Max-Planck-Institut

für

Astrophysik

ANNUAL REPORT 2006

Contents

1 General Information

1.1 A brief history of the MPA

The Max-Planck-Institut für Astrophysik, called the MPA for short, was founded in 1958 under the directorship of Ludwig Biermann. It was first established as an offshoot of the Max-Planck-Institut für Physik, which at that time had just moved from Göttingen to Munich. In 1979, after the headquarters of the European Southern Observatory relocated to Garching, Biermann's successor, Rudolf Kippenhahn, moved the MPA to its current site. The MPA became fully independent in 1991. Kippenhahn retired shortly thereafter and this led to a period of uncertainty, which ended in 1994 with the appointment of Simon White as director. The subsequent appointments of Rashid Sunyaev (1995) and Wolfgang Hillebrandt (1997) as directors at the institute, together with adoption of new set of statutes in 1997, allowed the MPA to adopt a system of collegial leadership by a Board of Directors. This structure has now been in place for ten years. The Managing Directorship rotates every three years, with Simon White the incumbent for the period 2006-2008. The institute has three external Scientific Members: Rolf Kudritzki, Riccardo Giacconi and Werner Tscharnuter.

The MPA was founded as an institute for theoretical astrophysics. Its initial mission was to develop the theoretical concepts needed to understand the structure and evolution of stars, the dynamics of magnetised interstellar media and other hot plasmas, the properties of relativistic particle populations, and the transition probabilities and cross–sections important for astrophysical processes, especially in rarified media. These efforts led to a variety of international collaborations and complemented the observational and instrumental activities carried out in other Max-Planck institutes. Since its foundation, the MPA has also had a concentration in numerical astrophysics that is unparalleled in any other institution of similar size.

In recent years, activities at the MPA have diversified and now include a wide range of data analysis and interpretation activities as well as purely theoretical or numerical work. Resources are channeled into specific areas where new instrumental or computational capabilities are expected to lead to rapid developments. Active areas of current research include stellar evolution, stellar atmospheres, accretion phenomena, nuclear and particle astrophysics, supernova physics, astrophysical fluid dynamics, high-energy astrophysics, radiative processes, the structure, formation and evolution of galaxies, gravitational lensing, the large-scale structure of the Universe and physical cosmology. Several previous research areas (solar and solar system physics, the quantum chemistry of astrophysical molecules, General Relativity and gravitational wave astronomy) have been substantially reduced over the last decade.

Various aspects of the MPA's structure have historical origins. Its administration (which is housed primarily in the MPA building) is shared with the neighboring, but substantially larger MPI für extraterrestrische Physik. The library in the MPA building also serves the two institutes jointly. The MPA played an important role in founding the Max-Planck Society's Garching Computer Centre (the RZG; the principal supercomputing centre of the Society as a whole). As a result, 10 posts at the computing centre, including that of its director and several other senior figures, are formally part of the MPA's roster. These posts are managed independently by the computing centre and by its governing bodies in consultation with the MPA. This arrangement has worked well and as a result a close working relationship is maintained between the MPA and the RZG.

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 focused plan is very effective at encouraging interaction between scientists (for example at the now traditional morning "scientific coffee") and makes for a pleasant and stimulating research environment.

Library

The library is a shared facility of the MPA and the MPE. The fact that it has to serve the needs of two institutes with differing research emphases – predominantly theoretical astrophysics at MPA and observational/instrumental astrophysics at the MPE – explains its size. At present the library holds about 22000 books and conference proceedings, reports and observatory publications and it holds subscriptions for about 200 journals and manages online subsriptions for about 400 periodical. In addition the library maintains an archive of MPA and MPE publications (monographs, reports, periodicals), two slide collections (one for MPA and one for the MPE), and it stores copies of the Palomar Observatory Sky Survey (on photographic prints) and of the ESO/SERC Sky Survey (on film).

The MPA/MPE library catalogue includes books, conference proceedings, periodicals, reports, observatory publications, doctoral dissertations, habilitation theses and links to other online publications. This catalogue and the corresponding catalogues of other MPI libraries on the Garching campus and elsewhere are accessible online via the internet from the library and from every office terminal or PC. Internet access to other bibliographical services, including electronic journals and the SCI, is also provided.

Additional technical services such as several PCs and terminals in the library area, copy machines, a microfiche reader/printer, a bookscanner, two laser printers, and a fax machine are available to serve the users' and librarians' needs.

In 2003 the "General-Verwaltung" (GV) launched the "Edoc" system in which all institute publications (MPA and MPE) are archived electronically and made accessible internally from the library homepage. The administration and maintenance of this system is carried out by the library staff (e.g. about 900 publications in 2006). The institute's library also takes part in the "VLib" (Virtual Library) project of the GV, which is the general information portal of the MPG providing a common surface under which various scientific information resources become available.

Computational facilities

Because of the heavy emphasis on numerical astrophysics at MPA, the provision of suitable computers and network connections is a critical element in achieving the institute's scientific goals. In practice computing needs are satisfied by providing both extensive in-house computer power and access to the supercomputers and the mass storage facilities at computing center Garching (RZG). The RZG and MPA try to coordinate their development plans to ensure continuity in the working environment experienced by the users. Several MPA mid-range computers are housed and operated at RZG.

The philososphy of MPA's computer system is to achieve the following requirements:

- every user has full access to all facilities needed
- scientific necessity is the driver for new acquisitions
- desktop PCs are provided for everyone, running under one operating system (Linux) and a fully transparent file and software system
- full data security due to multiple backups
- highest system security due to choice of operating system and firewalls
- fully redundant resources
- no maintenance or system tasks by users needed

With this approach MPA is achieving virtually uninterrupted, continuous service. Data loss over the past few years is below the detection limit, and duty cycles are well beyond the 99% level. Since desktop PCs are not personalized, hardware failures are quickly repaired by a complete exchange of the computer.

In addition to the desktop systems, of which none is older than four years and which (in 2006) amount to more than 140 fully equipped working places, users have access to central number crunchers (64-bit Opteron architecture), mainly through a batch system. The total on-line data capacity is beyond 100 Terabyte, individual user disk space ranges from 1 GB to 1 TB, according to scientific need.

All MPA scientists and PhD students may also get a personal laptop for the duration of their presence at the institute. These and private laptops may be connected to the in-house network, but to a subnet which is separated from the crucial system components by a firewall. In addition to the standard wired network (Gb capacity up to floor level, and 100 Mb to the individual machine), access through a protected WLAN is also possible.

The basic operating system relies on OpenSource software and developments. The Linux system is an in-house developed special distribution, including the A(dvanced) F(ile) S(ystem), which allows completely transparent access to data and a high flexibility for system maintenance. For scientific work, licensed software, e.g. for data reduction and visualization, is also in use.

The system manager group comprises two full-time and three part-time system administrators; users have no administrative privileges nor duties, which allows them to fully concentrate on their scientific work.

The most important resources provided by the RZG are parallel supercomputers, a PByte mass storage facility (also for backups), and the gateway to GWIN/Internet. The exchange of expert knowledge with RZG staff and regular mutual consultations are also very valuable.

In addition to the central MPA computer services, both the Planck Surveyor project and the SDSS group operate their own computer clusters. Both installations are designed in a similar fashion to the general system, and are maintained by the MPA system managers.

1.3 2006 at the MPA

The MPA Radio Observatory

In 2006 the MPA continued to expand and to diversify its activities. Perhaps the most dramatic new departure was the decision to become directly involved in observational radioastronomy. The Low Frequency Array (LOFAR) is a Dutch-led project to construct an interferometer at metre wavelengths made up of a very large number of very simple antennas. It will be the first major telescope where the effective beam is constructed in software during post-processing and it will have much larger computational requirements than traditional radio telescopes. This results in overlap with MPA numerical expertise which complements the project's strong scientific overlap with MPA interests in studying the epoch of reionisation, cosmic magnetism and the evolution of AGN. With the help of a large equipment grant from the MPG the MPA has therefore purchased a remote LOFAR station, a field of antennas which will be constructed on 2 hectares of agricultural land in a rural area about 50km north of Garching. This will be one of four such stations in Germany and will almost double the north-south resolution of the LOFAR interferometer. MPA is responsible for construction and operation of the station as well as for transfer of all data (around a Gigabit/second) to the main processing centre in Holland. The MPA scientist in charge is Benedetta Ciardi.

How to double your PhD students

A change of a different kind in 2006, was the institution of a formal ”workshop” to interview applicants for PhD places at MPA. This became necessary because of the increasing number of applications coming through the very successful International Max Planck Research School on Astrophysics which MPA runs jointly with MPE, ESO and the LMU Observatory. The enormous diversity in nationality and background of the applicants makes it very difficult to assess their abilities ”on paper” so the MPA WIR (the science faculty) decided to make a long shortlist and then to invite all candidates to visit at the same time. This allowed us to assess them personally, and allowed the applicants to learn about the institute and about possible PhD projects. In the end about 25 students came to the workshop, which produced such a high level of enthusiasm on the two sides that more than half the shortlist ended up being offered and then accepting a PhD post. Together with a few students coming in through the more traditional routes, this resulted in 19 new PhD students arriving at the beginning of the 2006/2007 academic year, more than twice the MPA's previous average annual student intake. This remarkable success was not lost on the other IMPRS institutes and it was decided to carry out a similar exercise jointly for all the IMPRS institutions in 2007.

Biermann Dynamics thanks to Alexander von Humboldt

2006 was the tenth year of the Biermann Lecture series at MPA. As in previous years we were lucky to be able to persuade an outstanding theoretical astrophysicist to spend time at the institute and to give a series of three lectures aimed at a broad astronomical audience. This year's lecturer, Scott Tremaine, spent considerably more than the usual month in Germany, taking advantage of a Humboldt Research Award to support an extended sabbatical leave in Munich. As a result, MPA staff and students were able to interact with Scott not only around the time of the Biermann Lectures, which, as in past years, filled the MPA lecture hall to capacity, but also at scientific coffee and a variety of other functions over a full 6-month period. Students at other institutions will also benefit from this stay since Scott used the time to finish a new edition of his famous Stellar Dynamics textbook with James Binney; the manuscript was sent to the publishers the week before the end of his stay. He came to the MPA soon after stepping after a number of years as the Chair of the Princeton Department of Astrophysical Sciences, and he left to take up a new position as John Bahcall's successor at the Institute for Advanced Study. The MPA and the AvH Foundation thus helped to smooth a transition which may be more dramatic than the distance between the institutions would suggest.

Three other Humboldt awardees were also resident at MPA during 2006. Alex Szalay (Johns Hopkins University) visited several times on his AvH Research Award and did much to promote the institute's involvement in Virtual Observatory activities. Piero Madau (University of California, Santa Cruz) is spending almost a full year on sabbatical in Munich in 2006/2007, again supported by an AvH Senior Research Award. He has been interacting closely with scientists both at MPA and at ESO. Finally, Julio Navarro (University of Victoria) returned to take several additional months from his Bessell Prize in order to continue Virgo Consortium projects in collaboration with MPA scientists.

International Exchanges

The numbers of international visitors at MPA have continued to increase in 2006. Although two Marie-Curie Research Training Networks, dedicated to Gamma-ray Bursts and to Type Ia Supernovae, came to an end this year, a third network dedicated to Multiwavelength Analysis of Galaxy Populations continues to be very active and is coordinated from MPA (by Guinevere Kauffmann). In addition a number of new channels have brought increased numbers of students and postdocs to the institute. In particular, the EU-funded Latin-American-European Network for Astrophysics and Cosmology (LENAC) is currently bringing around 10 South American students to the MPA each year for stays of between 2 and 6 months, and Marie-Curie Early Stage Training funds are bringing another 4 or 5 students from the EU and elsewhere for stays of similar length under a grant made to the European Association for Research in Astronomy (EARA, this association links MPA with major astronomy institutes in five other European countries). Bilateral postdoc exchange agreements between MPA and the Kavli Institute for Theoretical Physics (Santa Barbara), the Canadian Institute for Theoretical Astrophysics (CITA) and the Center for Astrophysics (Cambridge, MA) have also led to visits in both directions during the year.

The links between MPA and chinese astronomy continue to be strong despite the retirement in May 2006 of Gerhard Boerner, the founder and tireless supporter of these very fruitful exchanges. The original MPA partner group at the Shanghai Astronomical Observatory, led by Yipeng Jing, came to the end of its 5-year term in 2005, and 2006 saw the start of follow-on activity which was again supported by the Max Planck Society in recognition of the productivity of this Sino-German collaboration. Exchange visits in both directions continue, a joint workshop was held in Shanghai in autumn 2006, and this year also saw the appointment of the first postdocs to a joint programme in which the holders work on joint projects between the institutes and spend approximately half their time in each country. A new MPA Partner Group was also established at SHAO in 2006 under the leadership of Xiahou Yang; this group will work on hydrodynamical simulation of galaxy formation/evolution. The principal collaborating scientist at MPA is Volker Springel.

Public Outreach

The public outreach work at the MPA includes a very broad range of activities. Our scientists are involved in teacher education, they present public talks as well as lectures to school classes, they supervise undergraduates and high school students on small research projects and during internships, they guide tours groups through the institute (including architecture classes), they write articles for popular science magazines, and they act as interview partners for newspaper and television journalists.

Vom 15. bis zum 21. Juli fand der Wissenschaftssommer 2006 in München statt Foto: U.Dahl/WiD

One of the highlights of this year's public outreach was the participation of MPA in a science exhibition on the Marienplatz and Marienhof in downtown Munich. This event was organized by the initiative "Wissenschaft im Dialog" and was supported by the Federal Ministry of Education and Science as part of the "Science Summer" in the "Year of the Computer Sciences". On a big plasma screen MPA presented high-resolution movies of cosmic evolution and of supernova explosions. About 60000 visitors enjoyed the events at various places in central Munich.

Another outreach highlight in 2006 was an Open House on Sunday, October 15, when the whole Garching Campus celebrated the opening of the underground link to central Munich after several years of disruptive construction work. The MPA offered its roughly 1000 visitors a program of hourly talks, continuous slide and poster shows, our "Cosmic Cinema" multi-media presentation of science movies, the "astro consultation" in the coffee corner, and the possibility to observe the sun in Hα using a 20 cm telescope on the roof terrace of the institute. A real crowd puller was our Kindertag, a special program organized both for teenagers and for younger children. While kids aged 10–16 could enjoy themselves with astrogames and a computer quiz, kids between 5 and 10 had a lot of fun building and launching rockets and hot air balloons, manufacturing a "rainbow box" in which light was expanded into its spectral colors, and experiencing the phase transition of sublimating "Martian" (dry) ice.

1.4 How to reach us

- Postal address:

  MPI für Astrophysik
  Postfach 13 17
  D-85741 Garching
  Germany

- Telephone (country code 49):

  89-30000-0 (switchboard)
  89-30000-2214 (secretary)
  89-30000-2235 (FAX)

- Electronic address:

  e-mail:
  user-id@mpa-garching.mpg.de
  (initial + last name
  will reach most people,
  e.g. mdepner for Maria Depner)

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

- MPA (reference) library:

  phone: +49-89-30000-2305/6
  FAX: +49-89-30000-2378
  email: lib@mpa-garching.mpg.de
  URL: http://www.mpa-garching.mpg.de/libris.html
  homepage: only local access

2 Scientific Highlights

2.1 Magnetic fields in stellar core collapse

At the end of their thermonuclear evolution the inner cores of stars of initially more than 8 solar masses collapse within a few 100 milliseconds from a radius of a few 1000 kilometers to several tens of kilometers. The core, reaching densities which exceed those of atomic nuclei, transforms into a proto-neutron star. When the collapse of the core is halted by repulsive nuclear forces a very energetic shock wave forms near the core's edge. However, within a few ten milliseconds this prompt hydrodynamic shock wave stalls due to severe energy losses. According to the current paradigm, the stalled shock is revived after the post-shock layers of the core have been energized for several tenths of a second by neutrinos diffusing out of the central core. The neutrinos produced by the continuing neutronization of the core carry away the gravitational binding energy of the stellar core. The revived shock eventually blows off the stellar mantle and envelope yielding a supernova explosion. The details of this explosion mechanism are not yet fully understood. Besides the neutrino-matter reactions, convection and hydrodynamic instabilities are thought to play an important role.

Additional physical processes which are possibly important for core collapse and supernova explosions involve rotation and magnetic fields. Observations show that the surface layers of most massive stars rotate quite rapidly. If these stars retain their angular momentum until core collapse, and if a significant amount of this angular momentum will be concentrated in the stellar core, it will modify or even completely alter the dynamics of the supernova explosion. Although one does not expect that these requirements are fulfilled for all core collapse supernovae, they may hold for a small subset of "exotic" supernovae (about one in ten thousand), which are probably related to the phenomena of gamma-ray bursts. Concerning the strength and topology of the magnetic fields of massive stars the observational situation is even less clear. Prior to collapse the magnetic field strengths of stellar cores are probably intermediate between those of magnetized white dwarfs ($\sim 10^6$ Gauss) and neutron stars ($\sim 10^{12}$ Gauss). Although fields of this strength are dynamically unimportant for stellar cores (because of their high pressure), differential rotation and convection can considerably amplify the initial "seed" magnetic field during core collapse and in the subsequent neutrino heating phase. Once the initial field has become sufficiently strong, it will also modify or even completely alter the dynamics of the explosion. Whether this indeed occurs depends on the amount of differential rotation of the core, the initial strength of its magnetic field, and the rate and amount of field amplification.

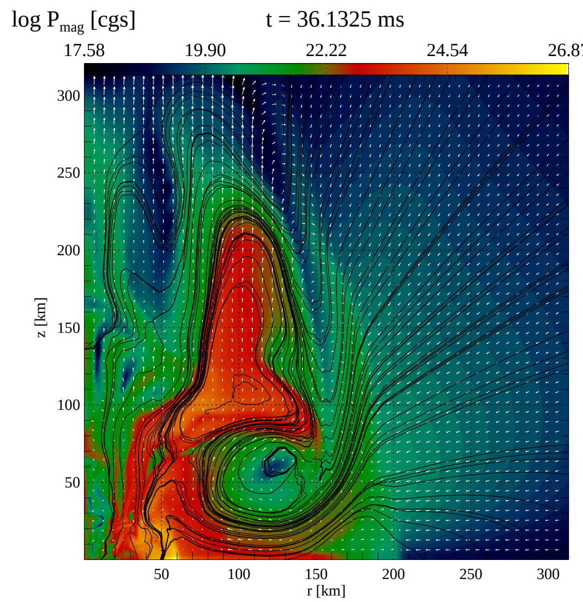

Figure 2.1: Magnetic energy density distribution (color coded), magnetic field lines, and flow field (vectors) of one of our core collapse models. Strong shearing motions lead to a complex magnetic field structure.

In order to study the possible combined effects of rotation and magnetic fields, we performed axisymmetric magneto-hydrodynamic numerical simulations using a simplified collapse model. We neglect neutrino transport entirely, use a simple approximation to the complex equation of state describing the thermodynamic conditions in the stellar core, and start our simulations with simplified initial stellar models (polytropes). As the state of rotation and magnetization of the pre-collapse core is still uncertain, both from observations and theory, we performed a parameter study varying both uncertain parameters. Compared with theoretical expectations and observational constraints we have considered quite rapidly rotating and very strongly magnetized initial models in our exploratory study, as only such extreme models give rise to significant changes in the collapse dynamics. On the other hand, our models cannot handle field amplification by the magnetic dynamo process due to the assumption of axisymmetry. Thus, we underestimate the amount of amplification of the core's initial magnetic field strength, which we compensate for by choosing stronger initial fields.

The approximations made in our study, in particular the missing treatment of the neutrino transport, limit its validity to the collapse phase and the immediate post-collapse evolution (up to a few tens of milliseconds past core bounce). Thus, instead of investigating the details of the neutrino driven explosion mechanism, we focussed on the modifications of the global dynamics of the explosion due to magneto-rotational effects.

In our models, the seed magnetic fields are amplified by a number of processes:

1. During collapse, the magnetic field is compressed along with the matter. This leads to an increase of the field strength by a factor of several hundreds or thousands.

2. During collapse, the core spins up due to angular momentum conservation, leading to faster and more differentially rotating core. By the process of winding the magnetic field strength grows linearly with time, the increase of magnetic energy being supplied by the energy available in form of differential rotation. In contrast to amplification by compression, this mechanism changes the topology of the magnetic field, transforming the initial dipole magnetic field into a predominantly toroidal one.

3. A differentially rotating magnetized fluid can be unstable against the so-called magneto-rotational instability, which leads to a fast exponential amplification of the magnetic field.

Further processes leading to field growth, such as a convective dynamo, are suppressed in our models by our approximations and the assumption of axisymmetry. The above processes give rise to a complex field topology (Fig. 2.1).

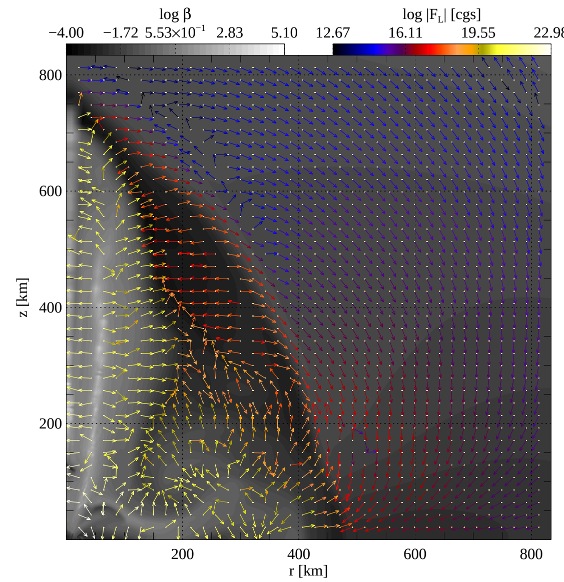

Figure 2.2: The structure of a bipolar outflow in one of our simulations. The ratio of magnetic to gas pressure is grey-shaded, and the vectors display the magnitude and the direction of the Lorentz force F_{L}. The jet is collimated by the magnetic field along the beam.

Once amplified sufficiently, the magnetic field has a pronounced influence on the flow dynamics. Its main effect is the transport of angular momentum along the field lines connecting different regions of the core. The magnetic field tries to enforce a state of rigid rotation. Thus, it slows down the central part of the core and weakens the centrifugal support in these regions. Consequently, a phase of secular core contraction occurs. The amount and speed of this contraction depends on the relative size of the centrifugal and pressure support of the core. Although a fairly gradual process in cores supported mainly by pressure, it can resemble a second collapse in cores supported predominantly by centrifugal forces. In the latter case, the structure of the inner parts of the core is altered considerably.

The effects of magnetic fields on the morphology of the shock wave are similarly pronounced. In most non-magnetized models the shock is almost spherical. Strong magnetic fields lead to a prolate deformation of the outflow, transforming the initially spherical shock wave into a mildly relativistic jet-like outflow directed along the rotational axis. The structure of this collimated outflow (Fig. 2.2) shows similarities with features well-known in simulations of relativistic jets.

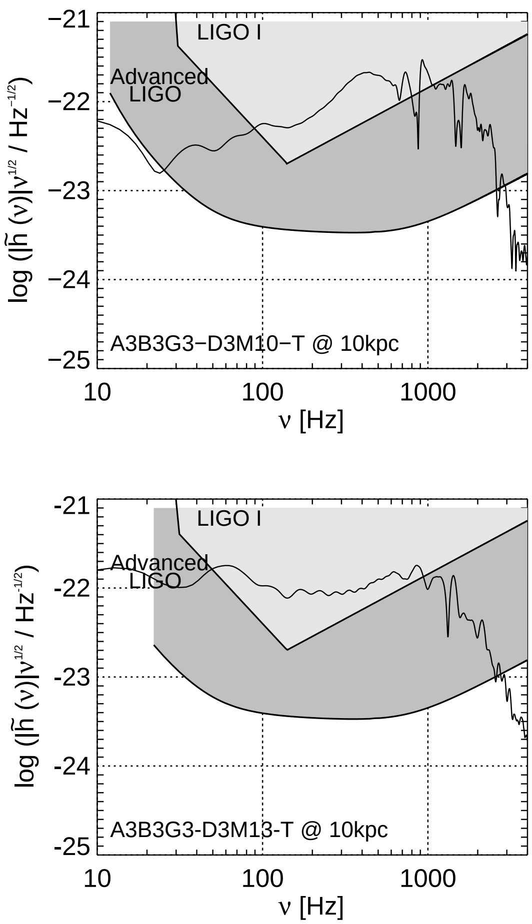

Figure 2.3: A comparison of the gravitational wave signals of a core collapse model with an initially weak magnetic field (left/top) and one with an initially strong magnetic field (right/bottom). The corresponding spectra (solid lines) are compared with the sensitivity curves of the LIGO gravitational wave detector (shaded regions). Note that the initial models differ only in the strength of their magnetic field. The strong field model ejects a bipolar outflow, which causes the flat part of the spectrum below 700Hz.

The modified dynamics of magnetically dominated core collapse events manifests itself in modifications of the gravitational wave signal emitted by the cores. Previous investigations of rotating, non-magnetic core collapse distinguish three basic signal types, depending on the core's initial rotation rate and the equation of state. Our models show a fourth signal type, which is emitted by models undergoing a secondary collapse triggered by angular momentum transport by magnetic fields. We also find that otherwise identical models emit different signal types depending on whether or not they are strongly magnetized.

A common feature observed for all models producing a jet-like outflow is a slowly varying positive signal amplitude during the late stages of the explosion. This distinctive gravitational wave signal is a direct consequence of the collimated axial outflow.

We also computed the frequency spectra of the gravitational wave signals of our models and compared them with the sensitivity of the LIGO gravitational wave detector. We find that the gravitational wave signals emitted by our core collapse models can be detected throughout the Milky Way, and that the spectral differences between magnetized and non-magnetized (or weak field) models are sufficiently large to allow for their discrimination (Fig. 2.3) (Ewald Müller).

2.2 The Supernova that Made the Crab Nebula

Researchers at the Max Planck Institute for Astrophysics have solved the puzzle of how the Crab Nebula was formed. Their elaborate computer simulations demonstrate that the expanding cloud of gas is debris from a star ten times more massive star than the Sun, whose explosion was driven by the powerful heating of neutrinos. These elementary particles were radiated in huge numbers when the stellar core collapsed to a neutron star.

When Chinese and Arab astronomers watched the sky in the spring of the year 1054 A.D., they discovered a new star in the constellation of Taurus. According to their historical records, the "guest star" became brighter during several weeks and could be observed by July for 23 days even in the daytime. It remained visible to the naked eye for about two years.

Now we know that they observed the birth of the Crab Nebula by a gigantic supernova explosion. After millions of years of quiet evolution, a massive star exhausted the supply of nuclear fuel, whose burning had provided the energy and pressure to stabilize it against the pull of its own gravity. When the nuclear flame in its center died, the stellar core collapsed within fractions of a second to a neutron star, a compact object with more mass than the Sun, but a diameter of only 20 kilometers. This neutron star is visible as the famous pulsar in the Crab Nebula, which sends periodic pulses of radiation as it spins around its axis 33 times per second.

Most of the star, however, was ejected in a vi-

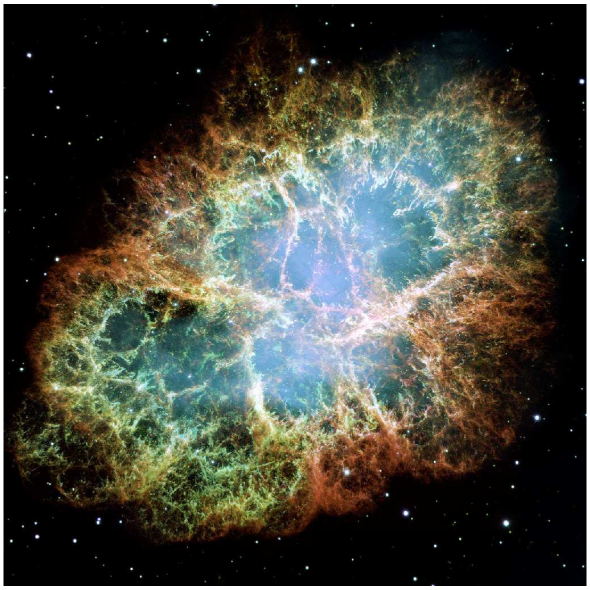

Figure 2.4: The Crab Nebula and the Crab pulsar, the gaseous and compact remnants of a supernova explosion that occurred in the year 1054 A.D. Relativistic particles, which are accelerated by the pulsar, cause the bluish glowing of the gas even 950 years after the explosion. The outer filaments consist mostly of hydrogen and helium from the disrupted star.

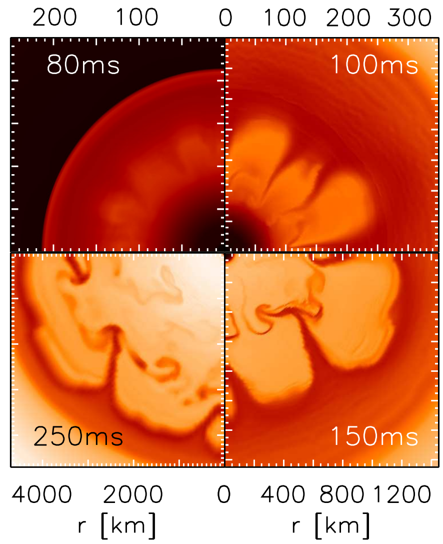

Figure 2.6: Snapshots from a two-dimensional computer simulation of the onset of the supernova explosion of a star with 8–10 solar masses. The displayed times are 0.08, 0.1, 0.15, and 0.25 seconds after the creation of the supernova shock (clockwise, beginning with the upper left panel). One can see rising bubbles of neutrino-heated matter, separated by narrow down-flows of cooler gas. The bubbles expand away from the nascent neutron star at the center and accelerate the stellar explosion. Note that the radial scale (in kilometers) changes by a factor of 20 from the upper left to the lower left panel. These anisotropies are the seeds of the asymmetries seen in the Crab remnant 950 years after the supernova event.

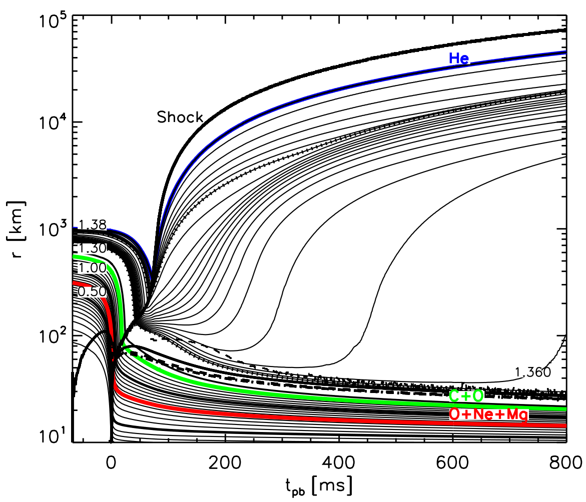

Figure 2.5: Computer simulation of the collapsing and exploding core of a star with 8–10 solar masses. The lines follow the radial positions of selected shells in the star as time evolves. The shock wave of the explosion is marked by the bold, rising, black solid curve. One can see a bifurcation developing between the matter that forms the central neutron star and the ejected gas that is driven outward by the heating of neutrinos. Colored lines indicate composition interfaces in the dying star and show that only little carbon and oxygen are thrown out in the explosion.

olent explosion with an energy roughly equal to what the Sun has radiated in its 5 billion years of life. The hot stellar debris flashed up as the new star reported by the Chinese and Arab astronomers, and is nowadays visible as the filamentary gas cloud of the Crab Nebula measuring six light-years across and still expanding with a velocity of 1500 kilometers per second (see Figure 2.4). It contains not only the chemical elements which the star has built up in a sequence of nuclear burning stages, first fusing hydrogen to helium, then helium to carbon, and then carbon to neon, magnesium, and oxygen, but also material like radioactive nickel, which was freshly assembled during the explosion. The helium richness of the nebula and the low abundances of carbon and oxygen were interpreted as hints that the exploding star had a mass of only about 8 to 10 solar masses, just sufficient to end its life as a supernova.

But how did the star blow up? What was the reason why the star was disrupted? A group of researchers of the Max Planck Institute for Astrophysics is convinced that they have now found the answer to this long standing conundrum. Their refined computer simulations reveal that neutrinos are the driving force behind the explosion. These elementary particles are produced in huge numbers in the very hot and extremely dense interior of the newly formed neutron star, mainly by reactions of electrons and positrons with protons and neutrons, the constituents of atomic nuclei. Having made their way to the surface of the neutron star, most of these neutrinos stream off, carrying away more than 99 percent of the energy liberated during the neutron star formation. Less than one percent of the neutrinos, however, is captured in the stellar gas surrounding the neutron star before being able to escape. The energy transfer by these neutrinos heats the gas and makes it boil like the fluid in a pressure cooker (see Figure2.6). The rising pressure finally accelerates the overlying stellar material and leads to the outburst of the supernova.

Although this theory for the onset of the explosion is 25 years old, proving its viability with detailed computer models turned out to be extremely difficult. Now at least for stars near the lower end of the mass range of supernova progenitors the models lend support to the theoretical idea. With the refined description of how neutrinos are created and interact in the matter in the supernova core, the Max Planck society research group was able to confirm that neutrino heating can indeed drive healthy explosions of stars like the one whose relics form the Crab Nebula. The new models agree nicely with observations that the energy of the Crab explosion was only about one tenth of that of a typical supernova. In contrast to previous simulations they also predict only small amounts of ejected carbon, oxygen, and nickel (see Figure 2.5). Moreover, the strong enrichment of the chemical composition of the remnant with exotic elements is absent and thus a conflict of the older models with the observed abundances of rare elements in the Milky Way Galaxy is solved. Since the disrupted star had a rather low mass and the explosion was sub-energetic with little production of radioactive material, other Crab-like supernovae must be expected to be fairly dim and therefore difficult to discover at great distances, although they could account for one third of all supernovae.

The computer models suggest that the Crab supernova was such a tremendously bright event only because it was just 6300 light-years from Earth. Compared to other supernovae it actually was a fairly unspectacular case. These computer models will tell us what we have to look out for in order to identify more such cases. (F. S. Kitaura, H.-Th. Janka, R. Buras, A. Marek, W. Hillebrandt.)

2.3 The source of radiation in gamma-ray bursts

Gamma-ray bursts (GRBs) are flashes of gamma-rays distributed isotropically on the sky. The gamma-rays, the so-called 'prompt emission' are followed by emission in X-rays and lower energy radiation. Through this afterglow they can be pinpointed on the sky, and their coincidence with distant galaxies establishes them as extremely powerful cosmic explosions. The power of the explosion appears to be released in a small volume and to involve a relatively small amount of mass. The energy of the explosion is carried by a flow moving with a speed close to the speed of light.

An observational connection to supernovae in conjunction with studies of the host galaxies provides compelling evidence for the connection of long duration (lasting a few tens of seconds) GRBs with the death of massive stars. Although less direct, there is substantial evidence that short duration (lasting less than a second) GRBs come from the coalescence of double neutron star systems.

The spectrum and the variability of the prompt gamma-ray emission have been studied in detail for thousands of bursts. The spectrum has a characteristic non-thermal appearance: a broken power law, with most of the energy emitted around the break, at a photon energy of $\sim$1 MeV (in the frame of the host galaxy: due to the cosmic redshift the break is actually observed at a few hundred keV). The light curves are very variable, and are often composed of a large number of spikes.

The mechanisms responsible for the gamma-rays seen as prompt emission remain controversial. Most studies have focused on synchrotron radiation from non-thermal particle distributions, such as could be produced in internal shock waves in the flow. This model places the source of radiation at a large distance from the central engine, where the flow is optically thin. For this mechanism to be efficient, the flow must be composed of slower and faster shells which coast with relativistic speeds relative to each other. There is a number of problems related to the synchrotron interpretation of the prompt emission (and with the patches proposed for these problems). Also, particle acceleration in relativistic collisionless shocks is not understood from first principles, so their energy distribution has to be assumed.

In addition to such optically thin radiation at large distances from the central engine ($\sim 10^{13--17}$ cm), all models also predict at least some radiation from the *photoshere* of the flow, much closer ($\sim 10^{11}$) cm to the source. The photosphere is the location where the flow becomes transparent, and where any radiation that was trapped at lower levels is released to the outside. The amount of trapped radiation, as well as its spectrum, depend on how and where it is produced. Radiation produced deep inside will be close to thermal equilibrium, but by adiabatic expansion its energy is lost by conversion to kinetic energy of the flow before it can escape. Significant radiation from the photosphere requires an internal energy source in the flow that is dissipated into radiation at optical depths between about 100 and unit (10^{10--11} cm).

Such a source exists in models for GBRs in which the energy flux from the central energy is initially magnetic (also called 'Poynting flux' models). If this magnetic energy is dissipated in the right place, it leads to both acceleration and internal heating of the flow. It turns out that a non-axisymmetric magnetic field in the central engine (like the inclined dipoles of pulsars) causes dissipation of magnetic energy by reconnection of neighboring field lines of different directions at just the right place in the flow, if one adopts the physical parameters inferred from observations.

This model makes clear predictions for the characteristics of the flow and the rate of magnetic energy dissipation at different radii. This makes the model predictive and accessible to detailed radiative transfer calculations. Analytical considerations show that, while radiation and matter are in approximate thermodynamic equilibrium deep inside the flow, heating of the electrons through energy dissipation leads to an increase of their temperature already at optical depths ~ 50. The frequent Coulomb collisions between the electrons guarantee that they maintain a thermal distribution in this region. Inverse Compton scattering of the underlying radiation field by the hot electrons close to the photosphere leads to a photon spectrum with a non-thermal appearance.

For quantitative calculations of this mechanism a Monte Carlo comptonization code has been developed. In a simulation, the electron temperature is determined by balancing the heating resulting from magnetic dissipation with the cooling by Comptonization. The calculations verify that the flow develops a hot photosphere with comoving electron temperatures of the order of ~ 30 keV

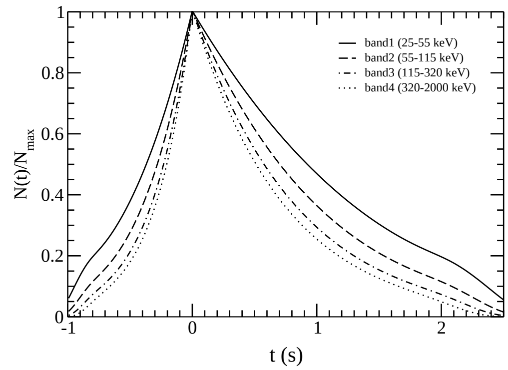

Figure 2.7: Photospheric spectrum of the reconnection model for GRB flows. Photon energies are in the central engine frame. For moderate and high luminosity-to-mass-flux ratio η, the spectra peak around 1 MeV. The flat high energy tail is the result of inverse Compton scattering of photons off hot electrons close to the photospheric radius. For low η dissipation stops below the photosphere and the resulting spectrum is quasi-thermal.

(and larger further out) for a large range of luminosities and mass fluxes of the flow. The emerging photospheric spectra have a broken power-law shape; the emission at photon energies above the break results from upscattering of soft photons by more energetic electrons at optical depths of order of unity (unsaturated Comptonization). The process is quite similar to the one that is believed to result in the non-thermal appearance of the spectrum of accreting black holes in X-ray binaries and Active Galactic Nuclei.

The overall appearance of the photospheric spectrum is very similar to the observed prompt emission while the model can also naturally account for the clustering of the break in the $\sim$1 MeV energy range (see Fig. 2.7). The strength of the photospheric emission depends on the characteristics of the flow such as the luminosity and the mass flux. The photospheric luminosity ranges from $\sim$ 3–30% of the total luminosity of the flow, making it a rather efficient way to power the GRB prompt emission.

In our magnetic dissipation model modulations of the characteristics of the flow (such as luminosity and mass flux) by the central engine translate directly into variations of the photospheric emission. Compared with other models, the spectral and temporal properties of the prompt emission thus offer direct clues to the operation of the central engine. For example, the observations show a correlation (the Amati relation) between the break

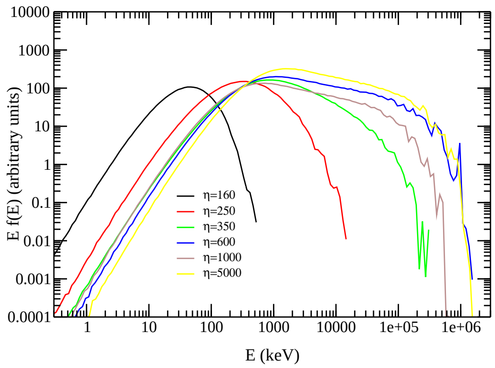

Figure 2.8: Narrowing of pulse width with photon energy, as predicted by the model for individual sub-pulses of the burst. Assumption is that he relation between luminosity and baryon loading deduced from the Amati relation, $\eta \propto L^{0.6}$, holds also within a burst.

in the spectrum and the total energy of the prompt emission, and an anticorrelation between the pulse width with photon energy. These are reproduced in the model if there is a tendency for more luminous flows to be characterized by higher luminosity-to-mass-flux ratio (see, for example Figure 2.8). In other words the photospheric interpretation of the GRB emission predicts that the more luminous flows are 'cleaner'. Whether a central engine such as a black-hole-disk system exhibits this kind of behavior is an interesting problem currently under investigation. (D. Giannios, H. C. Spruit)

2.4 Seismology of magnetars

On December 26th 2004 an undersea earthquake off the western coast of Sumatra triggered a deadly tsunami. The event was so violent, measuring over 9 on the Richter scale, that it left the Earth's crust ringing like a bell for days afterwards. Less than 48 hours after this catastrophic event, the Earth was hit by the most energetic blast of X-rays and gamma-rays ever recorded. The cause? A star-quake on a neutron star with an ultra-intense magnetic field, known as a magnetar, 50000 light years away from our solar system. And just as on Earth, the event left the star ringing - the first time this had ever been observed on a neutron star.

Seismologists studying the Sumatra earthquake used data from monitoring stations across the globe to pinpoint the exact location of the crust fracture, its size and the speed at which it broke. This, together with the frequencies and decay rates

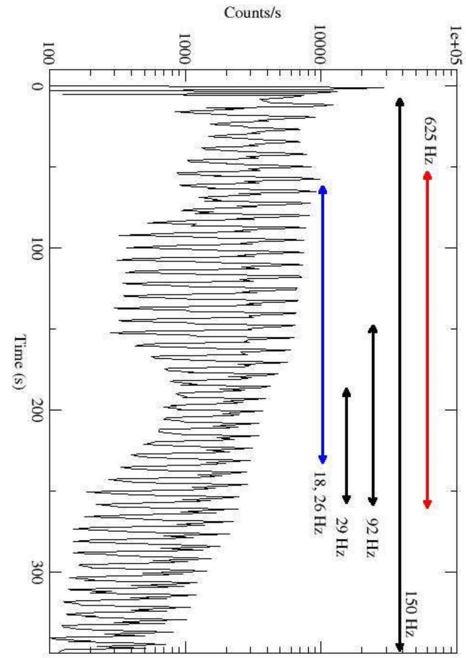

Figure 2.9: The X-ray light curve of the December 2004 event as recorded by the Rossi X-ray Timing Explorer (RXTE) satellite. After the initial bright flash there is a long decaying tail. This tail is due to emission from fireballs of plasma ejected during the flare that are then trapped by the field and evaporate slowly (see Figure 2.10). As the star rotates the fireballs swing in and out of view, giving rise to the slow pulsations clearly visible in the tail. The coloured arrows indicate the times at which the six strongest seismic vibrations appear (they are too rapid to be seen at this time resolution). Shown in red is the 625 Hz oscillation thought to be the first radial overtone of the shear modes. The black lines are thought to be lower frequency shear modes with different angular patterns. The blue line indicates lower frequency vibrations that must involve the stellar core as well as the crust.

of the long-lived vibrations, provides information about the composition of our planet. Now for the the first time we have the prospect of doing the same for neutron stars. Clearly we do not have the luxury of placing seismometers on the star - but the information we need is encoded in the X-rays and gamma-rays detected by orbiting telescopes.

But what can we hope to learn from neutron star seismology? Neutron stars are the densest objects in the known Universe, forming in supernova explosions that mark the death of stars several times more massive than the Sun. The compact object that remains, once material has been blown off in the explosion, contains a little more mass than our Sun but crushed into an object only 10-15 km in radius. Gravity is so strong that neutrons are squeezed out of atomic nuclei to form a core of nuclear fluid. Nuclear physicists do not know exactly what happens under these conditions: neutrons may even disintegrate into their constituent quarks, forming all kinds of exotic particles.

So in studying the composition of neutron stars we are testing the laws of physics in environments far beyond those that we can generate here on Earth. But how do we go about doing this? Nuclear models predict a certain relation between the mass and radius of the star. In principle if one can measure masses and radii for lots of different neutron stars, one should be able to identify the correct model. Unfortunately, measuring these parameters is extremely challenging. Masses can only be identified reliably for neutron stars in binary systems, where we can compute the orbit. Radii cannot be measured directly (the stars are too small for us to resolve the disk) and have to be inferred in other ways, such as by looking at the star's thermal emission. Most of these methods are extremely model-dependent and uncertain. Seismology offers a novel and extremely promising alternative.

So what triggers the seismic activity? Magnetars have magnetic fields of at least 1e15 G. That is one thousand times the field on a typical radio pulsar, and a staggering one thousand billion times stronger than the Earth's magnetic field. This field forms at birth, either by dynamo action during the supernova, or due to a high magnetic field parent star. The strong field gradually decays, and as it does the field lines become tangled and unstable. Eventually they snap and reconnect. This launches high energy flares, just as reconnection on the Sun launches solar flares. Giant flares, of the type responsible for the 2004 event, are very rare but involve catastrophic global rearrangements of the magnetic field. But why should field reconnection trigger a starquake? On a neutron star the field lines are anchored to the charged particles in the solid crust (the outer region of the star where intact nuclei still exist). For this reason it had long been suspected that the when the field lines snapped they should also break the crust, triggering seismic vibrations.

The first observations of this phenomenon, in the aftermath of the 2004 flare, were reported by Gianluca Israel (Rome) and his collaborators. Strohmayer and Watts then found evidence of seismic vibrations from a second magnetar that had emitted a giant flare 7 years previously. Refining our techniques, and using data from other satellites, we also conducted a more detailed analysis of the 2004 event. The star, it turns out, emitted a chord of at least seven different vibration frequencies (see Figure 2.9).

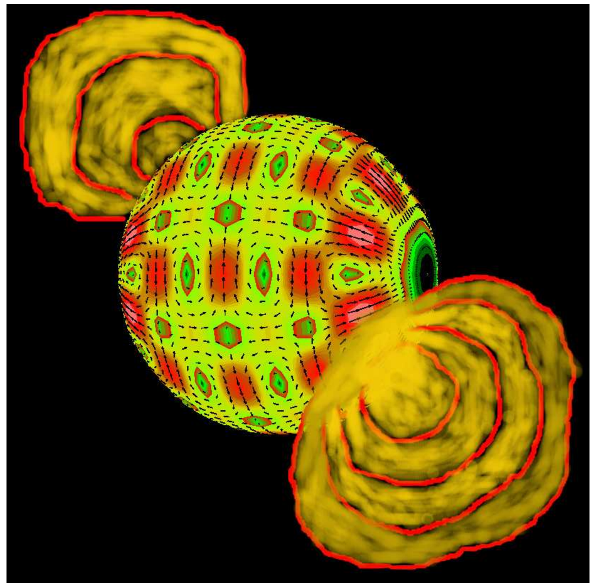

Figure 2.10: An impression of how a magnetar might look during the decaying tail of a giant flare. The surface of the neutron star is vibrating, with the colours and arrows indicating the magnitude and direction of the surface movements. Fireballs of plasma ejected by the flare and then trapped by the reconnecting field are also shown. The fireballs are responsible for the slow pulsations that we see in the X-ray light curve as the star rotates. How these fireballs interact with the seismic vibrations to cause the high frequency variations in the X-ray light curve is the subject of current research.

Neutron stars are extremely complex objects and many different types of oscillation are possible. The frequencies of the magnetar oscillations match, for the most part, the frequencies expected for the torsional shear oscillations of the neutron star crust. These primarily horizontal (non-radial) vibrations, restored by shear forces, had already been identified as the modes most likely to be excited by a starquake. Comparing the results of mode calculations to the observed frequencies we can start to deduce stellar properties. Particularly exciting has been the identification of what we think is a radial overtone of the shear modes. By comparing the high frequency overtone to the lower frequencies we have been able to estimate, for the first time, the thickness of a neutron star's crust. If this identification is correct it puts an extremely strong constraint on nuclear physics models.

It may even allow us to rule out a particular class of nuclear physics models called strange or quark star models. In these models neutrons in the stellar core disintegrate into quarks, which then react to form a stable fluid of up, down and strange quarks. Much effort has gone into working out how observations might distinguish strange stars from neutron stars, but the question has yet to be settled decisively. Where the two types of star do differ dramatically, however, is in crust composition and thickness. Computations by myself and my collaborator Sanjay Reddy (LANL) have now shown that torsional shear modes of strange star crusts have frequencies that do not fit the observations.

We are now working to refine our simulations of the seismic process, focusing in particular on the effects of the strong magnetic field on the oscillations, their excitation, damping and detectability. The last issue is particularly interesting. The environment around a magnetar in the aftermath of a giant flare is extremely complicated, being dominated by trapped plasma fireballs that completely change the emission conditions (Figure 2.10). Ultimately, however, our goal is to do what terrestrial seismologists take for granted: reconstruct a complete history of the starquake in order to learn whatever we can about the interiors of these fascinating stars. (Anna Watts)

2.5 Nature of the Galactic X-ray background

It has been known since the late 1970s that apart from bright X-ray point sources (mostly neutron stars and black holes in binary stellar systems) there is an unresolved X-ray emission distributed throughout the Milky Way. The origin of this "Galactic ridge X-ray emission", or the Galactic X-ray background, remained unclear for a long time. Numerous studies showed this emission to be strongly concentrated towards the Galactic plane. However the measured X-ray spectrum indicated that the emitting gas is so hot (kT >5–10 keV) that it cannot be bound within the Galactic gravitational well. The plasma must then be constantly outflowing and carrying away an enormous amount of energy, the source of which was not understood.

An alternative explanation of the Galactic X-ray background, proposed soon after its discovery, is that it is the superposition of X-rays from millions of Galactic point sources, too weak to be detected individually. This would eliminate the problem of keeping hot plasma bound to the Galactic plane. However it was difficult to rigorously test this hypothesis because there remained a large uncertainty with regard to the expected cumulative luminosities of different classes of faint Galactic X-ray sources.

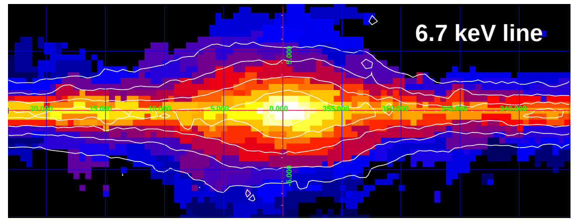

Figure 2.11: Map of the Galaxy in the 6.7 keV emission line (top) - a characteristic feature of the Galactic X-ray background emission - appears very similar to the map of the Galaxy in the near-infrared (bottom), dominated by emission of normal stars. The similarity of these two maps supports the hypothesis that the Galactic X-ray background emission is made of a large number of weak stellar type X-ray sources.

We have recently made a number of steps that significantly furthered our understanding of the nature of the Galactic X-ray background. First of all, we obtained high quality maps of the Galaxy in X-rays, which demonstrated that the X-ray surface brightness closely traces, both in the disk and bulge of the Galaxy, the near-infrared light produced by ordinary low-mass stars. This indicates that the amount of X-rays emitted every second in a given volume of the Galaxy is proportional to the total mass of stars contained in that volume. Addressing the same problem from a different angle, we determined the X-ray emissivity per unit stellar mass in the Solar neighborhood by direcly summing up the emission from faint X-ray sources located only tens to hundreds of parsecs away from the Sun. Remarkably, both results proved to be in good agreement with each other. We concluded that the Galactic X-ray background is made mostly of emission from a large number of accreting white dwarf binaries and coronally active stars (single and in binaries).

A point-source origin of the Galactic X-ray background entails several predictions for observations in hard X-rays. First, because in this scenario the main contribution to the background is provided by accreting white dwarf binaries, hard X-ray emission is expected to trace the near-infrared map of the Galaxy similarly to the softer X-rays, since white dwarf binaries belong to the normal (old) stellar population. Second, there must be an exponential cutoff in the spectrum of the X-ray background at energies 20–30 keV, since this corresponds to the maximum temperature of thermal emission produced through release of the gravita-

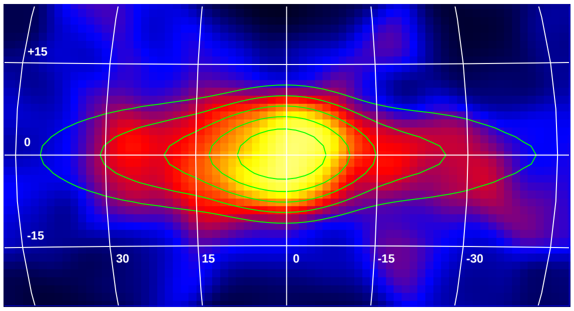

Figure 2.12: The map of the hard X-ray (17-60 keV) glow of the Milky Way obtained by INTEGRAL (false color map image) very well agrees with the near infrared image of the Galaxy (black countours). It strongly supports the idea that the bulk of this glow emission is provided by weak compact sources.

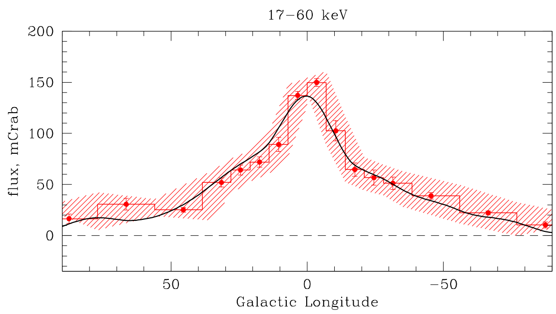

Figure 2.13: Brightness distribution of the Galactic ridge hard X-ray emission (red dashed area) along the Galactic plane overplotted with the brightness distribution of the Galaxy in near infrared spectral band (blue line).

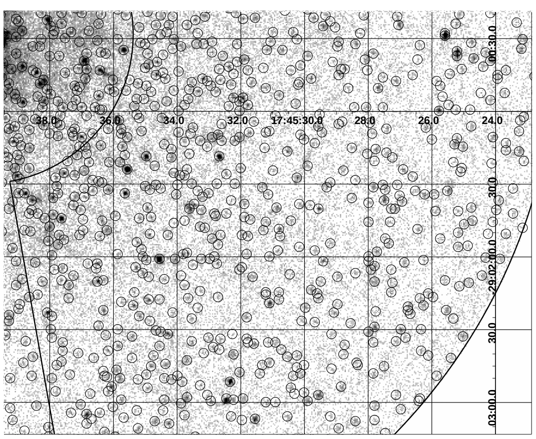

Figure 2.14: Image of the Galactic Center region taken by the Chandra observatory. Circles denote the positions of detected point sources.

tional energy of the accreting matter on a white dwarf surface ($kT \sim GM_{\rm wd}/R_{\rm wd}$).

We tested these predictions using the state-of-the-art hard X-ray imager IBIS on board the

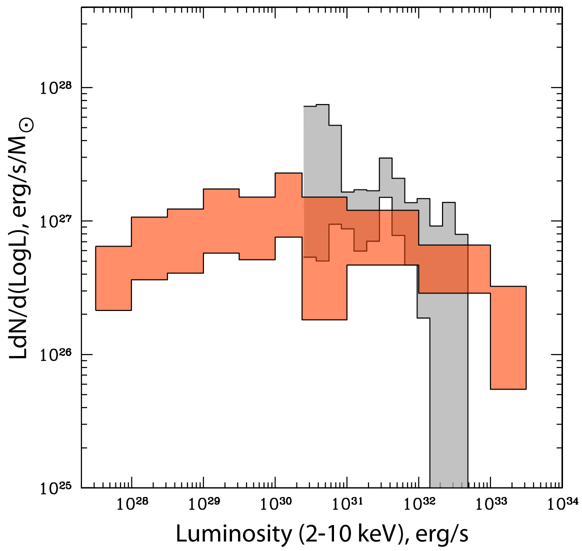

Figure 2.15: Luminosity functions of faint X-ray sources measured in the Solar vicinity (red area) and in the Galactic Center region (gray area). It can be seen that they are quite compatible with each other. The sources in the gray area explain at least 40-50 % of the total X-ray flux measured in the Galactic Center region, while still weaker sources expected to be present in this region by analogy with the Solar neighborhood, probably provide the remaining 50-60flux.

INTErnational Gamma-Ray Laboratory (INTEGRAL). Data collected by this instrument over four years of operation allowed us to map the weak hard X-ray glow of the Galaxy and measure its spectrum. The map does not correlate well with the gamma-ray map of the Milky Way, strongly suggesting that the hard X-ray emission in not generated through interaction of cosmic rays with the interstellar medium. Instead the intensity of the Galactic background in hard X-rays traces well the stellar mass density distribution, thus providing strong support to the idea that the bulk of Galactic background emission in this energy band is provided by weak compact sources. In particular, for the considered 17-100 keV energy band, the dominant contribution to the background emission should come from accreting white dwarf binaries. This result was strengthened by the detection of a high energy cutoff in the background spectrum.

However the ultimate answer as to whether the Galactic X-ray background is produced by point sources or by truly diffuse interstellar plasma can only be given by direct observations. The most suitable tool for this purpose is the Chandra X-ray observatory. This is because the angular number density of X-ray sources becomes so high at low fluxes that one needs arcsecond angular resolution (as provided by Chandra) to overcome the problem of source confusion.

We used approximately 1 Msec worth of Chandra observations of the Galactic Center region to demonstrate that point sources with X-ray luminosities higher than 10^{31} erg/s contribute at least 40% to the total X-ray background in this region. Furthermore, a comparison of the reconstructed luminosity function of Galactic Center point sources with the previously measured luminosity function of X-ray sources in the Solar neighborhood showed very good agreement between the two and suggested that the still unresolved 60% of the Galactic X-ray background is probably produced by coronally active stars and white-dwarf binaries with luminosities below 10^{31} erg/s, the current effective threshold of Chandra. (Mikhail Revnivtsev, Sergey Sazonov and Roman Krivonos)

2.6 Simulating the influence of cosmic rays on galaxy formation

Theoretical models of galaxy formation in the cold dark matter (CDM) cosmology have matured considerably over the past decade, yet large parts of the physics of star formation and its regulation by so-called "feedback" processes have remained poorly understood. In some sense the problem has even become more complicated than once believed, as it has been realized in recent years that supernova explosions of evolved stars are not the only important source of non-gravitational energy for evolving galaxies. For example, supermassive black holes, which can be found at the centers of nearly every galaxy, are now believed to play an important role during galaxy formation, shaping their properties in decisive ways. Furthermore, there are yet more "exotic" physical phenomena that also regulate star formation in galaxies in subtle but potentially crucial ways.

In fact, such an influence could come from magnetic fields and the relativistic charged particles that they lock into the local fluid by forcing them on gyro-motions around the field lines. These particles, called "cosmic rays", are thought to be generated abundantly at structure formation shock waves, and in supernova explosions. The cosmic rays provide a non-thermal pressure contribution to the gas that changes its hydrodynamic behaviour, an influence that – while well known to exist – has largely been neglected in galaxy formation models thus far.

Scientists at the Max-Planck-Institute for Astrophysics (MPA) have developed new hydrodynamical simulation methods that for the first time allow self-consistent studies of the joint influence of star formation, black holes and cosmic rays on galaxy formation. In principle, simulation models allow the study of even the most complicated and non-linear phenomena in nature, including those which are untractable by analytic calculations. However, practical limitations typically require substantial simplifications of the physics to make the problem accessible on today's computers. This is also the case for the treatment of cosmic rays, which poses in full generality a high-dimensional transport problem that is far too complicated for direct inclusion in cosmological simulations of structure formation.

A team at MPA composed of T. Ensslin, M. Jubelgas, C. Pfrommer and V. Springel has circumvented this problem by approximating the local momentum spectrum of cosmic ray particles with an isotropic distribution in momentum space of power-law form, together with a low-energy cut-off. Such a spectral shape provides a good match for the cosmic rays seen in our Galaxy, where they are known to contribute about a third of the total pressure in the interstellar medium. Assuming in addition that the local magnetic field is sufficiently tangled such that cosmic ray particles can only slowly diffuse away from the local medium, Ensslin and collaborators could arrive at a physically well motivated representation of the cosmic ray population in the smoothed particle hydrodynamics (SPH) code GADGET-2. For the first time, this model can account for dynamical effects of the cosmic ray pressure in simulations of galaxy formation.

As sources for cosmic rays (made up of relativistic protons in the model) they considered two physical effects, the production in supernova remnants and the acceleration at structure formation shock waves, where a small fraction of particles diffuses back and forth across the shock and gains energy each time (Fermi acceleration mechanism), up to ultra-relativistic energies. A realistic treatment of the shock acceleration requires an on-the-fly measurement of the Mach number of the shock, because only shocks with high Mach number are efficient particle accelerators. As a prerequisite for this work, the team therefore had to develop a novel method for dynamically detecting shocks in SPH and for determining their strength.

Interestingly, the new simulations predict that

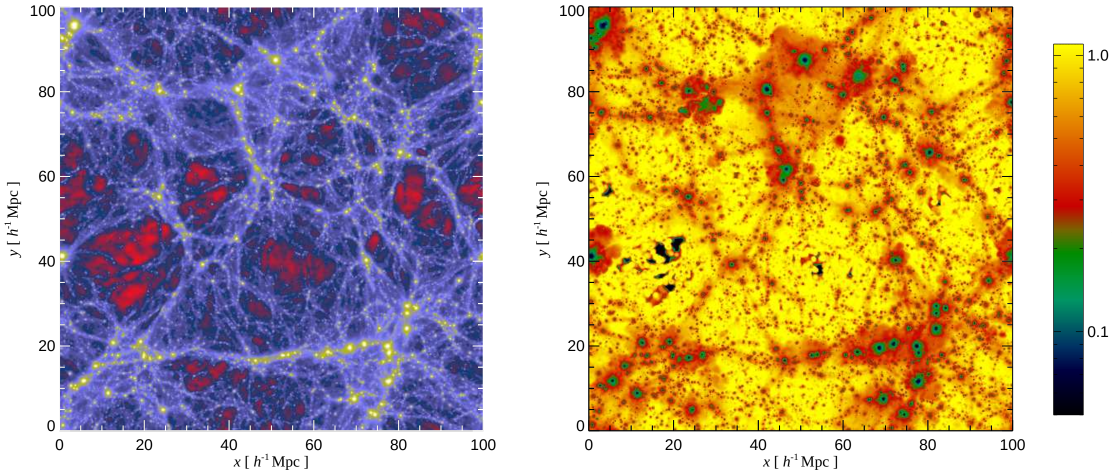

Figure 2.16: Projected gas density field (left panel) in a slice of thickness 20 h^{-1}Mpc through a non-radiative cosmological simulation at $z = 0$. The simulation includes cosmic ray production at structure formation shocks. The panel on the right shows the ratio of the projected cosmic ray energy density to the projected thermal energy density.

cosmic rays are preferentially produced in the accretion regions around halos and filaments, such that their relative contribution to the pressure is largest in voids (Figure 2.16). Since strong accretion shocks are found primarily in the high redshift universe, a considerable fraction of the dissipated shock energy ends up in cosmic rays instead of the thermal reservoir at these early times. At redshift $z \sim 10$, around $\sim 45\%$ of the internal energy of the gas is in the form of cosmic rays, while this ratio drops again to around $\sim 10\%$ at the present epoch, as a result of thermalization losses and the lower acceleration efficiency in the denser gas of collapsed structures.

Cosmic rays produced at shocks and in supernovae can also be found in the intracluster medium of rich galaxy clusters, where they modify the thermodynamic structure of clusters. In particular, the higher compressibility of a composite gas with thermal and cosmic ray pressure leads to a slight increase in the baryon fraction inside the cluster virial radii, and to small changes in the radial density and pressure profiles. The simulations also predict that the relative contribution of cosmic rays to the total pressure varies with radius, being comparatively low in the central parts. This presumable explains why the Sunyaev-Zeldovich signal of the simulated clusters is found to hardly change as a result of the cosmic rays. However, the X-ray emissivity can be boosted by up to 40% suggesting that 'precision cosmology' with clusters of galaxies will require a quantitatively accurate understanding of the non-thermal physics explored here.

The other source of cosmic rays considered, the strong shocks in supernova explosions, directly affect the interstellar media of star forming galaxies. The new results obtained at MPA show that it is particularly in small galaxies where the cosmic ray pressure can rise to a significant fraction of the total pressure, or even dominate it. Here the thermalization timescale of cosmic rays can be substantially longer than the ordinary cooling time of the thermal gas, such that the cosmic ray pressure can "puff up" the gas and be effective in delaying star formation in small galaxies. Indeed, in simulations of disk galaxies with a total mass of $\sim 10^9\,\mathrm{M}_\odot$ the star formation rate was reduced by up to a factor of 20 when cosmic rays were included, while for large galaxies of $\sim 10^{12}\,\mathrm{M}_\odot$ there was hardly any change. Figure 2.17 illustrates the cosmic ray pressure effect in edge-on views of the star forming gaseous disks for galaxies of two different masses. This tentalizing result suggests that the seemingly exotic physics of cosmic rays may play an important role in explaining the observed faint-end of the galaxy luminosity function, whose flat slope is in stark contrast with the steep rise of the dark matter halo mass function on the same scale. The two can only be brought into agreement if star formation in small halos is strongly suppressed. Cosmic ray physics appears to be one possible mechanism for this.

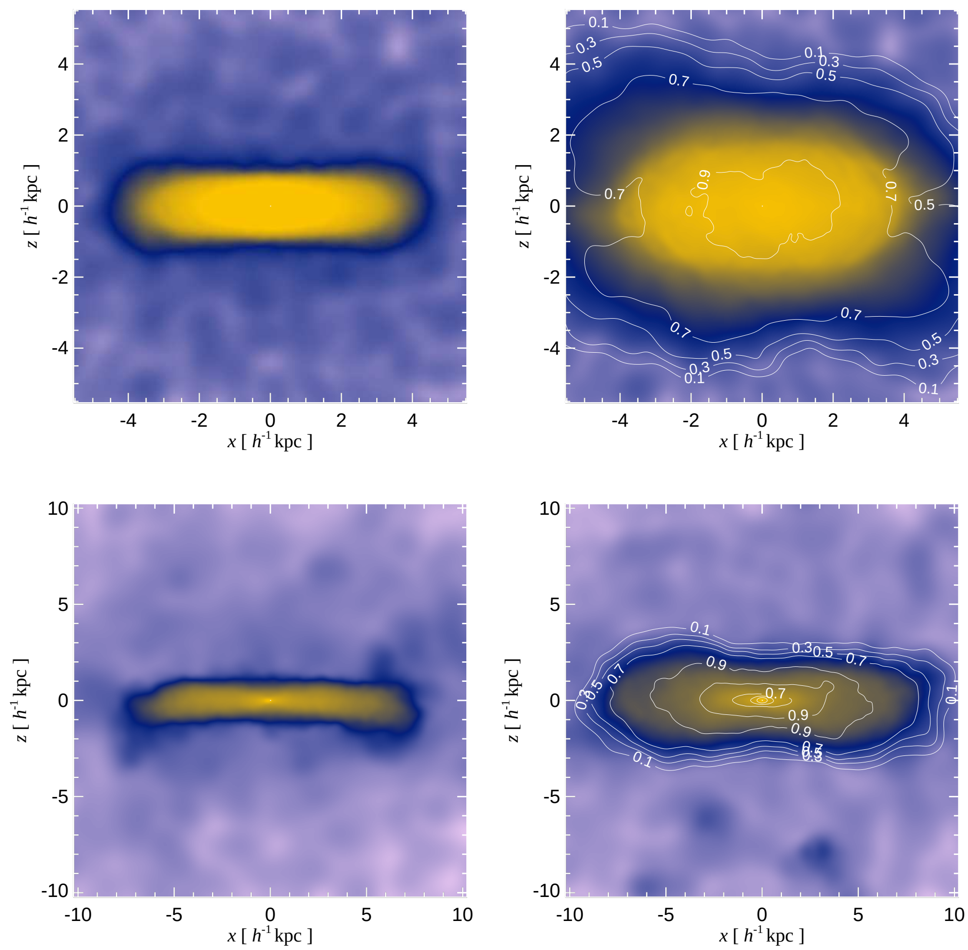

Figure 2.17: Effect of cosmic ray feedback on a star forming gaseous disk, seen edge-on. The top row shows results for a halo of mass 10^{10} $M_\odot$, the bottom for 10^{11} $M_\odot$. In both cases, a run without cosmic ray feedback is shown on the left, and one with cosmic ray production by supernovae on the right. The gas density field is colour-coded on a logarithmic scale. The contour lines show the contribution of the projected cosmic ray energy density to the total projected energy density.

These first results for the dynamical effects of cosmic rays in structure formation simulations highlight the need to augment N-body simulations of the dark matter with a hydrodynamical treatment that faithfully accounts for the rich physics of the baryons. The present models explored at MPA already account for a multiphase structure of the star-forming gas, for feedback and metal enrichment by supernovae, for black hole growth and its associated energy release, and for the production of cosmic rays. However, the future holds further challenges, including the task to include magnetic fields and radiative transfer self-consistently in simulations of cosmic structure formation. With respect to cosmic rays, it will be interesting to use the present model to make further testable predictions for future observatories like GLAST, which should be able to detect the gamma-ray flux produced by hadronic interactions of cosmic ray particles. (Volker Springel)

2.7 How do galaxies grow? Insights from large spectroscopy surves

Over the past 5 years, the study of galaxies has gained new impetus thanks to a new generation of very large photometric and spectroscopic surveys. Perhaps the most ambitious among these has been the Sloan Digital Sky Survey (SDSS), which is now close to completing a map of one quarter of the entire sky by determining the positions, brightnesses and distances of over a million galaxies.

The galaxy spectra obtained by the SDSS are of high enough resolution and quality to permit accurate measurements of nebular emission lines and stellar continuum absorption features. These measurements provide important constraints on the *physical properties* of the galaxies in the survey. The stellar absorption lines can be used to estimate the ages and metallicities of the stars in the galaxy and the amount of light emitted by the galaxy can then be converted into an estimate of its total stellar mass. The nebular emission lines are produced in ionized gas in the galaxy. The ratios of different line species can be used to diagnose whether the primary source of ionizing radiation is from hot young stars, or from matter accreting onto a supermassive black hole at the center of the galaxy. If the ionizing radiation is from young stars, the emission lines provide a direct measure of the star formation rate and gas-phase metallicity of the galaxy. If the radiation is from a central active nucleus (AGN) , the intensity of certain emission lines can be used to measure the accretion rate onto the central black hole.

Scientists at the MPA and at Johns Hopkins University in Baltimore, led by Guinevere Kauffmann and Tim Heckman, have developed the methodology and tools needed to exploit the information provided by surveys such as the SDSS. The availability of detailed physical information for unbiased samples of hundreds of thousands of nearby galaxies has led to wide variety of new insights into how galaxies have formed and evolved over cosmic time.

Traditionally, galaxies in the nearby Universe have been divided into two major classes: 1) elliptical galaxies, which have massive spheroids and red optical colours, and 2) spiral galaxies, which have actively star-forming blue disks. With the SDSS, correlations between between different galaxy properties can be studied and the distribution of galaxies in a multi-dimensional space of physical parameters can be quantified. One important result to emerge from this kind of analysis was the realization that the galaxy population is strongly bimodal: the two main classes of galaxy first recognized by Hubble in 1926 clearly occupy strongly disjoint regions in physical parameter space.

In a series of papers, the MPA group studied the relations between the stellar masses, sizes, internal structure, and star formation histories of galaxies. They showed that the galaxy population as a whole divides into two distinct families at a characteristic stellar mass of $\sim 3 \times 10^{10} M_{\odot}$. Below this mass, galaxies have young stellar populations and low densities and concentrations typical of disk systems. Above this mass, there is an abrupt transition to older systems with high densities and concentrations typical of massive spheroids.

This characteristic mass where galaxies transition from young to old is now believed to be an important clue in understanding so-called "cosmic down-sizing". Cosmic downsizing describes a scenario in which active star formation shifts to lower and lower mass galaxies as the Universe evolves. This paradigm appears to provide a good description of the properties of galaxies observed in very deep surveys, where properties such as masses and star formation rates can be measured out to significant look-back times.

Cosmic downsizing is seen as something of a paradox by theoreticians who try to understand how galaxies may have formed from the evolution of tiny density perturbations generated in the earliest moments of the Universe following the Big Bang. According to now-standard theory, the dominant matter component of the Universe consists of unseen dark matter that interacts only via gravitation. Dark matter does not undergo cosmic downsizing. The collapse of dark matter starts on small scales and proceeds to ever more massive structures. Understanding exactly why the behaviour of galaxies and dark matter should be so different remains one of the major challenges for theoreticians working on galaxy formation.

One possibility that is being actively investigated by many researchers is that some form of energetic output by the galaxy itself causes star formation to shut down in massive galaxies. Accretion onto the supermassive black holes that located at the centers of all bulge-dominated galaxies can in principle provide a source of energy that is not linked to the presence of young stars. The most plausible mechanism for transferring energy from the black hole to the gas surrounding the galaxy is via the jets that emerge at close to the speed of light from many galaxies with active nuclei. These jets emit synchrotron radiation and are most easily detectable at radio wavelengths.

In collaboration with Philip Best at the University of Edinburgh, the MPA team has recently turned its attention to identifying radio-loud sources in the SDSS data. Their findings support the hypothesis that radio jets are reponsible

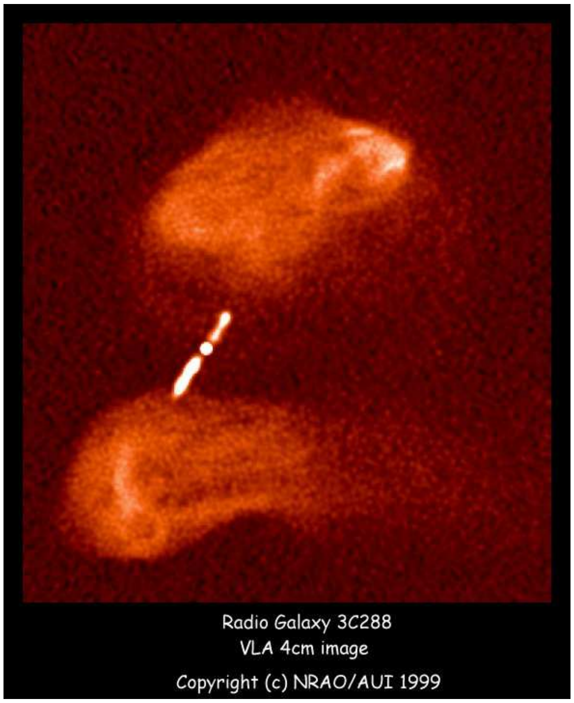

Figure 2.18: An example of a radio-loud active galaxy.

for shutting down galaxy growth – radio-loud active galaxies are found preferentially in the most massive galaxies in the Universe and intrguingly, the dependence of the radio-loud AGN fraction on galaxy mass appears to mirror the rate at which gas is predicted to cool from the hot atmospheres of these systems and form stars.

These results have also been found to extend to clusters of galaxies, which are gravitationally dominated by dark matter, but also contain vast quantities of hot gas. This hot gas cools by emitting X-ray radiation , thereby decreasing its temperature and allowing more gas to flow to the center in a so-called "cooling flow". The galaxy at the center of a galaxy cluster is located at the place where the gas density is expected to reach a maximum . One major mystery is why there is generally very little ongoing star formation in these objects. If gas condensing in the "cooling flow" was forming stars, one would expect to see evidence of young stellar populations in central cluster galaxies. Analysis of a large sample of central cluster galaxies in the SDSS revealed that these objects were more likely to host a radio-loud active galactic nucleus when compared to galaxies of the same mass that were not located in clusters. This work lends further credence to the hypothesis that radio jets are responsible for shutting down galaxy growth.

For the the very most massive galaxies in the nearby Universe with masses of 10^{12} solar masses, the fraction of radio-loud systems is found to approach 100 percent. It is interesting to speculate that this is not a coincidence and the scale of the largest galaxies in the Universe is set when radio jets are always turned on and the galaxy is permanently starved of any further supply of new gas.

Studies of radio galaxies may have much to teach us about how energetic feedback shuts down star formation in massive galaxies, but astronomers would still like to understand how galaxies do manage to form in the first place. In the standard theoretical scenario, galaxies form by the condensation of gas in gravitationally dominant dark matter halos. If the gas initially has the same angular momentum as the dark matter and conserves this angular momentum during its contraction, then a rotationally supported disk will form and its size can be predicted from theory.

The Galaxy Evolution Explorer (GALEX) satellite was launched by NASA in April 2003. It is an orbiting space telescope that is observing galaxies in ultraviolet (UV) light across 10 billion years of cosmic history . UV light is emitted primarily by massive young stars and it can hence be used as a very sensitive probe of the recent star formation in a galaxy. UV radiation is almost entirely absorbed by ozone in the upper atmosphere of the Earth so astronomers must obtain their observations from space.

One surprise discovery made by GALEX is that some early-type galaxies that look "red and dead" when viewed in optical light, turn out to have very extended outer disks that are only visible in the ultra-violet. An example of such a galaxy is shown in Figure2.19. The galaxy NGC 4265 only showed an oval-shaped ball of light when observed in visible light. In UV light one sees a disk with a beautiful set of spiral arms.

Recent work by the MPA group has extended this result to the entire population of elliptical galaxies in the local Universe. The analysis demonstrates that UV disks are a common phenomenon among this population. Interestingly, all elliptical galaxies where the central supermassive black hole is growing at an appreciable rate have outer UV-bright disks . This suggests that the disks contain a reservoir of gas necessary for ongoing growth of the central spheroids and supermassive black holes. The disks are subject to dynamical instabilities such as warps and bars, and gas will then flow inwards towards the nucleus of the galaxy. The galaxies that host UV disks are on average

Figure 2.19: This image highlights the hidden spiral arms (blue) that were discovered around the nearby galaxy NGC 4625 by the ultraviolet eyes of NASA's Galaxy Evolution Explorer.

quite different to those that host radio jets – radio AGBN are typically found in the very most massive galaxies and in galaxies that reside at the centers of rich clusters, whereas UV disks are typically found around smaller bulges and in lower density environments.

As the variety of data probing galaxies at different wavelengths accumulates, more and more pieces of the galaxy formation puzzle continue to fall into place. Direct measurements of the gas content of galaxies remain an elusive, but important missing link in understanding how galaxies form as a result of cooling in dark matter halos. Radio surveys of the atomic hyrogen content of galaxies have so far not kept pace with optical surveys, because of the very limited sensitivity of the available detectors. This situation is set to change over the next years and the MPA group is preparing to play a central role in new data acquisition and analysis that will shed light on this issue
(Guinevere Kauffmann).

2.8 Serving the New Millennium

In summer 2004 the Garching Supercomputer Centre of the Max Planck Society finally delivered results for the Millennium Run. At the time, this was the largest simulation of the evolution of cosmic structure ever carried out, and it had taken almost six months to get it through the centre's IBM-Regatta supercomputer; if it had been possible to run without breaks, it would still have taken a month to complete the job on a 512-processor partition. The simulation used the full 1 Tbyte of memory available, and by the time it was done it had produced about 20 Tbytes of archived output. These represent the distribution of dark matter in a 690Mpc cube of the Universe with enough spatial and mass resolution to see the dark matter concentrations corresponding to even quite small galaxies and with enough temporal resolution to reconstruct the formation history of every object.

Three years later, the Millennium Run remains the largest simulation of its type ever carried out, four different galaxy formation models have so far been built to populate it with galaxies, and well over 50 papers have been submitted for publication based wholly or partially on its numerical data. More than half of these are by authors who are unassociated with the Virgo Consortium, the international supercomputing collaboration which carried out the simulation. This has been possible because of a concerted effort to release the data in easily usable form. Their volume and complexity are such that sophisticated databases with a high-level query language are needed to promote effective public access. The Millennium Archive has been built as one of the principal activities of GAVO, the German Astrophysical Virtual Observatory, and it is currently the largest and most complete application of Virtual Observatory techniques to the publication of theoretical data from numerical simulations.

The public release of simulation data brings new challenges which are different from and go beyond those which must be faced when setting up a public archive for observational data. Many of these result from the great variety of relations between the various objects in the database, as well as from the many properties that can be assigned to each one. In practice, most users are not interested in the raw data from the simulation – the positions and velocities of the 10^{10} dark matter "particles" followed by the supercomputer – but rather in the properties of dark matter halos and galaxies, objects created from the simulation output through post-processing. Dark matter halos are the basic nonlinear units of the simulated universe. They have masses, sizes, angular momenta, velocity dispersions, shapes, concentrations, positions and velocities, in addition to internal substructures (subhalos) which are the remnants of objects which fell into them during their growth. The Millennium Archive contains information for about 7.5×10^8 halos and subhalos, all linked in a tree structure which describes how each object was built from those present at the immediately preceding time. This is the data structure used by the galaxy formation algorithms.

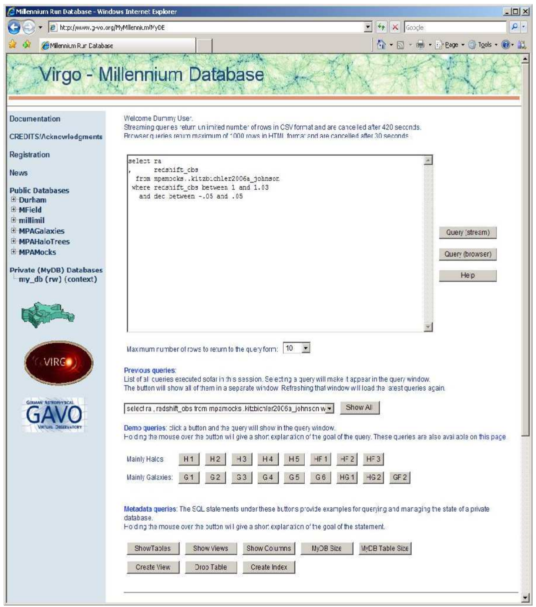

Figure 2.20: The web interface to the Millennium Simulation archie. The query shown selects all galaxies with redshifts between 1.0 and 1.03 in a 0.1 degree slice in declination from a database containing a deep mock survey of galaxies on a $1.4^o \times 1.4^o$ area of the sky.

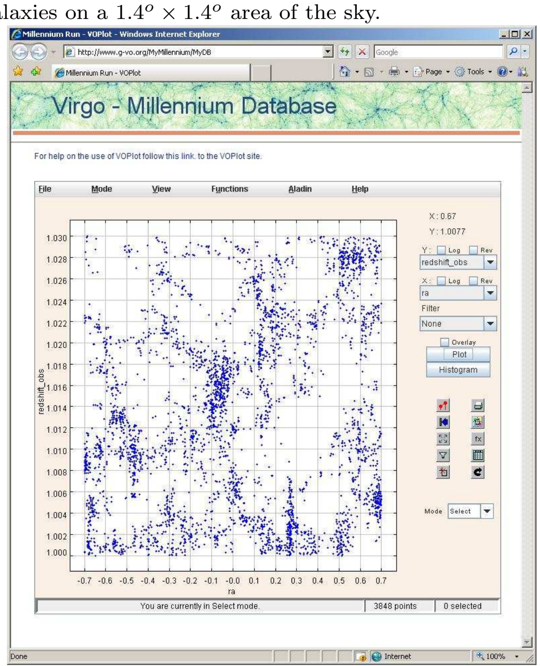

Figure 2.21: A plot made using the web-tool VOPlot of the positions in redshift and right-ascension of the galaxies returned by the query of 2.20

Galaxy formation is a complicated and uncertain process, and many physical models for its various aspects must be tried in order to establish those which best describe observed phenomena. A principal goal of the Millennium Run project is to provide a framework for comparing such models to observational data. It is thus important to make available simulated galaxy catalogues with a variety of assumptions about the physics of galaxy formation so that users can get a feel for the uncertainties involved. A galaxy catalogue for the full Millennium Run has about 10^9 entries. For each of these galaxies many properties can be calculated by the formation model and must be stored in the database, for example, redshift, position and velocity, stellar and gas masses, observer- and rest-frame magnitudes for a wide range of photometric bands, star formation rates, bulge-to-disk ratios, sizes, mean stellar ages and metallicities central black hole masses and accretion rates... In addition, pointers are needed to connect the galaxies present at different times, and these produce a tree data structure which gives the merger history of each galaxy and which parallels (but is different from) the halo formation trees.

A final issue which has to be addressed comes from the fact that users wish to use the Millennium Run for a wide variety of purposes and the“view” of the data which is most convenient for them depends on their project. Scientists interested in models for the build-up of nonlinear structures can work most efficiently with halo merger trees. Those interested in the growth of visible galaxies would rather use galaxy merger trees. Projects to study the dark matter structures around galaxies need efficient links between the galaxy and halo catalogues. Studies of the properties of the cosmic web are most easily carried out using a high-resolution map of the density field. Observers wishing to compare simulated results with real data often prefer to have the data tabulated along the past light-cone of a virtual observer, rather for the fixed time “snapshots” for which they were originally generated. They can then make a virtual survey (usually referred to as a “mock catalogue”) which is constructed with exactly analogous limitations (e.g. sky coverage, magnitude limit, and so on) as their real survey. This is very useful for investigating observationally induced selection effects, and a comparison of mock catalogues constructed from different galaxy formation models makes it clear which aspects of the observational data are sensitive to the physical effects which are being varied.

If a database is to be successful in serving data to a wide community, it must be easy to use, well-documented, robust, and support a sufficiently powerful Query Language that users can obtain the data they want in a short time and with a minimum of effort. In order to fulfil these requirements the MPA/GAVO group decided to use a relational database for storing the post-processing results of the Millennium database. Products stored so far include density fields sampled on a 256^3 grid, subhalo merger trees, galaxy merger trees obtained using semi-analytic simulation methods implemented independently at MPA and in Durham, and light cones derived from some of these galaxy catalogues, both deep pencil beams and shallow all-sky catalogues of a depth similar to the SDSS spectral sample.

A relational database offers a standardised view of data in terms of tables. Objects (for example halos or galaxies) are mapped to rows in the tables, with columns holding the individual properties, such as galaxy luminosities, halo masses, positions etc. Some of these columns can also hold pointers to rows in the same or other tables, indicating relations between the corresponding objects. For example galaxies point to the subhalos they are embedded in. The true strength of the relational approach is that there is a standard and intuitive query language (SQL) that makes use of this tabular view of the data. Users therefore do not need to learn the intricacies of data formats, something that is often a problem in simulation work. In a relational database this query language is implemented by efficient query engines that interpret the potentially complex requests and execute these in the most efficient way. Such query engines offer standard ways to tune the database for performance, adding tree-based indexes, or hash-tables to the tables, and deciding which route to take through the multiple tables.

To provide online access to the Millennium database, GAVO has implemented a web-based query interface (see Fig. 2.20). Apart from providing documentation and example queries, users can type in their own SQL queries and execute them. The results, which themselves are tabular, can be returned to the user in various formats, or they can be stored in a private database, that is assigned to registered users. This approach is directly modelled on the highly successful SDSS SkyServer database, in particular its CAS jobs service (http://cas.sdss.org/dr5/en/). One advantage of this is that users can cross-correlate their results with the main database for further analysis by joining their own tables to archive tables in their query.

For small output data tables users can directly visualise their results using a VOPlot applet created by the Indian Virtual Observatory. Figure 2.21 shows an example of this visualisation for the query shown in Figure 2.20. That query selected a slice of the light cone stored in MPAMocks..Kitzbichler2006a-Johnson pencil beam, restricted in redshift and declination. For queries producing larger results it is more useful to store the results on disk for further analysis using more powerful tools. It is also possible to use specially created adapters that pipe results to popular scripting languages (e.g. IDL and R), or to the TOPCAT standalone visualisation tool, originally created by StarLink and now maintained by the Euro-VO project. This makes it possible, for example, to explore 3-D representations of data on-line.

At the time of writing there are 117 registered users of the Millennium Archive site with local disk space allocated for storage and manipulation of the results of their queries. About 85% of these have successfully executed queries on the main databases. Roughly half appear to be already carrying out significant research programmes (more than 50 successful queries), while about 20% can be characterised as heavy users (more than 1000 successful queries). Currently 6×10^8 rows of data are being downloaded from the site per week. The user group is still growing rapidly and it will probably be several years before the archive's success in generating new science from the Millennium Simulation can be properly assessed. (Gerard Lemson and Simon White; the public databases and documentation can be found at http://www.mpa-garching.mpg.de/millenium).

2.9 Coherent structures in solar granulation and solar p-mode excitation

Helioseismology has provided us with a new 'window' to look inside our Sun. Through observing its oscillations with sufficiently high precision it is possible to constrain the profiles of sound speed, density, and mean molecular weight, and thus also of pressure and temperature, as a function of depth. While integral quantities such as the radius or the luminosity of the present Sun can be matched by adjusting model parameters used in solar structure and evolution calculations, the recovery of the depth profiles of thermodynamical variables, which

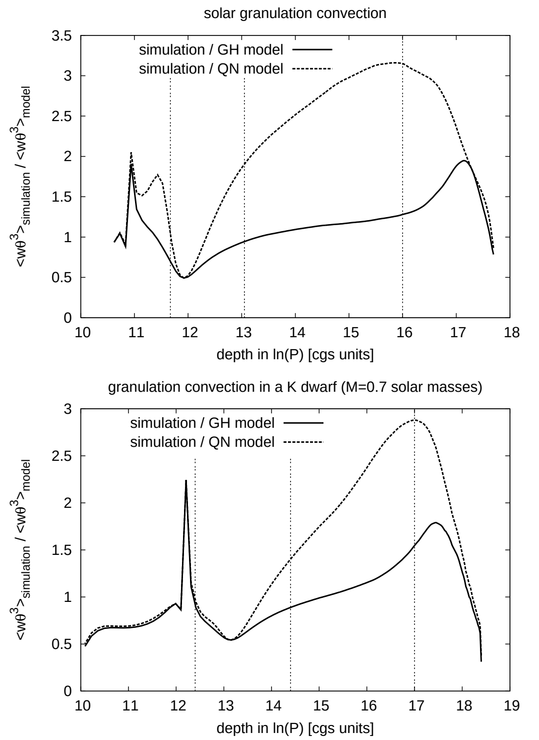

Figure 2.22: The top panel shows the ratio between the cross-correlation $\overline{w\theta^3}$ computed directly from the simulation and two different models (GH and QN) using the simulation data as input in the model expressions. The bottom panel shows the same quantity for an 0.7 $M_{\odot}$ K dwarf of solar abundance at an evolutionary age of $t \sim 6$ Gyr. The logarithmic, horizontally averaged gas pressure is used to denote depth, as it increases strictly with depth and resolves the different regions. The photosphere is located to the left of the first vertical line in both panels, followed by the superadiabatic layer below it (between the first and the second vertical line), and the quasi-adiabatic region (to the right of the second line). The bottom region (to the right of the third line) is influenced by the closed lower boundary assumed in the simulations. Note the solid line remains much closer to 1 in the quasi-adiabatic region.

is necessary to predict the helioseismological observables, is an independent and stringent test of our understanding of the interior of our Sun. Successful achievements of helioseismology over the past two decades include the determiniation of the depth of the solar convection zone as well as of the gradient of helium in its radiative interior, the provision of strong constraints on the core temperatures and thus solar neutrino production (which eventually led to observational evidence for the existence of neutrino oscillations), and the unveiling of the complicated rotational profile in the interior of the Sun. Under the name of asteroseismolgy this technique is now applied to an increasing number of stars including solar-like ones and white dwarfs.

Most of the information obtained from helioseismology is based on identifying the oscillation modes observed in the data and thus determining both their amplitudes and frequencies, as well as variations of these quantities with time. The dominant contribution to these oscillations are p-modes (pressure modes), sound waves trapped in the resonant cavity provided by the finite size of the Sun and the change of physical conditions as a function of location. Naturally, we can learn more about the solar interior, if we have a detailed physical understanding of how energy is injected into or dissipated from these p-modes. Stochastic excitation of p-modes by convection is considered to be the main mechanism which drives these oscillations. Mode frequencies, sound speed, and observed amplitudes imply that the strongest driving occurs just below the visible surface of the Sun. Numerical simulations of solar surface convection are an excellent tool to study mode driving. The signature of p-modes has indeed been found in simulations of several research groups. A direct calculation of the observed mode spectrum is not possible from such simulations, because only few modes fit within a simulation box with sufficient resolution for the up- and downflows at the granulation scale, where most of the kinetic energy resides. However, the simulations can be used to probe models of the excitation mechanism.

Refined models consider both the fluctuating velocity fields as well as fluctuations of entropy as sources for injecting energy into the modes. Usually, for the fourth order correlations of velocities and temperature, which appear in those models, the quasi-normal approximation is assumed. For this assumption to hold the fields have to behave similar to a Gaussian random distribution. The strong asymmetry between up- and downflows observed for the solar surface indicates that this approximation is fairly questionable. The same can be concluded from numerical simulations.

Coherent structures which are observed as broad upflow regions (granules) enclosed by a narrow intergranular network of downflows are by no means restricted to stellar convection. The same pattern is found for convection in the oceans of the Earth and in reversed form (narrow, rapidly rising plumes embedded in broad, slowly moving downflows) for convection in its atmosphere. To model the latter V.M. Gryanik (at AWI Bremerhaven) and collaborators have suggested a 'two-scale mass flux model'. It yields scaling relations for the fourth order moments which are also functions of the skewness of the velocity and temperature fields, whereas

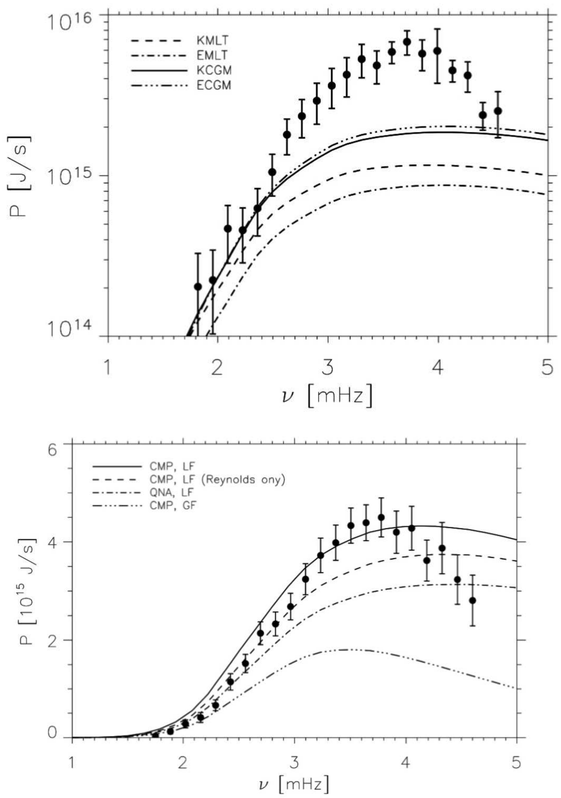

Figure 2.23: The top panel shows the power injected into solar p-modes per mode as a function of frequency as deduced from observations (dots with error bars) and from solar envelope models with different convection models and model atmospheres (solid curve indicates the physically most complete model). These models assume a quasi-normal distribution of fourth order correlations. The bottom panel shows the benefits from taking the flow topology into account (solid curve, other curves indicate the consequences of approximations made to the complete model). Note the linear scale for the power rate. The observed data are derived from observations with the GOLF instrument on board of SOHO and are a revision of the data shown in the top panel.

in the quasi-normal approximation they only depend on second order moments. Consequently, in the new model the fourth order correlations also depend on the asymmetry between up- and downflows as well as hot and cold drafts, in avereges computed at a given radius. With the parameters of the scaling relations constrained by asymptotic cases the model was found to yield very good results when probed with observational and simulation data from geophysics.

Is that model also applicable to the case of convection in the surface layers of the Sun or low mass stars ? To answer this question numerical simulations have been performed and evaluated in collaboration with F.J. Robinson (Yale University). Fig. 2.22 displays a fourth order cross-correlation, $\overline{w\theta^3}$, as an example (w and θ refer to velocity and temperature fluctuations relative to their horizontal mean, with their correlation products averaged horizontally and in time using snapshots from the simulation as input data). For the new model (GH) a considerable improvement is found in comparison with the quasi-normal approximation (QN) in the nearly adiabatic part of the simulation (between the second and third vertical line in both panels): the relative error is reduced from a factor of 2 – 3 down to 20% – 30%. Similar improvements are found for the other fourth order correlations. These results are corroborated by numerical simulation for the Sun performed with the code of Å. Nordlund and R.F. Stein by collaborators at the Obs. de Paris-Meudon (K. Belkacem, M.-J. Goupil, R. Samadi). For their case open instead of closed boundary conditions have been assumed at the top and bottom of the simulation box and a more detailed radiative transfer scheme has been used as well. The same improvement was found for the geophysical systems mentioned above, despite vast differences in equations of state, heating and cooling mechanisms, boundary conditions, and the role of stratification and compressibility. Since the common feature shared by all the analyzed systems is that of an interior, quasi-adiabatic convection zone with a filamentary flow and temparture structure, the shortcomings of the quasi-normal approximation in this part of stellar convection zones can indeed be assigned to the coherent structures which characterize this region and which are well accounted for in the new model.

As a result of previous collaboration with the seismology group at the Obs. de Paris-Meudon the usefulness of excitation rates of solar p-modes as an additional probe for solar structure models has been demonstrated (top panel of Fig. 2.23). Clearly, the existing models underestimated the driving of p-modes in the range of 2.5–4 mHz by a factor of 2–3. This frequency range is strongly influenced by the physics in the uppermost part of the quasi-adiabatic convection zone. Since the quasi-normal approximation clearly underestimated fourth order correlations (cf. Fig. 2.22), which in turn results in an underestimation of mode excitation rates, the two-scale mass flux model by Gryanik was considered a welcome alternative. Further work done in the seismology group at the Obs. de Paris-Meudon eventually led to a new 'closure model with plumes' applicable to mode excitation rate calculations. The predictions of this approach are now essentially in agree-

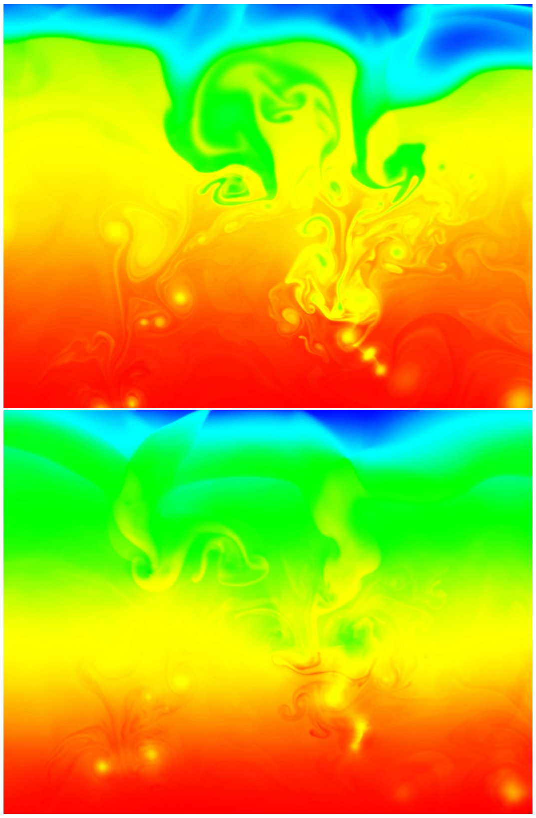

Figure 2.24: The top panel shows the temperature distribution in a subdomain of a solar granulation simulation in 2D with $\sim$ 1.8 km vertical and $\sim$ 2.8 km horizontal resolution. The bottom panel shows the density distribution in another snapshot. The upflow regions (yellow shaded regions in the top panel reaching nearly its top) are smooth even at this high resolution, confirming previous results (e.g., R.F. Stein and Å. Nordlund). The downflow regions are highly turbulent, though only below the visible surface (blue color shades in the top panel), where the strongest driving of solar p-modes should occur (green shades).

ment with the observed data (right panel, 1-σ error bars), except for the highest frequencies, which are strongly influenced already by the super-adiabatic layers that reach into the bottom part of the observable photosphere. As of now, the model requires second order moments from another convection model or simulations as input data. If the latter are not available, a deterioration of the agreement with observations has to be expected, when standard convection models are instead taken as a source for that data (compare the solid curve in the top panel with the dot-dashed one in the bottom panel of Fig. 2.23).

We expect further progress in this field from new numerical simulations of solar granulation performed at very high resolution. In collaboration with H. Muthsam (Univ. of Vienna) a new code, Antares, based on advanced numerical methods and grid refinements has been used to perform simulations in 2D. In a subrange of the entire simulation box they have a resolution of 2–3 km, an order of magnitude better than in previous (2D and 3D) simulations. Fig. 2.24 shows snapshots from these calculations. Vigorous secondary instabilities are formed around the downdraft plumes which create structures on a scale of 10 km and presumably even smaller. They give rise to a variety of acoustic phenomena and are currently investigated for their potential to provide a better understanding of the process of energy injection into p-modes. High resolution simulations in 3D have been started and even more detailed simulations are also planned for the 2D case. This in turn will help to further improve the models and in the end the predictive capability of helio- and asteroseismological analyses (Friedrich Kupka).

3 Research Activities

3.1 Numerical Hydrodynamics

The activities of the stellar hydrodynamics group at MPA in 2006 can be grouped into four major, partially overlapping research directions: development of numerical tools for simulating core collapse supernova, investigations of thermonuclear (type Ia) supernovae, studies of general relativistic core collapse, and simulations of solar convection (see also the sections on *Stellar Physics* and on *Nuclear and Neutrino Astrophysics*).

The modeling of core collapse supernovae (ultimately) requires an efficient solution of three-dimensional hydrodynamics coupled to the six-dimensional neutrino transport problem. To this end K. Kifonidis has continued his work on a new implicit/explicit, multidimensional radiation-hydrodynamics code, which will be able to efficiently exploit parallel computer architectures. The basic code version, which originally made use of Cartesian grids, was extended to handle general, structured curvilinear grids in collaboration with W. Högele, a student from the department of mathematics of the TU München staying for a half-year internship at MPA. Furthermore, new implicit algorithms were implemented whose performance is currently being evaluated.

Besides this more strategic and long-term project the activities of the core collapse supernova modelers aimed at further enhancing the capabilities of the existing simulation tools. B. Müller in his PhD work, supervised by H.-Th. Janka, significantly improved the performance and efficiency of the neutrino-hydrodynamics code VERTEX-PROMETHEUS. Combining the lepton number and energy transport equations he reduced the number of equations to be integrated without sacrificing the good numerical conservation of both fundamental quantities. During a two-month summer project R. Buras enhanced the stability of the VERTEX-PROMETHEUS code for large time steps. This improvement makes long-time cooling calculations of nascent neutron stars feasible, and will allow for the computation of the resulting neutrino light curves and spectra. In order to be also able to treat MHD effects M. Obergaulinger started developing a multi-dimensional neutrino radiation magneto-hydrodynamics code. This Ph.D project supervised jointly by Th. Janka and E. Müller is pursued in collaboration with M.A. Aloy and K. Kifonidis. The code is based on a flux-conservative formulation of the Eulerian MHD equations and on the comoving-frame equations of radiative transfer. For the solution of the hydrodynamic equations, several approximate Riemann solvers are applied, amongst them the *multi-stage* solver by E. Toro which considerably reduces the numerical viscosity of the scheme. The Boltzmann equation of radiation transport is approximated by a system of evolutionary equations consisting of the energy-integrated first two angular moments of the neutrino distribution function. The resulting system of partial differential equations is hyperbolic and is integrated by standard approximative Riemann solver techniques. Radiation and matter are coupled by a number of neutrino baryon reactions. As a first application, the nonlinear evolution of MHD Kelvin-Helmholtz instabilities is simulated.

Several projects were concerned with the study of the effects of relativistic gravity in core collapse. A. Marek studied the performance of an effective relativistic potential in 1D and 2D stellar core collapse simulations with and without neutrino transport during his PhD work supervised by H.-Th. Janka. Together with H. Dimmelmeier he tested the quality of such an approximate description of general relativistic effects against a more complete treatment of relativistic gravity.

H. Dimmelmeier, C. Ott (MPI for Gravitational Physics, Golm, Germany), I. Hawke (University of Southampton, U.K.), and E. Seidel (Louisiana State University, U.S.A.) performed comparison studies of supernova core collapse using (i) CoCoNuT a well-tested and accurate 2d/3d relativistic hydrodynamics code utilizing the conformal flatness approximation of space time, and (ii) Cactus/Whisky, a full-fledged general relativistic hydrodynamics tool developed at Golm. The simulations of rotational supernova core collapse performed with both codes have considerably extended the state-of-the-art in this field by combining in three dimensions without any symmetry restriction a fully relativistic treatment of gravity, a micro physical description of matter including deleptonization effects, and the best available initial models from stellar evolution. This work, which was done in collaboration with A. Marek and H.-T. Janka, has shown for the first time that the dynamical bar-mode instability in rotating protoneutron stars (also observed by other groups) is not confined to idealized conditions, but occurs in more realistic astrophysical situations too. The simulations have also yielded more realistic templates of the gravitational wave signal from supernova core collapse. Currently, H. Dimmelmeier, C. Ott (MPI for Gravitational Physics, Golm, Germany), A. Marek, H.-T. Janka, and E. Müller attempt to establish criteria to predict the dynamics of collapsing stellar cores from the rotational state of the stellar progenitor. The ongoing study shows that the influence of rotation was strongly overestimated in previous studies using a simplified model for the core matter. The new results will help to increase the probabilities to detect such events with gravitational wave detectors currently being built or already taking data.

A further study concerned with relativistic gravity dealt with neutron star oscillations. Together with N. Stergioulas (Aristotle University, Thessaloniki, Greece) H. Dimmelmeier advised the Diploma student K. Zagkouris (Aristotle University, Thessaloniki, Greece) to use the CoCoNuT code for simulations of axisymmetric oscillating neutron stars whose thermodynamics is described by a tabulated equation of state. This improves on previous studies which were limited to a simple analytic formulation of the equation of state, and extends the field of asteroseismology to rotating neutron stars. H. Dimmelmeier also provided the Ph.D. student E. Abdikamalov (SISSA, Trieste, Italy) of L. Rezzolla (MPI for Gravitational Physics, Golm, Germany) with the CoCoNuT code to investigate the collapse of neutron stars induced by a phase transition to quark matter. Such a transition, which results in a violent star quake, is accompanied by significant emission of gravitational waves, which could be observable by gravitational wave detectors.

The modeling of thermonuclear supernova explosions continued to be a major part of the activities of the group. Although Friedrich Röpke was on leave at the University of California at Santa Cruz, the work based on the group's combustion hydrodynamics code *SuCCESs* (Supernova Combustion Code for Explosion Simulations) continued and led to several new and exciting results.

A first set of simulations was completed in which it could be shown that the approach chosen by the group, i.e., large eddy simulations with a sophisticated local and dynamical sub-grid scale model for turbulence, and a level-set to track the burning front, is well justified. This could be done by means of a simulation carried out at the RZG by Friedrich Röpke and Wolfgang Hillebrandt, running on 512 processors of the IBM Regatta supercomputer over more than 1000 hours, numerically resolving length scales down to 800 meters in the core of the exploding white dwarf star. A second similar simulation with different ignition conditions was performed at the Supercomputer Center in Edinburgh in the framework of the European Infrastructure *DEISA*. The tera bytes of data obtained from both simulations imposed new challenges for post-processing and visualization which initiated a close collaboration with the RZG, but the work is not yet completed. Light curves were computed in collaboration with Sergei Blinnikov and the group at ITEP in Moscow and they fit those of observed type Ia supernovae surprisingly well. Also, for the first time, the predicted nuclear abundances from a (parameter-free) simulation could be compared directly with those reconstructed for a real supernova from a dense time series of spectra and, again, the agreement was quite good.

While in these simulations it was assumed that the mode of propagation of thermonuclear flames inside the white dwarf star is a subsonic deflagration, also the possibility of a transition to a detonation late in the explosion was re-investigated, because there seem to be indications from observed spectra that such a transition might take place at least in some supernovae. This work was done by Friedrich Röpke in collaboration with Jens Niemeyer's group at the University of Würzburg. They could add a module to the *SuCCESs* code that follows the detonation front, thought to be launched once the deflagration flame enters the regime of distributed burning, with a second level-set. A first set of simulations showed that, indeed, a late detonation can bring the explosion models closer to their observed counterparts. The new code was also used in Diploma thesis by Michael Fink to re-investigate the possibility that rather low-mass white dwarfs with He layers on top, the so-called sub-Chandrasekar-mass branch of type Ia supernova progenitors, might explode, triggered by the detonation of the helium. He could show that this is a robust explosion mechanism. However, the properties of these explosions do not agree with any of the observed type Ia supernovae. A possible explanation is that white dwarfs cannot accumulate enough He on their surface but rather burn the accreted He in flashes before it can detonate.

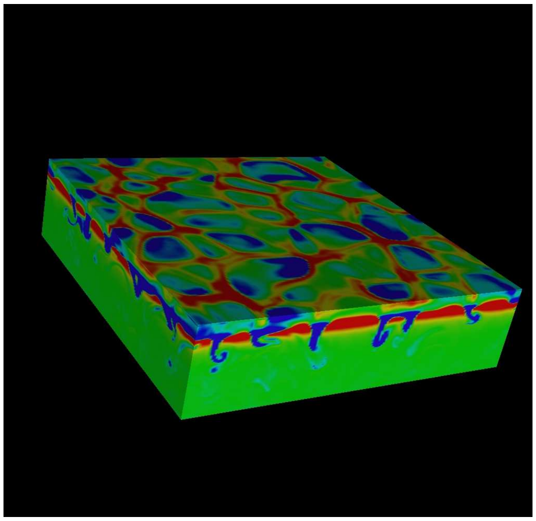

Figure 3.1: 3D numerical simulation of solar surface granulation. The figure presents a snapshot of the difference between the logarithm of temperature and its horizontal average. Cool, narrow downdrafts (blue) are embedded between hot upflow regions (red), as can be seen on both sides of the box (the top layers show a more complex, partially reversed pattern, but they are located already at the bottom of the chromosphere). Differences between up- and downflows are small in the interior (green areas on both vertical sides). This simulation run provides the boundary conditions for much higher resolution simulations that probe the detailed structure and properties of downflow regions (F. Kupka).

The collaboration of F. Kupka with H. Muthsam (Univ. of Vienna) on the numerical study of solar convection resulted in the first set of simulations of solar granulation which feature a local (grid) resolution of 2–3 km in part of the simulation domain with a realistic background (simulated at lower resolution and enclosing the domain of interest) and realistic micro-physics. Shearing instabilities, undetectable with standard grid resolutions of 20–30 km, could for the first time clearly be identified at the boundaries between up-flowing granules and down-flowing plume-like features. While these processes take place mostly underneath the observable surface, they may play an important role in how energy is fed into solar oscillations and how flow patterns underneath the solar surface are modified by the up- and down-flows. This study is now extended from the two dimensional to the three dimensional case using the super-computing facilities of the RZG. The grid refinement of the Antares simulation code (by H. Muthsam and co-workers) used for this work will also benefit the study of semi-convection, for which the code is reaching production stage (collaboration with H.C. Spruit).

R. Walder, in collaboration with D. Folini (ETH Zurich), analyzed supersonic turbulence in shock-bound interaction zones of colliding hypersonic flows. Such turbulence is thought to play a dominant role in star formation but is physically important also in wind-driven structures and probably gamma-ray bursts. They showed that the average properties of the interaction zone are well described by scaling laws obtained from dimensional analysis. The governing number is the upstream Mach number. Numerical simulations allowed to determine the scaling parameters and showed that the spatial scale of the turbulent structure scales with the width of the interaction zone and the upstream Mach number.

3.2 Stellar Astrophysics

In the field of *Stellar physics* the activities at MPA in 2006 concentrated on four major topics: (i) simulations of core core collapse supernovae, (ii) and of thermonuclear supernovae, (iii) constraining theoretical supernova models by observations, and (iv) understanding certain aspects of stellar evolution (see also the sections on *Numerical Hydrodynamics* and on *Nuclear and Neutrino Astrophysics*).

The simulations of core collapse supernovae involved a study of the importance of the magneto-rotational instability (MRI), and of the mixing processes occurring in the envelopes of exploding massive stars. M. Obergaulinger, E. Müller, M.A. Aloy, and H. Dimmelmeier investigated the collapse of rotating magnetized stellar cores, particularly focusing on the development of the magneto-rotational instability. In several simulations based on simplified core models (polytropes), they were able to resolve the fastest growing MRI modes. They observed an exponential growth of the magnetic field strength, leading to enhanced angular momentum transport and the formation of jet-like outflows. K. Kifonidis in collaboration with H.-Th. Janka, E. Müller, and T. Plewa (Flash Center, Univ. of Chicago) performed adaptive mesh refinement simulations to study the development of hydrodynamic instabilities in the mantle and envelope of exploding massive stars as a consequence of bipolar and quadrupolar asymmetries produced in the innermost ejecta by convective overturn in the neutrino-heating layer and by a newly discovered non-radial instability of the stalled accretion shock. The simulations revealed the importance of Richtmyer-Meshkov instabilities at the composition interfaces of the star after shock passage for triggering large-scale mixing of hydrogen deep into the stellar core and of metals far into the hydrogen layer, as required to explain the observational properties of SN 1987A. P. Mach (Univ. Cracow, Poland), a student staying on a ten months internship funded by DAAD at MPA, presently continues these studies for different stellar progenitor models.

In 2006 the European Research Training Network (RTN) "The Pysics of Type Ia Supernova Explosions" came to an end. Over its five years of operation it has accumulated photometry and spectroscopy for a total of 16 nearby supernovae which, with one exception (SN 2004aw was of type Ic) were all of type Ia. Meanwhile, most of the data have been reduced, calibrated, and were analyzed by researchers of the collaboration, including N. Elias de la Rosa, A. Pastorello, and S. Taubenberger from MPA, a challenging task, because the observations of each supernova were done with up to 12 different telescopes. It is planned to provide this unique set of data to other interested astronomers once the data reduction is completed for the full set which is forseen for the end of 2007. The data analyzed so far have already led to extremely interesting conclusions. It was found that otherwise almost identical supernovae can have distinctly different early spectra which may be the clue to map the accretion history of the white dwarf prior to the explosion. Although it was found that in order to calibrate their peak luminosities, a prerequisite for cosmic distance measurements, at least one second parameter should be considered. Most of this interpretive work was done by M. Stehle and P. Mazzali, together with other members of the collaboration.

Constraining theoretical supernova models by observations has become a very active field of research at MPA. P.A. Mazzali and collaborators discovered a Type Ic supernova in coincidence with an X-ray Flash, the weak analogue of a Gamma-Ray Burst, and observed the supernova, SN 2006aj with the ESO-VLT. In collaboration with visiting post-Doc D. Sauer he modeled the spectra and light curve of the supernova and showed that it is the result of the explosion of a star of initially $\sim 20\,M_{\odot}$. This, and the luminosity of the supernova, suggest that the collapse did not produce a black hole, as expected for supernovae belonging to the hypernova/GRB class, but rather a neutron star. The X-ray flash was probably produced by some magnetic activity on the surface of the nascent neutron star, which also could have increased the explosion energy to the slightly larger-than-normal value of 2×10^{51} ergs. The results were communicated in two publications in Nature. P.A. Mazzali, in collaboration with D. Sauer and K. Nomoto's group at Tokyo University, further modeled a set of SNe Ic in order to establish the range of properties and progenitors of these objects. In particular, they studied the "normal" low-energy SN 1994I, and the over-energetic, broad-lined, but still non-GRB SN 2004aw. P.A. Mazzali also continued the development of a fully three dimensional light curve and nebular spectrum synthesis code, which has been applied to the GRB-SN 1998bw.

Further observational studies of SNe Ic were pursued in the PhD work of S. Taubenberger, supervised by W. Hillebrandt. He went on investigating the observed properties of various kinds of supernovae. He has completed his studies on the peculiar Type Ic SN 2004aw, that provide further insight into a class of supernovae that has not been well studied so far. Issues like the intrinsic heterogeneity within this class, links between regular SNe Ic and hypernovae, and the presence or absence of helium in the ejecta are addressed in this work. In addition, basic physical parameters of the progenitor star and the explosion have been inferred by means of an analytical description of the light curves. The second object S. Taubenberger has concentrated on, SN 2005bl, is an under-luminous Type Ia supernova with unprecedentedly strong C II lines in its earliest spectrum, six days prior to maximum brightness. Spectral modeling, that has been performed in collaboration with S. Hachinger and P.A. Mazzali, indicates a carbon abundance at the photosphere of at least 8% at that epoch. This large amount of unburnt material, together with the low abundance of NSE elements, suggests very incomplete burning, and may shed light on the explosion mechanism underlying the group of under-luminous SNe Ia.

Besides SNe Ic, i.e., stripped core collapse supernovae, P.A. Mazzali also modeled the light curves and spectra of a number of thermonuclear supernovae (SNe Ia) observed through the European Supernova Collaboration and the EU-RTN on *The Physics of Type Ia Supernova Explosions*. He supervised PhD student M. Tanaka (Univ. Tokyo) in the development of a three-dimensional code for the calculation of early-time supernova spectra using the Monte Carlo approach. The properties of the outer supernova ejecta determined by this code have been published. P.A. Mazzali also worked on extracting the general properties of SNe Ia and to understand how they affect the use of these objects in cosmology. In collaboration with P. Podsiadlowski (Univ./ of Oxford) he investigated how the presence of stable iron group isotopes such as 54Fe and 58Ni can affect the light curve and the spectra of supernovae. They showed that a small change in the metallicity of the white dwarf progenitor can lead to uncertainties in the peak brightness of the supernova of the order of 20%, which is the size of the effect used for cosmology, while the shape of the light curve is not affected. Using the nebular spectra of 23 well-observed SNe Ia P.A. Mazzali determined the element distribution of their ejecta. His results, which are published in Science, suggest that the mode of explosion is similar in all SNe Ia, possibly a delayed detonation. In his diploma project supervised by P.A. Mazzali, S. Hachinger measured line ratios in different SNe Ia to establish observational trends, and examined the diversity of spectral properties among supernovae Ia of different luminosity.

Observational signatures of thermonuclear supernovae were also modeled by S.A. Sim, who worked on the implementation of Monte Carlo radiative transfer methods for the computation of light curves and γ-ray spectra from three dimensional models of SNe Ia. A new Monte Carlo code, which is both fully three dimensional and allows for an arbitrary orientation of the supernova relative to an observer's line of sight, has been developed, tested and applied to investigate several multi dimensional radiative transfer phenomena. The code has been used to show that both complex inhomogeneity, as predicted by modern SNe Ia hydrodynamic simulations, and any global departures from sphericity can affect light curve shapes as compared to those obtained with simpler one dimensional computations. These multi dimensional effects have ramifications for understanding aspects of the observed diversity in the SNe Ia population.

The studies in stellar evolution included the core helium flash, stars which show enhancement of α-elements (O, Na, Mg, Si, Ti, ...), the stellar properties of K giant stars showing radial velocity variations, and techniques to ensure a better scientific exploitation of asteroseismic data from the CoRoT mission.

M. Mocak, K. Kifonidis and E. Müller adapted a version of the 3D PPM-hydrodynamics code HERAKLES to model dynamic phases of stellar evolution, and in particular the core helium flash. For this purpose they have added thermal conduction, a stellar equation of state, and a nuclear reaction network to the basic hydrodynamics scheme. After extensive testing of the implementation, M. Mocak, in his PhD thesis supervised by E. Müller and

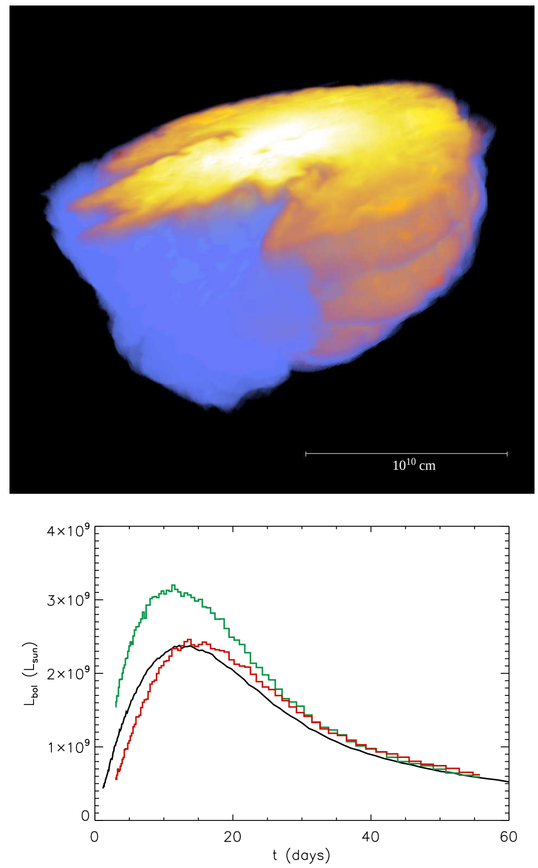

Figure 3.2: Upper panel: A three-dimensional simulation of an aspherical Type Ia supernova at 10 seconds after explosion. The white/yellow regions contain material that has undergone nuclear burning during the explosion and contains mostly heavy elements (iron-group, mostly ^{56}Ni.) The blue regions are unburned and consist primarily of carbon and oxygen. Only one hemisphere of the star is shown. Bottom panel: The aspherical distribution of burned material in the explosion means that the observed brightness depends on the direction from which the supernova is observer. The figure shows the brightness of the supernova (measured in units of the solar luminosity) as a function of time for two different directions of observation (the red and green curves) compared to the mean brightness, which is obtained by averaging over all directions. It can be seen that the observable light curves can be quite different from the mean light curve which could affect the interpretation of some observations of supernovae Ia (S.A. Sim).

A. Weiss, has begun using this code to study the hydrodynamic effects of the core helium flash in solar-type stars.

A. Weiss and coworkers investigated stars which show enhancement of α-elements (O, Na, Mg, Si, Ti, ...). New low-temperature molecular opacity tables were provided by J. Ferguson (Wichita State University, Kansas, USA) and their effect on stellar models was investigated together with

M. Salaris (Liverpool, UK) and D. Alexander (Wichita State). Grids of stellar models of various iron-to-hydrogen rations were then produced by A. Weiss for a project about new synthetic spectra (in collaboration with P. Coelho and B. Barbuy, Sao Paulo, Brazil, S. Charlot, Paris, G. Bruzual, Merida, Venezuela). With a similar approach the effect of element abundance variations (mainly in He, O, Na) on isochrones for globular clusters was investigated (Weiss, Salaris, Ferguson). It was shown that stars of different mixtures populate the same locus in the colour-magnitude diagram, as long as they are on the main sequence and red giant branch, but that they would separate on the horizontal branch. This would open the possibility of testing the predicted He-enhancement directly. In a large international collaboration, with coworkers from ESO (M. Döllinger, L. Pasquini), the Landessternwarte Thüringen (A. Hatzes), Padova (L. Girardi) and other institutions from Germany and Brazil, A. Weiss also investigated the stellar properties of K giant stars showing radial velocity variations, which can be due to either non-radial pulsations (allowing seismology of evolved stars) or extra-solar planets.

J. Ballot and collaborators have developed techniques to ensure a better scientific exploitation of future asteroseismic data from the CoRoT mission (successfully launched on December, 27). They have studied techniques to infer information on rotation speed and rotation-axis inclination of slowly-rotating solar-like stars (Ballot, Garcia & Lambert 2006). Constraining the inner rotation profiles of stars is crucial to understand the dynamical processes playing a role on their structure and their evolution. Asteroseismic information of a star is mainly derived from the spectrum of its oscillation modes. De-noising methods, based on a curvelet filtering (derived from wavelet), have been developed and checked. Such techniques will improve the analysis of spectra, especially making easier the identification of modes (Lambert et al 2006).

Two projects from stellar astrophysics were concerned with the sun and the physics of stellar surface layers.

U. Anzer in collaboration with F. Fárnik, S. Gunár, P. Heinzel and P. Schwartz (all Astronomical Institute Ondřejov, Czech Republic) continued the investigation of solar prominences. They completed the work on magnetic equilibria of filament extensions which have been observed in some extreme-ultraviolett (EUV) lines. They also applied their newly developed method for filament diagnostics to one particular filament observed on the disc and determined its geometrical structure. In addition, they calculated the Lyman continuum spectrum of hydrogen which is emitted by prominences on the limb and found a good agreement with observed spectra. Based upon some earlier studies they proposed a combined observational programme using both EUV lines and the X-ray continuum for the new Japanese satellite Hinode which can give more insight into the physics of prominences.

F. Kupka continued his study of non-local models of convection which explicitly account for observed asymmetries in up- and downflows. After detailed tests with numerical simulations (together with F. Robinson, Yale Univ.) and intercomparisons with applications of such models in neighboring disciplines (atmospheric sciences, oceanography) it was possible to explain the range of applicability of these models. In the absence of strong shear flows and sufficiently away from solid or stably stratified boundaries the models predict lower order moments of velocity and temperature fields with an order of magnitude higher accuracy than any other modeling approach. In collaboration with the Obs. de Paris-Meudon (K. Belkacem, M.-J. Goupil, R. Samadi) it was possible to apply a variant of this model to the case of p-mode oscillations in the Sun (and in α Cen A and B). While previous models underestimate the energy injected into the solar oscillations by an order of magnitude, the new model agrees with the observed data within 1 σ errors for most of the observed frequency range.

Solar research at MPA will profit in the future by an agreement between the MPA with the Institute for Solar Physics of the Royal Swedish Academy of Sciences for acquisition of observations with the Swedish 1-m telescope on La Palma, and for collaborative work on analysis and theoretical interpretation of the observations. MPA contact for this collaboration is H. Spruit.

Stellar astrophysics at MPA in 2006 was also concerned with compact binaries and accretion flows. The former, i.e. binary systems in which at least one of the two components is a compact star (white dwarf, neutron star, black hole), are of considerable astrophysical interest. One of the ongoing activities in the theory of stellar structure and evolution concerns the formation and evolution of such binaries. As an ongoing service to the community working on compact binaries H. Ritter has continued compiling the data for the regular updates of the "'Catalogue of Cataclysmic Binaries, Low–Mass X–Ray Binaries and

Related Objects"' which is available only on-line since 2003. In collaboration with U. Kolb (Open University, Milton Keynes), 7 releases (the latest as of 1 October 2006) of this catalogue have so far been issued (with the next release being due 1 July 2007). E. Meyer-Hofmeister in collaboration with V. Burwitz and J. Greiner (MPE) compared the new observational results for RX J0513.9-6954, the changes between the X-ray-low/optically-high and X-ray-high/optically-low states, with models of Kato & Hachisu and found that periodic changes in the mass overflow rate from the companion star are indicated.

3.3 Nuclear and Neutrino Astrophysics

The research activities in the field of *Nuclear and Neutrino Astrophysics* included the study of nucleosynthesis processes, the implementation of improved electron captures rates in the core collapse supernova simulation code, the successful explosion of 8–10 $M_\odot$ stars with O-Ne-Mg cores, the importance of various flow instabilities for neutrino driven supernova explosions, and neutrino-antineutrino annihilation in the vicinity of black-hole/accretion-torus systems.

The elemental and isotopic nuclear abundances of the ejecta of the type Ia supernova explosion models were computed in a post-processing step by Marius Gieseler, an MPA student. In order to obtain a good sampling of the data, nucleosynthesis reaction networks had to be integrated for typically 52^3 tracer particles. The results could be compared directly with observations. In particular, the mass of radioactive ^{56}Ni could be computed. Since the light curves of type Ia supernovae are powered by the decay fro Ni to Co and Fe, this allowed us to predict them without using any fitting parameters.

J. Pruet, R.D. Hoffman (both LLNL, California), S.E. Woosley (UCSC, Santa Cruz, California), in collaboration with H.-Th. Janka and R. Buras, investigated nucleosynthesis in the proton-rich ejecta of core collapse supernova models resulting from a new process, the so-called rapid neutrino-p process. In this process, the interaction of neutrinos with free protons leads to the production of neutrons, whose instantaneous capture helps to bridge p-process waiting-point nuclei and thus enables the formation of p-process nuclei with mass numbers $A > 100$ in neutrino-processed supernova ejecta.

I. Panov (ITEP, Moscow) in collaboration with H.-Th. Janka performed r-process calculations for neutrino-driven winds from newly formed neutron stars. The project was intended to explore the possibility, pointed out by Japanese groups, that for suitable density and temperature prevailing during the neutron-capture phase, strong r-processing is possible even at modest entropies. Significant differences compared to the Japanese results were found. The assumption of a time- and progenitor-independent outer boundary condition as used by these groups for describing the interaction of the neutrino-driven wind with the preceding supernova ejecta is fundamentally questioned by work performed by A. Arcones for her PhD project, supervised by H.-Th. Janka and L. Scheck. A. Arcones conducted hydrodynamic simulations of neutrino-driven winds from nascent neutron stars in core-collapse supernovae. These simulations reveal that a supersonic wind (and not a subsonic breeze as frequently considered) develops and is abruptly decelerated in a termination shock that forms when the fast wind collides with slower earlier supernovae ejecta. The properties of this reverse shock feature and their dependence on the neutrino wind conditions and on the progenitor star were investigated in spherical symmetry and in two dimensions. The parametric nucleosynthesis studies by I. Panov and H.-Th. Janka suggest that the reverse shock can have a significant impact on the nucleosynthesis taking place in the neutrino-driven outflow.

A. Marek as part of his PhD work, supervised by H.-Th. Janka, performed stellar core-collapse simulations with an improved description of electron captures on heavy nuclei provided by K. Langanke and G. Martínez-Pinedo (GSI, Darmstadt). The rates they employed are based on shell model Monte Carlo calculations for a large number of nuclear species in nuclear statistical equilibrium. The core-collapse studies reveal that convergence of the conditions in the stellar core until bounce is mainly driven by electron captures on free protons and less by electron captures on heavy nuclei. Using improved rates for non-conservative neutrino-nuclei scattering from the GSI-group in stellar core collapse simulations, B. Müller, in a start-up project for his PhD work supervised also by H.-Th. Janka, found that the high-energy tail of the emitted neutrino spectra is significantly reduced by energy losses of neutrinos in such collisions with heavy nuclei.

Collapse and supernova explosion of 8–10 $M_\odot$ stars with O-Ne-Mg cores were simulated by F.S. Kitaura in a collaborative project with H.-

Th. Janka and W. Hillebrandt. In this mass range of progenitor stars the viability of the neutrino-driven mechanism could be established and predictions of nucleosynthetic implications of this explosion scenario could be improved.

A. Marek, supervised during their PhD work by H.-Th. Janka, continued 1D and 2D simulations of stellar core collapse and post-bounce evolution for different progenitors with the VERTEX-PROMETHEUS code, employing a very sophisticated treatment of multi-group neutrino transport. A. Marek confirmed the importance of the low-mode SASI instability for the long-time behaviour of the stalled shock and for the neutrino-driven explosion mechanism. As previously seen for an 11.2 solar-mass star, A. Marek also discovered a neutrino-driven explosion in the case of a 15 solar-mass progenitor, occurring later than half a second after bounce and supported by the shock expansion in the course of a growing SASI mode. The simulations reveal the presence of g-mode instabilities in the neutron star, but the amplitudes are typically a factor of 100 lower than found by a group in Tucson, and these g-mode oscillations of the neutron star are not the cause of the explosion.

L. Scheck during PhD work, supervised by H.-Th. Janka, E. Müller, and K. Kifonidis, investigated the growth of low-mode non-radial (bipolar and quadrupolar) instabilities of the stalled accretion shock in supernova cores, a phenomenon termed SASI (standing accretion shock instability). In well chosen test problems for supernova conditions L. Scheck in collaboration with T. Foglizzo (CEA-Saclay, Paris) could demonstrate that the growth of this instability is indeed due to an advective-acoustic cycle and not a purely acoustic one, in agreement with linear analysis performed for toy-model setups by T. Foglizzo, his PhD student P. Galletti (CEA-Saclay, Paris), L. Scheck and H.-Th. Janka. Evaluating his large set of 2D and some 3D models, L. Scheck could also show that the low-mode instabilities that occur during the first second of the supernova explosion lead to global asymmetries of the mass ejection in the explosion, which by momentum conservation yield a reasonable explanation for the observed high natal velocities of many pulsars.

In his Diploma Thesis work R. Birkl, supervised by E. Müller in collaboration with M.-A. Aloy and H.-Th. Janka, performed ray-tracing calculations for neutrino-antineutrino annihilation in the vicinity of black-hole/accretion-torus systems. He explored the efficiency of energy deposition by this process for different geometries, taking into account relativistic effects as described by a Schwarzschild or Kerr metric.

3.4 High Energy Astrophysics

Above 40 keV the Earths atmosphere becomes an intense source of hard X-ray emission induced by cosmic rays. In this energy range the shape of the spectrum is determined by Compton scattering and photoabsorption, and is virtually independent of the incident cosmic ray spectrum. The spectrum emergent from the atmosphere in the energy range 25-300 keV has been calculated by Monte-Carlo simulations. Comparison with a recent measurement by the INTEGRAL observatory of the atmospheric hard X-ray emission and the cosmic X-ray background agrees shows agreement within 10%. This suggests a possibility of using Earth observations for in-orbit calibration of future hard X-ray telescopes (E. Churazov).

The giant outbursts of magnetars (neutron stars with a very strong magnetic field, $\sim 10^{15}$ G), are believed to result from magnetic 'star quakes'. They cause the star to oscillate, much like Earth does after an earthquake. Such oscillations have been observed in the strongest giant flare observed to date, from the Soft Gamma Repeater SGR 1806-20. As with the Earth, this opens the possibity of probing the interior structure of a neutron star by seismology. The star, it turns out, emitted a chord of at least seven different notes. By comparing the high and low frequencies it was possible to measure, for the first time, the thickness of the neutron star crust. This parameter is an important constraint on the nuclear equation of state. The observations pose particular challenges for strange star models, in which neutron stars are composed primarily of strange quark matter. Calculations showed that the seismic frequencies of strange stars should differ dramatically from those of neutron stars, and cannot be reconciled with the observations. This has consequences for our understanding of Quantum Chromodynamics (A. Watts, with T. E. Strohmayer (NASA GSFC) and S. Reddy (Los Alamos National Laboratory)).

Gamma-ray bursts

Theory of Gamma-ray bursts (GRB) remains a stimulating subject of research, with continual changes in views resulting from new observations and theoretical ideas. One of the key problems under discussion in the current literature concerns

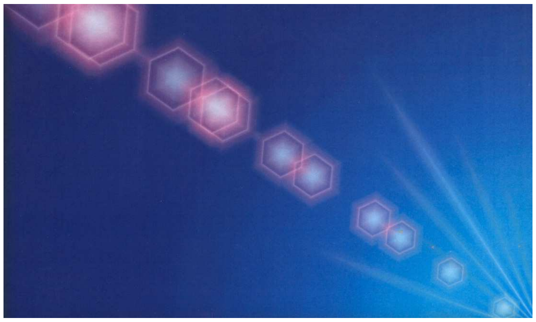

Figure 3.3: Artist's impression of the jet in a Gamma-ray Burst (D. Giannios; *picture: G. Drenkhahn*)

the location of the gamma-ray emitting region; another one the importance of strong magnetic fields for powering the relativisic outflow (near the speed of light) and the observed radiation of a GRB.

Existing model calculations for outflows in which the energy of the 'central engine' is extracted by a magnetic field (also called 'Poynting flux outflows') treat the magnetic field as axisymmetric. This model is also used for the jets in Active Galactic Nuclei (AGN). In 3 dimensions, however, such flows are unstable to kink-mode instabilities. Dissipation of magnetic energy by these instabilities can power the observed radiation, as well as accelerating the flow (see Drenkhahn in Annual Report 2002). The process now turns out to have rather different consequences in AGN jets and GRB. In AGN jets, rapid dissipation of magnetic energy by the instability causes the flow to become dominated by its kinetic energy flux at distances ~ 1000 gravitational radii (sub-parsec scales). The energy released by the instability can power the emission observed from the compact region called the 'blazar zone'. When applied to GRB outflows on the other hand, the model predicts more gradual magnetic dissipation. At the distance where the deceleration of the ejecta by interaction with the environment is expected (10^{16} cm), the flow still carries significant magnetic energy. (D. Giannios)

One of the most intriguing recent discoveries (made by Gamma-ray burst detectors on Swift) is the flaring activity in X-rays, seen in about half of the afterglow light curves. Such flares occur from minutes to $\sim$1 day after the prompt emission. This has led to the suggestion that they are caused by late central engine activity, but this would pose strong demands on the physics and energetics of the central engine. An attractive alternative is that flares are instead powered by the magnetic energy remaining in the flow at large distances from the source, and released when the ejecta are decelerated by the surroundings. Magnetic dissipation in this region can give rise to multiple, rapidly evolving and energetic flares. (D. Giannios)

Powerful magnetically dominated GRB outflows can be produced, not only in axisymetric models (as in the above) but also by a nonaxisymmetric rotating central engine ('AC model'). A classic example being the rotation-powered pulsar nebula. For GRB conditions, the dissipation of magnetic energy takes place around the photosphere of such a flow, producing Gamma-radiation much closer to the source than assumed in conventional models. The accompanying Research Highlight shows how Compton scattering in this region naturally produces spectra very similar the observed prompt emission. (D. Giannios, H. Spruit)

The connection between GRB and Supernovae (SNe) has been strengthened by an investigation of four pairs of GRBs-SNe with spectroscopically confirmed connection. These show a tight correlation between the peak spectral energy of GRBs and the peak bolometric luminosity of the underlying supernovae (SNe). Combined with the well-known relation between photon energy at the peak of the spectral energy distribution and the isotropic equivalent energy of GRBs, this result suggests that the critical parameter determining the GRB-SN connection is the peak luminosity of SNe, or equivalently, the mass of ^{56}Ni generated by the SN explosion. Application of the relation to Type Ibc SNe with normal peak luminosities indicates that if those normal SNe have GRBs accompanying them, the GRBs would be extremely soft and sub-energetic in gamma-rays, and hence easier to detect with X-ray or UV detectors than with gamma-ray detectors. (L.-X. Li)

In some GRBs (such as 060218, associated with SN 2006aja) a soft black-body component has been observed in the early X-ray afterglow, and interpreted as the signature of a supernova shock wave passing shtough the thick wind of the progenitor WR star. A closer look at this model, however, shows that it can reproduce the observations only if the progenitor WR star has an unrealistically large radius. (L.-X. Li)

Active galactic nuclei

A currently popular research theme is how the massive black holes were formed that are found as Active Galactic Nuclei (AGN) at the centers of Quasars and other galaxies (including our own). Most likely, they acquired a significant mass already around the time their host galaxies were formed, a process which can now be studied with numerical hydrodynamic simulations [B. Ciardi, I. Pelupessy (CMU, Pittsburgh) and T. Di Matteo (CMU, Pittsburgh)].

They continued to grow over billions of years, however. Initially they would have been very luminous objects (quasars), later at low luminosity in a so-called radiative inefficient, low accretion rate regime. In this later long-lasting phase, the accretion process by which the holes grew was always associated with relativistic jets: outflows at nearly the speed of light. The effect of these jets on their environment is regarded as an essential ingredient in the way galaxies are formed.

There now turns out to be a close relation between the measured kinetic energy output of AGN jets sitting in the cores of galaxy clusters, and their emission properties, in both the radio and the X-ray bands. The observed scaling between kinetic and radiative (bolometric) power, $L_{\rm kin} \propto L_{\rm bol}^{0.5}$ is well constrained, and is consistent with radiatively inefficient "jet-dominated" modes of accretion. With this relation the kinetic luminosity function can be derived for flat spectrum radio AGN, and the total integrated jet power in the local universe can be determined (i.e. $\approx 3 \times 10^{40}$ ergs s^{-1} Mpc $^{-3}$ at $z = 0$. Over the entire life of universe, the total energy deposited by AGN jets is $\approx 2 \times 10^{58}$ ergs Mpc^{-3}. Combining this with the local observed black hole mass density gives an average jet production efficiency (i.e. the fraction of kinetic energy liberated for unit accumulated black hole mass) of about 2-3%. However, since most of the power comes from low luminosity sources, which are not believed to contribute to a substantial fraction of the final black hole mass density, the actual efficiency of jet production during actively jet-driving phases must be significantly higher, possibly indicating that black hole spin extraction may play an important role in jet production. [A. Merloni, S. Heinz (MIT)].

The first results from a long (500 ksec) Chandra observation of M87 show a striking feature: a neat circular shell, with an outer radius of 2.8' (13 kpc). This ring of hard X-ray emission provides an unambiguous signature of a weak shock, driven by an outburst from the SMBH, traversing the M87 atmosphere. The observed spectral hardening corresponds to a temperature rise from 2.0 to 2.4 keV, which translates to a Mach number $M \sim 1.2$ for monoatomic gas with $\gamma = 5/3$. In addition, two additional surface brightness edges were detected (at radii of 0.6' and 1.2'). The 0.6' feature may be the gas just outside the "piston" driving the 2.8' shock, while the 1.2' feature is probably produced by a secondary outburst. [E. Churazov, W. Forman, C. Jones (CfA)]

Galaxy clusters

The distribution of elements heavier than Helium ('metals' in astrophysical parlance) in the gas filling the space between galaxies in a cluster ('cluster gas') is known to be inhomogeneous, peaking near the cluster's core. The abundance profiles seen are likely associated with the ejection of metals from the brightest cluster galaxy. The width of the observed abundance peaks is significantly broader than the central galaxy light distribution, however, suggesting that gas motions within the cluster gas are mixing the metals ejected from the galaxy. Treating this process in a diffusion approximation, constraints the characteristic velocities and spatial scales of stochastic gas motions have been derived for a sample of cool core clusters and groups. For the same sample the characteristic velocities and the spatial scales of the gas motions were calculated, assuming that the gas cooling losses are balanced by the dissipation of these same gas motions. A comparison of the derived spatial scales and the sizes of observed radio bubbles inflated in the ICM by a central active galactic nucleus (AGN) suggests that the AGN/ICM interaction makes an important (if not a dominant) contribution to the gas motions in the cluster cores. A more direct probe of the gas motions may be obtained from the shape of the emission lines: for lines of heavy ions the Doppler turbulent broadening is important. Hence iron ions are robust tracers of turbulent velocity fields in cluster cores. The linewidth of the Iron XXV Kα line varies along the projected radius and has been computed, depending on the direction and on the intensity of turbulent velocity. The next generation of X-ray telescopes will have enough resolution to test these findings. [P. Rebusco, E. Churazov, H. Böhringer (MPE), W. Forman (CfA)]

X-ray binaries

Rapid variations in the X-ray light curve, so-called burst oscillations, are observed during Type I X-ray bursts from accreting neutron stars. In the accreting millisecond pulsar XTE J1814-338 these oscillations were found to have an energy dependence that is quite distinct from the oscillations found in non-pulsars, and is inconsistent with all current models. [A. Watts, with T. E. Strohmayer (NASA GSFC), J. Hartman (MIT), D. Chakrabarty (MIT), J. Poutanen (Oulu)].

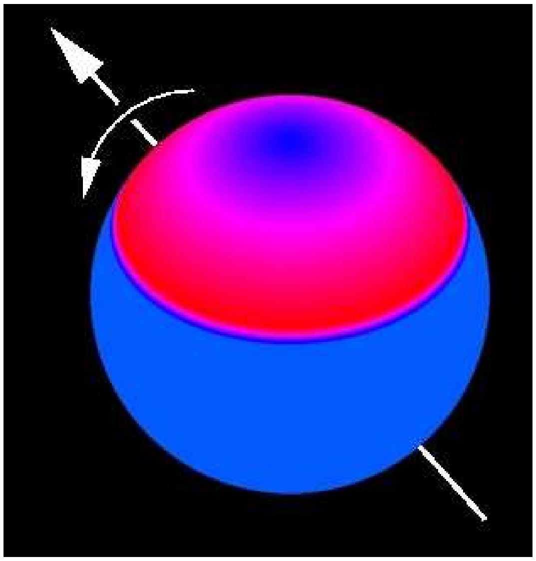

Figure 3.4: The temperature on the surface of a neutron star where accreted material is undergoing rapid explosive nuclear burning, giving rise to an X-ray burst. The red zones are hotter and the blue zones cooler. As the star rotates around its axis we see the hot areas move in and out of our field of view, giving rise to brightness variations known as burst oscillations. The unusual temperature pattern shown, with a cooler patch at the center of a hot spot, may explain some of the bizarre features of the oscillations (A. Watts)

The evolution of populations of high-mass X-ray binaries (HMXB) as a function of time after a star formation event can be studied by two methods. A method applicable to the Magellanic Clouds is to use archival optical data for a reconstruction of the spatially resolved star formation history. Comparing this with the spatial distribution of high-mass X-ray binaries, the time dependence of the HMXB population density following star formation can be found. Another way is to make use of the spiral structure in the spatial distribution of HMXBs in a spiral galaxy. Due to the delay between the time of star formation and the peak of the HMXB population, the spiral structure seen in the distribution of bright X-ray sources will be displaced from that observed in standard SFR indicators, such as Halpha emission. Evidence for such a displacement is indeed observed by Chandra in M51. [P. Shtykovskiy (Space Research Institute, Moscow), M. Gilfanov]

The famous high-mass X-ray binary SS433 was the first object in our galaxy discovered to produce a relativistic jet. Its X-ray emission varies with the orbital period of the binary, with the O-star companion eclipsing the accreting X-ray source (the jets are in the plane of the sky, the disk is seen edge-on). In addition to these eclipses, the X-rays are modulated by absorption in the powerful stellar wind from the optical star. The temperature profile in the X-ray emitting jet has now been determined from detailed observations of the orbital modulation with the RXTE observatory, under the assumption that the precessing accretion disk is geometrically thick, and using a geometrical model of the binary system. The hottest visible part of the X-ray jet is located at a distance of $l \sim 0.06 - 0.09a$, or $\sim 2 - 3 \times 10^{11}$ cm from the central compact object and has a temperature of about Tmax $\sim$ 30 keV. Appreciable orbital X-ray eclipses at the 'crossover' precessional phases were discovered, which puts a lower limit on the size of the optical component $R/a > 0.5$ and an upper limit on a mass ratio of binary companions $q = M_{\rm x}/M_{\rm opt} < 0.3 - 0.35$. The size of the eclipsing region can be larger than secondary's Roche lobe because of substantial photoabsorption by a dense stellar wind. This must be taken into account when evaluating the mass ratio from analysis of X-ray eclipses. [M. Revnivtsev, E. Filippova in collaboration with Special Astrophysical Observatory (Nizhnij Arkhyz, Russia) and Sternberg Astronomical Institute (Moscow, Russia)]

In a program of identifying new X-ray sources from INTEGRAL, RXTE and SWIFT observations, 6 new nearby AGNs and two galactic high mass X-ray binaries were identified, as well as two new cataclysmic variables, presumably intermediate polars. [M. Revnivtsev, R. Sunyaev in collaboration with Space Research Institute (Moscow, Russia) and Kazan State University (Kazan, Russia)]

X-ray binaries usually form as descendants of initially normal binary stars. Exceptions occur in globular clusters, where the density of stars is so high that isolated neutron stars and black holes can form X-ray binaries by capturing a companion from the surrounding field of stars. Is the star density in the bulge of a galaxy high enough to produce X-ray binaries in this way? The question can now be answered with accurate data from the Chandra X-ray observatory of the bulge of M31 (the Andromeda nebula). The frequency, per unit stellar mass, of X-ray point sources increases dramatically in the inner $\approx$ 1 arcmin of this galaxy. This is the first evidence of dynamical formation of low mass X-ray binaries in the dense stellar environment near the center of the galaxy, similar to the process taking place in globular clusters. The luminosity function of surplus sources near the center of M31 is similar to that of globular cluster sources and differs from the luminosity function of field sources, which presumably have a primordial origin. A theoretical study has been started of the formation of X-ray binaries in dense stellar environments, with particular emphasis on the previously unexplored high velocity regime typical for galactic bulges. (R. Voss and M. Gilfanov)

X-ray background

Early in 2006 the INTEGRAL observatory performed a series of four 30 ksec observations with the Earth disk crossing the field of view of the instruments. The modulation of the aperture flux due to occultation of extragalactic objects by the Earth disk was used to obtain the spectrum of the Cosmic X-ray Background(CXB) in the energy band 5-100 keV. The shape of the spectrum is consistent with that obtained previously by the HEAO-1 observatory, while the normalisation is $\sim$10% higher. The increase relative to the earlier adopted value of the absolute flux of the CXB near the energy of maximum luminosity (20-50 keV) has direct implications for the total energy release from supermassive black holes and for their growth at the epoch of the CBX origin. (E. Churazov, S. Sazonov, R. Sunyaev, M. Revnivtsev in collaboration with the INTEGRAL project team).

The X-ray background of the sky consists of a component associated with our own galaxy, and a component of extragalactic origin, distributed uniformly over the sky. With scan and slew observations of the Rossi X-ray Timing Explorer (RXTE) the best quality map so far of the Galactic background emission has been obtained. This was done utilizing the fact that the Galactic background emission contains a very strong emission line at 6.7 keV, while practically all contaminating bright point sources do not have such an emission line. The Galactic background X-ray emission traces the infrared surface brightness of the Galaxy very well. (M. Revnivtsev, S. Molkov and S. Sazonov)

Thanks to its wide field of view, IBIS on INTEGRAL is quite sensitive to the Galactic background emission at higher energies, while at the same time the imaging capabilities of the coding aperture telescope make it possible to account for the flux from bright Galactic point sources. The longitude and latitude profiles of the background emission derived from 3 years of observation with INTEGRAL are again in good agreement with the Galactic distribution of stars obtained from infrared observations. This, along with the measured hard X-ray spectrum of the Galactic ridge emission strongly indicates its stellar origin. The emissivity of the ridge in the energy band 17-60 keV agrees with that of the local (in the Solar neigborhood) population of accreting magnetic white dwarf binaries — the dominant contributors to the GRXE at these energies. In addition, the shape of the obtained Galactic background spectrum can be used to determine the average mass of white dwarfs in such systems in the Galaxy as $\sim 0.5 M_\odot$. The total hard X-ray luminosity of the GRXE is $L_{17-60\mathrm{keV}} = (3.7 \pm 0.2) \times 10^{37}$ lum in the 17–60 keV band. At energies 70–200 keV no additional contribution to the total emission of the Galaxy apart from the detected point sources is seen. (R. Krivonos, M. Revnivtsev, E. Churazov, R. Sunyaev)

To further constrain other possible contributions to the X-ray background from the Galaxy, deep observations of the Galactic Center (GC) region with Chandra Observatory were used. At distances of $2' - 4'$ from Sgr A*, at least $\sim 40\%$ of the total X-ray emission in the energy band 4-8 keV originates from point sources with luminosities $L(2 - 10keV) > 10^{31}$ erg/sec. From a comparison of the source number-flux function in the GC region with the known luminosity function of faint X-ray sources in the Solar vicinity, it can be concluded that Chandra has already resolved a large fraction of the cumulative contribution of cataclysmic variables to the total X-ray flux from the GC region. This comparison in addition indicates that most of the yet unresolved $\sim 60\%$ of the X-ray flux from the GC region is likely to be produced by weak cataclysmic variables and coronally active stars with $L(2-10keV) < 10^{31}$ erg/sec. The bulk of the Galactic X-ray background is therefore produced by discrete sources. [M. Revnivtsev, S. Sazonov, in collaboration with Center for Astrophysics (Cambridge, USA)]

The origin of the extragalactic component of the X-ray background has been a source of controversy. One of the possibilities is that it just consists of unresolved, distant AGN. This has now been tested with the all-sky hard X-ray survey recently completed by the INTEGRAL observatory. It provides an unbiased sample of local active galactic nuclei, including those surrounded by large amounts of cold gas which absorbs the softer X-ray radiation, making such objects invisible below few keV. The hard X-ray luminosity function measured from the INTEGRAL survey has a canonical double power-law shape, with a break at $L \sim 10^{43.4}$ erg/s (17–60 keV). To apply this result to the X-ray background problem, one needs to know how the properties of AGN have changed with cosmic time. It turns out that both the spectral shape and intensity of the cosmic X-ray background are reproduced if the distribution of absorption columns in AGN has not changed significantly since $z \sim 1.5$, while the AGN luminosity function has experienced pure luminosity evolution. (S. Sazonov, M. Revnivtsev, R. Krivonos, E. Churazov, R. Sunyaev) Apart from AGN, X-ray binaries in normal galaxies can also contribute to the background. Their effect turns out to rather modest, however, about 8% from high-mass X-ray binaries and less than 2% from low-mass XRB. [I. Prokopenko (Space Research Institute, Moscow), M. Gilfanov]

3.5 Accretion

When a neutron star orbits around a black hole, angular momentum emitted in the form gravitational waves causes the orbit to shrink. If the orbit is sufficiently close, the two will eventually merge in a violent event in which mass is ejected and a powerful burst of gravitational waves is emitted. What is left is a black hole with some mass still remaining in orbit around it. Such events, though rare, are among the most likely sources of gravitational radiation to be detected in the future, and a good candidate for the origin of gamma-ray bursts (GRB). These possibilities can now be tested in detail with relativistic hydrodynamic simulations of such mergers. The computations reveal that between $0.05 M_\odot$ and $0.25 M_\odot$ can remain in orbit around the black hole for many orbits. These torus masses were estimated to be sufficient for providing the energy that is needed to explain the recently observed, well-localized short gamma-ray bursts by ultrarelativistic, collimated outflows that are powered by neutrino-antineutrino annihilation (R. Oechslin and H.-Th. Janka). Such outflows were simulated by M.-A. Aloy, H.-Th. Janka, and E. Müller. The jet profiles for the computed set of models were used to make predictions for the redshift, fluence, and energy distributions of short-hard bursts. These theoretical predictions were compared with the current data of short-hard gamma-ray bursts with known redshifts [H.-Th. Janka, M.-A. Aloy, P. Mazzali, and E. Pian (Istituto Naz. di Astrofisica, Trieste)].

The so-called soft spectral state in X-ray binaries is interpreted as arising from accretion of gas via a disk reaching inward to the last stable orbit, and its complement, the hard state, from an inner advection-dominated hot accretion flow surrounded by a truncated outer disk. The observations, however, show a more complex picture, in particular the existence of cool gas in an innermost region during the hard state. An explanation for this intermediate spectral state is called for. Such a state can occur when, following a decrease in the mass flow rate, during the change from disk accretion to a hot inner flow, a gap forms in the disk and matter recondenses from the advection-dominated flow down to an inner disk. Analytically evaluated condensation rates seem to indicate that these results provide a further step in understanding black hole accretion physics. The results are valid for stellar and supermassive black holes. [F. Meyer and E. Meyer-Hofmeister, B. F. Liu (National Astronomical Observatories, CAS, Kunming, China)].

X-ray transients with very low accretion rate have recently been detected. Their X-ray brightness is rather variable. The questions arising are how such low mass overflow rates come about, and, whether a thermal/viscous instability in the disk can cause the observed variability. Results point to the existence of a very large number of undetectable binaries with very low mass overflow rates. (F. Meyer and E. Meyer-Hofmeister)

The X-ray spectrum of an accretion disk around a black hole depends on the rotation rate of the hole. Provided both the observational data and the theoretical models to interpret them are sufficiently accurate, this effect can be used to measure the spin of accreting black holes. Using the best models and data presently available, spins of $a_* \sim 0.75$ and ~ 0.65–0.75 are found for GRO J1655-40 and 4U 1543-47. Thus, neither black hole has a spin approaching the theoretical maximum $a_* = 1$. From a similar spectral analysis of the X-ray continuum that employs a fully relativistic accretion-disk model, it appears that the compact primary of the binary X-ray source GRS 1915+105 is a rapidly-rotating Kerr black hole: $a_* > 0.98$. [L.-X. Li with J. E. McClintock, R. Shafee, R. Narayan (CfA), R. A. Remillard (MIT), S. W. Davis (UC Santa Barbara)]

3.6 Interaction of radiation with matter

Numerous physical problems require a detailed understanding of the radiative transfer of photons environments ranging from the intergalactic and interstellar media to stellar or planetary atmospheres. The full solution of the seven dimensional radiative transfer equation is still beyond our computational capabilities in many astrophysical situations. An increasing effort has been devoted to the development of radiative transfer codes based on a variety of schemes and approximations. However, few analytical solutions exist that can be used to test the codes. B. Ciardi, in collaboration with I.T. Iliev (CITA, Toronto), A. Maselli (MPA, Garching) and others, has set up a number of numerical tests which are currently used by many groups to compare different approaches.

Surveys of high-redshift galaxies identified as Lyα emitters (LAEs), are an important tool for studying the reionization history of the young universe and the properties of the intergalactic medium (IGM) at high redshift. Only an accurate treatment of the line transfer, together with proper modeling of the evolution of the ionization state of the IGM will produce a reliable theoretical background for the interpretation of LAE survey data. A. Maselli together with A. Verhamme and D. Schraerer, have developed a numerical scheme for the resonant transfer of Lyα line photons. The code accounts for both hydrogen and dust opacity in arbitrary 3D density/temperature/velocity configurations and follows the Lya radiation transfer for one or multiple point/diffuse sources. The code has been successfully tested for several geometric configurations and has been shown to be able to reproduce many of the Lyα line profile morphologies which characterize observed galaxies.

3.7 Galaxy Formation and the Intergalactic Medium

Hydrodynamical Simulations

The cosmology group at MPA leads the world in using state-of-the-art hydrodynamical simulations to study the formation and evolution of galaxies as well as the influence that galaxies may have on their surrounding gaseous medium.

In collaboration with the Virgo Consortium, V. Springel and S.D.M. White are engaged in a project entitled GIMIC (Galaxy-Intergalactic Medium Interaction Calculation), carried out as part of the DECI initiative of the Distributed European Infrastructure for Supercomputer Applications (DEISA). Re-simulations of 5 spheres drawn from the Millennium Run are being carried out, with star formation, supernova feedback, galactic winds and multi-species metal enrichment followed explictly in the simulations. These simulations will, for the first time, allow the extraction of very long lines-of-sight through the Lyman-α forest and allow detailed comparisons with available quasar absorption line data to be carried out. V. Springel (in collaboration with J. Schaye (Leiden) and T. Theuns (Durham)) is also running a comprehensive grid of simulations of the formation of galaxies on the Bluegene/L supercomputer of the LOFAR telescope in Groningen to investigate how different physical assumptions for the regulation of star formation by feedback affect the simulation predictions.

The origin of intergalactic magnetic fields is still a mystery. T. Enßlin has investigated how efficiently galactic winds can provide an intense and widespread 'seed' magnetization. Semi-analytic simulations of magnetized galactic winds coupled to high-resolution N-body simulations of structure formation were used to estimate lower and upper limits for the fraction of the IGM which can be magnetized up to a specified level. They find that galactic winds are able to seed a substantial fraction of the cosmic volume with magnetic fields. Most regions affected by winds have magnetic fields in the range $10^{-12} < B < 10^{-8}$ G, while higher seed fields can be obtained only rarely and in close proximity to wind-blowing galaxies. These seed fields are sufficiently intense for a moderately efficient turbulent dynamo to amplify them to the observed values.

Much effort has also gone into developing realistic simulations of galaxy clusters. C. Pfrommer, T. Enßlin, V. Springel and K. Dolag performed high-resolution simulations of a sample of 14 galaxy clusters to study the effects of cosmic rays (CRs) on thermal cluster observables such as X-ray emission and the Sunyaev-Zel'dovich effect. The modeling of the cosmic ray physics includes adiabatic CR transport processes, injection by supernovae and cosmological structure formation shocks, as well as CR thermalization by Coulomb interaction and catastrophic losses by hadronic interactions. They find that while the X-ray luminosity can be boosted by up to 40 per cent, the integrated Sunyaev-Zel'dovich effect is only slightly affected.

Figure 3.5: A temperature map of the gas in a high-resolution simulation of the formation of a galaxy cluster. Cooler material associated with individual galaxies and with filaments that feed the cluster can clearly be seen highlighted against the hot intracluster medium (K. Dolag).

In collaboration with Italian scientists, K. Dolag used hydrodynamical simulations to study galaxy populations inside clusters and to study the thermodynamic state of the gas in the external regions of clusters. K. Dolag has also worked on measuring the magnetic power spectrum and the magnetic autocorrelation function from magneto-hydrodynamical simulations of galaxy clusters. The structure of the magnetic field was found to correlate strongly with the dynamical state of the cluster.

V. Springel constructed hydrodynamical simulation models of the hot galaxy cluster 1E0657-56 (the 'bullet cluster'). Based on deep Chandra exposures, the inferred velocity of the 'bullet' in this merging system is of order $\sim 4700\,\mathrm{km\,s^{-1}}$, which is unusually high and appears difficult to reconcile with the expected velocities of merging dark matter substructures in the ΛCDM cosmology. This could either mean that the system is an exceedingly rare peculiarity, or supply tentative evidence for new physics, like a 'fifth force' in the dark sector. However, the simulations of Springel and G. Farrar (New York Univ.) show that an easier explanation seems more likely, where the inferred velocity is in fact a substantial overestimate of the real velocity, due to incorrect assumptions about the dynamical state of the pre-shock gas.

Semi-analytic Models

Semi-analytic models of galaxy formation provide a complementary way of modelling the evolution of galaxies in a cosmological context and are able to provide considerable insight into understanding galaxy *populations*.

G. Kitzbichler and S.D.M. White used the Millennium Simulation to explore the high-redshift predictions of the most recent models. Luminosity functions, stellar mass functions and number counts were calculated from mock observational catalogues produced from the simulation and were compared to data from the EGS and COSMOS surveys . First comparisons gave promising results and a number of mock galaxy catalogues have been made publicly available at www.mpa-garching.mpg.de/Millennium. In collaboration with D. Elbaz (CEA, Saclay) the dependence of star formation activity on the local galaxy density was analyzed. First results indicate that the strong correlation that is observed for galaxies at the present day , has apparently reversed at earlier epochs. The relation measured in the real Universe appears to exhibit a more rapid evolution than in the model.

G. De Lucia and J. Blaizot used semi-analytic models grafted onto the Millennium Simulation to study the hierarchical formation of the brightest cluster galaxies (BCGs). The stars in these special galaxies form very early and in many small progenitors. The galaxies are, however assembled surprisingly late: half their final mass is typically locked-up in a single galaxy after redshift ~ 0.5. Because most of the galaxies accreted over cosmic time have little gas and red colours, late mergers do not change the apparent age of BCGs. Model results appear to be in qualitative agreement with observational data. G. De Lucia and J. Blaizot have made their model publically available.

L. Wang, G. Kauffmann, C. Li and G. De Lucia developed a new method for modelling galaxy clustering using high resolution numerical simulations. The simulation is used to specify the positions and velocities of the galaxies. Galaxy physical properties such as stellar mass and star formation rate are parametrized using simple functions that depend on the mass of the halo when the galaxy was last a central dominant object, and the time when the galaxy first becomes a satellite. This method provides a way of using the observed abundances and correlation functions of galaxies measured from large redshift surveys to constrain the relation between stellar mass and dark matter halo mass, and to understand how the recent star formation histories of galaxies depend on mass and on the location of the galaxy within the surrounding dark matter distribution.

Co-evolution of Galaxy Bulges and Supermassive Black Holes

In recent years, it has become clear that the evolution of galaxies and their central supermassive black holes must be tightly linked. A great deal of effort is being devoted to understand the physical nature of this connection, and the impact that energy liberated by an accreting black hole may have on the host galaxy.

On the modelling front, D. Sijacki and V. Springel implemented a novel scheme for active galactic nuclei (AGN) heating in a low accretion rate regime in cosmological simulations of galaxy cluster formation. It was found that the central regions of galaxy clusters are affected significantly by AGN activity, resolving the so-called cooling flow problem and, at the same time, yielding realistic BH masses and accretion rates at different redshifts.

M. Ruszkowski and T. Enßlin used magnetohydrodynamical simulations to study whether magnetic fields can stabilize the bubbles inflated by radio jets. Contrary to previous claims, their results suggest that other mechanisms, such as viscosity, are most likely responsible for stabilizing the bubbles. The treatment of viscous fluids in an astrophysical context has been the subject of investigation by Sijacki and Springel, who have developed a novel implementation of physical viscosity in the parallel TreeSPH code GADGET-2. Among other results, they were able to show that physical viscosity does indeed have a stabilizing effect on buoyantly rising bubbles in clusters.

In a collaboration with scientists from CfA, V. Springel studied the growth of AGN using numerical simulations of galaxy mergers that incorporate black hole growth and quasar feedback. In a series of papers led by P. Hopkins, they have explored a new model for quasar lifetimes which allowed them to predict the quasar luminosity function in various passbands, and its evolution with redshift. They also showed that if quasar activity is identified with the formation of spheroids in the framework of the merger hypothesis, then properties of the red galaxy population can be predicted from the model with high accuracy. Using the comprehensive set of hydrodynamical merger simulations carried out by the group, B. Robertson found that the $M_{\rm BH} - \sigma$ relationship is expected to evolve very little with redshift, and that gas dissipation plays an important role in explaining the observed tilt of the fundamental plane of elliptical galaxies. In a paper led by T.J. Cox, the group further demonstrated that gas dissipation during mergers is required to match the kinematic structure of observed elliptical galaxies.

Using a more observational approach, A. von der Linden and G. Kauffmann studied the properties of radio-loud AGN in a sample of 625 nearby groups and clusters selected from the Sloan Digital Sky Survey. The study concluded that brightest group and cluster galaxies (BCGs) have a higher dark matter content than non–BCGs of comparable stellar mass, and that they do not follow the typical scaling relations of elliptical galaxies. BCGs were found to be more likely to host a radio-loud AGN than other galaxies of the same stellar mass. It was demonstrated that the radio-loud AGN properties of both BCGs and non-BCGs could naturally be explained if this activity is fuelled by cooling from hot gas surrounding the galaxy. Using observational estimates of the mechanical output of the radio jets, the time-averaged energy output associated with recurrent radio source activity was estimated for all group/cluster galaxies. The conclusion of the analysis was that unless the efficiency of converting AGN mechanical energy into heating increases by 2-3 orders of magnitude between groups and rich clusters, radio-mode heating will not balance radiative cooling in systems of all masses.

Visiting graduate student C. Li , G. Kauffmann, L.Wang, and S. White analyzed the clustering of 90,000 narrow-line AGN drawn from the the SDSS. The cross-correlation between AGN and a reference sample of galaxies was computed and compared to results for control samples of inactive galaxies. On scales larger than a few Mpc, AGN were found to have have almost the same clustering amplitude as the control sample. On scales between 100kpc and 1Mpc, AGN were clustered more weakly than the control galaxies. Mock catalogues constructed from high-resolution N-body simulations were used to interpret this anti-bias, showing that the observed effect is easily understood if AGN are preferentially located at the centres of their dark matter halos. The study also included an analysis of the incidence of very close companions around AGN and concluded that galaxy-galaxy interactions cannot explain the activity seen in the majority of the objects in the sample.

G. Kauffmann studied a volume-limited sample of massive bulge-dominated galaxies with data from both the Sloan Digital Sky Survey and the Galaxy Evolution Explorer (GALEX) satellite. In this sample, the SDSS spectra sample the light from the bulge-dominated central regions of the galaxies. The GALEX NUV data provide high sensitivity to low rates of global star formation in these systems. It was found that there is a much larger dispersion in NUV-r colour than in optical g-r colour and that nearly all the galaxies with bluer NUV-r colours are AGN. Both GALEX images and SDSS colour profiles demonstrate that the excess UV light is always associated with an extended disk. The scenario suggested by a detailed analysis of the data is one in which the source of gas that builds the bulge and black hole is a low mass reservoir of cold gas in the disk. The presence of this gas is a necessary, but not sufficient condition for bulge and black hole growth. Some mechanism must transport this gas inwards in a time variable way. As the gas in the disk is converted into stars, the galaxies will turn red, but further gas infall can bring them back into the blue NUV-r sequence.

V. Wild and G. Kauffmann have been working on new, more sensitive methods for constraining the detailed recent star formation history of galaxies. Application of the method to bulge-dominated galaxies in the SDSS is allowing the incidence of recent starbursts in these systems to be quantified in detail.

D. Gadotti applied his image decomposition code to the images of a few hundred galaxies and AGN from the SDSS DR2 sample, obtaining structural parameters and colors of galactic components (bulges, disks and bars). In collaboration with G. Kauffmann, he studied how these components relate to each other and the extent to which AGN differ from normal galaxies. The study revealed that bulge size is the single most important parameter related to black hole activity. In collaboration with L. Athanassoula, he has also compared the structural properties of simulated and real barred galaxies.

G. De Lucia has also continued her collaboration with various members of the EDisCS Consortium. In particular, she has studied the evolution of the colour-magnitude relation from high redshift to the present day. Her analysis has shown that faint red galaxies become increasingly important with decreasing redshift or, in other words, the faint end of the colour-magnitude relation becomes increasingly populated at lower redshift. These findings clearly indicate that the red-sequence population of high-redshift clusters does not contain all progenitors of nearby red-sequence cluster galaxies. A significant fraction of these must have moved onto the red-sequence below $z \sim 0.8$.

Re-Ionization

One of the most debated issues in the theoretical modelling of cosmic reionization is the impact of low mass gravitationally-bound structures. B. Ciardi has carried out the first numerical investigation of the role of such minihaloes, which serve as self-shielding screens of ionizing photons. She finds that, depending on the details of the minihalo formation process, their effect on the overall progress of reionization can range from modest to significant. An important, related issue, is under which circumstances such small-mass halos can form. Collapse and cooling require the presence of molecular hydrogen, so studying the formation/destruction of such species is of basic importance. J. Jasche, B. Ciardi and T. Enßlin have studied the effect of cosmic rays on primordial chemistry, finding that in certain environments, cosmic rays can actually promote molecular hydrogen formation.

Another important issue is the role of very massive, metal-free stars in the first stages of reionization. B. Ciardi has investigated the physics of the transition from an early epoch dominated by massive Pop III stars to a later epoch dominated by familiar low-mass Pop II/I stars, as well as the impact of Pop III stars on reionization. U. Maio, B. Ciardi and K. Dolag are now studying the same transition by means of numerical simulations. An alternative way to study the evolution of the stellar IMF is to exploit the detection of high redshift GRBs and their relation with the SFR. B. Ciardi is currently investigating this issue in more detail.

A wealth of information on the reionization history is likely to be obtained by the next generation of radio telescopes. In fact, it has long been known that neutral hydrogen in the IGM may be directly detectable in emission or absorption against the CMB radiation at the frequency corresponding to the redshifted 21 cm line. B. Ciardi has used numerical simulations of cosmic reionization and of the related 21 cm emission line to produce synthetic radio maps as seen by a LOFAR-type telescope, finding that, if reionization occurs relatively late, the telescope will be able to detect HI structures on arcmin scales.

A. Maselli has investigated the possibility of constraining the mean neutral hydrogen fraction ($x_{\rm HI}$) from the extent of the quasar $\rm H_{II}$ region measurable in high-z quasar spectra. The study finds that observations can provide only rough estimates of $x_{\rm HI}$, since the measured $\rm H_{II}$ region size typically underestimates the real size.

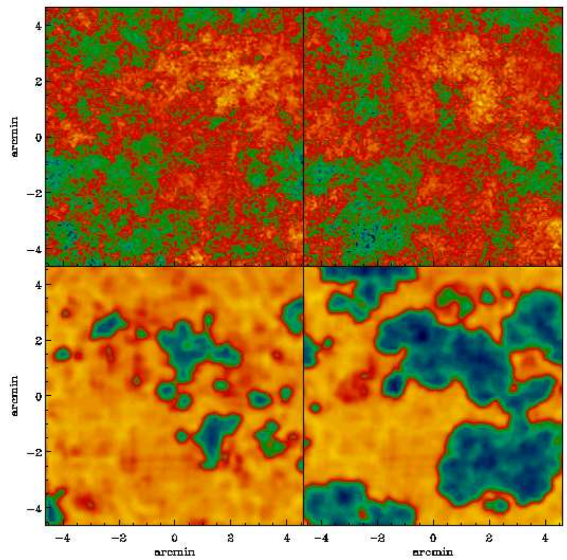

Figure 3.6: Maps of CMB temperature anisotropies (upper panels) and differential brightness temperature of 21cm line emission from neutral hydrogen (lower panels), expected from a model in which IGM reionization is complete at redshift 8 (left panels) and 13 (right panels). Yellow (blue) indicate high (low) values of the temperatures (B. Ciardi).

3.8 Large-Scale Structure, Dark Matter and Gravitational Lensing

The cold dark matter (CDM) model has been very successful, but the ultimate verification of this model would be to "see" or map the dark matter that is predicted to surround every galaxy. B. Metcalf, S. White and S. Hilbert have shown that this is possible with the use of radio telescopes now being planned and built to observe radiation coming from the hyperfine transition of neutral hydrogen in the early universe ($10 < z < 300$). With enough sensitivity and resolution, the distribution of all matter, all the way back to this early time, could be imaged through its gravitational effects at a signal-to-noise ratio in excess of ten. Such a map and its correlations with observations in other wavelengths would revolutionize the study of dark matter and galaxy formation.

The gravitational lensing of high redshift 21 cm radiation can also be used to measure many cosmologically relevant parameters such as the total matter density, the equation of state for dark energy, the density of baryons and the spectrum of initial density fluctuations to accuracies far exceeding those possible with any other proposed method. This would provide invaluable information on the nature of the mysterious dark energy that is causing the universe's expansion to accelerate and on the physics of the very early universe that created the large scale density fluctuations we see today. B. Metcalf and S. White performed an initial study of cosmological parameter estimation through a technique called gravitational lensing tomography using the 21 cm radiation.

Because type Ia supernovae are good standard candles they are a unique probe of gravitational magnification. B. Metcalf introduced a method for determining if dark matter is dominated by macroscopic compact objects (MCOs) (for example brown dwarfs, white dwarfs or primordial black holes) or microscopic particles (WIMPS, axions, LSP, etc.) by using the distribution of supernova brightnesses at high redshift. The analysis showed that MCOs can be ruled out as the sole constituent of dark matter and an upper limit on the density of MCOs was estimated. With the much larger sample of supernovae expected from the SNAP satellite and planned ground-based surveys, a mass fraction in MCOs as small as a few percent will be measurable using the lensing method.

E. Hayashi studied the shape of the gravitational potential of galaxy-sized dark matter halos in cosmological simulations. In collaboration with J.F. Navarro (University of Victoria) he found that dark matter halos become more triaxial towards their centre. This has significant implications for the shapes of rotation curves in disk galaxies and for the X-ray surface brightness profiles of galaxies and galaxy clusters. E. Hayashi also studied the cross-correlation between galaxies and mass in the Millennium simulation. Together with S.D.M. White, he developed a simple model which accurately describes the clustering of mass around galaxies. This model is useful for comparisons with observational studies which probe the large scale distribution of matter, for example, weak gravitational lensing analyses.

O. Möller created a comprehensive code that allows the calculation of strong lensing statistics for a large galaxy sample using a wide range of analytical mass profiles. Observational effects can be taken into account as well as the environment of galaxies. Using a large mock-light cone created by M. Kitzbichler from semi-analytic galaxy catalogues , this code was used to create a mock sample of lens galaxies. It was demonstrated that the code could predict the observed statistical properties of lens systems correctly.

H. Sandvik, O. Möller and S. White addressed the recent discovery from N-body simulations that the clustering of dark matter haloes of given mass depends on their formation history. A generalisation of the standard one dimensional excursion set method permits a discussion of filaments and pancakes, along with dark matter haloes. The analysis demonstrated that if the formation history of a halo depends on the size of its progenitor filaments and sheets, an effect similar to that observed in simulations may be accounted for. H. Sandvik also extended his model-independent method for cluster mass reconstruction, to allow for inclusion of weak lensing data.

In collaboration with L. Gao (Durham) S. White extended his studies of assembly bias, the fact that the clustering amplitude of dark matter halos depends not only on their mass but also on other properties which reflect details of how the halos were assembled. They were able to show significant (and independent) dependences on formation time, concentration, substructure and spin.

F. Kitaura and T. Enßlin developed a new fast algorithm for reconstructing the large-scale cosmological ATLAS structure of the Universe using galaxy redshift surveys. It is designed to take into account noise, incompleteness, and masks, which often plague such surveys.

3.9 The Cosmic Microwave Background

Work led by A.J. Banday has focused on the nature of the anisotropy data collected by NASA's *WMAP* satellite, with particular emphasis on understanding the physical nature and accurate removal of the Galactic foreground component.

A detailed study of the foreground spectral properties observed in the first-year *WMAP* data has been undertaken. The anomalous low-frequency emission was found not to be connected with a hard synchrotron component spatially correlated with the Galactic dust (as initially claimed by the *WMAP* team), but with the dust itself. Furthermore, this emission showed signs of spatial variation in its spectral behaviour on the sky by a factor of $\sim$ 2 from cloud to cloud. The synchrotron component was determined to have a steep spectral index, as expected from lower frequency observations. Unexpectedly, the diffuse free-free emission was demonstrated to be fitted by a well-known spectrum at K and Ka band, but with a derived emissivity corresponding to a mean electron temperature of 4000-5000 K. This is inconsistent with estimates from Galactic HII regions – the origin of the discrepancy is unclear.

In order to account for the variations in foreground spectral behaviour across the sky, a solution to the CMB component separation problem has been proposed based on standard parameter estimation techniques. A parametric spectral model is assumed for each signal component, and the parameters fitted on a pixel by pixel basis. Ultimately, the method should allow the foreground uncertainties to be rigorously propagated through to CMB power spectrum estimation and cosmological parameter inference. Such a component separation strategy will be of great importance for Planck and high-sensitivity polarisation measurements. The method is currently being applied to the *WMAP* three year data release.

Although the use of parametric fitting methods to the CMB data should ultimtely provide one of the more robust and accurate methods for foreground removal, the current sensitivities of CMB measurements are such that fits to templates of the foreground emission provide an adequate solution to the component separation problem. A new approach to foreground removal (WIFIT) has been proposed that does not rely on prior knowledge about the foreground components. Instead, the necessary information is extracted directly from the microwave sky maps. The method has been successfully applied to the *WMAP* first-year data.

A final method for performing component separation is based on Independent Component Analysis (ICA). This method is one of a class of so-called "blind" algorithms, in that it makes no specific assumptions about the number or statistical nature/morphology of the foreground components. Applied to the *WMAP* three-year data, the method yields an estimate of the CMB sky with an angular power spectrum in close agreement with that of the *WMAP* team.

J. Chluba and R.A. Sunyaev studied the details of cosmological hydrogen recombination at redshifts in the range $z \sim 200 - 2000$, focusing on the release of photons during this epoch. The hydrogen recombination spectrum was computed in a frequency range $\nu \sim 0.1 - 3500$ GHz including the main collisional processes and following the evolution of all the angular momentum sub-states separately taking into account up to 100 shells. It was shown that $\sim$ 5 photons per hydrogen atom are released at $z > 800$. These distortions of the Cosmic Microwave Background (CMB) spectrum have

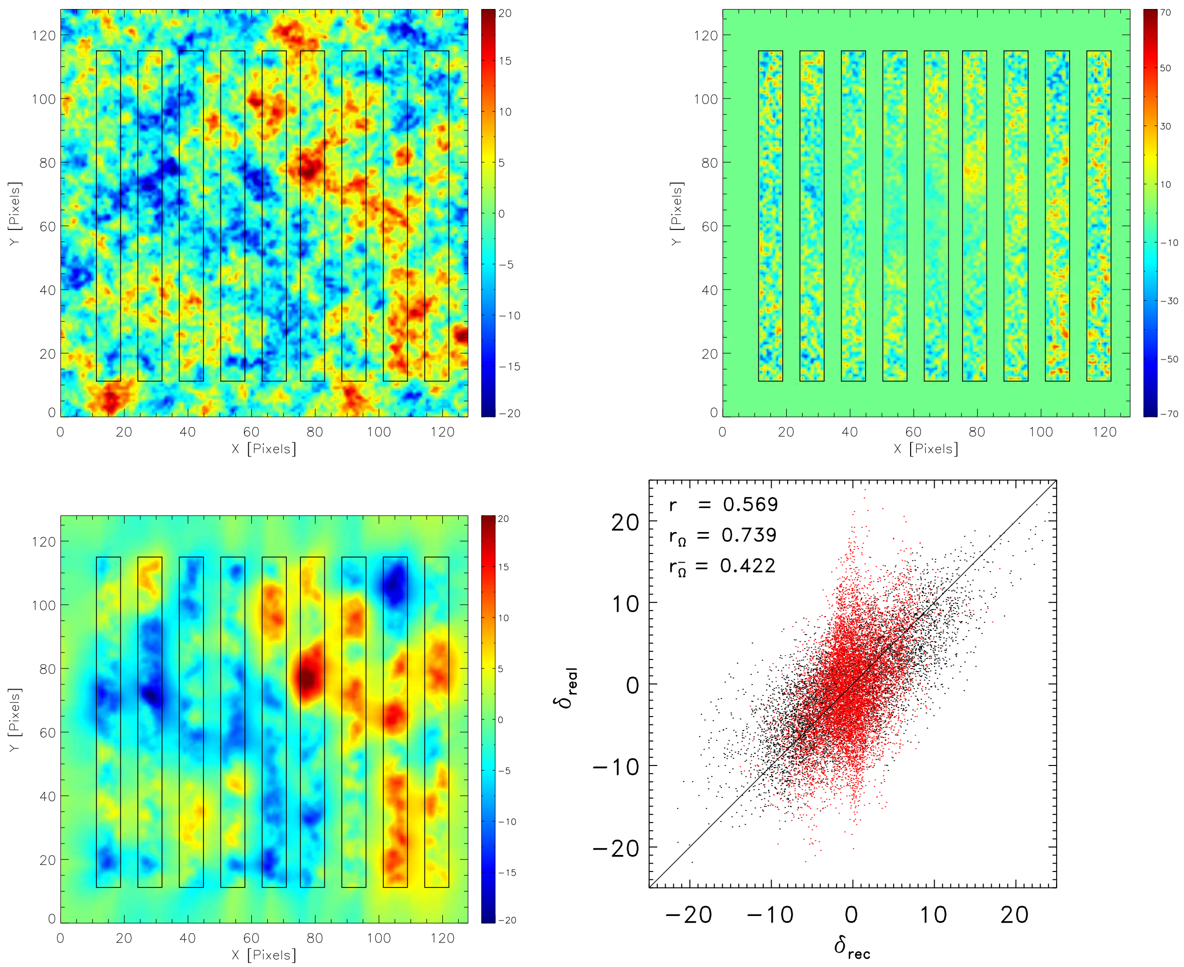

Figure 3.7: Reconstruction of simulated large-scale structures with ATLAS. The upper left plot shows the true underlying over-density field. The observed noisy data along stripes given in the upper right plot result from multiplying the signal by a windowing function, that is one in the observed region and zero in the unknown region, and adding a noise to it that increases in the radial direction. The lower left plot represents the reconstruction, in which the suppresion of the noise and signal enhancement in the observed region can be seen, and also the correct propagation of the information into the un-sampled regions. We see in the lower right plot the pixel to pixel correlation between the real- and the reconstructed density field, split into the sampled (black dots) and the un-sampled region (red dots). The spreading of the red dots shows the propagation of the information about the density fluctuations thanks to the correlation function. The values of the r correlation coefficients are higher than the ones obtained when neglecting the windowing (by assuming zero over-densities in un-sampled regions), even in the observed region (F. Kitaura, T. Ensslin).

a very peculiar spectral dependence, which exceeds the level of $\Delta I/I \sim 10^{-7}$ at frequencies below $\nu \sim 2\,\mathrm{GHz}$, and may become observable in the future. Furthermore, it was shown that percent-level corrections to the ionization history arise, which may be important for the accurate analysis of future CMB data.

K. Dolag, V. Springel, M. Maturi (ITA Heidelberg) and A. Waelkens investigated the Rees-Sciama effect by using a constrained high-resolution hydrodynamical simulation to probe the details of the signal and a linear matched filter to fix an upper limit on its amplitude. The Rees-Sciama effect from the local universe peaks at low angular frequencies on the sky and has a minimum/maximum amplitude of 0.3μK/0.8μK. Even if its quadrupole is well aligned with the CMB quadrupole, its amplitude is not sufficient to explain observed inconsistencies with the concordance Λ-CDM model in the current WMAP data.

T. R. Jaffe continued previous studies into a surprising correlation between a non-standard topological model of the Bianchi Type VIIh and the WMAP data. In particular, the release of the three-year data for WMAP allowed additional tests that enabled her to rule out the influence of year-to-year systematic effects as well as foregrounds.

3.10 Quantum mechanics of atoms and molecules, astrochemistry

An interesting probleme in the gravitational collapse scenario of early structure formation is the cooling of primordial gas to allow small mass objects to form. As the neutral primordial gas is a poor radiator at low temperatures ($T \leq 10^4\,\mathrm{K}$), molecular hydrogen is needed for further cooling down to temperatures ($T \sim 100\,\mathrm{K}$). The formation of molecular hydrogen is catalyzed by the presence of free electrons. Therefore J. Jasche, B. Ciardi and T. A. Enßlin developed a computer code to study the effects of ionizing cosmic rays on the thermal and chemical evolution of primordial gas. They found that cosmic rays can provide enough free electrons for the formation of molecular hydrogen, and can therefore increase the cooling ability of such primordial gas under certain conditions.

The HeH Rydberg molecule confined by a cylindrical harmonic potential has been studied by J.M.H.Lo, M.Klobukowski, D.Bielińska-Wąż, E.W.S.Schreiner, and G.H.F.Diercksen. They find that confinement affects this molecule differently than strongly-bound diatomic molecules. The confinement does not dramatically vary the bond lengths for the low-lying electronic states of HeH, and the bond lengths could be either stretched or compressed. The excited states are not necessarily more strongly bound by the potential, and some of the states become less bound when the confining potential is applied.

The energy spectra and oscillator strengths of two, three and four electrons confined by a quasi-two-dimensional attractive Gaussian-type potential have been calculated for different strength of confinement and potential depth by T.Sako and G.H.F.Diercksen using the quantum chemical configuration interaction method employing a Cartesian anisotropic Gaussian basis set. A substantial red shift is observed for the transitions corresponding to the excitation into the center-of-mass mode. The oscillator strengths, concentrated exclusively in the center-of-mass excitation in the harmonic limit, are distributed among the near-lying transitions as a result of the breakdown of the generalized Kohn theorem.

W.Krämer has studied basic exothermic binary reactions of potential astrophysical relevance. His previous investigations demonstrated the importance of resonance states for the performance of the reactions. Resonances are quasi-bound vibration-rotation levels lying just above the relevant dissociation threshold of a molecular system stabilized by rotational centrifugal barriers. They are intermediately populated during the reaction process and depending on their quantum characteristics they either reproduce the energy levels of the initial reaction partners or they can stabilize the reaction process radiatively through spontaneous radiative decay to bound vibration-rotational levels of the reaction product or via non-radiative transition processes. The diatomic or triatomic molecular systems studied so far within the project are formed in weak interactions with small binding energies. The number of bound vibrational states in such weakly bound molecular complexes is relatively small and the handling and assignment of these states therefore does not cause major difficulties. The situation becomes much more complex in strongly bound systems where already the number of bound vibrational states becomes very large without taking into account the even much larger number of connected rotational states. Characterizations of highly excited states in such systems on the basis of individual quantum numbers becomes impossible. It is therefore reasonable to inquire whether these states may be understood from a diametrically opposite point of view, assuming that in these states individual quantum structures are washed out. A statistical theory of the energy levels can be applied in these cases which is able to describe the general appearance and the degree of irregularity of the level structures. Different statistical methods such as the *density of states* or the *nearest-neighbor level spacing distribution* representations are applied in a first step of this research project to describe the general patterns of the energy level structures and dipole moment properties of the interstellar triatomic ions HN_2^+, HCO^+, and HOC^+ and their deuterated isotopomers. After investigating the capabilities of different statistical methods a future step will be to develop a connection between appropriate statistical properties and temperature dependent macroscopic properties such as for example reaction probabilities or rate constants.

Quantum mechanical applications of H_2 pair interactions, which are an important subject of research in the field of collisional and radiative effects in the interstellar medium, have been studied by J. Schäfer. The motivation of starting activities in this field is due to the well established assumption that about 85% of the baryon mass of the Milky Way is still undetected, located in the Halo far outside the optical disk, and to a smaller amount at solar Galactic radius with an estimated mass contribution of 50%. There are some reasons to assume that the Halo masses are primordial H_2 gas and He condensed in a fractal structure, in thermal equilibrium with the cosmic microwave background radiation, and therefore hardly observable. A plausible reason for detecting hydrogen solids at solar Galactic radius are sufficiently available condensation sites at sufficiently low temperature ($\approx$ 3K) prior to star formation which makes the H_2 gas stick to solid H_2 surfaces. Spectroscopic evidence for hydrogen solids has been found by doing quantum mechanical calculations of pair H_2 emission bands in the wavelength range between 6 and 12 μm, i.e., both molecules of a pair at nearest neighboring distance undergo a rotational dipole moment transition and emit one infrared photon. Ten approximate zero-phonon pair transition bands have been used to explain the four typical features measured in the ISO-SWS mission (1995-97) which are well-known and usually claimed to be emitted by polycyclic aromatic hydrocarbons (PAHs). The source of the chosen measured spectrum, observed with a slit of 14 $\times$ 20 arcsec^2, is located in the photodissociation region of the nebula NGC7023, at a proximity of 430 pc, in a distance range of (8.6 - 17.2)$\cdot 10^3$ AU north of the B-type star HD 200775. Signatures of solid hydrogen emission of the seven pure parahydrogen bands are the dipole pair transitions, the accurately fitting frequency positions of the bands and the typical zero-phonon band widths valid also for comparable sources. The frequencies of the three ortho-para H_2 bands have not been determined because they need extra analysis. Experimental confirmation of the ten solid hydrogen bands is not available yet because only a few absorption bands and no emission band of rotational pair transitions have been measured so far in the lab.

4 Publications and Invited Talks

4.1 Publications in Journals

4.1.1 Publications that appeared in 2006 (212)

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Birkl, R., M.-A. Aloy, H.-Th. Janka and E. Müller: Neutrino pair annihilation near accreting, stellar-mass black holes. Astron. Astrophys.

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Cordier D., A. Pietrinferni, S. Cassisi and M. Salaris: A large stellar evolution database for population synthesis studies. III, Inclusion of the full Asymptotic Giant Branch phase and web tools for stellar population synthesis. Astrophys. J.

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Foglizzo, T., L. Scheck and H.-Th. Janka: Neutrino-driven convection versus advection in core collapse supernovae. Astrophys. Journal.

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Kupka, F., and F.J. Robinson: On the effects of coherent structures on higher order moments in models of solar and stellar surface convection. Mon. Not. R. Astron. Soc.

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Maino, D., S. Donzelli, A. J. Banday et al.: CMB signal in WMAP 3yr data with FastICA. Mon. Not. R. Astron. Soc.

Meyer, F., B.F. Liu and E. Meyer-Hofmeister: Re-condensation from an ADAF into an inner disk - the intermediate state of black hole accretion? Astron. Astrophys.

Natarajan, P., De Lucia, G., Springel: Substructures in lensing clusters and simulations. Mon. Not. Roy. Astron. Soc.

Oechslin, R., H.-Th. Janka and A. Marek: Relativistic neutron star merger simulations with non-zero temperature equations of state. I. Variations of binary parameters and equations of state. Astron. Astrophys.

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4.2.2 Publications available as electronic file only

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`http://users.physik.tu-muenchen.de/sfb375/Server/gaissach2006/index.html`

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`http://www.mpa-garching.mpg.de/RKcat/`
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`http://vizier.cfa.harvard.edu/viz-bin/VizieR?-source=B/cb`
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4.3 Books and popular articles

G. Börner: Schöpfung ohne Schöpfer? dva Verlag
– Echo des Urknalls. Physik in unserer Zeit. **37** No.6, 264–265 (2006).

Enßlin, T.A.: Der Nachhall des Urknalls. Physik Journal. **5** Nr. 12, 24–27 (2006)

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– Supernovae, Hypernovae und verschmelzende Sterne. In: Kosmische Spurensuche — Astroteilchenphysik in Deutschland. Forschungszentrum Karlsruhe GmbH, Karlsruhe, 48–49 (2006).

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– How to blow up a star. Scientific American, **295**, part no 4, 42–49 (2006).
– Rozsadzic gwiazde. Swiat Nauki. **11** 36–43 (2006).

V. Springel: Die Millennium Simulation: Mit einem Superrechner auf den Spuren von Galaxien. Sterne und Weltraum **11**, 30–40 (2006).

4.4 Invited review talks at international meetings

E. Churazov:
– The Fourth Harvard-Smithsonian Conference on Theoretical Astrophysics "The History of Nuclear Black Holes in Galaxies", (Boston, USA, 15.05.-18.05) – The 6th INTEGRAL Workshop, "The Obscured Universe", (Moscow, Russia, 2.07.-08.07) – MPA/ESO/MPE/USM Joint Astronomy Conference, "Heating vs. Cooling in Galaxies and Clusters of Galaxies", (Garching, Germany, 6.08.-11.08) – The 6th Microquasar Workshop, "Microquasars and Beyond", (Como, Italy, 20.09.-22.09)

B. Ciardi:
– "TIARA Reionization Workshop" (Hsinchu, Taiwan, 13.2.–3.3.) – "TIARA winter school on cosmology" (Hsinchu, Taiwan, 13.2.–17.3.) – "The End of the Dark Ages - From First Light to Reionization" (Baltimore, USA, 13.3.–15.3.) – "IAG-LENAC XIII advanced school of astrophysics" (Foz do Iguazu, Brazil, 6.4.–12.4.) – "IAU XXVIth General Assembly" (Prague, Czech Republic, 14.8.–25.8.)

G. De Lucia: "Workshop on Massive Galaxies over Cosmic Time II" (Tucson, November 1-3) – "Cosmic Frontiers" (Durham University, July 31 - August 4) – "Galaxies and Structures through Cosmic Times" (Venice, March 26 - 31)

H. Dimmelmeier:
Invited Plenary Talk, "Understanding Neutron Stars" Meeting, (Alicante, Spain, 25.09.-27.09.)
– Invited Plenary Talk, "3rd Annual Meeting of the European Network on Theoretical Astroparticle Physics (ENTApP) ILIAS/N6", (Paris, France, 12.12.-14.12.)

T.A. Enßlin: "Long Wavelength Astrophysics", IAU General Assembly 206 (Prague, 21.8.)

M.Gilfanov: "High Energy Astrophysics - 2006" (Moscow, Russia, 25.12.–28.12.)

W. Hillebrandt: 13th Workshop on Nuclear Astrophysics (Ringberg Castle, 3. 4. – 3. 4.)
– DEISA Symposium, Perspectives in High Performance Computing (Bologna, 4. 5. – 5. 5.)
– From Stars to Galxies: Building the pieces to build up the Universe (Venice, 16. 10. – 20. 10.)

H.-Th. Janka: "Astrophysics and Nuclear Structure" Workshop (Hirschegg, Austria, 15.01.–21.01.)
– "Supernova and Gamma-Ray Burst Remnants" Workshop (Santa Barbara, USA, 06.02.–10.02.)
– "Nuclear Astrophysics" Workshop (Ringberg Castle, 03.04.–08.04.)
– "Neutrino 2006" Conference (Santa Fe, USA, 13.06.–19.06.)
– "The Obscured Universe" Workshop (Moscow, Russia, 02.07.–08.07.)
– "Core Collapse Supernovae and their Host Galaxies" Workshop (Paris, France, 02.10.–04.10.)
– "Texas in Australia" Symposium (Melbourne, Australia, 11.12.–15.12.)

G. Kauffmann:
–"The Fourth Harvard-Smithsonian Conference on Theoretical Astrophysics:The History of Nuclear Black Holes in Galaxies", (Cambridge, 15.5.–18.5.)
– "Cosmic Frontiers" (Durham, 31.7.–4.8.)
– "Heating vs. Cooling in Galaxies and Clusters of Galaxies", (Garching, 6.8.–11.8.) – "The End of the Dark Ages - From First Light to Reionization" (Baltimore, USA, 13.3.–15.3.) – "IAG-LENAC XIII advanced school of astrophysics" (Foz do Iguazu, Brazil, 6.4.–12.4.)

P. Mazzali:
– ”Supernovae and Gamma-Ray Bursts” at the meeting ”One Millennium after SN1006”, Hangzhou, China, May 23-27
– ”Asphericity in GRB Supernovae” at the conference ”Swift and GRBs” Venice, Italy, 5-9 June
– ”The connection between Supernovae and GRB/XRF” at the meeting ”Triggering Relativistic Jets” Ensenada, Mexico, 1-5 Sept

E. Müller: Invited talk, Workshop on “Gravitational wave data analysis” (Paris, France, 15.11.)

M. Ruszkowski: ”Review of heating mechanisms in clusters of galaxies”, invited review talk at ”Heating vs. Cooling in Galaxies and Clusters of Galaxies” – MPA/ESO/MPE/USM Joint Astronomy Conference, Garching (6.8. - 11.8)

S. Sazonov: Workshop “The keV to TeV connection”, Rome (17.10.–19.10).
– Conference “High Energy Astrophysics Today and Tomorrow”, Moscow (25.12.–27.12.)

V. Springel:
– Harvard-Smithsonian Conference “The History of Nuclear Black Holes in Galaxies” (Cambridge, USA, 15.-18.5.)
– “The Obscured Universe”, 6th INTEGRAL Workshop (Moscow, Russia, 2.-8.7.)
– Invited Review, Session on “The Origins of Massive Black Holes and Quasars at High Redshifts”, 11th Marcel Grossmann Meeting (Berlin, 23.-29.7.)
– “Galaxies, Super-massive Black Holes and the Cosmic Web”, 7th Sino-German Workshop (Shanghai, China, 25.-28.9.)
– “The End of the Dark Ages - From First Light to Reionization” (Baltimore, USA, 13.3.–15.3.) – “IAG-LENAC XIII advanced school of astrophysics” (Foz do Iguazu, Brazil, 6.4.–12.4.)

H. Spruit:
Review at the Sixth Microquasar workshop (Como, Italy, 20.9.)
– Plenary talk at the 23rd Texas Conference on Relativistic Astrophysics (Melbourne, Australia, 14.12.)

A. Watts: Invited talk COSPAR Meeting Session 1.3 (Different manifestations of neutron stars) (Beijing, China, 17.07-21.07)
– Invited talk (Special Session on Magnetars), American Astronomical Society High Energy Astrophysics Division Meeting (San Francisco, USA, 04.10-07.10)

A. Weiss: “From Stars to Galaxies: Building the pieces to build up the Universe” Conference, (Venezia, Italy, 16.10.–20.10.)

S. White: Heineman Prize Lecture: AAS meeting, (Washington, 8.1.–13.11.).
– The Millennium Simulation and the Local Group: Aspen winter workshop (Aspen, 5.2.–9.2.).
– Numerical cosmology - recreating the Universe in a supercomputer: Lectures presented at the Bibliotheka Alexandrina, (Alexandria, Egypt, 22.3–30.3.)
– Nonlinear Structure Formation: the growth of galaxies and larger scale structures: Lectures to the IAGUSP/LENAC Summer School, (Foz do Iguacu, Brasil, 6.4.–12.4.).
– Large-scale Structure: Insights from the Millennium Simulation: Review at ”Cosmic Frontiers” (Durham, 31.7.–4.8.).
– Feedback and Galaxy Formation: Review at ”Heating versus Cooling in Galaxies and Clusters of Galaxies” (Garching, 7.8.–11.8.)
– Lecture to the Gesellschaft deutsche Naturforscher und Aertzte ”Alles Aus Nichts: die Ursprung unseres Universums”, (Bremen, 16.9.)
–Large-scale modelling of the evolution of galaxies: From Stars to Galaxies – conference in honour of Cesare Chiosi, (Venice, 16.10.–3.11.).
– Galaxy Growth in a LCDM Universe: Massive Galaxies over Cosmic Time II, (Tucson 28.10.–3.11.)

– Physics and Evolution of Galaxies: Review for "Towards the European ELT", (Marseille, 27.11.–1.12.).

4.4.1 Public talks

G. Börner: Urania Berlin (2.6.) und Hameln (19.9.)

B. Ciardi: Galaxies and the History of the Universe. Tag der offenen Tür" (MPA, Germany 15.10.)

T.A. Enßlin: Volkssternwarte Bonn (30.11.)
– summer school on dark matter and dark energy, Bad Honneff (20.7.)

E. Müller: Ringberg Castle (25.06.)
– Gymnasium Ober-Ursel (11.07.)
– Gymnasium Gernsheim (12.07.)
– Gymnasium Offenbach (13.07.)
– Deutsches Museum Bonn (27.09.)
– Akademie für Lehrerfortbildung, Dillingen (13.10.)
– Am Ende ein neuer Anfang: Vom spektakulären Tod der Sterne. MPA, Tag der offenen Tür (15.10.)

B. Müller: Im Sternenfeuer geschmiedet: Die Herkunft der schweren Elemente. MPA, Tag der offenen Tür (15.10.)

H. Ritter: Astronomischer Verein Basel (8.12.)
– PD Dr. Hans Ritter: "Warum strahlen Sterne? Tag der offenen Tür. (MPA, Germany 15.10.)

V. Springel: CeBIT Hannover, Day of Supercomputing (11.3.)
– Planetarium Nürnberg (22.3.)
– Volkssternwarte München (24.3.)
– Volkssternwarte Berlin (3.5.)
– Wie Supercomputer das Universum enträtseln Tag der offenen Tür. (MPA, 15.10.)
– Karl-Schwarzschild-Lecture, Physikalischer Verein Frankfurt am Main (1.11.)
– Volkssternwarte Ingolstadt (14.12.)

H. Spruit: Wie sehen schwarze Löcher aus? MPA, Tag der Offenen Tür, Garching (15.10.)

R. Walder: Seniorenuniversitaet Zurich (14.11.) Winterthur (6.12.), Liechtenstein (7.12.)

S. White: Alles aus Nichts. Der Ursprung des Universums. MPA, Tag der Offenen Tür, Garching (15.10.)

5 Personnel

5.1 Scientific staff members

Directors

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

External Scientific Members

R. Giacconi, R.-P. Kudritzki, W. Tscharnuter.

Emeriti

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

Staff

M.A. Aloy (till 15.12.) A.J. Banday, J. Ballot, J. Blaizot, G. Börner (till 30.4.), J. Bolton (since 1.10.), J. Braithwaite (till 31.8.), P. Cerda-Duran (since 1.10.), J. Chluba, B. Ciardi, E. Churazov, R. Collet (since 1.10.), G. De Lucia, N. De la Rosa (since 1.12.), H. Dimmelmeier, K. Dolag, T. Enßlin, D. Gadotti, D. Giannios, M. Gilfanov, B. Groves (till 31.10.), E. Hayashi, H.–T. Janka, G. Kauffmann, K. Kifonidis, F. Kupka, L.X. Li, A. Maselli, P. Mazzali, Z. Meliani (till 20.3.), B. Metcalf (since 15.9.), A. Mizuta (till 30.10.) A. Merloni, O. Möller, T. Morris (till 15.8.) E. Müller, R. Oechslin, E. Olsson (since 1.9.), A. Pastorello (till 31.5.), M. Reinecke, M. Revnivtsev, H. Ritter, F. Röpke, M. Ruszkowski (since 1.6.) H. Sandvik, D. Sauer (since 1.9.), S. Sazonov, C. Scannapieco (since 1.9.), S. Sim, V. Springel, H.C. Spruit, A. Watts, A. Weiss, V. Wild.

Associated Scientists:

U. Anzer, H. Arp, G. Börner (since 1.5.), G. Diercksen, W. Kraemer, E. Meyer–Hofmeister, J. Schäfer, H.-C. Thomas, R. Wegmann.

Sofja Kovalevskaja Program

S. Charlot (till 51.5.), B. Panter (till 30.9.).

Alexander von Humboldt Awardees

P. Madau (since 1.8.), J. Navarro (1.5.–30.6.), S. Tremaine (1.7.-31.12.)

Ph.D. Students

[1] A. Arcones*, M. Baldi*, A. Bauswein (since 1.11.), R. Birkl (since 1.6.), A. Bogdan* (since 1.9.), S. Bonoli* (since 1.9.), M.A. Campisi* (since 1.9.), M. Carrasco-Kind* (since 1.9.), J. Cuadra* (till 31.10.), C. D'Angelo* (since 1.9.), E. Donoso* (since 1.9.), D. Docenko*, M. Frommert (since 1.6.), A. Gallazzi* (till 30.9.), M. Grossi* (since 1.9.), Q. Guo* (since 1.3.), N. Hammer, S. Hilbert, G. Hütsi*

[1] *IMPRS Ph.D. Students

(till 30.9.), T. Jaffe* (till 31.10.), J. Jasche (since 15.10.), P. Jofre-Pfeil* (since 1.9.), F. Kitaura*, A. Kitsikis*, M. Kitzbichler*, M. Kromer (since 1.9.), T. Mädler (since 1.4.), U. Maio*, A. Marek*, M. Mocak*, R. Moll (since 1.10.), B. Müller (since 1.1.), M. Obergaulinger, M. Petkova* (since 1.9.), M. Pierleoni* (since 1.9.), P. Rebusco*, M. Righi*, L. Scheck (till 30.9.), D. Sijacki*, S. Taubenberger, M. Vogelsberger (since 1.9.), A. von der Linden*, R. Voss*, A. Waelkens (since 1.1.), L. Wang, J. Wang*, F. Xiang*, B. Zink (till 31.8.),

Diploma students

R. Birkl (till 31.5.), J. Donnert (since 1.10.), M. Fink (till 31.12.), S. Hachinger (since 1.3.), J. Jasche (till 15.10.), I. Maurer (since 1.9.), B. Möbis (since 1.12.), R. Pakmor (till 31.12.),

Technical staff

Computational Support: H.-A. Arnolds, B. Christandl, N. Grüner, H.-W. Paulsen (head of the computational support), M. Reuter.
PLANCK Programmer: H.-M. Adorf, U. Dörl, R. Hell, W. Hovest, J. Rachen, T. Riller.
Secretaries: M. Depner, G. Kratschmann, K. O'Shea, C. Rickl (secretary of the management).
Library: E. Chmielewski (head of the library), C. Hardt, R. Schurkus.

Staff news

B. Ciardi: became PI for the MPA participation in LOFAR (the LOw Frequency ARray) through construction of a Remote Station near Garching.

B. Ciardi: obtained a 5-year W2 position.

T.A. Enßlin: was tenured as a staff member of MPA.

M. Revnivtsev received the "Zeldovich medal of COSPAR" by the Russian Academy of Sciences.

M. Revnivtsev: Habilitation in Moscow: "Sky surveys with INTEGRAL and RXTE observatories: origin of the background X-ray emission of the Galaxy and the nature of variability of emission of black holes and neutron stars" (December 2006).

Ph.D. theses 2006

Jorge Cuadra-Stipetich: Stars in the Galactic Centre: Sources and Probes of the Accretion Flow. Ludwig-Maximilians-Universität, München.

Anna Gallazzi: Modeling and interpretation of galaxy spectra: the stellar populations of nearby galaxies. Ludwig-Maximilians-Universität, München.

Gert Hütsi: Cosmic sound: Measuring the Universe with baryonic acoustic oscillations. Ludwig–Maximilians–Universität, München.

Tess Jaffe: Morphological Studies of the CMB: Non-standard Models and Foregrounds. Ludwig-Maximilians-Universität, München.

Leonhard Scheck: Parametric Studies of Hydrodynamic Instabilities in the Supernova Core by Two- and Three-Dimensional Simulations. Technische Universität München.

Burkhard Zink: Black hole formation from non-axisymmetric instabilities in quasi-toroidal stars. Ludwig–Maximilians–Universität; München.

Diploma theses 2006

Michael Fink: Doppelte Detonationen in Sub-Chandrasekhar-Supernova-Modellen. Technische Universität München.

Jens Jasche: "On the coupling between cosmic rays and primordial gas". Leibniz Universität Hannover.

Rüdiger Pakmor: The imprint of the dynamical state on the structure of magnetic fields in simulated galaxy clusters. Technische Universität München.

Ilya Saverchenko: Interacting Galaxies: Matching Simulations to Observations. Technische Universität München.

5.2 Visiting scientists

Name	home institution	Duration of stay at MPA
Petr Baklanov	ITEP, Moscow	28.6.–27.7.
Isabelle Baraffe	ENS Lyon, France	22.10.–21.11.
Serena Bertone	Univ. of Sussex, UK	7.3.–28.3.
Maria Paola Bottino	University of Milan	06.06. – 08.09.
Sergey Blinnikov	ITEP Moscow	20.6.-31.7.
Carlos Bornancini	Obs. Astr. de Cordoba, AR	20.10.–21.12.
Carmelita Carbone	SISSA, Italy	13.3.-28.4.
		1.10.–31.12.
Carlos Cardenas	Santiago, Chile	04.09.–18.09.,
Matias Carrasco-Kind	(Univ. Cat. de Chile)	9.1.–8.6.
Gilles Chabrier	ENS Lyon, France	22.10.– 21.10.
Ruixiang Chang	Shanghai Observatory	since 15.11.
Emilia de Rossi	Conicet, Argentina	1.10–15.12.
Jonathan Dursi	CITA, Toronto, Canada	1.11.–30.11.
Celine Eminian	Univ. of Sussex, U.K.	1.11 – 22.12.
Jason Ferguson	Wichita State Univ., Kansas	24.5.–18.7.
Stanislav Gunar	Astr. Inst. Ondrejov, Czech	15.1.–14.4.
Luigi Guzzo	INAF Brera, Italy	1.10.–31.12.
Jake Hartman	MIT	04.09-22.09.
Nail Inogamov	Landau Inst., Moscow	14.10.–14.12.
Natasha Ivanova	CITA	8.11–2.12
Patrik Jonsson	(Lick Obs. and UCSC)	22.9.–21.10.
Chiaki Kobayashi	Astron. Obs. of Japan	24.2.–23.3.
Roman Krivonos	HEA Dept., Moscow	22.3.–15.6.
		4.10.–28.11.
Jounghun Lee	Seoul Univ, Korea	1.7.–19.8.
Cheng Li	Hefei, China	1.1 – 20.5.
Malcolm Longair	Cavendish Lab., U.K.	16.10.–15.12.
Alexander Lutovinov	HEA Dept. Moscow	22.10.–25.11.
Patryk Mach	Cracow University, Poland	since 6.10.
Rubens Machado	University of São Paulo	since 11.9.
Piero Madau	Lick Obs. and UCSC	since 1.8.
Keiichi Maede	Univ. of Tokyo	2.8.–20.8.
Matteo Maturi	University of Padova, ITA Heidelberg	1.4.–30.6.
Marcello M. Miller Bertolami	La Plata University, AR	19.1.–19.7.
Petar Mimica	Univ. of Valencia	27.9.–17.10.
Sergey Molkov	HEA Dept. Moscow	12.1.–11.6.
Alessia Moretti	Univ. of Padova, Italy	till 30.3.
Dimitij Nadyozhin	ITEP Moscow	2.3.–2.5.
Julio Navarro	Univ. of Victoria, Canada	1.5.–30.6.
Sergey Nayakshin	Univ. of Leicester, U.K.	27.3.–26.4.
Roderik Overzier	Leiden Univ., The Netherlands	1.8.–30.8.
Maria-Josefa Perez	La Plata Univ., AR	4.8.-20.12.
Elena Pian	INAF - Trieste Observatory, Italy	5.7.-15.8.
Lorenzo Piovan	Padova University	15.3.–15.9.
Juri Poutanen	University of Oulu, Oulu, Finland	5.9–31.10.
Elena Rasia	Univ. of Padova, Italy	1.2.–30.4.
Elena Rossi	JILA, Boulder	15.5.–15.7.
Gregory Rudnick	NOAO Tucson, USA	17.4.–30.4.
Tokuei Sako	Tokyo, Japan	03.08.–21.09.

Name	home institution	Duration of stay at MPA
Nikolai Shakura	Sternberg Inst. Moscow	1.10.–31.10.
Maurizio Salaris	Liverpool John Moore University	6.2.–6.7.
Aldo Serenelli	Institute for Advanced Study, Princeton	2.6.–8.7.
Shiyin Shen	Shanghai Observatory	since 15.11.
Pavel Shtykovskyi	Space Research Institute, Moscow	1.3–29.5
		22.9–18.12
Federico Stasyszyn	Univ. de Cordoba, AR	22.9.–24.12.
Kandaswamy Subramanian	IUCAA, Pune	10.10.–21.11.
Masaomi Tanaka	Univ. of Tokyo	2.8.–20.8.
Sergey Tolstov	ITEP Moscow	3.9.-7.10.
Martin Topinka	Astron. Inst. of CAoS, Prague	till 28.2.
Sergey Tsygankov	HEA Dept. Moscow	4.10.–23.12.
Scott Tremaine	Princeton University	1.7.–31.12.
Victor Utrobin	ITEP Moscow	till 30.1.
		1.10.–30.11.
Sandro Villanova	Padova University	18.5.–1.7.
Rolf Walder	Zurich, Switzerland	6.11.–20.12.
Huiyuan Wang	Hefei, China	1.1.–20.5.
Jesus Zavala	National Univesity of Mexico	16.2.-30.5.