of our sun, in a time span of a few seconds.

Their extreme properties make GRBs one of the most actively debated mysteries in astrophysics. Though many suggestions have been made for the 'central engine' of these bursts, most of these struggle with the combination of a short time scale and the large amount of energy involved. Generally accepted, however is that, whatever the physical nature of the central engine, it must deposit an amount of energy exceeding 10^{51} erg into into a region with little mass (the ratio of rest mass to amount of deposited energy, or 'baryon load' must be $\sim 10^{-5}$) within a time of the order of seconds. If the energy is put into this small amount of mass, the result is a relativistically expanding (Lorentz factor $\Gamma > 100$) 'fireball' or jet.

In order to produce a GRB various scenarios involving rotating compact objects (i.e. black holes or neutron stars) have been proposed. In one of them (Spruit, MPA) the rapidly spinning neutron star in an X-ray binary is suddenly magnetized to a high field strength (through a sequence of events involving gravitational wave instability), and drives a magnetically powered GRB fireball. Other models involve accretion of several solar masses of matter onto a stellar mass black hole. Specific scenarios of this class are mergers (of two neutron stars, or of a neutron star and a black hole), and collapsars. In the latter scenario, which has been proposed by Stan Woosley, the bursts are triggered by the supernova–like implosion of the rapidly rotating stellar core of a rotating massive star of several ten times our sun's mass. The collapsing core forms a rotating black hole of a few solar masses, which then grows by sucking in the remaining stellar matter within about ten seconds. Due to its angular momentum this matter temporarily forms a differentially rotating accretion torus around the central black hole before it is eventually swallowed by the hole. In a complicated and still rather hypothetical process the liberated gravitational binding energy of the accreted matter leads to energy deposition preferentially in regions near the rotation axis and close to the horizon of the black hole. This in turn causes a collimated relativistic outflow or jet (actually two jets propagating in opposite direction along the rotation axis). This then gives rise to a gamma-ray burst when the flow has been accelerated to ultra–relativistic velocities ($\Gamma > 100$) and has propagated to sufficiently large distances (many stellar radii).

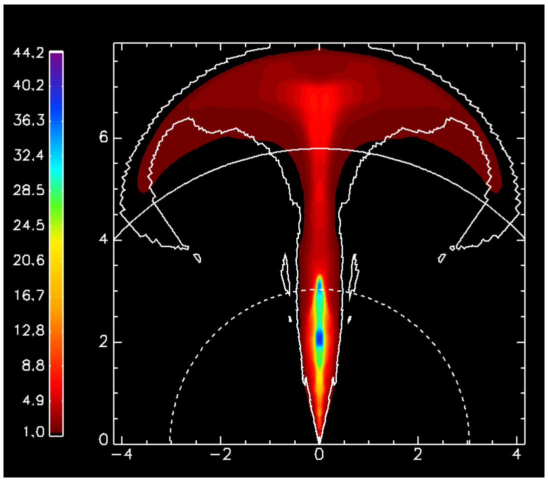

Figure 2.14: Lorentz factor for the model with a constant energy deposition rate of $10^{51}\,\mathrm{erg\,s^{-1}}$ about 1.8 s after shock breakout. A Lorentz factor of 10 corresponds to a velocity of 99.5% of the speed of light c. The numbers on the axes give the length in units of 100 000 km. Dashed and solid arcs mark the stellar surface and the outer edge of the exponential atmosphere, respectively. The other solid line encloses matter with a radial velocity larger than $0.3c$, and a specific internal energy density larger than $0.05\,c^2$.

The collapsar scenario predicts that a GRB is accompanied by a supernova–like event, because the jet not only makes a GRB, but explodes the star, too. This prediction is supported by observations of supernovae SN 1997cy and SN 1998bw, which seem to require an order of magnitude more energy than a common supernova and which are likely associated with GRB 970514 and 980425, respectively. Such an association is also suggested by the afterglow light curves of some GRBs (990425, 980326, 970228). The collapsar model has the attractive feature that the amount of matter available for accretion (and thus the maximum energy available for the GRB) is one to two orders of magnitude larger than for merging compact objects. On the other hand, the duration of the jet is set by the collapse time scale of the star, i.e. no very short bursts are possible, and the engine is deeply embedded in a star which the jet must penetrate in order to make the GRB.

Recently, astrophysicists at the MPA in col-

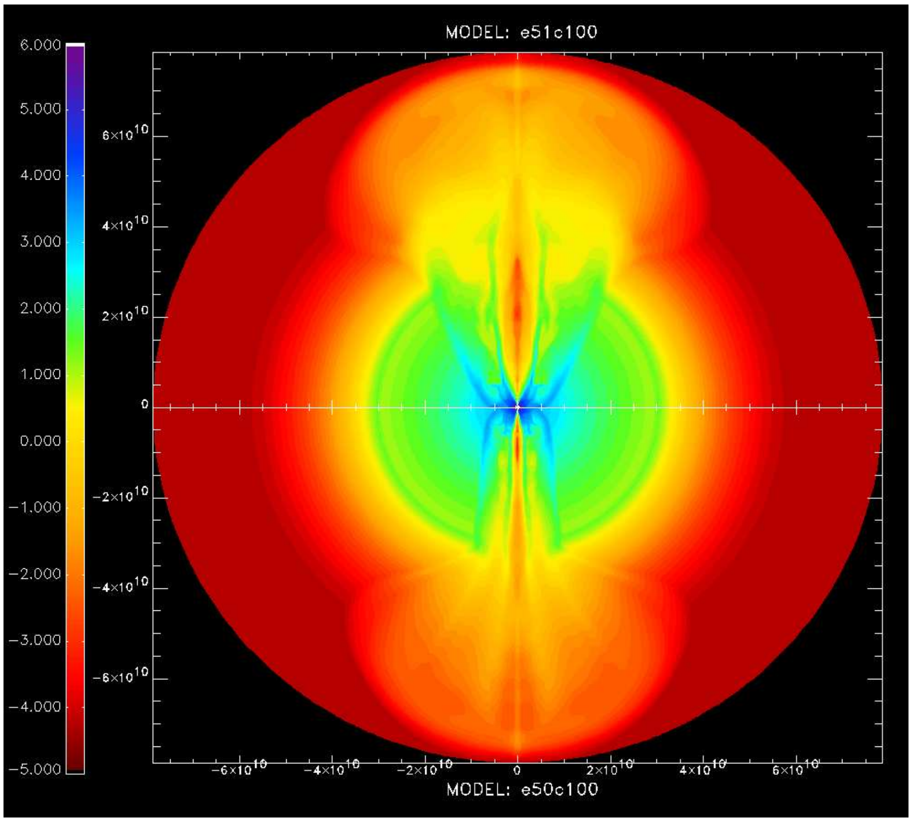

Figure 2.15: Rest–mass density for the models with a constant energy deposition rate of $10^{51}\,\mathrm{erg\,s^{-1}}$ (top half) and $10^{50}\,\mathrm{erg\,s^{-1}}$ (bottom half), respectively, about 1.8 s after shock breakout. The numbers on the axes give the length in units of centimeters.

laboration with researchers from the University of Valencia in Spain and from the University of California at Santa Cruz have performed the first multi–dimensional relativistic simulations of jets from collapsars. The simulations are based on a rotating helium star whose evolution was computed by MacFadyen & Woosley. The iron core collapse of this star does not produce a successful outgoing shock, but instead forms a black hole surrounded by a compact accretion torus. When the central black hole has acquired a mass of $\sim 3.7\,M_\odot$ the axisymmetric relativistic simulations are started.

In a consistent collapsar model a jet will be launched by any process which gives rise to a local deposition of energy and/or momentum. Such a process was mimicked by depositing energy at a prescribed rate homogeneously within a 30° cone around the rotation axis. A model has been investigated with a constant energy deposition rate of $10^{50}\,\mathrm{erg\,s^{-1}}$ and $10^{51}\,\mathrm{erg\,s^{-1}}$, and another one with a variable energy deposition rate with a mean value of $10^{50}\,\mathrm{erg\,s^{-1}}$. The constant rates roughly bracket the expected energy deposition rates of collapsar models, while the varying rate mimics time–dependent mass accretion rates.

The main results of the axisymmetric relativistic simulations are:

The energy deposition gives rise to a relativistic jet, and to a supernova–like explosion (Figs. 2.14 and 2.15). The jet reaches the stellar surface intact after having propagated over a distance of more than 200 000 kilometers. This result probably also holds for other less specific initial conditions. The propagation of the jet after breakout (i.e. after reaching the stellar surface) depends on the density stratification of the circumstellar medium. The simulations discussed here assume that the density decreases exponentially to a value of $10^{-5}\,\mathrm{g/cm^3}$ at 1.8 stellar radii, and is constant further out. Once outside the star the jet accelerates considerably, and also starts to spread sideways with sub–relativistic speed. When it reaches the homogeneous part of the circumstellar medium the rate of lateral expansion increases strongly ($\Gamma \sim 5$) and a mushroom-shaped bubble forms (Fig. 2.14).

The opening angle of the jet ($\sim 8°$) is considerably smaller than the angular width of the energy deposition region (30°). Moreover, the jet possesses a highly collimated ($\sim 1°$), ultra–relativistic core in which the Lorentz factor reaches a value of almost 50 at the end of the simulation about 2 s after shock breakout (Fig. 2.14). The jet core contains a mass of about 8×10^{-4} solar masses with an average Lorentz factor $\Gamma \sim 4$. For larger energy deposition rates, the jet and in particular its surrounding cocoon, a region of turbulent gas flow, are less collimated because a jet which is driven harder also expands more strongly laterally (Fig. 2.15).

Due to the high degree of collimation of the outflow an observer looking at the collapsar almost along the rotation axis will see a much brighter gamma–ray burst than the total energy output would produce, if it were radiated isotropically in all angular directions.

The rest–mass density and the internal energy vary strongly in space and time within the jet giving rise to a very inhomogeneous baryon load, i.e. the concept of baryon load or baryon contamination as a global parameter is useless. Instead it is more appropriate to discuss the efficiency of energy conversion in terms of incremental baryon loads considering only matter within a given range of Lorentz factors. The average baryon load of the jet is ~ 1 at the end of the simulation, but some parts of the flow have a baryon load of 10^{-5} or less. Hence, most matter in the jet (about two solar masses) moves with a Lorentz factor smaller than 3, and only 2×10^{-6} solar masses have a Lorentz factor larger than 10. However, as the maximum Lorentz factor is found to increase rapidly after shock breakout, a maximum Lorentz factor of several hundreds might be reached before the central engine is switched off.

At the end of the simulations the jet has reached a radius which is still about a thousand times smaller than the distance at which the fireball becomes optically thin. Determining the observational character of the GRB requires computation of the further evolution of the jet. (Miguel Angel Aloy, Ewald Müller)

2.9 Radioactive elements from supernovae

Hydrogen and helium, the lightest of the chemical elements and by far the most abundant ones in the Universe, were created together with tiny amounts of lithium, within the first ten minutes after the Big Bang. All other elements were bred by many generations of stars over millions and billions of years. At the enormous densities and temperatures in the stellar interior, light atomic nuclei collide and produce heavier elements in fusion reactions.

Stars with more than about ten solar masses develop iron cores in a sequence of nuclear burning stages, which, starting from hydrogen, lead to the formation of helium, carbon, oxygen, magnesium, neon, silicon, sulfur and, finally, iron and nickel. Since iron has the most tightly bound atomic nucleus, no further energy release by nuclear fusion reactions is possible at this stage. Therefore a star with an iron core faces a catastrophic death. Under its own weight, a stellar core with roughly the mass of the Sun collapses to an extremely dense object, a neutron star, which has a diameter of only 20 kilometers and a mean density comparable to that of atomic nuclei. At the same time an explosion wave is launched which is ejects the mantle and envelope layers of the dying star in a supernova explosion. In this spectacular cosmic event the ashes of the star's nuclear burning stages are swept into the surrounding space and mixed into the interstellar medium. Many generations of such stars, born from interstellar gas and dust and destroyed in supernova explosions, have gradually enriched the Universe with the chemical elements heavier than hydrogen and helium.

Roughly one supernova blows up in the Universe every second, most of them however in very distant galaxies and therefore invisibly far away, although a supernova can be as bright as a whole galaxy for several weeks. In our own galaxy, the Milky Way, supernova explosions are a rather rare phenomenon, expected to happen only once or twice per century. Therefore astronomers were extremely lucky when on February 23, 1987, the death of a blue supergiant star in the Large Magellanic Cloud, a small satellite galaxy of the Milky Way only 150.000 light years away, offered the spectacular display of a 'nearby' supernova explosion. The

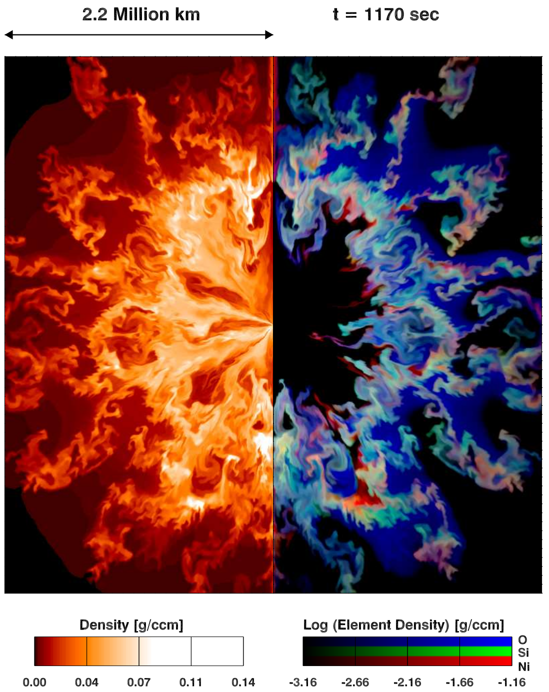

Figure 2.16: Snapshot from a two-dimensional simulation of the explosion of a blue supergiant star with 15 solar masses at a time 1170 seconds after the stellar core had collapsed to a neutron star. In the left half of the figure the density is shown in a region with a radius of about 2.2 million kilometers, in the right half three color images of the mass densities of radioactive nickel (red and pink), silicon (green, light blue, whitish) and oxygen (deep blue) are superposed. One can see that the ejecta of the explosion are inhomogeneous and anisotropic, and the original onion-shell structure of the exploding star was shredded. Nickel is concentrated in dense, fast-moving clumps.

famous Supernova 1987A (SN 1987A) was the closest such event for several hundred years, visible even with the naked eye. Astronomers used this unique chance to follow the expansion of the ejected gas essentially from the first outburst of bright light.

During the first seconds of the explosion radioactive elements and isotopes like ^{56}Ni, ^{57}Ni, and ^{44}Ti are freshly synthesized in the deep interior of the exploding star, in the immediate vicinity of the newly formed neutron star. The energy release by the decay of these radioactive nuclei powers the emission of light from a supernova after a few months. In this phase the lightcurve shows an exponential decline due to the radioactivity of the daughter nucleus produced by the decay of ^{56}Ni, ^{56}Co, which decays further to ^{56}Fe with a half-life of 77 days. After several years ^{44}Ti is the dominant energy source. The brightness of the supernova during these phases allows one to draw conclusions on the amount of radioactive material which was produced during the explosion, provided the distance to the supernova is known. Comparing the observations with theoretical models yields important information about the energy of the explosion, about the processes which caused and accompanied the explosion, and about the structure of the dying star.

After the ejecta have become transparent, gamma-rays from the decay of radioactive nuclei can also be measured directly. SN 1987A, however, had a real surprise for theorists. X-rays and gamma-rays were detected much earlier than predicted, at a time when the expanding star was still very opaque and radiation could only escape from the hydrogen envelope. This meant that radioactive nuclei must have been transported from the site of their creation near the center into the hydrogen envelope of the exploding star. Moreover, spectral features indicated that iron was concentrated in clumps which were moving at speeds of several 1000 kilometers per second, much faster than the iron velocities expected from models. Even more, the observed lightcurve and spectra could only be reproduced by assuming that some mixing process had destroyed the initial ‘onion shell’ structure of the star, where layers containing the lighter elements are stratified on top of shells containing the heavier nuclei.

Multi-dimensional hydrodynamic simulations provide an explanation for these astonishing findings. Researchers from MPA and from the Nicolaus Copernicus Astronomical Center in Warsaw have calculated the first two-dimensional models in which the entire evolution of an exploding star was followed, from the moment of the formation of the supernova shock until the shock penetrated through the surface of the star several hours later. The simulations take into account the physical processes that supply the shock with energy in the first second, and include the production of radioactive elements by explosive nuclear burning in the layers which are compressed and heated by the shock. Application of so-called adaptive mesh refinement techniques allow for an automatic increase of the numerical accuracy in regions where small structures had to be resolved. The effective resolution was the highest used for this type of simulations so far.

During the explosion, already shortly after the formation of the supernova shock, convective processes around the nascent neutron star begin to destroy the spherical symmetry of the exploding star. When the shock gains momentum and moves away from the center to propagate through the silicon, oxygen and helium shells into the hydrogen envelope, the interfaces of these layers become unstable whenever the shock slows down because it runs through a region with flatter density profile. Mixing of regions with different chemical composition sets in, and the interaction of the early postshock convection with the instabilities at the composition interfaces leads to inhomogeneities and anisotropies on large scales. Not only is the original onion-shell structure of the star shredded but also the radioactive products of explosive burning are distributed over a large range of radii and velocities, as shown by Fig. 2.16. A high density of ^{56}Ni (the red and pink spots in the right half of the figure) is found in clumps and knots located along extended filaments of material which is denser than the surrounding gas (compare with the left half of the figure). The deep blue regions contain mostly oxygen, while silicon is abundant in green, light blue, and whitish fragments. The fastest of the clumps with high nickel concentrations have penetrated far into the helium shell, and move significantly faster than the ambient helium at the time shown in the figure.

The occurrence of such fast-moving metal-enriched clumps in the model and their maximum velocities of more than 4000 kilometers per second are in good agreement with observations. Fragmentation and clumpiness of the ejecta seem to be a generic phenomenon for supernova explosions of massive stars. This can be concluded indirectly from the analysis of lightcurves and spectra of SN 1987A and a number of other supernovae, but more directly from X-ray images of the gaseous remnants of supernovae which blew up hundreds or thousands of years ago. Examples are the ROSAT pictures of the Vela remnant or recent measurements for the 320 year old Cassiopeia A (Cas A) remnant by *Chandra*, NASA's orbital X-ray Observatory. X-rays are particularly suitable for observing the diffuse nebulae of hot gas that was expelled in the disruption of the star. The spectral information obtained by *Chandra* reveals that clumps composed mostly of iron are spatially separated from more compact and brighter knots that carry predominantly silicon and sulfur (Fig. 2.17). The iron-rich features seem to be located near the outer edge of the remnant, indicating that this material from deepest in the star has been moving with the largest velocities. The explosion appears to have turned the dying star inside out.

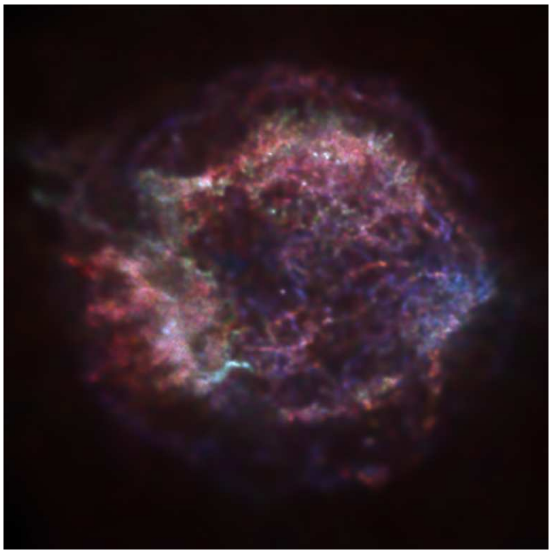

Figure 2.17: X-ray image of the Cassiopeia A supernova remnant obtained by the *Chandra* observatory. Spectral information from three different energy bands was combined and shows compact and bright silicon- and sulfur-rich knots (green, white and blue) and fainter iron-rich features, which have been flung farthest by the explosion that created Cas A.

Long-lived radioactive nuclei can also be detected in supernova remnants, if they are produced in significant amounts during the explosion and the remnant is not too far away. While ^{56}Ni and its daughter nucleus ^{56}Co decay quickly, ^{44}Ti, which is expelled with the iron-rich clumps seen in Fig. 2.16, has a much longer half-life, and offers the possibility to be observed in sufficiently young and nearby supernova remnants. Indeed, the COMPTEL telescope on the *Compton Gamma-Ray Observatory* has found gamma-ray line emission from ^{44}Ti decay to the ground state of ^{44}Ca in Cas A. Knowing the distance to Cas A and the age of the remnant, the measured gamma-ray flux was used to estimate the ^{44}Ti production by the supernova about 320 years ago.

Such estimates require the use of the half-life of the radioactive nucleus. In case of ^{44}Ti, however, this depends on the remnant evolution, because ^{44}Ti has very interesting decay properties. Its decay mode is pure orbital electron capture, i.e., the nucleus captures an electron from the inner bound orbits of the surrounding electron cloud. This means that fully ionized ^{44}Ti is stable, and partial stripping of the innermost electrons can lead to a significantly longer effective half-life than the measured laboratory value of 60 years for neutral ^{44}Ti. The initial ^{44}Ti mass can be calculated in a straightforward way by using this measured half-life only if the temperature stays low enough so that ^{44}Ti never gets highly ionized for some time during the expansion of the supernova remnant.

Researchers at MPA and MPE together with colleagues from RIKEN, Japan, showed that this is not necessarily the case, if ^{44}Ti is concentrated in the dense clumps mainly consisting of iron, an assumption which is supported by the multi-dimensional models of supernova explosions. A reverse shock is launched when the supernova shock has swept up an amount of circumstellar gas mass that is comparable to the ejecta mass. This shock travels inward through the expanding ejecta and heats the titanium carrying iron clumps. Exploratory studies based on an analytic model for the remnant evolution demonstrate that the ionization of ^{44}Ti can be so strong that the ^{44}Ti production by the supernova is overestimated by up to a factor of three, if the delay of the ^{44}Ti decay is not taken into account. These conclusions depend on various parameters, and more detailed multi-dimensional simulations are needed to reduce the theoretical uncertainties about the distribution and density of the iron clumps and their reheating by the reverse shock. Bridging the timespan from the moment when the shock breaks out through the stellar surface to the remnant phase several hundred years later, starting with detailed initial models of the explosion, will be a major challenge for future multi-dimensional simulations. (Thomas Janka, Konstantinos Kifonidis, Wolfgang Hillebrandt)

2.10 The First Stars

After the Big Bang, only two elements were present in the Universe: hydrogen and helium. All other elements (called 'metals' in astrophysical parlance) have been synthesized by nuclear fusion in generations of stars. The Sun – a member of the latest generation of stars, called Population I – has a metal fraction of 2%. Obviously, there must have been a very first generation of stars which formed out of metal-free matter. These First Stars are called Population III. The oldest known stars have a metal content of 10^{-4} or more, and therefore do not represent the first stars. They belong to Population II. Although there is no doubt that at some time Population III stars must have formed, lived and died (because they added the first metals to the interstellar matter out of which Population II formed), all searches for completely metal-free stars have so far failed. Where is Population III?

There are several proposed explanations for the failure of searches for Population III. One is that only stars much more massive than the Sun formed out of metal-free material. Such stars live only some 10 million years (or shorter) and then explode as a Supernova, returning the metals created in their interior to the interstellar material. Compared to the age of the Sun – 4.6 billion years – or the age of the Universe – around 14 billion years – the era of the first stars in this case would represent only a very brief period and would have vanished without leaving any evidence to their existence - except for the heavier elements. A reason why only massive stars may have formed out of metal-free gas clouds might be that such clouds need to cool efficiently during their gravitational contraction. The cooling is done by radiating photons. Metal atoms, with their many energy levels, radiate much more efficiently than hydrogen and helium. Although it is now known that hydrogen molecules can also provide cooling, the process is not as efficient as when heavier elements are present. In addition, if temperatures in the cloud get high enough, and the radiated photons are too energetic, the hydrogen molecules themselves are distroyed. This backreaction is one of the difficulties in theoretical simulations of star formation in a metal-free environment. Such numerical calculations have recently been performed by scientists at MPA, the Massachusetts Institute of Technology and the University of Illinois (T. Abel, G. Bryan and M. Norman), and indeed seem to indicate a preference for massive star formation in Population III (Fig. 2.18).

However, there *is* a class of stars in the Galaxy which is more metal-poor than typical Population II stars: the so-called *ultra metal-poor stars*, with a metallicity of only 1/1000 of the Sun. These are found only as field stars in the Galactic halo. Analysis of their spectra shows that their metal abundances look as if only one su-

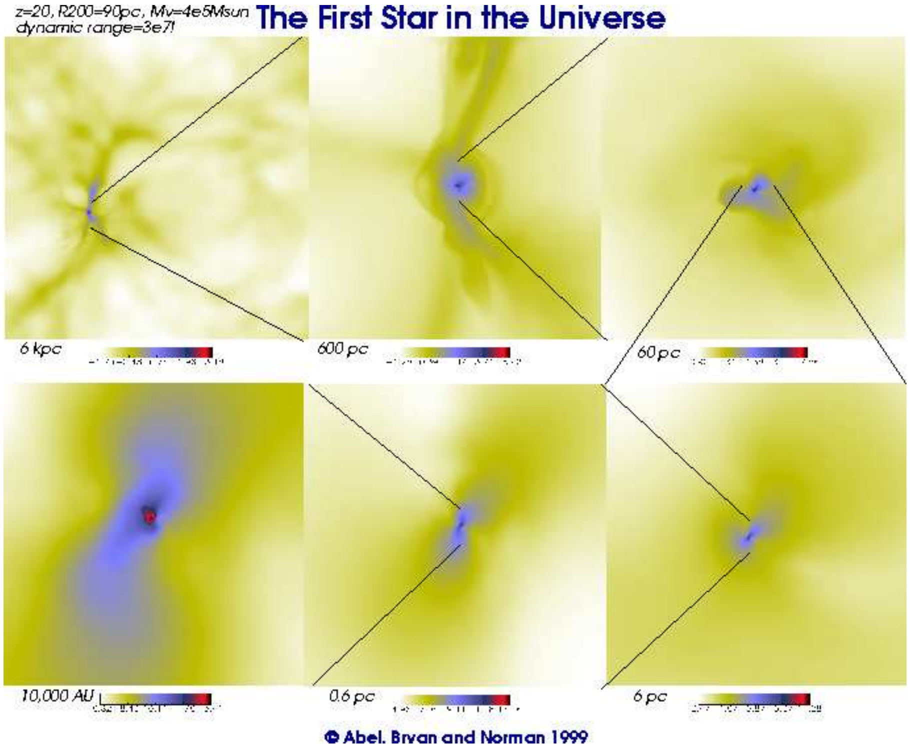

Figure 2.18: Simulation of primordial star formation. In five steps of a factor 10 we zoom into the core of a metal-free gas cloud. The (red) central condensation might become a star of the first generation. Its mass is of order 100 $M_\odot$ (a hundred solar masses). Simulation by Abel, Bryan, and Norman 1999.

pernova contributed to them. The Sun, for comparison, has a metal mixture resulting from the combination of stellar debris from many stars of different masses and various generations. Only very few ultra metal-poor stars have been found – only about a hundred after 15 years of searching.

Are these the long-sought Population III stars? If so, why do they have non-zero (but very low) metallicity? If not, what are they and how do they relate to Population II, which is the dominant population of the halo, including the famous globular clusters? To answer this question, we (A. Weiss and H. Schlattl of MPA, S. Cassisi of the Observatory of Teramo, and M. Salaris of the John Moores University of Liverpool) have investigated the evolution of metal-free stars of about 1 $M_\odot$. At this mass, a Population III star could have formed in the very earliest phases of the Galaxy but still be present today. Such stars supply the energy radiated from the surface by the fusion of hydrogen into helium, just like the Sun does, but one nuclear processing cycle (the CNO-cycle) is not available to them, because these (and other) elements are absent. Their central regions get so hot towards the end of core hydrogen burning that the next nuclear burning phase – the conversion of helium to carbon – begins at a time when there is still some unburnt hydrogen around. This is quite different from 'ordinary' stars, where the two burning phases (hydrogen- and helium-burning) are well separated. As soon as the first carbon (it is called 'primary' carbon because it is created from primordial helium) is available in sufficient amounts, the remaining protons (hydrogen nuclei) can immediately enter the CNO-cycle. This leads to a very rapid release of the final energy available from hydrogen burning. This very short and energetic burning phase has been termed the *CNO-flash*.

Fig. 2.19 compares the evolution of a 1 $M_\odot$ star of (about) solar composition with one of zero metallicity. The general evolution is similar: for example, the stars evolve to ever higher luminosity, and, after the main-sequence phase, to lower effective temperatures. But three striking differences are evident: (i) The track of the Population III star is shifted to the left and up

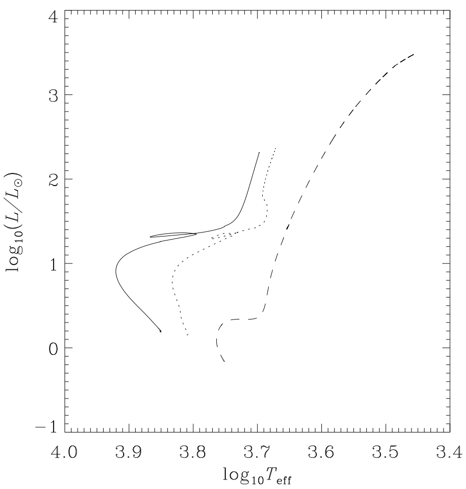

Figure 2.19: Evolution of three stars of $1\,M_\odot$. Dashed line: solar metallicity. Solid: a Population III star (no metals). The dotted line is a Population III star which, after its formation, has been polluted at its surface with of $0.01\,M_\odot$ of solar metallicity matter.

compared to the Population I evolution, i.e. the star has a hotter surface and is more luminous. This is due to the lack of metals, which makes the star more transparent to radiation. (ii) The track ends at much lower luminosity. This is due to the higher central temperatures. Both tracks end when helium burning starts at a temperature of about 10^8 K. (iii) The Population III track displays a loop to higher $T_{\rm eff}$. This is the phase of the CNO-flash. Unfortunately, the duration of this loop is only about 10 million years, and it is unlikely that astronomers will be lucky enough to observe one of these dramatic excursions.

If we assume that the ultra metal-poor stars are indeed genuine Population III stars, then there are two ways to explain their observed non-zero surface metallicities: generation of metals within the star, and pollution of the surface by a nearby supernova. The first possibility is unlikely for the heavier elements because low-mass stars themselves produce only light elements. However, it would be interesting, if elements of the CNO-cycle could be produced inside the star before the onset of helium burning. We have identified such nuclear paths (during hydrogen burning), but found them to be less important than carbon production by early helium burning. We have also investigated the second possibility, by polluting our zero metallicity stars with matter of solar composition, which we then allowed to be mixed and transported (by diffusion) to the interior. While the outer evolution is changed significantly (see Fig. 2.19, dotted line), the interior evolution is not, because the metals from the outside do not have enough time to reach the central regions. The CNO-flash loop therefore is still present. However, due to the increased opacity of the outer regions, temperatures in the outer stellar layers are not quite as high as in the non-polluted case (solid line). Interestingly, for 'standard' assumptions about the amount and composition of the polluting material we obtain a dilution of the surface abundances which corresponds roughly to the difference between Population II and III. Maybe the ultra metal-poor stars are First Stars after all, albeit polluted ones?

One of our aims is to predict some signatures which would be unique to such stars so one can tell observers what they have to look for. The CNO-flash is one such signature, the higher-than-usual surface temperatures another one. Finally, we find that at the end of the evolution, when helium ignites violently, interesting and complicated nucleosynthesis and mixing processes might occur, resulting in very peculiar surface abundances. However, this work is still in progres, as is the search for Population III. (Achim Weiss)

3 Research Activities

3.1 Stellar physics

Structure and evolution of stars. Stars are an important component of the universe and a major source of information about its structure and history. The long-standing tradition of research in stellar structure theory at the MPA is still carried on by a small group (A. Weiss, H. Ritter, and coworkers). Their activities focus on the evolution of low- and intermediate-mass stars.

The evolution of single stars is studied using a direct descendant of the original Kippenhahn–Weigert–Hofmeister stellar evolution code. It is among the most advanced codes available worldwide and it is continually being updated and improved, both in its numerical efficiency and in its physical inputs. The effort devoted to code development means that less time is left over for large scale model-library calculations. The advantage, however, is that better results are obtained in studies of individual objects. One example is the highly accurate solar model produced by H. Schlattl with this code. Solar and stellar models are usually computed with different programs because of their very different efficiency requirements. The code has also been applied to Population III stars using an extended nuclear network. It is run on all large workstations at the MPA and RZG.

Two major recent research highlights of the stellar structure group were 1) the calculation of the Garching Solar Model (as part of Sonderforschungsbereich 375) and its successful application to several issues in axion & neutrino physics, 2) the analysis of the ages of globulars clusters by Salaris, Degl'Innocenti and Weiss that demonstrated that these objects were younger than commonly believed, resolving the so-called "age-problem". The results on globular clusters were derived on purely theoretical grounds. Since then, HIPPARCOS parallax observations have confirmed that globular clusters do indeed have ages of 14 Gyr or less. The research on low-mass stars is done in close collaboration with several Italian groups (Padua, Teramo, Pisa) and with M. Salaris (Liverpool).

An ongoing project on the Planetary Nebulae Luminosity Function is expected to come to fruition in the near future. The PNLF is one of the major distance indicators used for extragalactic objects. P. Marigo (now Padua, formerly MPA), together with M. Groenewegen and A. Weiss, have been working on a theoretical model that will explain its observed properties. This work uses a synthetic model of intermediate mass stars based on the full stellar calculations available at MPA.

The infrared properties of late-type stars of the same mass range are being studied by M. Groenewegen. This work is being pursued in collaboration with European colleagues on a number of major telescopes around the world. Once the observations are obtained, theoretical radiation transport models are used to infer mass loss rates in these objects. Groenewegen has also studied biases in HIPPARCOS parallax data, in particular their effect on the inferred distance to the LMC.

The "clump" and planetary nebulae luminosity function projects both make use of synthesis methods. A. Weiss and coworkers at ESO have used the same methods to show that certain elements are more abundant in the stars of elliptical galaxies than observed in the solar neighborhood. As a result, A. Weiss, in collaboration with C. Chiosi and his group in Padua, have initiated a project to extend the Padua stellar library to the regime of non-solar abundance ratios. This library is widely used in population synthesis models, such as the one maintained by S. Charlot (currently visiting the MPA from Paris). A. Weiss and G. Worthey (Davenport and MPA visitor) have started a project aimed at understanding the influence of non-solar abundance ratios on the observed integrated spectral line strengths of galaxies. Another future area of activity will be the application of population synthesis methods in analyzing the properties of the young globular clusters observed in interacting galaxies. Eventually the stellar evolution group hopes to provide in-house models for the galaxy evolution group. An improved treatment of convection in massive stars will also be implemented in the stellar evolution code.

Binary systems. Research in the group is not limited to studies of single stars, but also includes some aspects of binary evolution (Ritter). The MPA has a long-standing collaboration with the Astronomy Group of the University of Leicester (UK), the Department of Physics and Astronomy at Louisiana State University, Baton Rouge (USA), and the Astronomy Research Group of The Open University, Milton Keynes (UK). The aim is to study the long term evolution of compact binaries. There has been emphasis in recent years on the potential influence of proximity effects on the formation and evolution of millisecond pulsars, and on the evolution of long-period systems with stable mass transfer from a giant (for which an analytical solution exists). Current and future projects will include full numerical computations of the evolution of compact binaries including the effects of illumination and consequential angular momentum losses, and the spin-up of millisecond pulsars in long-period low-mass binaries.

Stellar diagnostics and extragalactic stellar astronomy In the current era of 8m class telescopes, it has become possible to apply precise stellar diagnostics to external galaxies. The MPA through its connection with the Institut für Astronomie und Astrophysik of the Ludwig-Maximilian-Universität München has taken an active part in this development. R.P. Kudritzki and his group have developed basic diagnostic techniques to analyze the spectra of luminous blue supergiants and hot post-AGB stars. These have been applied by supergiants in Local Group galaxies to determine the composition of individual stellar objects, to study stellar winds as a function of metallicity and to develop a very promising new extragalactic distance indicator, the "Wind Momentum – Luminosity Relationship". These techniques have also been used to interpret the physical nature of extreme $Ly\alpha$ emitting galaxies at high redshift that have been detected with FORS at the VLT.

Planetary Nebulae can also be used to investigate the structure of galaxies. They are used as distance indicators or to determine the mass-to-light ratios and dark matter content in the outskirts of galaxies. Very recently, R.P. Kudritzki and R.H. Mendez have used the VLT to study the Virgo galaxy NGC 4697. Hundreds of PNs were detected and measurements of their radial velocities will lead to an extremely accurate determination of the kinematics of this galaxy. As a by-product of this work, an international collaboration including Kudritzki and Mendez have detected "intra-cluster PN" and a corresponding population of stars between the galaxies in the Virgo-cluster. The existence of a substantial mass of stars outside of galaxies may provide an interesting challenge for theoretical models of galaxy formation.

Comets. The cometary group at MPA specializes in large-scale magnetohydodynamic (MHD) calculations of the interaction of the solar wind with the plasma tail of a comet. Rudolf Wegmann used time-dependent three-dimensional MHD calculations to study how the cometary plasma tail reacts to solar wind disturbances. Simulations including chemical reactions within the cometary coma have been developed and are used to investigate the distribution of water ions in comets. This work is carried out in collaboration with K. Jockers and T. Bonev (both MPI für Aeronomie, Katlenburg/Lindau). Finally, Rudolf Wegmann and Hermann-Ulrich Schmidt, in collaboration with K. Dennerl and J. Englhauser (both MPE), used model calculations of the charge exchange between heavy solar wind ions and neutral molecules in the cometary coma to explain the X-ray fluxes of comets measured using the ROSAT satellite.

3.2 Nuclear and Neutrino Astrophysics

For more than two decades, nuclear and neutrino astrophysics have been major areas of research at MPA, and the activities of the group have recently expanded to include simulations of mergers of neutron stars and black holes – potential candidates for at least some of the γ-ray bursters – models of thermonuclear supernova explosions, and the observational aspects of nucleosynthesis. Nevertheless, the physics of core-collapse supernovae remains an active field of research. It is also part of the special research project ("Sonderforschungsbereich") 375 of the Deutsche Forschungsgemeinschaft at the Technical University of Munich. This work includes investigations of the explosion of neutron stars near their limiting minimum mass by Wolfgang Hillebrandt in collaboration with Kotsuke Sumiyoshi, Hideyuki Suzuki, and Shoichi Yamada (all from Tokyo), as well as the development of new methods to calculate the transport of neutrinos in dense nuclear matter. Recently Markus Rampp, Hans-Thomas Janka, and Shoichi Yamada (University of Tokyo) achieved a major breakthrough. They found a fast way to solve for neutrino transport in 2-dimensional hydrodynamical simulations of supernova explosions. In addition, Stephen Hardy (a Marie-Curie-Fellow at MPA), Hans-Thomas Janka, and Georg Raffelt (Werner-Heisenberg-Institut) calculated neutrino opacities in dense matter taking into account nucleon-nucleon correlations and magnetic field effects. This work, which showed how neutrino emission from a newly-born neutron star can become non-radial, may provide an answer to the question of why so many neutron stars are found with very high velocities. As shown by Hans-Thomas Janka and Georg Raffelt, these velocities cannot be explained by neutrino oscillations.

The work on core-collapse supernovae has not only focused on micro-physics. Multi-dimensional simulations of the events were carried out using hydrodynamic codes developed at MPA. Wolfgang Keil, together with Hans-Thomas Janka, discovered that the interior of a newly-born neutron star is unstable against (Ledoux-) convection, an effect that boosts the neutrino luminosity considerably and adds to the plausibility of the neutrino-driven explosion mechanism for supernova of types Ib,c and II. Hans-Thomas Janka and Georg Raffelt used the models to establish new bounds on the properties of non-standard neutrinos. Finally, a newly developed AMR-code was used to compute multi-dimensional effects on the nucleosynthesis during the explosion phase, in particular on explosive oxygen burning. In a thesis supervised by Ewald Müller and Hans-Thomas Janka, Konstantinos Kifonidis constructed the first set of 2–dimensional simulations with realistic micro-physics to extend to 16,000s after core bounce and to make parameter-free predictions both for the abundances and for the spatial distribution of radioactive ejecta.

Neutrinos also play an important role in neutron star – neutron star and neutron star – black hole mergers since most of the energy liberated in these events is first emitted in form of weakly interacting particles. It is believed that the annihilation of neutrinos into $e^+ - e^-$ pairs may give rise to γ-ray bursts and may explain a sub-class of the observed bursts. State-of-the-art simulations of such mergers in three spatial dimensions were carried out by Hans-Thomas Janka, Max Ruffert (now at the University of Edinburgh) and Thomas Eberl (a Diploma student), in collaboration with Kohji Takahashi, Markus Rampp and Gerhard Schäfer (University of Jena). Although General Relativity was neglected, most of the relevant micro-physics and the emission of gravitational wave emission in the post-Newtonian approximation were included and the final result is convincing: this class of models cannot explain the most energetic bursts.

A new direction of research is thermonuclear combustion in stars. The most interesting applications are to novae and (type Ia) supernovae. In the case of a nova, the interesting question is how turbulent convection interacts with nuclear fusion of hydrogen on the surface of a white dwarf star, a problem which is rather similar to forest fires. For type Ia supernovae, on the other hand, the main question is how a thermonuclear burning front, fusing carbon and oxygen into ^{56}Ni, propagates in the degenerate matter of a massive white dwarf. Since the flame front is very narrow (only a fraction of a millimeter thick), the physical problem is very similar to that in combustion engines. Recently, type Ia supernovae have attracted considerable interest since they are thought to be good tools to measure cosmological parameters such as the expansion rate and the deceleration/acceleration of the Universe. Observations of this particular class of supernovae at high redshift seem to indicate that the expansion of the Universe is accelerating, possibly due to a positive cosmological constant.

In a series of papers, Wolfgang Hillebrandt, Jens Niemeyer (now at University of Chicago), Martin Reinecke and Martin Lisewski, in collaboration with Stan Woosley of the University of California and Alan Kerstein of Sandia National Laboratory at Livermore, have demonstrated that nuclear burning starts out as a subsonic deflagration wave. Hydrodynamically generated turbulence accelerates the wave to a few percent of the speed of sound. Depending on the initial conditions, this effect may be sufficient to unbind the white dwarf. The models also indicate that the explosion energy (and therefore the luminosity) of a thermonuclear supernova will depend on the nuclear composition of the white dwarf, opening the possibility of evolutionary effects in the lightcurves of the high-redshift sample. The numerical tools necessary for these simulations, i.e. a front capturing/tracking hybrid scheme, coupled to a finite-volume method with a sub-grid model to treat unresolved (turbulent) motions, were developed by the group. Simulations of classical novae have also been performed by Andreas Kercek, Wolfgang Hillebrandt, and Jim Truran (University of Chicago).

In addition to numerical simulations, the group has also become involved in more experimental and observationally oriented work. In a joint project with ESO, PhD student Gertrud Contardi compiled a set of bolometric light-curves of well studied type Ia supernovae. Her results show that the correlation between peak luminosity and shape of the lightcurve found in the blue and visual light bands does not hold for the bolometric light-curves, indicating that this correlation reflects opacity effects and not the energetics of the explosion. The group also analyzed the γ-ray flux in the lines of radioactive ^{44}Ti and found that because of the neglect of important atomic physics, previous determinations of the Ti-abundance are probably off by a factor of a few. Finally, Klaus Knie and Wolfgang Hillebrandt were succesful in their attempt to find radioactive isotopes on Earth that were produced by supernovae. In collaboration with Günter Korschinek, Thomas Faestermann, and Claus Wallner from the Technical University, and Jürgen Scholten from the University of Kiel, the group used accelerator mass-spectrometry with a sensitivity of 10^{-19} and found a few atoms of radioactive ^{60}Fe in deep ocean sediments. These are interpreted as the fingerprints of a supernova that exploded near the solar system a few million years ago. The work will be continued using probes from different locations and searching for other nuclei, such as ^{244}Pu.

The work of the group has profited from major national and international collaborations (DFG-SFB 375, DFG-Schwerpunkt "Analysis und Numerik von Erhaltungsgleichungen", INTAS- and ISTC- projects with several Russian institutes, ASCI-projects at Chicago, and Santa Cruz and Livermore). It has also benefited from access to top-end computers, which are necessary in order to carry out extremely big computations and to analyze and visualize the huge sets of computer-generated data.

3.3 Numerical Hydrodynamics

At the MPA there have been major achievements over the past two years in the development of new state–of–the–art numerical methods and codes and in the application of these codes to front–line astrophysical problems, including the simulation of relativistic flows (Harald Dimmelmeier, José Antonio Font, Tobias Leismann, Ewald Müller, Leonhard Scheck), the modeling of neutrino transport in core collapse supernovae (Hans-Thomas Janka, Markus Rampp), the simulation of turbulent thermonuclear burning in nova and type Ia supernovae (Anton Gröbl, Wolfgang Hillebrandt, Andreas Kercek, Martin Lisewski, Martin Reinecke), and the simulation of nucleosynthesis and clump formation in core collapse supernovae (Hans-Thomas Janka, Konstantinos Kifonidis, Ewald Müller, Tomasz Plewa) (see also section 2.8).

One major project, led by Ewald Müller, has been the development of methods and codes for the simulation of relativistic flows which occur in jets produced in active galactic nuclei and galactic X–ray binaries, in gamma–ray burst sources, in accretion flows onto neutron stars or black holes, and during the formation or merging of neutron stars and black holes.

In a successful long-term collaboration funded by a bilateral agreement between the Spanish research council (CSIC) and the MPG, and by the local government of the province of Valencia, Miguel Angel Aloy, José Mª. Ibáñez, José Mª. Martí (University of Valencia) and Ewald Müller have developed a versatile, highly efficient and parallelized 3D relativistic hydrodynamic code called GENESIS, which solves the relativistic fluid equations in an arbitrary static background spacetime metric using state–of–the–art high-resolution shock-capturing numerical methods. The code can accurately handle ultra–relativistic flows up to velocities of 0.999 999 999 99 times the speed of light. Relativistic flows with such large velocities have never been simulated before.

GENESIS was used to study, for the first time ever, the propagation and stability of 3D relativistic jets using a Minkowski background spacetime. GENESIS was also used to model (again for the first time) 2D axisymmetric relativistic jets from collapsars using a Schwarzschild background spacetime. The simulations demonstrated that a relativistic jet forms as a consequence of an assumed local energy deposition near the rotation axis of the collapsar and that the resulting flow is highly collimated, spatially very inhomogeneous, and strongly time dependent. After shock breakout the flow expands sideways with mildly relativistic velocities, but the beam remains very well collimated, and the maximum Lorentz factor increases to ~ 50.

José Antonio Font, Ewald Müller and Florian Siebel in collaboration with Philip Papadopoulous (University Portsmouth) have begun to work on the development of a full GR hydrodynamic code coupled to a solver for the Einstein field equations. The code utilizes null foliations of spacetime and a characteristic formulation of the hydrodynamic and Einstein field equations. The project is part of an international collaboration called GRACE, which involves researchers with expertise in both numerical relativity and relativistic astrophysics from South Africa, Spain, the UK, the USA and Germany. The new tool will allow the MPA's simulations of black hole–neutron star mergers, performed by Thomas Eberl, Hans-Thomas Janka and Max Ruffert (now at the University of Edinburgh), to be extended into the regime of General Relativity.

Another major project has been the development of an adaptive mesh refinement (AMR) code, which allows one to achieve very high spatial resolution with the minimum number of computational zones, and hence the minimum computational cost. This feature of AMR is crucial for a variety of astrophysical problems where the range of spatial scales to be resolved can extend over many orders of magnitude. The collaboration with Tomasz Plewa (Copernicus Center Warsaw) was vital for the success of the project. He provided a basic 2D AMR code as input. In collaboration with Konstantinow Kifonidis and Ewald Müller, the code was then extended to 3D and to self–gravitating, multi-component flows with thermonuclear burning. This new code AMRA (AMR for Astrophysics) has been used by Konstantinos Kifonidis to investigate the nucleosynthesis due to explosive silicon and oxygen burning, and clump formation in core collapse supernovae. For the first time, it was possible to simulate in 2D the propagation of the supernova shock from its formation out to the stellar envelope. The results show that all previous simulations of Rayleigh–Taylor mixing in core collapse supernovae, which could only cover the evolution later than 300 sec after core bounce, have been started from overly simplified initial conditions since they neglected clump formation within the first minutes of the explosion.

While AMR can help to overcome resolution problems if the interesting parts of the flow cover only a small fraction of the computational domain, it is of no use for other astrophysical flow problems that involve a wide range of length scales and that have flow structures that fill the entire volume. Such a situation is encountered, for example, when simulating turbulent combustion in stars (novae, type Ia supernovae), or in car engines. Instead of an adaptive grid refinement, one has to deploy large–scale eddy simulations (LES) widely used by engineers. Here the large scales are hydrodynamically simulated and the physics of the unresolved scales is described by a so–called sub–grid model. Moreover, if narrow burning fronts occur in the flow, front–capturing/tracking algorithms are also required.

Martin Reinecke, Wolfgang Hillebrandt, Jens Niemeyer (now at University of Chicago) and Anton Gröbl, together with Ruppert Klein (Konrad–Zuse–Zentrum, Berlin), have modeled deflagration fronts in reactive fluids. The astrophysical application are the turbulent deflagration fronts in white dwarfs undergoing a type Ia supernova explosion. The simulations utilized a level set method, which treats the front as a mathematical discontinuity. The level set algorithm was coupled to a LES code based on the finite-volume PROMETHEUS code (also developed at MPA) endowed with a sub–grid model. The same techniques have been used by Anton Gröbl and Wolfgang Hillebrandt to simulate hydrogen combustion in a solid container under terrestrial conditions. This project demonstrated that techniques developed for astrophysical flow problems can also be applied to study combustion in car engines, because the same basic physical processes are involved.

A third major project in numerical hydrodynamics is the coupling of hydrodynamics and neutrino transport in core collapse supernovae. All current treatments of neutrino transport in multidimensional simulations are deficient in their description of the neutrino interactions in dense matter and in their handling of semi–transparent regions where the transport mode changes from diffusion to free streaming. Recently interest has turned towards direct solutions of the Boltzmann transport equation. In the so–called S_N scheme, the Boltzmann equation is solved by a discretization of spatial, angular, energy and time variables. However, this method is too costly when the situation requires a large number of angular and energy bins, or when generalization to more than one spatial dimension is desired. At MPA, Markus Rampp and Hans-Thomas Janka have developed another accurate and efficient way to handle neutrino transport, which is expected to be superior to the competing S_N method. They use the discretized moment equations and determine the Eddington factor present in these equations by solving the angular dependent Boltzmann equation. In 1D this approach is flexible, efficient and as accurate as the S_N method, but allows for a better angular resolution, and can be generalized to the multi–D case without requiring excessive computer time. Currently, they apply their method to spherical core collapse, and to the first dynamical post–bounce simulations with a Boltzmann treatment of the neutrinos. The method also allows the explosion physics to be treated more realistically and will provide accurate predictions of neutrino luminosities and spectra of core collapse supernovae for terrestrial neutrino detectors.

3.4 High Energy Astrophysics

Nearly all major developments in modern high energy astrophysics, such as the establishment of cosmological distances to the γ-ray bursts or the discovery of millisecond phenomena in accreting neutron stars, are driven by observations in the X/γ–ray energy domain. This why the principle goal of the group led by Rashid Sunyaev is to complement the theoretical development of the field with the state-of-the-art data analysis of the experimental data.

The research carried out in high energy astrophysics at MPA ranges from studies of Galactic compact sources – accreting black holes and neutron stars– to studies of extragalactic sources such as γ-ray bursts and hot intergalactic gas in clusters. The similarities in the underlying physical processes and the use made of information from modern space observatories bind these diverse subjects together. The group is actively using the data from the ROSAT, MIR-KVANT, ASCA, GRANAT and RXTE observatories and is preparing to analyse future data from the Chandra, XMM, ASTRO-E, INTEGRAL and SPECTRUM-X missions. The group also provides scientific support for future missions that will lead to substantial progress in high resolution X–ray spectroscopy and microsecond timing.

X–ray binaries

The high timing resolution of RXTE has recently opened the possibility of observing the fast variability of X–ray sources. The MPA H.E.A. group has made good use of this new facility by studying accreting black holes.

Comptonization of soft seed photons in a hot, optically thin electron cloud near the black hole is thought to produce the hard X–ray radiation with a near power law spectrum in the standard X-ray band. The deviations in the spectrum caused by the reflection from the optically thick accretion disk are small, but are of crucial importance for understanding the geometry of the accretion flow. With this in mind, M.Gilfanov and E.Churazov, in collaboration with M.Revnivtsev of IKI, undertook a systematic spectroscopic/timing study of three black hole binaries using RXTE observations. They found a tight correlation between the spectral parameters and the characteristic noise frequency and interpreted this in terms of an inward shift of the inner boundary of the optically thick accretion disk accompanied by cooling of the Comptonization region, increase in reflection efficiency and rise of the characteristic frequencies (see also section 2.5). They analyzed the data in a novel way, using a frequency resolved spectral analysis method, and found that at high frequencies, the reflected component fails to follow variations of the comptonized radiation, thus placing an important constraint on the size of the reflecting region.

Further driven by the mounting evidence that the characteristic frequencies of the black holes power density spectra are intimately linked to the inner edge of the accretion disk, E.Churazov and M.Gilfanov, in collaboration with S.Trudolyubov of IKI, concentrated on the famous Galactic superluminal source GRS1915+105, which has exceptionally rich data from RXTE. They found a clear correlation of the QPO frequency change and the frequency itself which fits remarkably well the expected dependence between the viscous time scale and the Keplerian frequency in the radiation dominated accretion disk. This makes the inwards/outwards motion of the inner edge of the accretion disk on a viscous time scale a likely explanation of the sometimes bizarre behavior of the source. The correlation of the QPO frequency with the luminosity and temperature of the soft component also fits this picture.

Another puzzle, which attracts a lot of attention, is the transient behavior of the vast majority of black holes in the low mass X–ray binaries (BHLMXB). However, two objects in the Galactic Center region (1E1740.7–2942 and GRS1758–258), which probably belong to the same class, are persistent though variable sources. If thermal instability of the accretion disk in the region of partial hydrogen ionization is responsible for the outbursts of BHLMXB's, then the non-transient behavior of these two sources would imply that the black holes have low mass and that the orbital periods are short.

The above mentioned source - 1E1740.7-2942 - has many additional peculiarities. In particular it is believed to be located inside a dense molecular cloud. This opens a unique possibility of studying the source properties through its impact on the dense environment. R.Sunyaev and S.Grebenev (IKI) considered how the UV photons emitted in the outer parts of the accretion disk produce a region of ionized hydrogen around the source that is markedly different from conventional HII regions. Using radio data, they obtained strong constraints on the disk UV and EUV spectra.

Quasars and microquasars

GRS1915+105 is one of three known Galactic microquasars – accreting X-ray binaries that show superluminal motion of the radio jets. The jets in these sources are believed to be a scaled down version of jets in radio galaxies and quasars. Driven by this concept, C. R. Kaiser, R. Sunyaev and H. C. Spruit developed an analytical model for the radio synchrotron emission caused by a shock front traveling along a conical, magnetized plasma jet. This model is equivalent to the internal shock models for jets in extragalactic radio sources and it successfully explains the temporal and spectral behavior of the observed radio emission of galactic microquasars during outbursts. It can explain why these objects have semi-permanent jets and resolves some of the difficulties of the old plasmon models (see also section 2.7

C. R. Kaiser has also developed an analytical method of studying the observed distribution of radio emission from powerful radio galaxies. The method makes use of radio maps of moderate angular resolution and allows the properties of the radio jets and of the gas around them to be quantified. The results are in good agreement with direct X-ray measurements of the external gas density in the vicinity of Cygnus A. Kaiser also developed a simplified method that will allow the environments of large numbers of radio-loud AGN to be analyzed in a uniform way.

In a collaboration with P. N. Best (Leiden University) and J. Dennett-Thorpe (Groningen University), C. R. Kaiser has started an observational campaign to investigate and interpret the Faraday rotation measured towards a sample of extragalactic radio sources. This study will constrain the gas density and the magnetic field strength in the vicinity of these objects and will study the variation of these quantities with redshift and/or radio luminosity. The first set of radio observations have been taken and the project is expected to be completed in early 2000.

γ–ray burst studies

The year 1997 marked the beginning of the "afterglow era" in Gamma-Ray Burst (GRB) studies. The fast and accurate localizations of GRBs by the BeppoSAX observatory were crucial for establishing the connection between GRBs and the sources of decaying X-ray, optical, and radio emission lasting for weeks and months after the main event. The missing element was the observation immediately after a burst, when the Lorenz factor of the relativistic expansion is believed to be maximal. An archival search of the GRANAT database performed by M.Gilfanov, in collaboration with R.Burenin, A.Tkachenko and O.Terekhov of IKI and A.Vikhlinin of CfA, resulted in the discovery of such early afterglows for several bright GRBs. Most interestingly, an abrupt change of the spectral index near the end of the main burst was found for the two brightest events. In the framework of the fireball theory, this change might correspond to the moment when the synchrotron emission from the external shock exceeds that of the internal shocks. Remarkably, the afterglow light curve follows a nearly perfect power law over five decades in time.

The GRANAT mission has operated successfully for a total of 9 years. Recently, R.Sunyaev in collaboration with researchers from IKI (Russia), DSRI (Denmark) and CESR (France) released a catalog of cosmic γ–ray bursts detected by the WATCH and PHEBUS instruments aboard this observatory. The PHEBUS catalog is made publicly available through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA/GSFC.

R. Popham, in collaboration with S. Woosley and C. Fryer (both UC Santa Cruz), studied black holes accreting at extremely high rates of 0.01 to 10 solar masses per second. These are currently the leading candidates for the GRB central engines. They found that for accretion rates of more than a few hundredths of a solar mass per second, and for rapidly spinning black holes, neutrino-antineutrino annihilation can produce the pair fireball which is believed to result in a gamma-ray burst.

S. Mao and H.J. Mo studied the connection between the incidence of gamma-ray bursts and the observed global star formation history of the Universe. They found that a model in which the rate of gamma-ray bursts is proportional to the star formation rate can reproduce the observed properties of GRBs quite well. The model predicts that the redshift distribution is peaked at $z \sim 1$; about 15 percent of the hosts have $z > 2.5$. It was also found that the host galaxies of gamma-ray bursts are quite faint (most have I-band magnitudes between 21.5 and 28), and small (most have semi-major axis smaller than one arc second). These predictions are confirmed by the dozen GRB host galaxies observed so far.

Clusters of galaxies

Spatially resolved X–ray data are a valuable source of information on the dynamic state of clusters of galaxies. E.Churazov and M.Gilfanov (in collaboration with Bill Forman and Christine Jones of CfA) developed a robust and computationally efficient method for making 2D gas temperature distribution maps of clusters. For example, they produced a gas temperature map of the Centaurus cluster. The galaxies exhibit a bimodal velocity distribution and there is an excess in the X–ray surface brightness to the South-East of the cluster center. This indicates that either there are two subgroups in the process of merging, or that two groups are simply projected onto each other. The temperature map removes this degeneracy. Much higher quality data will soon be available from Chandra and XMM and work is in progress to update the methods accordingly.

Radio astronomy provides another important way of probing the clusters. Torsten Enßlin is involved in two observational campaigns to measure the magnitude and the morphology of the magnetic field in clusters. One is a 74 MHz VLA observation of the Coma cluster and its environment carried out in an international collaboration bringing together many experts in low-frequency radioastronomy such as P. Kronberg (Univ. Toronto), R. Perley (NRAO-Socorro), N. Kassim (NRL-Washington), L. Feretti (Univ. Bologna). The second project is to synthesize Faraday rotation maps of the Mpc-sized 'cluster radio relics' in Abell 2256. These observations will allow intra-cluster magnetic fields to be probed on a cluster wide scale and the maps will be compared with the results of MHD cluster formation simulations carried out at the MPA by Klaus Dolag.

3.5 Accretion

Recent improvements in X-ray observations have raised important theoretical questions about the nature of accretion onto compact objects, white dwarfs, neutron stars, black holes and protostars. The similarity of the physics of accretion processes around stellar and supermassive black holes allows discoveries about stellar systems to be extended to Active Galactic Nuclei (AGN). The RXTE and ASCA spacecraft continue to provide a wealth of detailed information about accreting X-ray binaries, providing new constraints on theoretical models.

Much of the work on accretion carried out at MPA focuses on the understanding of accretion processes near black holes. The TMR Network 'Accretion onto Black Holes, Compact Stars and

Protostars', coordinated by Henk Spruit of the MPA, funds collaborations between 7 different European institutes. Joint projects focus on understanding the radiation from AGN and Galactic black hole candidates, the origin of the strong time variability observed in almost all accreting compact objects, and on compact objects as central engines for jets and Gamma-ray bursts.

One key question for accretion flows around black holes is how the accretion occurs near the central object, via a thin disk or as an advection-dominated accretion flow (ADAF). Using the ADAF model, one is able to model spectra from stellar and supermassive black holes in various energy bands. One missing link in the theory has been reason for the transition from disk accretion to the ADAF. Friederich Meyer has demonstrated that the transition can be understood by considering the physics of the equilibrium between the thin disk and the corona above it. A model for the evaporation of the inner accretion disk to a corona has now been developed at the MPA and it is expected that detailed comparisons with observations will enable further refinements to be made.

New observational data on transient X-ray sources has renewed interest in understanding the outburst behaviour. X-rays from the inner regions heat the outer accretion disk and thereby prevent the early launch of a cooling wave that would cut off the outburst. This irradiation also explains the near-exponential decay of outburst luminosity that is typically observed (Hans Ritter, in collaboration with Andrew King, Leicester, UK). Evaporation has a decisive effect on the outburst cycle. By formation of an inner hole in the standard thin accretion disk, the early onset of instability is prevented, resulting in a long lasting quiescence followed strong outburst. This is what is observed in many X-ray novae (Emmi Meyer-Hofmeister).

The MPA group has also studied the innermost regions of the disk around accreting neutron stars or white dwarfs. They have developed new insight into the physics of the flow from the accretion disk to the neutron star surface and have come up with a remarkable result: at luminosities $L > L_{edd}/100 \sim 10^{36}$ erg s^{-1}, the flow smoothly passes to the neutron star surface and forms a rapidly rotating optically thick layer which spreads in latitude, supported against gravity by radiation pressure. This layer is very thin (less than 1 km) and has very high sound speed (of the order of 20,000 km s^{-1}). In this situation, various hydrodynamical instabilities give rise to a high-frequency noise in the registered flux of X–ray radiation, which should extend up to 10–40 kHz. These frequencies exceed by almost two orders of magnitude the maximal frequencies of the noise produced in the accretion discs around black holes of stellar mass. These theoretical predictions are a key motivations for the construction of a new, post-RXTE satellite, LASTE, which will have an effective detecting area of more than 10 square meters. It should then be possible to test the presence of high-frequency noise and quasi-periodic oscillations in the discussed frequency range.

Mikhail Revnivtsev and Rashid Sunyaev have analysed RXTE data and have demonstrated that the power spectra of accreting stellar-mass black holes and neutron stars–bursters differ drastically. The power spectra of black holes decline abruptly above several hundred Hz, whereas those of atoll-sources spread up to 1 to 2 kHz, the detection limit of the RXTE detectors. Nail Sibgatullin has studied the efficiency of accretion onto rapidly rotating neutron stars and found that for a disk in counterrotation to the neutron star, the energy release may reach 65% of $\dot{m}c^2$.

Robert Popham and Rashid Sunyaev have used a numerical code to study the optically thin interface between the disk and a weakly magnetized neutron star. In the hot gas, soft photons from the denser neutron star surface are converted into hard X-rays by inverse Compton scattering, producing the power-law X-ray spectrum observed in many low-mass X-ray binaries. Popham proposed that dwarf nova oscillations and the kilohertz oscillations in X-ray binaries could arise from non-axisymmetric features at the point of transition from the cool, dense disk to a hot thin boundary layer.

Hans Ritter has demonstrated that the spin-up of binary neutron stars to millisecond periods by accretion is severely limited when it occurs at super-Eddington rates. Most of the transferred material is ejected instead of accreted. This has a significant effect on the evolutionary paths of such binaries.

The analysis of the cyclotron radiation from accretion columns on strongly magnetized white dwarfs is a way of deriving system parameters for the 'AM Her' class of mass transfering binaries. Optical observations of X-ray detected sources have greatly increased the knowledge of this subgroup of cataclymic variables (Hans-

Christoph Thomas). There are indications that in cataclysmic binaries, the origin of the accretion disk viscosity in quiescence lies in the magnetic fields of the secondary stars.

Recent discoveries of extrasolar planets at small orbital radii, or with significant eccentricities, indicate that interactions between massive planets and the disks of gas and dust from which they formed are vital for determining the final shape of planetary systems. Philip Armitage showed that if this interaction occurs at an early epoch, when the protoplanetary disc is still massive, then rapid planet growth through accretion causes an otherwise stable disc to fragment into additional planetary mass bodies when the planetary mass reaches 4-5 Jupiter masses (see section 2.6). It was suggested that such catastrophic planet formation could account for apparent differences in the mass function of massive planets and brown dwarfs, and the existence of young stars that appear to have dissipated their discs at an early epoch. Subsequent gravitational interactions will lead to planetary systems comprising a small number of massive planets in eccentric orbits.

3.6 Interaction of radiation with matter

Sergei Sazonov (Moscow, Space Research Institute, visiting MPA) and Rashid Sunyaev have analyzed how single Compton scattering of photons in a hot, optically thin medium can broaden spectral lines. Analytical formulae were derived describing the resulting line profiles, which are applicable if the energy of the incident photons and the temperature of the scattering plasma are both mildly relativistic. Such conditions are met in various astrophysical environments, namely in the intergalactic medium in clusters, in the coronae of accretion disks around black holes and in plasma streams outflowing from a neutron star during X-ray bursts. The measurement of Compton-broadened lines (both at X-ray and at lower frequencies) is thus an efficient diagnostic of astrophysical plasmas. In preparation for upcoming X–ray missions, Sazonov and Sunyaev are currently modeling the predicted X-ray spectra of various classes of objects, taking into account the Compton–broadening effect, This research has led to an interesting result: an isotropic ensemble of relativistic electrons preferentially scatters low energy photons backwards. This asymmetry causes the albedos of the hot coronae of compact objects to increase and the photon path in a hot plasma cloud to lengthen. The latter in turn affects the shapes of forming Comptonization spectra and the time delays between soft and hard radiation from variable X-ray sources.

Turning to another limit of cold matter, Rashid Sunyaev and Eugene Churazov (in collaboration with Leonid Vainshtein and Dmitry Uskov of Lebedev Institute, Moscow) have studied the distortions in the shape of the lines due to the Compton scattering by electrons bound in neutral atoms and molecules. Because of differences in the structure of their energy levels, each element leaves unique imprints on the scattered spectra. The technique known as "Compton profile measurements" has been used for decades in laboratories to probe the inner electron shells of heavy atoms. In astrophysics it may pave a way for measuring the helium abundance in distant objects using fine X–ray spectroscopy.

Particularly line–rich spectra arise when cold matter (e.g. molecular tori in AGNs) is illuminated by hard X–ray radiation. The lines in such spectra are due to fluorescence, while the continuum is due to Compton scattering by the electrons. The central square degree of our Galaxy may also become a laboratory for high resolution spectroscopic measurements. It has the highest mass concentration of molecular gas in the Galaxy and harbors many bright compact X–ray sources. It is also known to host a powerful diffuse X-ray source with luminosity of $\sim 10^{37}$ erg/sec. The presence of the fluorescent line of neutral iron at E=6.4 keV proves that emission reprocessed by cold neutral matter contributes significantly to the observed X-ray radiation. M.Gilfanov and R.Sunyaev used data from the Japanese ASCA satellite to study the morphology of the reprocessed emission using the 6.4 keV fluorescent line emission as a tracer. The brightness of the fluorescent emission peaks strongly at the position of Sgr B2, the most massive of the giant Galactic Center molecular clouds. The spectrum of the Sgr B2 and the enormous equivalent width of the 6.4 keV line, ~ 2 keV, reveal the unique nature of this source as a rare case in which only reprocessed emission reaches the observer. The primary radiation is hidden, either because of absorption or because of geometrical effects. One possibility is transient activity of the supermassive black hole in the Galactic Center, Sgr A*, ~ 400 years ago.

3.7 Cosmic Microwave Background

Planck Surveyor, the third Medium-Sized Mission (M3) of ESA's Horizon 2000 Scientific Programme, is scheduled for launch in early 2007. Over a two–year period its two instruments (known as HFI and LFI) will map the Cosmic Microwave Background over the entire sky with unprecedented resolution, sensitivity and frequency coverage. The primary goal of the mission is the measurement of the angular power spectrum of primordial fluctuations. With its many frequency channels and its broad spectral coverage, *Planck* will be ideally suited to decompose the microwave sky into its individual physical components. *Planck* is expected to discover of order 10^4 high-redshift point sources such as radio-, sub-mm, and infrared galaxies. Depending on cosmology, up to 10^5 galaxy clusters will cast detectable Sunyaev-Zel'dovich shadows on the cosmic microwave background. The Galaxy contributes synchrotron, dust, and free-free emission in microwaves, and the planets, the Moon, the Zodiacal light and perhaps even asteroids and comets will add local components. The capability of *Planck* to detect and isolate foreground components will undoubtedly become its richest heritage. For the MPA, with its orientation towards cosmology and extragalactic astrophysics, participation in the *Planck* project offers a unique opportunity and an outstanding challenge.

Planck is being planned and developed by a European consortium led by one Principal Investigator for each instrument. The MPA is the only German partner and is formally involved with both instruments. Simon White is a Co-I on both *Planck* instruments. Rashid Sunyaev is a Co-I on HFI, and a Scientific Associate on LFI. Tony Banday and Matthias Bartelmann are Scientific Associates on both HFI and LFI.

All of *Planck* data processing, archiving, and information exchange will be carried out within the *Integrated Data and Information System* (IDIS). MPA is involved in the overall development of all aspects of IDIS, and has specific responsibility for developing and implementing one of the IDIS components. The second responsibility of MPA within the *Planck* consortium is to build up and operate the archive for all mission data products. The total amount of *Planck* data is estimated to reach 0.5 TB. The third task of MPA is the coordination of the development of a complete data-simulation pipeline.

To fulfil these three tasks and to further develop *Planck* related science activity, MPA is setting up a heterogeneous group of scientists, scientific programmers, and software developers, led by Matthias Bartelmann. Tony Banday contributes his detailed experience with CMB-related experiments, gained within the COBE consortium. While all positions related to software development will substantially be funded by the German Space Agency (DLR), the scientists' positions will be added from MPA funds. The MPA *Planck* group has already produced prototype software both for data simulation and for later integration into IDIS. A dedicated workstation cluster is being built up to satisfy the high computational demands of the growing group.

The MPA expects to be involved in many aspects of the science from *Planck*, in particular those involving foregrounds, for example, Compton scattering during reionisation or by galaxy clusters, gravitational lensing of primordial fluctuations by the foreground mass distribution, emission by foreground sources in our own and other galaxies.

The study of distortions of the CMB in the directions of galaxy clusters is a rapidly developing field in observational cosmology. At the MPA, Rashid Sunyaev has been leading an effort to advance theoretical modelling of these effects.

Antonaldo Diaferio and Rashid Sunyaev (in collaboration with Adi Nusser from TECHNION, Israel) used high-resolution N-body simulations to investigate how thermal motions of electrons in the intracluster medium and the peculiar velocity of clusters can affect the secondary anisotropies in the CMB through the thermal (tSZ) and kinematic (kSZ) Sunyaev-Zeldovich effects. This study demonstrated that simultaneous pointed observations of superclusters in the millimeter and submillimeter bands with upcoming CMB experiments such as *Planck* will be able to separate the tSZ and kSZ contributions and constrain the evolution of the velocity field in large overdense regions.

The dramatic improvement in data quality achieved by several experimental groups as well the great sensitivities of the upcoming *Planck* and FIRST satellites, have motivated a more accurate theoretical description of SZ effects, taking into account the relativistic corrections related to the high thermal velocities of electrons. Sergei Sazonov (Moscow, Space Research Institute, visiting MPA) and Rashid Sunyaev have carried out analytic calculations of these effects. They showed that the main correction is about 10 per cent in the Rayleigh-Jeans region of the CMB spectrum and comparable to the magnitude of the non-relativistic effect in the Wien part of the spectrum. These results have been confirmed by two groups, Japanese (Itoh and collaborators) and British (Challinor and Lasenby). The derived formulae demonstrate that the radial peculiar velocities of clusters may be determined accurately in the next decade.

Future experiments will explore the primordial polarization of the CMB. Sazonov and Sunyaev have recently carried out a re-analysis of polarisation effects by clusters.They find that most of the emergent polarization arises from the presence of a quadrupole component in the CMB angular distribution. The expected signal is small, but potentially measurable in combined observations of hundreds of clusters. Signals from high-redshift clusters will reflect the quadrupole anisotropies seen from remote locations in the Universe and at past epochs. A detailed investigation of this is being carried out in collaboration with Alexei Starobinsky from Landau Institute for Theoretical Physics (Moscow).

In an important series of papers written at MPA, Uros Seljak (long-term MPA visitor, now at Princeton University) and Matias Zaldarriaga (IAS Princeton, also an MPA visitor) analysed how gravitational lensing by foreground material distorts the pattern of primordial fluctuations in the CMB. In particular, they showed that measurements of such distortions will not only provide an important check on the consistency of the basic cosmological paradigm, but should also resolve some of the most troublesome parameter degeneracies.

Seljak and Zaldarriaga also showed that the evolution of the large-scale linear gravitational potential expected in open or cosmological-constant dominated universes can be measured directly by cross-correlating the primary CMB fluctuations with the projected mass density field reconstructed from lensing distortions. This provides an independent constraint on global cosmological parameters. Seljak continues to visit MPA regularly for one month a year and is a *Planck* LFI and HFI Associate through the MPA.

Tony Banday has been involved in the analysis of the COBE-DMR sky maps. Together with S. Zaroubi and K. Gorski (ESO), he showed that the non-Gaussian signal detected in the publicly available DMR sky maps is due to a systematic artifact in the data. He has also used the maps to set limits on global rotation and shear in the early Universe in collaboration with A. Kogut and G. Hinshaw of NASA's Goddard space-flight center.

3.8 Numerical Cosmology

Numerical simulations are a primary tool for many aspects of the MPA's scientific work. In extragalactic astronomy and cosmology they are used to study the formation, evolution and internal structure of galaxies, the growth of large-scale structure in the Universe, the lensing properties of the dark matter distribution, the evolution of the intergalactic medium both in galaxy clusters and along the line-of-sight to quasars, and the early collapse of pregalactic objects. The development of numerical codes for such work is a major activity in the group led by Simon White, but these codes and the simulations they produce are used by many others in the institute and elsewhere. In addition, other groups have developed special purpose code or imported external codes suited to specific problems.

Much activity in this area is carried out as part of the Virgo Supercomputing Consortium. The principal code of this collaboration, Hydra, is currently being rewritten in standard message-passing form to allow computation on a wide range of platforms. This is a major effort (to finish in early 2000) with substantial support from the Computing Centre of the MPG in Garching and from the Edinburgh Parallel Computing Centre. A second code, Gadget, has been written entirely at MPA over the last two years (by Volker Springel) and is available in versions for serial and parallel machines as well as for the Grape special purpose hardware. Both of these codes combine N-body and Smoothed Particle Hydrodynamics techniques to follow mixtures of gas, dark matter and stars. Hydra is best suited to simulation of large volumes, and Gadget to detailed simulation of individual objects. A highlight of recent Virgo code development was the production in Garching of a stripped-down version of Hydra which made it possible to carry out the Hubble Volume simulations on the Garching T3E. These 10^9-particle simulations were able to follow the development of structure along the past light-cone of the observer over a large fraction of the observable universe. They allow a precise characterisation of the statistics of the large-scale structure, and in particular of the galaxy cluster population expected in ongoing large observational surveys such as the Sloan Digital Sky Survey. Each simulation produced 0.7 Tbyte of raw output data and analysis of these data has required the development of new visualisation and data-management techniques.

A major thrust of current simulation work at MPA is the development of new techniques for the detailed study of galaxy clusters. Thus Klaus Dolag and Matthias Bartelmann have simulated the growth of magnetic fields during cluster collapse, finding surprisingly strong turbulent amplification, Catherine Cress has followed the pollution of the intracluster medium with heavy elements as a result of the formation and evolution of galaxies, and Volker Springel has simulated formation of a rich cluster with such high resolution (better than $10^8 M_\odot$ and 1 kpc) that the dark matter cores of almost 5000 individual "galaxies" still survive in the final object. In the last two projects semianalytic galaxy formation methods are combined with simulations to allow treatment of star formation and stellar evolution within galaxies. This approach has been pioneered at MPA and allows much more direct comparison of simulation and observation than has previously been possible.

Over the last two years MPA has produced several other interesting simulation results. Tom Abel, in collaboration with Mike Norman of NCSA, Illinois (a Humboldt Fellow at MPA) carried out 3-D simulations of the collapse of one of the "first stars"; an object of a few hundred solar masses is produced naturally from cold dark matter initial conditions (see also section 2.10). Tom Theuns, an EC-funded TMR fellow, simulated structure in the intergalactic medium (with J. Schaye and G. Efstathiou of IoA Cambridge) showing that its temperature can be measured from the Lyα forest absorption in quasar spectra; an application to Keck data appears to detect the second reionisation of helium at $z \sim 3$. Karsten Jedamzik and Jens Niemeyer simulated the formation of black holes at the quark-hadron phase transition, showing that objects of stellar mass may be produced. Volker Springel teamed up with P. Duc (also IoA Cambridge) to model the dynamics of interacting galaxies; they were able to reproduce the properties of the nuclear starbursts in several observed systems. Finally, Simon White and Amina Helmi (a Leiden student supervised under the EARA agreement) followed the evolution of the star streams produced when a small satellite is accreted and disrupted by the Milky Way. A comparison of their results with Hipparcos data on nearby stars led to the discovery of such debris streams in the solar neighbourhood (see section 2.2 for more details).

3.9 Gravitational Lensing

Strong lensing, the generation of multiple or highly distorted images of background sources by an intervening mass concentration, has traditionally been the primary application of lensing. Multiply-imaged QSOs provide extremely accurate mass measurements of lensing galaxies inside their Einstein radius, although the mass profile can not be uniquely inferred from the observables. S. Mao, in collaboration with H.-J. Witt, has shown that quadruple image positions obey a number of universal relations that are independent of the galaxy's mass profile and that agree well with observed systems. In contrast, a corresponding "universal" relation for the magnification ratios of highly magnified images is sometimes grossly violated. An investigation of the quadruple system B1422+231 by S. Mao & P. Schneider demonstrated that the flux ratios of the bright images *require* the lensing galaxy to have substructure on scales $\leq$ 1kpc. The properties of spiral galaxies as lenses have been studied by M. Bartelmann and A. Loeb (CfA). In contrast to previous work, they accounted for extinction by dust in these systems. This work was then extended by M. Bartelmann to predict the frequency of spiral lens systems at the very faint limiting QSO magnitudes that will be achieved by NGST.

The frequency of giant arcs in clusters of galaxies depends on the abundance of rich clusters at redshifts of $z \sim 0.3$, which in turn depends on the cosmological model. In a collaboration led by M. Bartelmann, the cosmological simulations from the GIF collaboration have been used to predict the arc abundance; the comparison with the known population of arcs argues strongly against a cluster-normalized Einstein-deSitter model and is most compatible with an open model.

Galactic microlensing events, which are caused by the lensing of bright background stars by foreground stellar-mass objects, are now detected routinely by a number of different groups. The original purpose of microlensing surveys was to ascertain whether the dark matter halo in our Galaxy is made up of MACHOs, but their results have had an impact on many other astrophysical fields. For example, S.Mao and collaborators from Munich Observatory have performed a quantitative analysis of the spectrum of a star in the Galactic bulge taken at caustic crossing. Because the star was magnified by a factor ~ 25, it was possible to investigate its detailed properties and derive an estimate of its age. S. Mao also studied another microlensing event that displayed a clear parallax effect – the motion of the Earth around the Sun was reflected in the light curve of this event – and derived the relative transverse velocity of the lens.

Weak gravitational lensing, the distortion and magnification of faint high-redshift galaxies by the intervening mass distribution, has been the dominant research area of the MPA group for the last few years. M. Bartelmann and P. Schneider have recently written a detailed review article on the subject. In a diploma thesis supervised by M. Bartelmann, M. Schirmer has re-reduced all of the publically available HST cluster data and obtained mass reconstructions for the clusters . In addition, he has demonstrated how the lensing strength depends on the surface brightness of the galaxy images, thus allowing the determination of the relative distances as a function of surface brightness (lens parallax method).

The redshift evolution of the abundance of rich clusters provides an extremely useful measure of the underlying cosmological model. The masses of clusters are much simpler to predict than their luminous properties, such as their optical light or X-ray luminosity. This is why selecting clusters purely according to mass is very valuable. In addition, it is interesting to see whether any halos are found with extremely high mass-to-light ratios. P. Schneider developed a weak-lensing statistic for selecting halos by mass – the so-called aperture mass $M_{\rm ap}$ – and in collaboration with G. Kruse, determined the abundance of observationally detectable halos in various cosmological models. They concluded that $\sim$ 10 halos per square degree would be found in deep, high-quality optical images in an EdS Universe, and considerably more for lower-density cosmological models; a weak lensing survey of $\sim 25\mathrm{deg}^2$ would be able to distinguish between some of the most popular cosmological models with high significance. K. Reblinsky and M. Bartelmann showed that the selection of clusters using $M_{\rm ap}$ yields samples which are more complete and contain fewer false-positive detections than cluster selection using the Abell criteria.

Because $M_{\rm ap}$ is a scalar quantity which can be obtained directly from the observed image ellipticities, it is a very convenient measure of the so-called cosmic shear, the weak distortion of galaxy image shapes by the tidal field induced by the distribution of matter on large scales. The observed properties of $M_{\rm ap}$ have been investigated using blank-field surveys. The theoretically-predicted properties of $M_{\rm ap}$ can be studied using ray-tracing through the mass distribution in high-resolution N-body simulations. There have been two major studies using the GIF simulations carried out at the MPA, one led by K. Reblinsky and collaborators, the other led by B. Jain. Analytic predictions based on empirical fits to the power spectrum of cosmic density fluctuations and/or the Press-Schechter model for dark-matter halo abundances turned out to be surprisingly accurate. Now that wide-field lensing surveys are on the brink of producing their first results, this combination of state-of-the-art cosmological simulations and lensing studies will be of utmost importance for a quantitative interpretation of cosmic shear data.

On the observational side, members of the MPA are involved in a number of important weak-lensing projects. For example, (1) P. Schneider and T. Erben have teamed up with H.-W. Rix and C. Wolf (MPIA, Heidelberg) to obtain a large imaging data set with the WFI@ESO 2.2 meter for studying galaxy-galaxy lensing. Five nights have been allocated for this program in Oct. 1999. (2) D. Clowe is leading a project, in collaboration with colleagues in Cambridge and Paris, to study the mass distribution between multiple clusters, with the aim of finding massive filaments connecting them. This project has received 15 nights at various major telescopes. (3) T. Erben and P. Schneider – together with L. van Waerbeke (CITA) and Y. Mellier and R. Maoli (IAP, Paris) – are involved in the weak-lensing analysis of a wide-field imaging survey from the UH12K camera at the CFHT, for which 32 nights have been allocated over a period of two years. (4) The same collaborators have succeeded in obtaining 32 hours of time with FORS@VLT for studying cosmic shear in ~ 60 fields spread randomly over the sky. This was the largest GO program in the first semester of regular VLT operation. (5) In a collaboration between researchers at MPA and the ST-ECF at ESO, parallel data from the STIS instrument on-board HST are being analyzed in order to study cosmic shear on small angular scales; this collaboration was deeply involved in shaping the current STIS parallel program.

In parallel to these ongoing observational programs, T. Erben is currently studying ellipticity measurements of very faint sources and deriving corrections for PSF effects on real CCD images. This is essential for a detailed quantitative interpretation of the lensing results. One result that has already emerged from these efforts is the highly significant detection of a mass concentration without any obvious luminous counterpart in two independent wide-field images. This proves the first example of a mass-selected dark matter halo with large M/L (see section 2.1). A preliminary analysis of UH12K data from project (3) above has yielded several more strong candidates for dark clusters. Another recent observational result by D. Clowe and collaborators is the optical and IR identification of the $z = 1$ cluster 2016+112 both as an overdensity of color-selected galaxies, and as a weak lensing mass peak.

3.10 Quantum mechanics of atoms and molecules; astrochemistry

Ever since mankind started to use tools it has been looking for materials with special, predefined properties. Today, research and development in chemical and pharmaceutical industry is directed primarily towards finding and synthesizing compounds, pharmaceuticals and materials with pre-defined properties. The atomic structure of most compounds and materials is known and understood through experimental studies and computer simulations. Reliable methods have been developed to calculate properties of compounds and materials of known structure. The methods have become widely used in research and development for the prediction of properties of new compounds, pharmaceuticals and materials and in the development of novel environmentally sustainable technologies. The ultimate goal for the technological application of theoretical and computational molecular sciences and molecular engineering is, however, the accurate and reliable prediction of chemical structures with pre-defined physical and chemical properties and/or biological activity. Developing the methodology and software for the quantitative property-structure relationship approach, as opposed to traditional quantitative structure-property relationship, is undoubtedly an ambitious and difficult task. Nevertheless, it is most timely to challenge this scientifically and technologically important issue. Presently, the OpenMol project pursued by Geerd Diercksen involves researchers from computational chemistry and computer science from Belfast, Bratislava, Nagoya, Sapporo, Tartu, and Torun. The project is focussed on capturing the chemical knowledge necessary for understanding the quantitative property-structure relationship, on formalising it and on developing generic, analytic, synthetic and numerical problem-solving methods.

Concerning computational studies of molecular properties and dynamics Geerd Diercksen has concentrated his research interests on the study of Rydberg molecules and clusters, both in isolation as well as in the condensed phase. A wealth of detailed spectroscopic information is available for Rydberg states of molecules in isolation and for atoms and molecules as foreign particles in liquid helium. Many of these experimental data cannot by explained by the available models like the quantum defect theory for Rydberg states of isolated systems and the standard bubble model for defect centers confined in helium matrices. The challenges of interpreting the unexplained spectral features include, among many others, the coupling of the Rydberg electron and the nuclear rotation-vibration of the molecular core and the dynamics of electronically excited defect centers in liquid helium. These studies are an ambitious and difficult task because standard quantum chemical methods are not directly applicable and new models have to be developed that describe correctly the physics and are amenable to computation. They are pursued in co-operation with colleagues from Calcutta, Tokyo and Torun (Dorota Bielinska-Waz, a Humboldt Research Fellow).

In the Molecular Physics group W.P. Kraemer is working on the development of new methods for studying basic reaction types occuring in various interstellar environments as well as on the interpretation and prediction of rotation-vibrational sprectra of small molecular species. Rigurous theoretical methods based on quantum mechanical principles (so-called *ab initio* methods) have served in the past as valuable tools assisting in the interpretation of experimental results and especially the interpretation of molecular spectra with the help of *ab initio* calculations has been of fundamental importance for the recent progress in molecular spectroscopy. Since his early calculations of the spectral properties of isolated electronic states W.P. Kraemer now concentrates his research in this field on analysing the spectra of interacting electronic molecular states. Therefore in collaboration with colleagues from the University of Wuppertal and from the NRC Canada spectroscopic effects due to the coupling of electronic and nuclear motions are studied for Renner-Teller degenerate triatomic molecules. In this special case the couplings lead to well-defined shifts and splittings of the rovibrational levels. For a number of molecules of this type the complete rotation-vibration spectra were predicted and some of these results have led to a re-interpretation of experimental results derived from recent measurements using the Coulomb explosion imaging technique. Whereas the Renner-Teller effect can still be treated within the framework of the fundamental Born-Oppenheimer approximation, the interpretation of the spectral properties of other interacting systems such as for instance a series of close-lying Rydberg states requires to go beyond this approximation. Together with P.-Å. Malmqvist (University of Lund, Sweden) W.P. Kraemer has determined the non-adiabatic coupling terms between pairs of the lower lying Rydberg states for the light eximer system HeH. Calculated individual transition rates as well as total radiative and non-radiative lifetimes for some of these states were obtained in perfect agreement with recent experimental findings.

In the other field of main interest W.P. Kraemer studies basic interstellar reactions such as radiative association, photodissociation, and electron-ion dissociative recombination using a rigorous quantum mechanical state-to-state approach. Essential in the theoretical treatment of the first two reaction types is the accurate characterization of the long-living rotation-vibrational resonance states, which are quasi-bound states with energies slightly above the lowest dissociation limit of the molecular system. The *ab initio* determination of these states is mostly trivial in the case of diatomic molecules but becomes a very difficult task for general triatomics. At the present stage of this project W.P. Kraemer together with colleagues from the Academy of Science in Prague have succeeded to calculate some of these states for weakly bound triatomic species applying a specially developed perturbational approach. The theoretical treatment of the dissociative recombination reaction can be limited in a few cases to the calculation of purely electronic resonances, but has to go beyond the Born-Oppenheimer approximation in the more general case. A computational scheme for simple diatomic species along these lines is presently under development.

4 Publications and Invited Talks

4.1 Publications in Journals

4.1.1 Publications that appeared in 1999

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Thomas, D. and G. Kauffmann: Probing star formation timescales in elliptical galaxies. In: Spectroscopic dating of stars and galaxies, Workshop held at Annapolis, Maryland 1999, Eds. I. Hubeny, S. Heap, R. Cornett. PASP Conference Proceedings series.

Thomas, H.-C., K. Beuermann, V. Burwitz, K. Reinsch and A.D. Schwope: RX J1313.2–3259, a long-period Polar discovered with ROSAT. In: Cataclysmic Variables: a 60th Birthday Symposium in Honour of Brian Warner, Eds. P. Charles, A. King, D. O'Donoghue. New Astronomy Reviews.

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4.3 Popular article and books

Popular articles and books 1999

Banday, A.J., R. Sheth and L. Da Costa (Eds.): MPA/ESO Cosmology conference, Evolution of Large-Scale Structure: from Recombination to Garching. PrintPartners Ipskamp, Enschede 1999, 398 pages.

Börner, G.: Der Zufall in der Astronomie. In: Der Zufall, Nova Acta Leopoldina NF 79, Nr. 308, 1999, 27–48.

Börner, G.: Der Kosmos – ein einziges Labor? Südd. Zeitung, 12.1.1999.

Börner, G.: Singularities of Spacetime. The Discovery of a New Universe(in Japanese). Gakken, Tokyo 1999, 158–163.

Börner, G.: Kosmologie. Lexikon der Physik, Spektrum Akademischer Verlag, 1999

Börner, G.: Vom Urknall zum Universum. Bayrisches Fernsehen 1999, and Zur Debatte, Zs. der Kath. Akademie, 1999.

Diaferio, A.: Gruppi compatti: una tappa obbligata. l'Astronomia 200, 34–43. Milano 1999.

Diaferio, A.: The large-scale distribution of galaxies. Annals of the Marie-Curie Fellowship Association. Brussels 1999.

Schmidt, H.U.: Deutsches Museum, Broschüre "Die Sonne unser nächster Stern", München 1999.

Schneider, P., J. Ehlers and E.E. Falco: Gravitational Lenses. Springer-Verlag, Second Printing 1999.

4.4 Invited talks

T. Abel: "H2 in Space" Paris, (28.9.–1.10.)

G.Börner: Intern. Conference of "Two Decades of Numerical Astrophysics" (Port Douglas, Queensland, 5.7.–9.7.)

A. Diaferio: 1st Princeton–PUC Workshop on Astrophysics "Omega" (Pucon, Chile, 11.1.–14.1.)

A. Diaferio: IAU Colloquium 174 "Small Galaxy Groups" (Turku, Finland, 13.6.–18.6.)

M. Gilfanov: X-ray Astronomy'99. Stellar Endpoints, AGN and the Diffuse Background (Bologna, 6.09–10.09)

M. Gilfanov: The 5th CAS-MPG Workshop on High Energy Astrophysics (Urumqi, 20.09–25.09)

M.G. Haehnelt: ESO workshop "Black Holes in Binaries and Galactic Nuclei" in Honour of Prof. R. Giacconi (Garching, 6.9.–8.9.)

M.G. Haehnelt: Annual meeting of TMR network "Galaxy Formation", (Asiago, 31.8.–4.9.)

M.G. Haehnelt: Ringberg workshop "Galaxies in the Young Universe" (Ringberg, 2.8.–6.8.)

M.G. Haehnelt: Workshop "The Physics of the IGM and the Large Scale Structure of the Universe" (Haifa, 20.6.–25.6.)

M.G. Haehnelt: Oort workshop (Leiden,27.5.–28.5.)

W. Hillebrandt: Colloquium of the DFG-Priority Research Program "Analysis and Numerics for Conservation Laws" (Magdeburg, 1.2.–3.2.)

W. Hillebrandt: Conference on Computational Physics (CCP99) at the American Physical Society Centennial (Atlanta, USA, 23.3.–26.3.)

W. Hillebrandt: Aspen Workshop on Type Ia Supernovae (Aspen, 14.6.–25.6.)

W. Hillebrandt: Intern. Conf. “Two Decades of Numerical Astrophysics” (Port Douglas, Australia, 5.7.–9.7.)

W. Hillebrandt: Intern. Workshop on “Astronomy with Radioactivities” (Schloß Ringberg, 29.9.–2.10.)

W. Hillebrandt: 10th Annual October Astrophysics Conference in Maryland “Cosmic Explosions!” (Univ. of Maryland, College Park, USA, 11.10.–13.10.)

H.-Th. Janka: XVth Particles and Nuclei International Conference “PANIC 99” (Uppsala, 10.6.–16.6.)

H.-Th. Janka: WE-Heraeus-Ferienkurs für Physik “Materie unter extremen Bedingungen – Quantenstatistik in Plasma- und Astrophysik” (Prerow, 3.10.–16.10.)

K. Jedamzik: ”Inner Space/Outer Space: The Interface between Cosmology and Particle Physics” (Batavia, 26.5.–29.5.)

K. Jedamzik: 2nd ESO/MPA Conference ”The First Stars” (Garching, 4.8.–6.8.)

K. Jedamzik: ”COSMO-99: International Conference on Particle Physics and the Early Universe” (Trieste, 27.9.–2.10.)

G. Kauffmann: “Structure and Dynamics of Galaxies” (Venice, 18.3-19.3.)

G. Kauffmann: STIS Workshop “Spectrophotometric dating of Stars and Galaxies” (Annapolis, 25.4.-29.4.)

G. Kauffmann: Ringberg Workshop “ Satellite Galaxies” (Ringberg, 27.6-2.7.)

G. Kauffmann: XVth IAP Meeting “Dynamics of Galaxies: from the Early Universe to the present” (Paris, 9.7.–13.7.)

G. Kauffmann: “Gravitational Lensing: Recent Progress and Future Goals” (Boston, 25.7.–30.7.)

G. Kauffmann: Ringberg Workshop “Galaxies in the Young Universe” (Ringberg, 2.8.-6.8.)

G. Kauffmann: ESO Workshop “Black Holes in Binaries and Galactic Nuclei” (Garching, 6.9.-8.9.)

G. Kauffmann: Royal Society Discussion Meeting on “The Formation of galaxies” (London, 3.11-4.11.)

W. Kraemer: 4th International Conference “Dissociative Recombination: Theory, Experiment and Applications” (Naesslingen, 16.6. – 20.6.)

W. Kraemer: 11th European Seminar on Computational Methods in Quantum Chemistry (23.9. – 25.9.)

S. Mao: “Gravitational Lensing: Recent Progress and Future Goals” (Boston, 25.7.–30.7.)

F. Meyer: “5th CAS–MPG Workshop on High Energy Astrophysics”: (Urumqi, 20.9.–25.9.)

F. Meyer: 60th Birthday Symposium in Honour of Brian Warner “Cataclysmic Variables” (Oxford, 12.4.–16.4.)

E. Meyer-Hofmeister: “5th CAS–MPG Workshop on High Energy Astrophysics”: (Urumqi, 20.9.–25.9.)

H.J. Mo: 15th IAP meeting “Galaxy Dynamics: from the Early Universe to the Present” (Paris, 9.7.–13.7.)

H.J. Mo: “Galactic Disks” (Heidelberg, 3.10.–7.10.)

E. Müller: Workshop “Computational Sciences and Engineering” (Ascona, Switzerland, 2.5.–7.5.)

E. Müller: Joint European and National Astronomical Meeting 1999 “Gravitational Waves Astrophysics” (Toulouse, 6.9.–11.9.)

H. Ritter: 60th Birthday Symposium in Honour of Brian Warner “Cataclysmic Variables” (Oxford, 12.4.–16.4.)

J. Schäfer: International Conference: “Molecular Hydrogen in Space” (Paris, 28.9. - 1.10.)

P. Schneider: “VLT Opening Symposium” (Antofagasta, Chile, 1.4.–4.4.)

P. Schneider: “Perspectives on Radio Astronomy: Scientific Imperatives at cm and m Wavelengths” (Amsterdam, 7.4.–9.4.)

P. Schneider: “Gravitational Lensing: Recent Progress and Future Goals” (Boston, 25.7.–30.7.)

P. Schneider: “Galaxies in the young universe” (Schloß Ringberg, Tegernsee, 2.8.–6.8.)

R. K. Sheth: “Cosmic Flows” (Victoria, Canada 13.7.–17.7.)

H.C. Spruit: DFG Rundgespräch ‘Cataclysmic Variables’ (Andreasberg, 21.2.–24.2.)

H.C. Spruit: IAU Symposium 195 “Highly Energetic Physical Processes ...” (Bozeman, Montana 5.7.–10.7.)

H.C. Spruit: Workshop “Gravitational Wave Astrophysics” at the JENAM’99 Conference (Toulouse, 10.9–11.9.)

H.C. Spruit: “5th CAS–MPG Workshop on High Energy Astrophysics”: (Urumqi, 20.9.–25.9.)

H.C. Spruit: ISSI workshop ‘Solar Variability and Climate’ (Bern, 27.–30.6.)

R. Sunyaev: NATO Advanced Study Institute “The Neutron Star—Black Hole Connection” (Crete, 7.6.–18.6)

R. Sunyaev: Annual Meeting of the Astronomische Gesellschaft (Goettingen, 20.9.–25.9.)

R. Sunyaev: Enrico Fermi School “Plasma Astrophysics” (Varenna, 6.7.–16.7.)

R. Sunyaev: ESO Workshop “Black Holes in Binaries and Galactic Nuclei” (Garching, 6.9.–8.9.)

R. Sunyaev: “VLT Opening Symposium” (Antofagasta, Chile, 1.4.–4.4.)

S.D.M. White: Aspen Winter Astrophysics Meeting “The Local Group” (Aspen, Colorado, 25.1.–29.1.)

S.D.M. White: “VLT Opening Symposium” (Antofagasta, Chile, 1.4.–4.4.)

S.D.M. White: “Structure and Dynamics of Galaxies” (Venice, 18.3.–19.3.)

S.D.M. White: The David N. Schramm Memorial Symposium “Inner Space/Outer Space II” (Fermilab, Illinois, 25.5.–29.5.)

S.D.M. White: Ringberg Workshop “ Satellite Galaxies” (Ringberg, 27.6–2.7.)

S.D.M. White: IAP Summer Symposium “Galaxy Dynamics: From the Early Universe to the Present” (Paris, 9.7.–13.7.)

S.D.M. White: Ringberg Workshop “Galaxies in the Young Universe” (Ringberg, 2.8.–6.8.)

S.D.M. White: ESO/MPA conference “The First Stars” (Garching, 4.8.–6.8.)

S.D.M. White: ESO Workshop “Black Holes in Binaries and Galactic Nuclei” (Garching, 6.9.–8.9.)

5 Personnel

5.1 Scientific staff members

Directors

W. Hillebrandt, R. Sunyaev, S.D.M. White (managing)

Scientific Member

R.-P. Kudritzki

Staff

T. Abel (July 15 – Sept 30), U. Anzer, P.J. Armitage (since Oct 1), A. Banday, M. Bartelmann, G. Börner, M. Brüggen, E. Churazov, D. Clowe, C. Cress, F. Daigne (since Oct 1), A. Diaferio (till Sept. 14), G.H.F. Diercksen, T. Enßlin (since Sept 1), J.A. Font–Roda (since Sept 1), M. Gilfanov, M. Groenewegen, M. Haehnelt, S. Hardy, H.–T. Janka, K. Jedamzik, V. Joergens (till Jan. 14), C. Kaiser, G. Kauffmann, A. Kercek, L. King (since March 1), W.P. Kraemer, R.–P. Kudritzki, S. Mao, H.J. Mo, E. Müller, J.C. Niemeyer (on leave since Oct. 1, 97), R. Popham, H. Ritter, H. Schlattl (since Oct. 1), P. Schneider, R.K. Sheth (till Sept. 30), H.C. Spruit, K. Takahashi (till Aug. 31), T. Theuns, H.–C. Thomas, R. Wegmann, A. Weiß, S. Zaroubi.

Emeriti

H. Billing, R. Kippenhahn, F. Meyer, H.U. Schmidt, E. Trefftz.

Scientists associate:

H. Arp, E. Meyer–Hofmeister, J. Schäfer.

Ph.D. Students

T. Abel (till September 30), R. Banerjee (since June 1), R. Casas, G. Contardo (since October 1), C. Cramphorn, B. Deufel, H. Dimmelmeier, K. Dolag, G. Drenkhahn (since March 1), T. Erben (since Jan. 1), H.-J. Grimm (since Nov. 1), H. Hämmerle (since Oct. 1), F. Hansen (since Oct. 1), K. Kifonidis, G. Kruse, M. Lisewski, S. Marri, H. Mathis, C. Morales–Merino (since March 1), N. Przybilla, M. Rampp, K. Reblinsky, J. Rehm, M. Reinecke, H. Schlattl (till Sept. 30), J. Schmalzing (till Sept. 30), F. Siebel (since Nov. 1), V. Springel (till Sept. 30), C.F. Vollmer (since Nov. 1), N. Yoshida,

Diploma students

C. Brauner (since Oct. 1), M. Ferwagner (till Feb. 28) A. Groebl (till Nov. 5), H. Hämmerle (till Aug 17.), M. Hagen (since Jan. 1), F. Linke (since Dec. 1), R. Pfrogner (since March 1), D. Sauer (since Dec. 1), L. Scheck (since July 1) M. Schirmer (till Sept. 20).

Alexander von Humboldt awards

C. Hogan (Seattle, USA), 14.5. – 24.7.; J. Paldus (Waterloo, Canada), 2.6. – 31.8.; R.E. Williams (Baltimore, USA); 1.5. – 11.8.

Alexander von Humboldt fellowships

L. Girardi (Porto Alegre, Brazil), till Febr. 28, D. Munshi (Triest, Italy), since March 1; D. Bielinska–Waz (Torun, Poland), since Oct. 1.

DAAD–fellowships

C. Morales–Merino (Tlaxcala, Mexico) since March 1; N. Yoshida (Copenhagen, Denmark) since Oct. 1.

EC–fellowships

C.P. Dullemond (since Oct. 1), S. Hardy, L. King (since March 1), G. Ogilvie (till Sept. 30), T. Theuns.

5.1.1 Staff news

H.–T. Janka: Offer for Full Professorship at NORDITA, Copenhagen (declined).

G. Kauffmann was appointed to a C3 post under the Max–Planck Society's special programm for the promotion of women in science.

P. Schneider: Offer for Full Professor (C4), University of Bonn (accepted).

5.1.2 Diploma and Ph.D. theses 1999

Diploma theses:

A. Gröbl: "Simulation von Flammenfronten in Wasserstoff–Luft–Gemischen", Technical University Munich.

M. Ferwagner: "Mehrdimensioale Diffusionschemata für Neutrinos in Neutronensternen", Ludwig–Maximilians–University; Munich.

H. Hämmerle: "Untersuchung zum Halo von Galaxien in Galaxienhaufen mit Hilfe des Gravitationslinseneffektes" Ludwig–Maximilians–University; Munich.

M. Schirmer: "Entfernungsbestimmung schwacher Hintergrundgalaxien anhand des Gravitationslinseneffektes", Ludwig–Maximilians–University; Munich.

Ph.D. theses:

J. Colberg: "Parallel Supercomputer Simulations of Cosmic Evolution", Ludwig–Maximilians–University; Munich.

H. Schlattl: "The Sun, a Laboratory for Neutrino– and Astrophysik", Technical University; Munich.

J. Schmalzing: "On Statistics and Dynamics of Cosmic Structure", Ludwig–Maximilians–University; Munich.

5.2 Visiting scientists

Name	home institution	Duration of stay at MPA
R. Adamczak	(Toruń, Poland)	16.10.–20.12.
M.A. Aloy	(Valencia, Spain)	1.10.–31.10.
C. Benoist	(ESO, Garching)	1.10.98–30.9.
M. Bernardi	(ESO, Garching)	1.10.–31.12.
D. Bielińska–Wacź	(Toruń, Poland)	29.4.–28.5.
		since 1.10.
S.I. Blinnikov	(Moscow, Russia)	14.6.–13.8.
E. Branchini	(Groningen, Netherlands)	10.10.–15.10.
S. Cassisi	(Teramo, Italy)	12.4.–3.5.
		22.11.–3.12.
I. Černušak	(Bratislava, Slovak Republic)	1.11.–12.12.
S. Charlot	(Paris, France)	1.5.–31.5.
		since 1.10.
T.T. Chia	(Singapore)	15.6.–31.8.
C. Chiosi	(Padua, Italy)	9.11.–15.12.
P. Ciecielacg	(Warsaw, Poland)	15.4.–10.6.
Z.G. Deng	(Beijing, China)	18.7.–21.11.
P. Denissenkov	(St. Petersburg, Russia)	1.3.–10.4.
W. Dubitzky	(Belfast, Northern Ireland)	16.1.–22.1.
		30.7.–4.8.
		16.10.–17.10.
		22.10.–24.10.
W. Duch	(Toruń, Polen)	4.8–27.8.
C.P. Dullemond	(Leiden, Netherlands)	since 1.10.
A. Emelyanov	(Moscow, Russia)	20.11.–23.12.
J. Faulkner	(Santa Cruz, USA)	since 1.9.
J. Frank	(Baton Rouge, USA)	18.5.–16.8.
C. Fryer	(Santa Cruz, USA)	3.9.–4.10.
O. Gerhard	(Basel, Switzerland)	15.2.–14.5.
O. Goussev	(St. Petersburg, Russia)	till 14.4.
M. Gramann	(Tartu, Estonia)	15.4.–24.4.
S.A. Grebenev	(Moscow, Russia)	1.11.–22.12.
P. Heinzel	(Ondrejov, Czech Republic)	1.3.–31.3.
		1.5.–31.5.
A. Helmi	(Leiden, Netherlands)	9.8.–20.8.
		12.4.–23.4.
		22.11.–3.12.
C. Hogan	(Seattle, USA)	14.5.–24.7.
N.A. Inogamov	(Moscow, Russia)	18.4.–17.7.
		1.11.–23.12.
N. Ivanova	(Oxford, UK)	1.7.–30.9.
P. Jensen	(Wuppertal, Germany)	7.3.–20.3.
		3.10.–15.10.

Name	home institution	Duration of stay at MPA
M. Karelson	(Tartu, Estland)	16.1.–22.1.
		15.10.–30.10.
		3.12.–18.12.
J. Karwowski	(Torun, Poland)	5.5.–4.6.
V. Kellö	(Bratislava, Slovak Republic)	5.1.–1.2.
		15.11.–12.12.
P. Kilpatrick	(Belfast, Northern Ireland)	12.1.–22.1.
		10.7.–13.8.
		16.10.–25.10.
J.-P. Kneib	(Toulouse, France)	7.6.–4.7.
A. Kritsuk	(St. Petersburg, Russia)	18.4.–17.7.
		29.8.–28.9.
I. Kryukov	(Moscow, Russia)	1.6.–30.6.
B. Lanzoni	(Paris, France)	6.5.–20.5.
Q.B. Li	(Beijing, China)	16.7.–17.9.
W. Lin	(Beijing, China)	1.1.–31.12.
B.F. Liu	(Kunming, China)	1.5.–15.8.
A. MacFadyen	(Santa Cruz, USA)	3.9.–4.10.
M. Makita	(Kobe, Japan)	15.1.–14.3.
L. Mashonkina	(Kazan, Russia)	14.9.–13.12.
F. Masset	(London, UK)	2.8.–9.8.,
		22.–27.11.
S. Matarrese	(Padova, Italy)	since 1.9.
M. Medved	(Banska' Bystrica, Slovak Republic)	1.11.–30.11.
B. Menard	(Paris, France)	19.4.–15.8.
J. Miralda-Escude	(Philadelphia, USA)	19.7.–18.8.
S. Molykov	(Moscow, Russia)	20.11.–23.12.
P.K. Mukherjee	(Calcutta, India)	27.4.–14.5.
		28.10.–27.12.
D. Munshi	(Triest, Italy)	since 1.3.
D. Nadyozhin	(Moscow, Russia)	30.6.–29.8.
J. Niemeyer	(Chicago, USA)	2.4.–30.4.
K. Nomoto	(Tokyo, Japan)	1.8.–15.8.
A. Nusser	(Haifa, Israel)	2.3.–16.3.
		15.9.–30.9.
G. Ogilvie	(Cambridge, UK)	till 30.9.
J. Paldus	(Waterloo, Canada)	2.6.–31.8.
I. Panov	(Moscow, Russia)	1.10.–30.11.
T. Plewa	(Warsaw, Poland)	1.3.–31.8.
N. Pogorelov	(Moscow, Russia)	1.6.–30.6.
M.G. Revnivtsev	(Moscow, Russia)	20.01–27.02.
		9.04.–15.06.
		26.08.–25.10.
P. Ruiz-Lapuente	(Barcelona, Spain)	till 14.2.
		since 28.10.
T. Sako	(Tokyo, Japan)	1.8.–31.8.

Name	home institution	Duration of stay at MPA
M. Salaris	(Liverpool, UK)	12.4.–11.5.
		9.11.–8.12.
F. Sasaki	(Sapporo, Japan)	8.8.–7.9.
S.Y. Sazonov	(Moscow, Russia)	2.2.–20.3.
		17.4.–30.5.
		23.8.–25.10.
		6.11.–22.12.
R. Schulte–Ladbeck	(Pittsburgh, USA)	21.3.–2.4.
U. Seljak	(Cambridge, USA)	till 23.1.
N.I. Shakura	(Moscow, Russia)	16.8.–15.9.
J. Shi	(Peking, China)	1.7.–30.11.
N.R. Sibgatullin	(Moscow, Russia)	5.2.–4.3.
		17.4.–16.5.
		25.6.–24.8.
S. Sild	(Tartu, Estonia)	19.4.–14.5.
		18.10.–18.12.
P. Soldán	(Durham, UK)	1.6.–30.6.
V. Špirko	(Prague, Czech Republic)	1.6.–31.7.
A.A. Starobinsky	(Moscow, Russia)	14.9.–13.10.
N. Sugiyama	(Kyoto, Japan)	26.7.–25.8.
R.E. Taam	(Evanston, USA)	7.7.–29.7.
O.V. Terekhov	(Moscow, Russia)	1.7.–31.7.
A. Timokhin	(Moscow, Russia)	8.2.–7.5.
A.Y. Tkachenko	(Moscow, Russia)	1.7.–31.7.
G. Tormen	(Padova, Italy)	31.1.–6.2.
		21.3.–27.3.
		24.5.–29.5.
		5.7.–16.7.
		22.8.–28.8.
J.W. Truran	(Chicago, USA)	3.8.–17.8.
		28.9.–6.10.
M. Urban	(Bratislava, Slovak Republic)	5.1.–1.2.
		22.7.–5.8.
M.A. Urbaneja Perez	(La Laguna, Spain)	12.6.–2.7.
V. Usov	(Jerusalem, Israel)	4.9.–17.9
V. Utrobin	(Moscow, Russia)	15.3.–14.6.
L. van Waerbeke	(CITA, Canada)	30.1.–13.3.
M. Viel	(Padova, Italy)	since 1.10.
W. Vieser	(Kiel, Germany)	1.7.–31.8.
R.E. Williams	(Baltimore, USA)	1.5.–11.8.
S.E. Woosley	(Santa Cruz, USA)	10.8.–3.10.
X.B. Wu	(Beijing, China)	since 12.12.
B. Wybourne	(Torun, Poland)	5.8.–4.9.
G. Worthey	(Davenport, USA)	4.6.–15.7.
X.Y. Xia	(Tianjin, China)	18.7.–21.11.
G.Z. Xie	(Kunming, China)	1.10.–30.11.
S. Yamada	(Tokyo, Japan)	22.7.–12.8.
S. Yamamoto	(Nagoya, Japan)	22.7.-21.8.