Max-Planck-Institut
für
Astrophysik

Annual Report 2007

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. A major event in 2007 was the appointment of Martin Asplund as a new director. Martin arrived in September 2007 and will formally be considered a Wolfgang Hillebrandt's successor. The institute also has three external Scientific Members: Rolf Kudritzki, Riccardo Giacconi and Werner Tscharnuter.

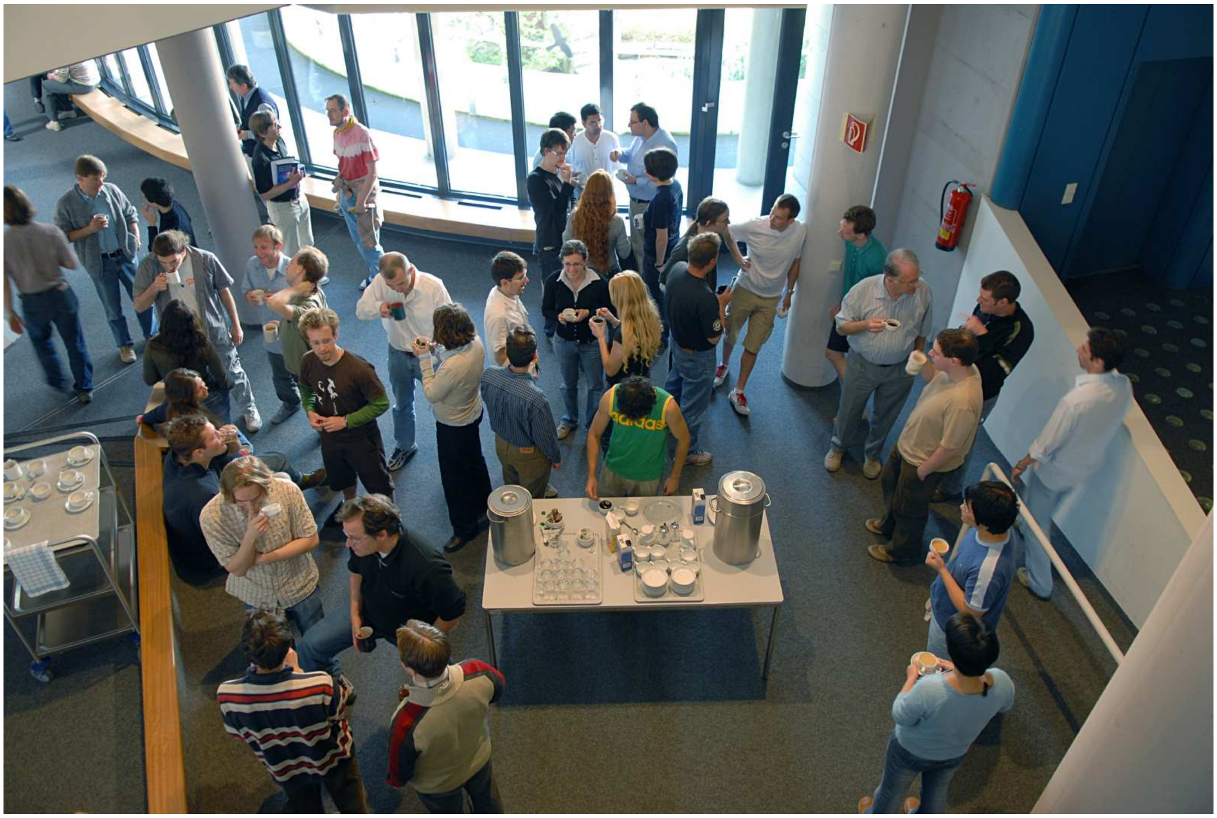
The MPA was founded as an institute for theoretical astrophysics. Its initial mission was to develop the theoretical concepts needed to understand the structure and evolution of stars, the dynamics of magnetised interstellar media and other hot plasmas, the properties of relativistic particle populations, 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, as well as about 6500 reports and observatory publications, and it holds subscriptions for about 200 journals and manages online subscriptions for about 400 periodicals. The current holdings occupy about 1900 meters of shelf space. In addition the library maintains an archive of MPA and MPE publications, two slide collections (one for MPA and one for the MPE), a collection of approximately 300 CDs and videos, 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, doctoral dissertations, and habilitation theses and links to other online pblications. 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 colour bookscanner, two laser printers, and a fax machine are available to serve the users' and the librarians' needs.

The "General-Verwaltung" (GV) keeps campus licenses for online electronically accessible journals whereas individual institutes subscribe only to print copies of selected journals at a reduced price. The online journals are accessible via the institute's library homepages. In addition, access to the back files from several large publishers is provided via a national license kept by the Deutsche Forschungsgemeinschaft.

In 2003 the 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 people (e.g. ca. 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.

For lack of office space elsewhere in the institute four guest desks with PCs have recently been set up in the library's reading hall.

The library is run by three people who share the tasks as follows: Mrs. Chmielewski (full time; head of the library, administration of books and reports), Mrs. Hardt (full time; interlending and local loans of documents, "Edoc", and relocation of books), and Mrs. Schurkus (half time; administration of journals)

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 the Max Planck Society's Garching supercomputer Centre (the RZG).

The design, usage and development of the MPA computer system is organized by the Computer Executive Committee in close consultation with the system administrators. This group also evaluates user requests concerning resources or system structure. In addition it meets RZG representatives on a bi-monthly basis to discuss issues concerning MPA's requirements at the RZG. RZG and MPA try to coordinate their development plans to ensure continuity in the working environment experienced by the users. Furthermore, MPA participates actively in discussions of potential major investments at the RZG. Common hardware acquisitions by the two institutions are not unusual. Presently, MPA has two Linux-clusters (the larger one with 504 processors, 1008 GB core memory, and 46 TB disk space) and one SGI-Altix (128 Intel Madison processors, 256 GB main memory, 2 TB disk space) system located at RZG. The most important resources provided by the RZG are parallel supercomputers, PByte mass storage facilities (also for backups), and the gateway to GWIN/Internet.

The philosophy 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 services. 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 2007) amount to more than 150 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 170 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 well separated from the crucial system components by a firewall. Apart from the standard wired network (Gb capacity up to floor level, and

100 Mb to the individual machine), access through a protected WLAN is possible, too.

The basic operating system is relying on Open-Source software and developments. One MPA system manager is actively participating in the Open-Source community. 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 in use, too. Special needs requiring Microsoft or Macintosh PCs or software are satisfied by a number of public PCs and through servers and emulations.

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.

In addition to the central MPA computer services, both the Planck Surveyor project and the SDSS group operate their own computer clusters. The former installation is designed in a similar fashion as the general system, and is maintained by an MPA system manager. The SDSS system is MS Windows based, and administered both by an MPA- and an additional SDSS-manager.

1.3 2007 at the MPA

A new director

Two of the MPA's directors will be retiring over the next few years, Rashid Sunyaev in 2011 and Wolfgang Hillebrandt in 2012. In order to ease this major transition, the institute decided a couple of years ago to begin searching for an early replacement for one of the two who could be in place well before either retirement and so able to participate fully in selecting the second replacement. A small "Futures Committee" within the institute began a broad search for candidates and a number of people visited the MPA in order to get to know the institute and to talk to our senior scientists.

The outcome of this procedure was a consensus that our ideal candidate was Martin Asplund, a 37 year old Senior Research Fellow (the equivalent of Full Professor) at the Australian National University in Canberra. Martin's interests are primarily in stellar astrophysics. He is particularly known for his work on spectral line formation in fully three-dimensional simulations of stellar atmospheres. This has major ramifications for element abundance determinations using stellar spectroscopy; Martin's most striking result so far was a recalibration of the solar oxygen abundance by a factor of almost 2. Martin's interests would continue and extend the institute's activity in stellar astrophysics, making him a natural successor to Wolfgang Hillebrandt.

The MPA request to appoint Martin went through all the Max Planck Society's appointments procedures very smoothly, but took longer than expected because of some unfortunate timing accidents (e.g. the 2006 soccer World Cup forced the Society's 2006 annual meeting to be held early, causing a critical step in the appointment to be postponed for several months!). The institute breathed a collective sigh of relief when it became clear in summer 2007 that Martin would indeed be able to accept our offer, and would move to Germany with his wife and three small children in September 2007.

The MPA Radio Observatory

In 2006 the MPA decided to become directly involved in observational radioastronomy through participating in the Low Frequency Array (LOFAR, a Dutch-led project to construct an interferometer at metre wavelengths made up of a very large number of very simple antennas. LOFAR 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. The MPA is purchasing 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 five such stations in Germany and will almost double the north-south resolution of the interferometer. The site is already prepared and the antennae will be delivered in 2008. 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, who also chairs the Science Working Group of German LOFAR participants.

Field where the antennas for the LOFAR station will be constructed

Identifying prospective PhD students

In 2006, the MPA held a "workshop" to interview those highly ranked applicants to the International Max Planck Research School on Astrophysics who expressed interest in coming to the institute. This worked so successfully that the IMPRS partner institutions decided to hold a similar workshop for the graduate school as a whole in 2007. More than 40 prospective students (roughly a quarter of all applicants) were invited to visit, giving presentations and talking to potential research supervisors. Nearly half of these showed interest in coming to MPA. In the end, the institute made about 15 offers and more than two thirds were accepted. This joint procedure was felt to be very successful by all participants and it was decided to continue it with minor modifications in future years. Not surprisingly, it turns out to be much easier to assess foreign applicants for PhD places if one has an opportunity to interact with them personally.

Biermann lectures on the first instants of Creation

2007 was the eleventh year of the Biermann Lecture series at MPA. This year's lecturer was Andrei Linde, a well-known Russian cosmologist who now works at Stanford University. Andrei and his wife (who is also a well-known theoretical physicist) have been regular visitors to Munich over the last few years, spending part of their summers at the LMU's Sommerfeld Centre for Theoretical Physics. Andrei is particularly renowned for his contributions to the theory of cosmic inflation and for his ideas about the nature of the Big Bang. He also has a reputation as a superb lecturer. Because of the broad interest in these topics among the Munich physics/astrophysics community, it was decided to hold the 2007 Biermann lectures in the conference room of the new MPE building, rather than in the substantially smaller MPA seminar room which was used in previous years. This turned out to be a wise decision because there was standing room only at the lectures, even after the MPE room had been expanded to its full size.

The MPA Visiting Committee

The MPA's Scientific Evaluation Committee (the "Fachbeirat") visited the institute again at the end of October 2007. For this year's visit the six members of the regular committee (J.R. Bond (chair), L. Bildsten, C. Franssen, L. Maraschi, R. Narayan, D. Reimers) were joined by two additional observers (Herbert Gleiter und Roland Sauerbrey) who were appointed by the Max Planck Society to participate in the evaluations of all six institutes in our research group (the MPA and MPE, the MPI for Astronomy in Heidelberg, the MPI for Radiastronomy in Bonn, the Albert Einstein Institute in Golm and the MPI for Solar System Research in Lindau). The idea is that the observers will meet the upper administration of the Max Planck Society, together with the chairs of the six Visiting Committees, in order to provide a comparative overview of the quality and impact of the Society's research in our field.

The visit passed smoothly with the Visiting Committee apparently impressed again by the quality and diversity of MPA research. In particular, they were happy to meet the institute's new director, Martin Asplund, and to have a chance to get to know him and his research plans. The Committee also had strong and fruitful iteractions with junior institute members which allowed them to form a clear picture of how the MPA functions from their point of view, and so to make recommendations for how to smooth relations and to avoid the occasional problems which arise as the institute grows in size and the fraction of students and postdocs increases.

International Exchanges

The numbers of international visitors at MPA continued to increase in 2007. A Marie-Curie Research Training Network dedicated to Multiwavelength Analysis of Galaxy Populations is coordinated from MPA (by Guinevere Kauffmann) and has been very active. In addition a variety 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 brought half a dozen South American students to the MPA in 2007 for stays of between 2 and 6 months, and Marie-Curie Early Stage Training funds brought 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 strong connections between MPA and astronomy in China showed up in many activities in 2007. The new cooperation with the astrophysics and cosmology department of the Shanghai astronomical Observatory (SHAO) supported by funds from MPG, includes a vigorous exchange programme which culminated in a one-month extended workshop on high energy astrophysics and on galaxy formation. The new partner group of the MPA at SHAO was mainly responsible for the organisation of this meeting. About 15 students and scientists from SHAO and the University of Science and Technology of China (USTC) in Hefei visited MPA during October/November of 2007 to discuss joint projects with colleagues from MPA, and to enjoy several days of formal lectures and seminars. The first two post-docs in the joint programme of SHAO and MPA began their time at MPA in October following a year spent in Shanghai. In addition there were visits of MPA scientists to various universities and institutes in China, and visitors to MPA from other places in China besides Shanghai. Several students from China are enrolled in the IMPRS at Garching.

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.

Particular highlights of MPA public outreach activities are our Open House events. Usually organized campus wide every second year, these events took place annually in the past couple of years, mostly in the context of special festivities. While in 2006 the whole Garching Campus celebrated the opening of the underground link to central Munich

Telescope on the roof during the "Long Night of Science", October13, 2007

after several years of disruptive construction work, it was the 50th anniversary of the foundation of the Research Campus Garching in 2007. On this occasion a "Long Night of Science" (Lange Nacht der Wissenschaft) was organised for the first time on Saturday, October 13. The MPA offered its roughly 1000 visitors a program of hourly talks until midnight, continuous slide and poster shows, our "Cosmic Cinema" multi-media presentation of science movies, the "astro consultation" in the coffee corner, guided tours through the institute, a slide show of latest astronomical observations in the entrance hall, and the possibility to observe the night sky using a 20 cm telescope on the roof terrace of the institute. The experiment of having an evening event was a complete success, although some visitors (and MPA staff) regretted that the late hours excluded organizing the real crowd puller of the previous year, our Kindertag, a special program for young children but also for teenagers. 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.

The "Cosmic Cinema", a multi-media computer presentation of MPA research highlights, which uses interactive and technologically advanced forms of computer visualization and animation, has been updated and extended several times since its first version of 1999. New films about a number of topics have been added (e.g. the Sun, cosmic magnetic fields, planet formation), and now in 2007 a new edition with a significantly enlarged glossary and plenty of supplementary movie material (this time on DVD instead of a set of CD-ROMs) has been composed with the help of internship students. The Cosmic Cinema has found an extraordinarily large public resonance and was widely advertised by the popular astronomy magazine "Sterne und Weltraum". It is available for free to libraries, planetaria, and school classes, and it is sold to interested individuals through orders to our library. Roughly 300 copies have been distributed so far.

The "Girls Day" is another public outreach activity which was held for the first time at MPA on April 26, 2007. This event is organised nationwide by the 'German Federal Ministry of Education and Research' and the 'Federal Ministry for Family and Women' every year. Its purpose is to arouse the interest of girls for astrophysics, and to encourage them to decide for this traditionally male-dominated career. Information on our activity was announced on the general webpage for the 'Girls' Day". We offered 30 places to girls aged between 14 and 16. After one week all the places were booked. Four female scientist at student and postdoc level (Mona Frommert, Paula Jofre-Pfeil, Paola Rebusco, Vivienne Wild) gave short talks and were really peppered with questions by the girls. More general information about the "Girls' Day" can be found at: *http://www.girls-day.de*

Girls aged between 14-16 listening to the interesting talks during the Girls Day, April 26, 2007

2 Scientific Highlights

2.1 The magneto-rotational instability in supernova cores

Having exhausted its thermonuclear fuel in consecutive burning phases a star of more than about eight solar masses develops a growing core consisting predominantly of iron group nuclei. Eventually this core collapses from a radius of a few 1000 to several tens of kilometers within a few 100 milliseconds. The collapse comes to an abrupt halt due to repulsive nuclear forces, when the density in the core's center exceeds that of nuclear matter. As a consequence of this so-called bounce a proto-neutron star forms, and a shock wave is launched. Propagating through the surrounding matter the shock wave uses up most of its energy to dissociate iron group nuclei into free nucleons. A huge amount of gravitational binding energy is released during the collapse and emitted by the star in form of neutrinos. However, a small part of the binding energy (1%) is transfered from the escaping neutrinos to the matter behind the shock wave, thereby reviving the stalled shock and triggering a supernova explosion.

Despite considerable improvements of the numerical models, the explosion mechanism of core collapse supernovae is not yet understood in full detail. The main difficulty arises from the necessity of an accurate treatment of the radiation hydrodynamics of the stellar plasma and the neutrinos, which is technically extremely demanding. Furthermore, we have only an incomplete knowledge of the physics of matter at and particularly well above nuclear matter density. We are also still uncertain regarding the potential importance of various additional physical effects, among those stellar rotation and magnetic fields being possibly the most important ones.

Previous studies focusing on the potential influence of magnetic fields have shown that they can alter the dynamics of the explosion significantly. Magnetic field can cause rapid transport of angular momentum and collimated outflows, if they are sufficiently strong already before collapse. Although current stellar evolution models predict relatively weak pre-collapse magnetic fields, there is the possibility that the pre-collapse fields are strongly amplified during the post-bounce evolution by hydromagnetic instabilities. In particular, the magneto-rotational instability (MRI) may amplify the magnetic fields to a dynamically important strength, if there is considerable differential rotation in the core, a condition that is almost certainly fulfilled after core bounce.

A rotating fluid endowed with a weak magnetic field is unstable against the MRI if its angular velocity decreases with radius. In this case, seed perturbations grow exponentially. They saturate when their energy becomes comparable to that of the unperturbed background. Then, the flow becomes turbulent, and efficient transport of angular momentum due to magnetic (Maxwell) stresses sets in.

The role of the MRI in astrophysical systems has been studied in great detail for accretion discs around compact objects. MRI-driven turbulence is supposed to be the main agent by which fluid elements lose their angular momentum, enabling them to spiral onto the compact object. This assertion is based on a large number of analytic studies and numerical simulations. However, as the structure and physical properties of stars and accretion discs are qualitatively different, and as there is a lack of detailed simulations taking into account their specific properties, the possible impact of the MRI on stars and, in particular, on supernova cores is unclear.

One of the main difficulties in numerical simulations of the MRI results from the dependence of its growth rate on the wavelength of the unstable mode. All modes of wavelength λ longer than a certain threshold λ_{min} grow exponentially, but rapid growth is only encountered for $\lambda \gtrsim \lambda_{\mathrm{min}}$. The wavelength of fastest growth is proportional to the initial magnetic field strength. Thus, only very short modes (wavelengths of several centimeters) grow rapidly for the field strengths one expects in supernova cores.

In a simulation, it is necessary to use a computational grid where the fastest growing modes are resolved by at least a few zones. Since λ_{min} is several orders of magnitude smaller than the radius of the core, the simulation has to cover an large range of spatial scales. Furthermore, realistic simulations of the MRI are necessarily of three dimensional nature, i.e., the resulting computational requirements exceed the resources of current day computers. Hence, the study of the MRI has to be split in two parts. *Local* simulations focus on the fastest growing, shortest wavelengths of the MRI using highly resolved simulations of a small, representative part of the entire system taking into account the influence of the not modelled larger scales by suitably chosen boundary conditions. *Global* simulations treat the large length scales of the problem either by neglecting the subtleties of the MRI physics at small scales at all or by approximating this physics with a suitable sub-grid model. Up to now, global MHD supernova simulations have employed unrealistically strong initial magnetic fields relying on an efficient amplification of a much weaker seed field by the MRI on sub-grid scales.

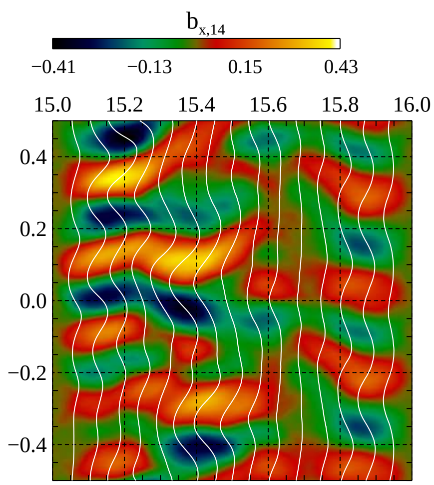


Figure 2.1: Color coded radial component of the magnetic field in units of 10^{14} G for an axisymmetric MRI model at time $t = 2.4$ ms. The white lines are poloidal field lines. The abscissa and ordinate correspond to the radial and the vertical (z) axes of the computational grid, respectively.

We study the evolution of the MRI in supernova core collapse using local simulations, both in axisymmetry and in three dimensions, neglecting neutrino transport and using a simplified equation of state. Our computational grid covers a region of about one or two kilometers cubed in the equatorial plane of a core. We use *shearing-disc* boundary conditions, i.e., a version of the shearing-sheet boundaries used in simulations of accretion discs that allow us to include global gradients of, e.g.,

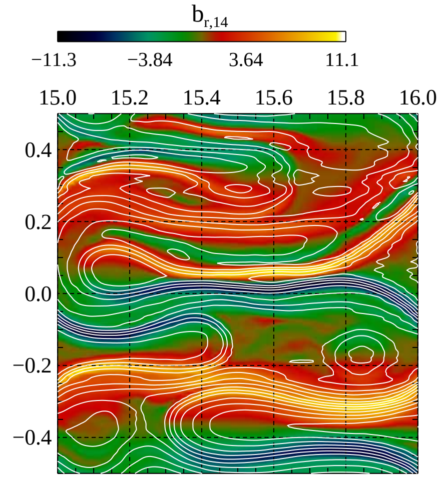


Figure 2.2: Same as Fig. 2.1, but at time $t = 11.7$ ms.

the density. In the following, we describe the evolution of models with a uniform vertical initial field.

Our axisymmetric simulations confirm the rapid growth of seed perturbations on a time scale of about ten milliseconds, unless the MRI is suppressed by a stable entropy gradient. The growth of the instability proceeds through the development of *channel modes*, radial flows of alternating orientation stacked along the vertical direction which lead to a stretching of the magnetic field along the channels, thereby causing a large radial magnetic field component (see Fig. 2.1).

These channel flows are fairly stable; in fact, they are known solutions of the axisymmetric MHD equations. No breakdown of these coherent flows into small scale turbulence is observed, and the MRI does not saturate. Instead, the channels merge as the field strength grows, and at late epochs the flow is dominated by a small number of large-scale up-flows and down-flows (see Fig. 2.2). Not limited by turbulent saturation, the field strength reaches several 10^{15} G before Maxwell stresses lead to a rapid transport of angular momentum, disrupting the initial rotational profile.

Relaxing the assumption of axisymmetry, we find that after an initial epoch of channel flow mediated MRI growth *parasitic instabilities* of, e.g., Kelvin-Helmholtz type dissolve the channel modes into small scale turbulence (Fig. 2.3). At this point, the growth of the instability saturates. Despite the lack of coherent structures the Maxwell stresses are only slightly weaker than in the axisymmetric model, and the resulting angular momentum transport is able to modify the rotational profile considerably on time scales relevant for the explosion, i.e., within several tens of milliseconds.

Even after the disruption of the channel flows into small scale turbulence, coherent structures can develop in the flow by spontaneous self-organization. We observe the reappearance of channel-like flows in one of our models after about 50 milliseconds (Fig. 2.4), the flow pattern being roughly axisymmetric and extending over the entire computational domain. The consequences are similar to that of a channel flow in axisymmetry: huge Maxwell stresses grow, disrupting the rotational profile within a few milliseconds. For different initial field configurations or different entropy gradients the evolution is considerably different. In particular, we observe the development of magneto-convective modes for Rayleigh-Taylor unstable stratifications.

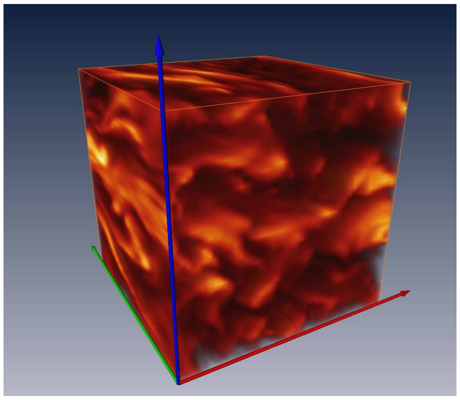


Figure 2.3: Volume rendered magnetic field strength of a 3D MRI model at time $t = 35.1$ ms. The arrows indicate the coordinate axes: the red, blue, and green arrows correspond to the radial, vertical, and angular direction, respectively.

From our simulations we can conclude that the MRI in a supernova core can grow fast enough to affect the explosion dynamics. It will amplify weaker initial fields than the ones typically assumed in global simulations leading to strong Maxwell stresses. However, to assess the detailed dependence of the amplification on the (global) parameters of the system, further investigations are needed. (Martin Obergaulinger and Ewald Müller).

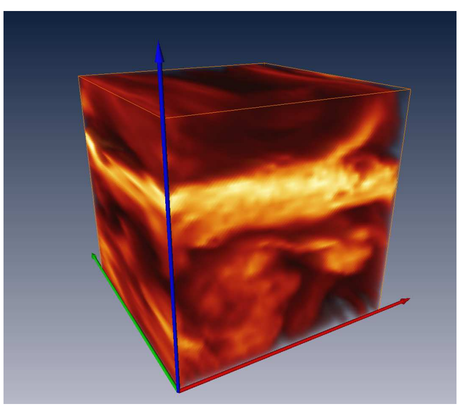


Figure 2.4: Same as Fig. 2.3, but at time $t = 52.5$ ms.

2.2 Detecting solar gravity modes: a challenge to probe the solar core

Helioseismology is a fantastically accurate way to probe the solar interior. The internal structure and dynamics of the Sun are revealed by observations of oscillation modes visible at its surface as fluctuations of intensity or velocity. For instance, analyzing acoustic modes (known as 'p modes' since they are driven by pressure forces) provides a detailed sound-speed profile deep inside the Sun, very close to the centre (down to $0.05\mathrm{R}_\odot$). Helioseismology allows an accurate measurement of the position of the base of the convective envelope, provides a precise value of the surface helium abundance, and even puts strong constraints on neutrino fluxes originating in the nuclear core. Dynamical properties of the solar interior are also derived from p modes. The rotation rate is accurately measured in almost the whole convective zone, and also in the radiative region down to $0.2R_{\odot}$. Unfortunately observed p modes do not carry information on the rotation below this limit: since the radial modes (i.e., the modes with degree $l = 0$, which are the most penetrating) are insensitive to rotation. The most penetrating modes which are sensitive to the rotation are dipolar ($l = 1$) modes which cannot put constraints on the rotation below $0.2R_{\odot}$.

Going deeper requires the detection of another class of oscillation modes: the gravity modes (or 'g modes'), driven by the buoyancy force. These modes have long periods (greater than 40 min.) compared to p modes which have typical periods of 5 minutes. They are trapped below the convective envelope, within the radiative region, and reach the surface as evanescent waves with very small amplitudes. Detecting these tiny oscillations is highly challenging but remains the best – if not the only – way to constrain properties of the very deep core of the Sun. Since 1976, solar g modes have been hunted without success. This year, by using 11-year-long data provided by the GOLF (Global Oscillations at Low Frequency) instrument aboard the SoHO spacecraft, a collaboration of European scientists from the Service d'Astrophysique in CEA (Saclay, F), the Max-Planck Institut für Astrophysik, the Instituto de Astrofísica de Canarias (Tenerife, E) and the Observatoire de la Côte d'Azur (Nice, F) have made the first unambiguous detection of a signal fully compatible with g modes. GOLF is a resonant scattering spectrophotometer designed to measure the mean line-of-sight velocity displacements of the solar photosphere. Thus it provides long time series of velocity fluctuations, from which an oscillation power spectrum is directly obtained by Fourier analysis. Instead of searching for g modes directly in the oscillation spectrum as peaks or multiplets, this team has looked for the cumulative effects of several $l = 1$ g modes ($l = 1$ modes must have the highest apparent amplitudes). Gravity modes with the same degree l are expected to have almost regularly spaced periods. This constant spacing, denoted ΔP_l, is usually called the 'large separation' and different solar models predict values of ΔP_1 within a range of 22–27 min. Such a periodicity should be detected in the 'second spectrum', defined as the Fourier spectrum of a selected range (for this study, a typical range of 2–10 hours) of the oscillation spectrum. Figure 2.5 shows the second spectrum obtained with GOLF data compared to a model. A clear peak appears around 24 min, where ΔP_1 is expected. A statistical study confirms the high significance of the peak.

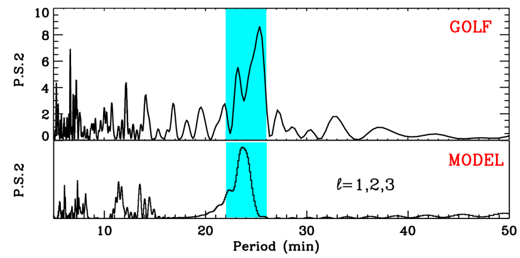


Figure 2.5: Second spectrum, normalized by the standard deviation of noise, obtained with real GOLF data (top). It is compared with synthetic data derived from a model (bottom). The strong peak around 24 minutes is interpreted as the large separation of dipolar g modes ΔP_1.

A detailed analysis of the amplitudes and the phases of relevant peaks in the second spectrum makes it possible to reconstruct a signal which can be compared to predictions of g modes deduced from different solar models. The detected g-mode signature is compatible with models using the old standard solar surface abundances, but not with models assuming new metal-poorer abundances, as recently revised by Asplund and collaborators. This result is in agreement with results deduced from p modes. Moreover, the detected signal appears to favor models with a core, below ~0.1–$0.15R_{\odot}$, spinning on average several times (typically 3–5) faster than the surrounding radiative region. Finally this detection can be explained only if g modes do not appear in the oscillation spectrum as narrow peaks but if they have non-negligible widths. This is the case if their lifetimes are finite, if they are re-excited for instance at the base of the convective zone, or if they are split by magnetic effects.

This new detection will stimulate further theoretical studies of the rotation and the magnetic field deep inside the Sun and also further observational analyses with current and next-generation instruments. (Jerome Ballot)

2.3 The properties of Type Ia Supernovae exposed

Type Ia Supernovae are the explosion of a White Dwarf star, the residual core of a star with an initial mass of 3-8 solar masses. When such stars exhaust their fuel, they expand and eject their outer envelope in a Planetary Nebula, leaving behind the hot inner part, a White Dwarf with a mass of about a solar mass. If left to itself, a White Dwarf would just cool off. However, if it is part of a binary system the White Dwarf may accrete mass from the companion star. White Dwarfs can explode if they reach ∼1.4 solar masses, because then electron degeneracy pressure, which keeps the star from collapsing under its own gravity, loses its battle.

White Dwarfs are composed of Carbon and Oxygen and substantial nuclear energy is still available. As the White Dwarf begins to collapse this material is ignited, and rather than collapsing further, a nuclear blast wave consumes the star in a second, creating an explosion 5 billion times brighter than our Sun. SNe Ia are the brightest of all SNe, but their luminosity varies by almost a factor of ten. However, since dim SNe Ia brighten and fade very quickly, whereas luminous ones do so much more slowly, it is possible to calibrate their luminosity. SNe Ia can give distances which are good to about 7% - equal to the best of astronomical distance indicators.

Using SNe Ia to measure cosmological distances, in 1998 two groups realized that the expansion of the Universe is currently accelerating. This only makes sense if the Universe is filled with some form of Dark Energy not unlike the Cosmological Constant which Einstein suggested might work against Gravity to make the Universe stable. In this, the simplest explanation for the accelerating Universe, Dark Energy is tied to space itself: space has an energy associated with it, and as space doubles in volume the amount of dark energy per volume remains fixed (whereas the density of matter drops as the volume increases).

Given the importance of these results, if we are to trust them, and better yet improve on them, we need to understand how exactly SNe Ia explode, what is the nature of their progenitors, and how predictable is the explosion. This is not simple. While it is clear that the explosion will completely disrupt the White Dwarf and produce a large amount of heavy elements, many competing theories have been proposed as to how exactly this happens. It is the production of heavy elements that makes the SN bright. The heaviest element that can be produced is ^{56}Ni. This is a radioactive isotope that decays into ^{56}Co with a half-life of ∼8 days, and thence to ^{56}Fe – a stable isotope – with a half-life of ∼77 days. These decays produce ?-rays and positrons that deposit their energy in the exploding star, producing optical light. Thus, the luminosity of a SN Ia indicates how much ^{56}Ni was produced. In a typical SN Ia, about half of the mass of the White Dwarf is transformed to ^{56}Ni. This mass is however not constant, as the variation in SN luminosity indicates. The challenge is now to understand what makes the SN produce different amounts of ^{56}Ni, and what makes the observed relation between luminosity and ligh curve shape.

Theoretically, there are two ways to explode a White Dwarf. A supersonic explosion (a detonation) can transform the entire star into ^{56}Ni in less than 2 seconds, producing plenty of energy to explode the star and lots of light. However, the outcome of such an explosion will always be the same, and the SN would be made only of Nickel, Cobalt and Iron, defying observations that a) the ^{56}Ni mass varies, and b) intermediate mass elements such as Silicon are also present. These elements are the product of partial burning. One way to obtain partial burning is for the star to expand as it explodes. This can happen in a subsonic explosion (a deflagration). In this case the explosion proceeds more slowly, energy is deposited in the White Dwarf, which begins to expand while burning is still taking place, so that by the time the outer layers burn the density is too low for them to burn completely (Fig. 2.6).

This scenario explains most observations, but even the most refined 3D calculations seem unable to match the properties of observed SNe: they never produce enough energy. ? As often happens in astronomy, a clue to the way out of a conundrum is offered by data. In the last 10 years, several correlations have been found for SNe Ia beyond that between luminosity and light curve shape. In particular, we showed that the width of the nebular Fe emission lines in spectra about 1 year after the explosion also correlates well with the SN luminosity. These lines reflect the presence and distribution of ^{56}Ni. The observed correlation then indicates that ^{56}Ni is produced in the centre of the SN, and that the more it is produced, i.e. the more of the star is burned, the bigger is the ^{56}Ni sphere.

On the other hand, to probe the outer part of the SN very early data are essential. We thus embarked on a major observational programme, which led to a EU-RTN, to observe SNe Ia with high precision and frequent time coverage. In fact, as the SN expands, deeper and deeper layers of the ejecta become visible. We wanted to obtain scans of the SN ejecta similar to tomography, hoping that mapping the burning products would show us what the correct burning mechanism was, and hopefully point to the nature of the progenitor.

In order to assess with any accuracy the properties of the explosion, the observations must be reproduced with theoretical models. We have developed over the years codes that describe the physics of SN light curves and spectra, and with the help of

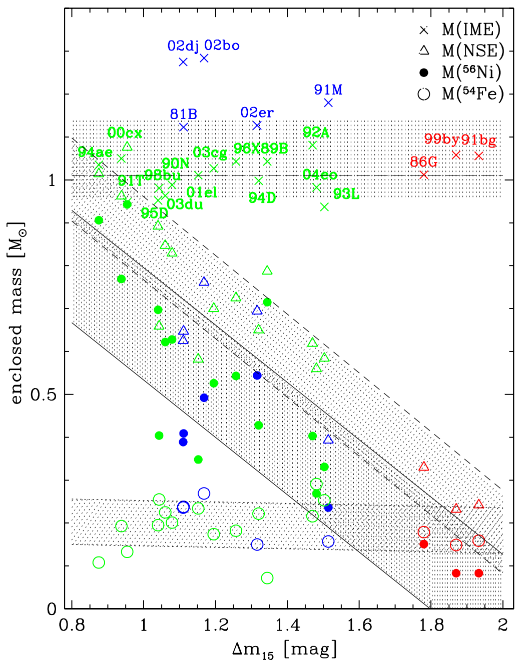


Figure 2.6: The Zorro Diagram: Distribution of the principal isotopic groups in SNe Ia. The enclosed mass of different elements is shown versus decline rate Δ m(15), a proxy for SN luminosity. In the deepest part of all SNe, a roughly constant amount of stable Fe and Ni is found. ^{56}Ni (filled circles) is correlated with SN luminosity: slow decliners have more. The sum of all Fe-group isotopes (triangles) determines the opacity. Silicon, which represents Intermediate Mass Elements, is located outside the Fe-group elements, and its outer extent (crosses) is similar for most SNe.

theoretical explosion models we matched the data with very good precision. This gives us confidence that we understand the ingredients we used late-time spectra to study the composition of the inner ejecta, and early-time spectra to derive the composition of the outer ejecta. The result was very surprising. In the innermost part, all SNe Ia contain initially not only ^{56}Ni, which decays to ^{56}Co and ^{56}Fe, but also a small but constant amount of other stable iron-group isotopes, which do not make the SN bright. The ^{56}Ni content is highly variable, ranging from 1/10 the mass of the Sun to a solar mass. We established that the outer boundary of the distribution of ^{56}Ni is directly linked to the amount of ^{56}Ni produced. This means that essentially all the inner part of the star is completely burned. Already this suggests some degree of self-organization of the explosion.

The next step of the investigation was to determine the location of silicon. This represents the partially burned material, which is visible early-on in SN Ia spectra and is therefore produced in the outer layers. Following the evolution of the spectra, we determined the innermost location where Si is present. In an explosion, the outer material moves faster. Material moving in our direction produces blue-shifted absorption lines. The observed decrease of the blueshift over time indicates that material of progressively lower velocity, located in deeper layers of the ejecta, is causing the absorption. Meanwhile, material that is further out becomes too dilute to absorb radiation. We found that the minimum velocity of silicon is highly variable from SN to SN, but it coincides very well with the outer Fe velocity. This again indicates that complete burning (to iron) incinerates the inner part of the White Dwarf.

The absence of incomplete burning products and of unburned material in the deepest layers is a challenge for even the most advanced 3D deflagration models. To establish the extent of the silicon distribution (i.e. of incomplete burning) it is necessary to determine the outer velocity of silicon is lower. This can be obtained from the earliest data, when the highest velocity material is visible. Surprisingly, we found that almost all SNe have the same maximum silicon velocity. This means that roughly a constant fraction of the star is burned, either completely (to iron) or incompletely (to silicon), regardless of the SN luminosity. Thus, the explosion seems to be able to regulate itself, so that if less complete burning occurs, it is compensated by more incomplete burning, and vice versa.

This behaviour suggests that a particular type of explosion, called delayed detonation, is responsible for most, possibly all SNe Ia. In this mode the explosion starts subsonically, burning the inner part of the star to iron group isotopes. However, before burning dies, a detonation sets in that destroys the rest of the star. If the transition from subsonic to supersonic burning takes place at high densities, as would be the case if the deflagration was weak, then the detonation burns most of the White Dwarf at high density to iron-group isotopes. Otherwise, if the deflagration was strong and the star expanded sufficiently, the detonation occurs at low density and it can only partially burn the star - to silicon and other Intermediate Mass Elements. Still, in both cases what we see indicates that most of the star is burned. The details of the explosion still need to be understood, but our results are likely to have identified the single mechanism that is responsible for the explosion. (Fig.2.7) If a single, predictable explosion mechanism creates the large

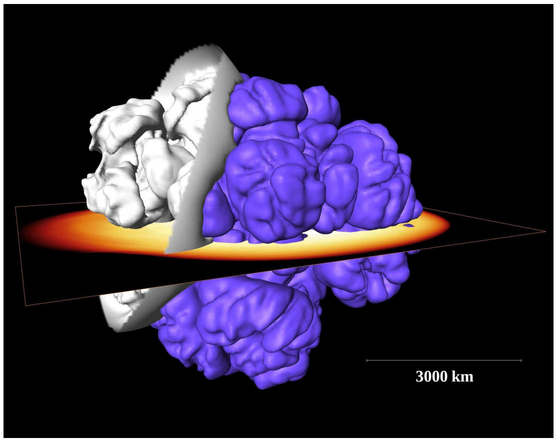


Figure 2.7: Delayed detonation model of Type Ia supernova explosions. This snapshot from a three-dimensional simulation (Röpke & Niemeyer, 2007) shows the detonation front (white isosurface) wrapping around the nuclear ashes left behind from the deflagration phase (deflagration flame shown in blue) and burning most of the remaining fuel material. The extent of the white dwarf star is shown as the density contour in the equatorial plane.

observed spread of SN properties by just changing one parameter, the initial strength of the explosion, we can confidently and accurately calibrate the luminosity of SNe Ia and use them as bright beacons with which we can explore the depth of the Universe (Paolo Mazzali).

2.4 Lyα heating and its impact on early structure formation

The study of the high redshift intergalactic medium (IGM) has recently attracted increasing attention as the new generation of low frequency radio telescopes, e.g. `LOFAR`, `MWA` and `PAST/21cmA`, promises to open an unexplored observational window on the high-z universe. In fact, these facilities should be able to detect the 21 cm line associated with the hyperfine transition of the ground state of neutral hydrogen, either in absorption or in emission against the Cosmic Microwave Background (CMB) radiation. In order for the line to be visible, the spin temperature, which regulates the population of the levels, needs to be decoupled from the CMB temperature. While at $z > 20$ collisions efficiently decouple the two temperatures, at lower redshift scattering with the Lyα photons emitted by the first stars is the most efficient process. In addition, Lyα photons could be able to heat the IGM temperature above the CMB temperature and render the 21 cm line visible in emission.

The advantage of Lyα photons over other heating sources, such as x-rays, is that the Lyα photons can travel cosmological distances and quickly build up a more homogeneous background.

The IGM heating from Lyα photons can also have a feedback effect on structure formation. In the standard cosmological scenario, the first objects to collapse typically have small masses, corresponding to virial temperature $T_{vir} < 10^4$ K. The formation and evolution of these structures is heavily affected by feedback effects. It has been noted that objects with virial temperatures of few thousand degrees forming in an IGM pre-heated by Lyα photons, would have a reduced post-collapse overdensity and would be more vulnerable to feedback effects such as molecular hydrogen dissociation and photoevaporation.

All this makes it worthwhile to investigate further the effect of Lyα photons on the IGM temperature evolution.

MPA scientists, in collaboration with R. Salvaterra (Università Milano Bicocca), have estimated the Lyα background, J_α, expected from the first stars, assuming that they are metal-free. Two different stellar mass distributions (or Initial Mass Functions, IMFs) have been considered: Very Massive Stars (VMS) with mass of 300 $M_\odot$ and a Salpeter IMF. It is found that at the highest redshifts a VMS IMF may dominate the photon production, while at $z < 26$ the situation may be reversed because of the contribution from the small-mass long-living stars. The background J_α has been used to calculate the evolution of the IGM temperature, T_k, determined by Lyα photon heating. In Figure 2.8 the temperature evolution is plotted as a function of redshift for a VMS (upper panel) and Salpeter (lower) IMF. The solid line represents the IGM temperature in the absence of Lyα heating. As expected, the temperature is higher with a Salpeter IMF, reflecting the behavior of the Lyα photon production.

Lyα heating can have a feedback effect on the formation of small mass halos. To study the impact of Lyα feedback the IGM entropy, $K_{IGM} = T_k/n_{IGM}^{2/3}$, can be compared with the entropy generated by gravitational shock heating, $K_0 = T_{vir}/n(r_{vir})^{2/3}$, where n_{IGM} is IGM number density, while T_{vir} and $n(r_{vir})$ are the virial temperature and the number density at the virial radius of a halo. As the ratio K_{IGM}/K_0 increases, the Jeans smoothing effects due to the IGM entropy become more significant, the central pressure and density of the halos decrease, together with the accreted

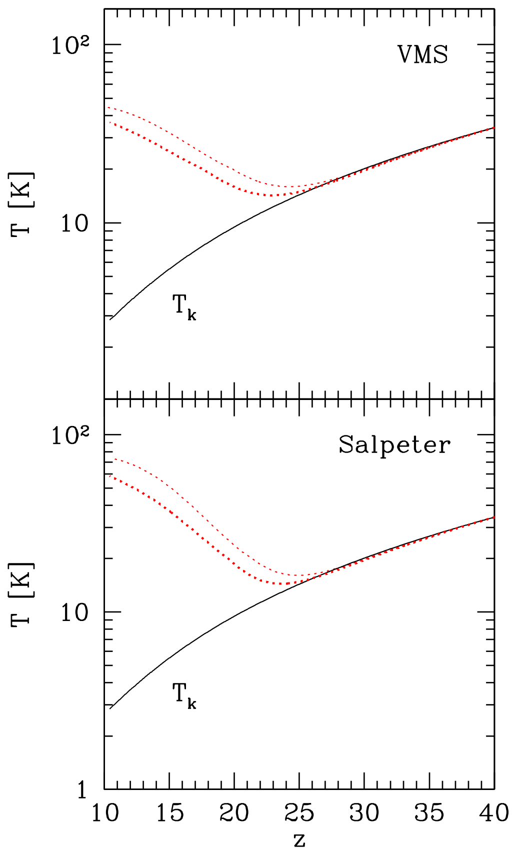


Figure 2.8: Temperature evolution for VMS (upper panel) and Salpeter (lower panel) IMF. The IGM temperature is plotted (dotted lines), together with the value in the absence of Lyα heating (solid). Thick (thin) lines refer to the case in which the feedback effect on structure formation from Lyα photons is included (excluded) (see text for details).

gas fraction and gas clumping. As a consequence, the amount of gas going into stars is likely to decrease and the halo becomes more vulnerable to feedback effects. Because of the reduced amount of gas available for star formation, also J_α and T_k become smaller (see Fig. 2.8 thick dotted line). As an example, the gas fraction in halos of mass in the range $10^5 - 5\times10^6$ M$_\odot$ (depending on redshift) is less than 50% (for the smallest masses this fraction drops to 1% or less) compared to a case without Lyα heating.

As already discussed, heating of the IGM from Lyα photons has important consequences for the observation of 21 cm line from neutral hydrogen. The quantity that the planned generation of radio telescopes will observe is the differential brightness temperature, δT_b, between the CMB and a patch of neutral hydrogen. For HI with optical depth τ and spin temperature T_s at redshift z, δT_b can be written as:

$$\delta T_b = (1 - \mathrm{e}^{-\tau})\frac{T_s - T_{\rm CMB}}{1+z}. \tag{2.1}$$

The value of the spin temperature is crucial for the observability of the line and depends on $T_{\rm CMB}$, T_k and J_α. In particular, as is clear from the above equation, the line becomes visible only if T_s is different from $T_{\rm CMB}$, otherwise $\delta T_b = 0$ and there is no signal. If $T_{\rm CMB} > T_s$ then $\delta T_b < 0$ and the line can be seen in absorption against the CMB, otherwise it is in emission. The expected evolution of temperatures and δT_b is shown in the upper and lower panel of Figure 2.9, respectively. Here the spin temperature is shown as a function of redshift together with $T_{\rm CMB}$ and T_k in the absence of a Lyα background (upper and lower dotted-dashed lines, respectively). The dotted line is T_s in the absence of a Lyα background, while the solid (dashed) lines are for a Salpeter (VMS) IMF. In all cases the effect of the Lyα feedback is included.

The presence of a Lyα background is crucial for the observability of the line, as Lyα photon scattering is extremely efficient in coupling the spin temperature to the gas temperature (dashed and solid lines compared to the dotted line in the upper panel of Fig. 2.9). Without Lyα background T_s would be equal to $T_{\rm CMB}$ below $z \sim 20$ and, as a consequence, $\delta T_b = 0$. Nevertheless this mechanism is not able to heat the IGM above $T_{\rm CMB}$ before $z \sim 15$. Thus, if Lyα photons are the only heating source in the early universe and the reionization process is ongoing at very high redshift, we expect to observe the 21 cm line in emission only when the IGM is substantially ionized, while at

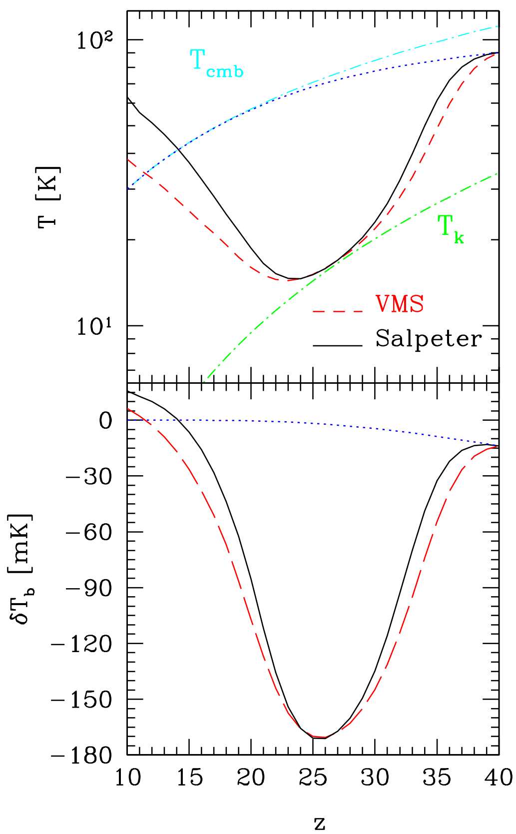


Figure 2.9: *Upper panel*: Evolution of the spin temperature for a Salpeter (solid lines) and a VMS (dashed) IMF, and in the absence of a Lyα background (dotted). $T_{\rm CMB}$ and T_k in the absence of a Lyα background are plotted as upper and lower dotted-dashed lines, respectively. *Lower panel*: Evolution of the differential brightness temperature. Lines are the same as in the upper panel.

earlier times we expect to observe it in absorption. In the absence of Lyα feedback, the heating by Lyα photons is effective in raising the IGM temperature above T_{CMB} already at $z \sim 17$.

In summary, once the IGM is heated by the Lyα photons above the CMB temperature, the 21 cm line associated with the hyperfine transition of the ground state of neutral hydrogen can be visible in emission against the CMB. This happens at $z < 15$, while at higher redshift, in the absence of other heating sources (e.g. x-rays) we expect to observe the line in absorption. Thus, for the detection of the emission line, the reionization history becomes critical as the peak of the emission (in terms of fluctuations of the differential brightness temperature) is expected when roughly half of the volume is ionized but the ionized regions do not completely overlap.

Lyα heating also affects the subsequent formation of small mass objects by producing an entropy floor that may reduce the central pressure and density of gas within halos, as well as the accreted gas fraction and clumping, thereby of decreasing star formation in the halos and rendering them more vulnerable to molecular hydrogen dissociation and photoheating. (Benedetta Ciardi)

2.5 Fine-scale structure of Dark Matter haloes

Although there is much observational evidence for Dark Matter (DM), only its gravitational effects have so far been detected and its nature remains unclear. Particle physics provides us with some natural DM candidates, for example, the lightest supersymmetric partner of the known particles or the axion. Even though such WIMPs (Weakly Interacting Massive Particles) are very weakly interacting, there are both direct and indirect detection schemes which may soon reach the sensitivity needed to see them. Direct detection is based on elastic scattering of the DM particles off nuclei in a laboratory detector (for SUSY WIMPS) or on resonant interactions with photons in a microwave cavity (for axions). Indirect detection exploits the expectation that DM particles can annihilate, producing observable gamma-rays. Both schemes have already been used to hunt for DM, but with only one highly controversial claim of a detection to date.

Since the cross-sections of DM particles are extremely small, all detection experiments have

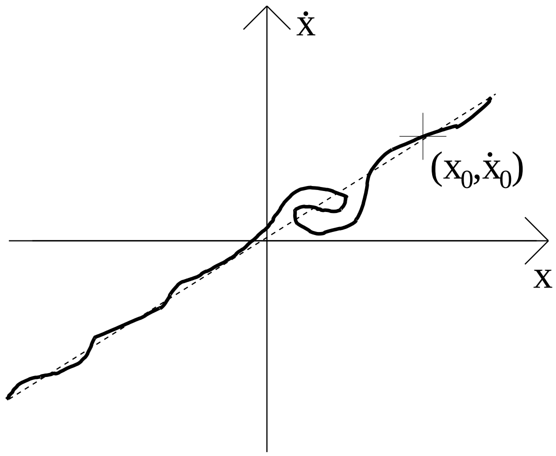


Figure 2.10: An illustration of the fine-grained phase-space structure expected for Cold Dark Matter (CDM). CDM particles are found only at positions and velocities on the thick line. Effectively they occupy a 1-dimensional subregion of this 2-dimensional phase-space (in reality this would be a 3-dimensional subspace of 6-dimensional phase-space). The thickness of the line reflects the very small initial velocity dispersion of the CDM particles. At early times when the density field is near-uniform, there is only one stream at each point. As overdensities collapse, the phase-space sheet winds up. This produces multiple streams at positions within nonlinear objects. At locations where the number of streams changes, the CDM density is very high. These are so-called caustics and are well known from geometrical optics and catastrophe theory.

to overcome substantial backgrounds and a good knowledge of the expected signal would be very helpful in isolating it. Predicting the signal requires input from two main sources: particle physics and astrophysics. Particles physics specifies the range of cross-sections and masses and astrophysics provides information on the distribution of DM particles.

Both direct and indirect detection schemes are sensitive to fine-scale features in the DM distribution. The DM is apparently cold: at early times, before nonlinear structure collapsed, its velocity dispersion at each point was very small. Evolution from such initial conditions produces streams and caustics within later nonlinear structures (see 2.10). Low stream numbers at any given location can result in a clumpy distribution of velocities, while caustics can give rise to very high local CDM densities. These features may influence the expected signal in direct and indirect detection experiments. For example, caustics might boost up the annihilation flux due to their high density.

Currently it is not clear how important these small-scale features really are. A large number of streams, for example, will result in a smooth velocity distribution with no distinct features due to individual streams. If caustics form from low-density streams, the effective boost factors may be negligible. Previous attempts to estimate these effects have been very limited, relying on highly simplified models for the DM distribution.

The main tool which modern cosmologists use to study the nonlinear regime of cosmic structure formation is direct numerical simulation. So-called N-body simulations follow the motions of a set of "particles" which can be considered as a Monte-Carlo sampling of the underlying DM distribution. Such simulations are limited by the available computing resources to a sparse sampling of the DM phase-space, and it is not possible to resolve the fine-scale structure of individual sheets and caustics at the level needed to address the DM signatures expected in current direct and indirect detection experiements. For example, the caustics in the main body of the Milky Way's halo cannot be resolved by current simulations. Even the largest so far are at least four orders of magnitude below the required particle numbers.

In order to make progress on these problems, Mark Vogelsberger, Simon White, Volker Springel (all MPA) and Amina Helmi (University of Groningen) invented a new technique which is able to resolve these structures in current state-of-the-art simulations of evolution from general CDM initial conditions. Their new method is based on evaluating the geodesic deviation equation along the trajectory of each individual DM particle. This means, in simple terms, that each particle is surrounded by a virtual cloud of close neighbors and the code follows the distortion of this small cloud as the particle moves. The density of the stream in which a particular DM particle is embedded can be calculated from the distortion tensor that describes the deformation of its virtual cloud. Whenever the particle passes through a caustic, its cloud turns inside out. This can be detected as a sign change in the determinant of the distortion tensor. This new approach allows the fine-grained phase-space structure to be studied in cosmological simulations for the first time.

This new technique has been implemented within the current version of Volker Springel's GADGET code. This task is quite straightforward since the method only requires an additional differential equation to be solved for each particle. This is the tensor differential equation that describes how the distortion tensor evolves, as driven by the gravitational tidal field. Further modifications of the simulation code make it possible to track caus-

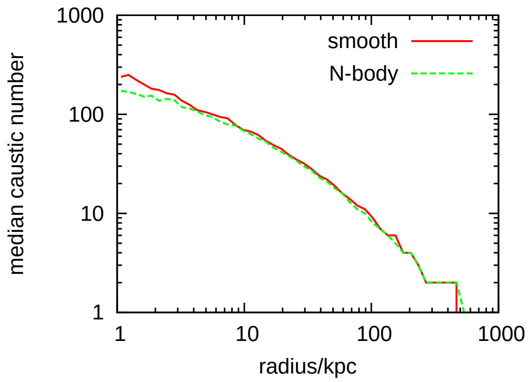


Figure 2.11: This plot shows the median number of caustics passed after a given amount of evolution by particles at each radius within a spherically symmetric model halo. The red line is calculated for test particle orbits in the exact smooth potential, whereas the green line shows results for an N-body simulation of the same system. There is excellent agreement down to the resolution limit of the simulation, demonstrating that caustics can indeed be identified robustly in a full N-body simulation.

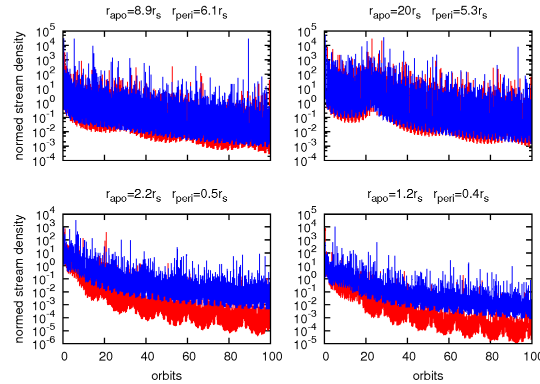


Figure 2.12: Stream density decrease for orbits in spherically symmetric (blue) and triaxial (red) NFW DM halos. The underlying halo model is a fit to profiles observed in cosmological simulations. Triaxiality leads to a more rapid stream density decrease in the inner halo where the potential is significantly non-spherical. This implies that individual streams near the Sun should have low densities, and thus that many of them are needed to make up the local halo density. As a result the local velocity distribution of DM particles should be quite smooth.

tics in a very robust way. It turns out that the identification of caustics in the DM density distribution does not suffer much from numerical artifacts. This is demonstrated in Fig. 2.11 which shows a test calculation using a spherically symmetric halo model. The median number of caustics passed after a given evolution time is plotted as a function of particle distance from halo centre. This number is higher in the inner regions where dynamical time-scales are shorter. A test particle calculation carried out in the exact, smooth gravitational potential (red) is compared to the result of the GADGET integration of the full N-body system (green). It is striking that agreement is almost perfect. Deviations show up only below the softening length of the simulation. This demonstrates that caustic identification is very robust. The stream density itself is somewhat more sensitive to numerical parameters, but a comparison between smooth and N-body integrations shows reasonable agreement here also, provided care is taken to use an appropriate softening.

A straightforward application of this method is to estimating annihilation boost factors due to caustics. Since the technique directly reveals the stream density for each particle, the intra- and inter-stream annihilation rates can be integrated up along its trajectory. Summing these rates over a given time period produces an estimate of the total annihilation flux, including that due to caustics. This can be compared to the estimate based on the local mean density (and ignoring streams and caustics) to get the boost factor. Since the caustic identification is robust, the estimated boost factors should be accurate. The technique also allows the structure of annihilation radiation images of CDM halos to be predicted.

Another application is to estimating the number of DM streams near the Sun. This is relevant for direct detection experiments on Earth. A simple model of the Milky Way's halo that takes into account its triaxial shape, can be used to demonstrate that at least 10^5 streams should pass through each point in the solar neighbourhood. This large number is a consequence of the rapid decrease in stream density as DM particles orbit within the halo. It turns out that stream densities in general decrease as $1/(t/t_{\rm orbital})^3$ (Fig. 2.12), and that some chaotic orbits are expected for which the stream density decreases even faster (quasi-exponentially). Thus a very large number of streams is required to make up the local mean halo density. Direct detection experiments should discover a smooth distribution of DM particle velocities, with no evident signals from individual streams. (Mark Vogelsberger and Simon White)

2.6 Cosmology and imaging the cosmic mass distribution

The stars and gas seen in galaxies account for only a few percent of the material in the Universe. Measurements indicate that 24% of the mass is in the form of *dark matter* – an apparently invisible form of matter never yet seen on Earth. Even stranger is the recent discovery that about 72% of the density consists of *dark energy* – an unknown material that is causing the expansion of the universe to accelerate. The natures of these two substances are the most central questions in cosmology today. Many observational techniques, telescopes and satellites have been used To study their properties and many others have been proposed for the future. We have found that perhaps the most promising method for investigating both these mysteries is through studying the gravitational lensing of radiation coming from the hydrogen atoms that existed before the first stars and galaxies formed.

As light travels to us from distant objects its path is bent slightly by the gravitational effects of the things it passes. This effect was first observed in 1919 for the light of distant stars passing close to the surface of the Sun, proving Einstein's theory of gravity to be a better description of reality than Newton's. The bending causes a detectable distortion of the images of distant galaxies analogous to the distortion of a distant scene viewed through a poor window-pane or reflected in a rippled lake. The strength of the distortion can be used to measure the strength of the gravity of the foreground objects and hence their mass. If distortion measurements are available for sufficiently many distant galaxies, these can be combined to make a map of all the foreground mass.

This technique has already produced precise measurements of the typical mass associated with foreground galaxies, as well as mass maps for a number of individual galaxy clusters. It nevertheless suffers from some fundamental limitations. Even a big telescope in space can only see a limited number of background galaxies, a maximum of about 100,000 in each patch of sky the size of the Full Moon. Measurements of about 200 galaxies must be averaged together to detect the gravitational distortion signal, so the smallest area for which the mass can be imaged is about 0.2% that of the Full Moon. The resulting pictures are unacceptably blurred and are too grainy for many purposes. For example, only the very largest lumps of matter (the biggest clusters of galaxies) can be spotted in such maps with any confidence. A second problem is that many of the distant galaxies whose distortion is measured lie in front of many of the mass lumps which one would like to map, and so are unaffected by their gravity. To make a sharp image of *all* the mass in a given direction requires more distant sources and requires many more of them. We have shown that radio emission coming to us from the epoch before the galaxies had formed can provide such sources.

About 400,000 years after the Big Bang, the Universe had cooled off sufficiently that almost all its ordinary matter turned into a diffuse, near-uniform and neutral gas of hydrogen and helium. A few hundred million years later gravity had amplified the non-uniformities to the point where the first stars and galaxies could form. Their ultraviolet light then heated the diffuse gas back up again. During this reheating and for an extended period before it, the diffuse hydrogen was hotter or cooler than the radiation left over from the Big Bang. As a result, it must have absorbed or emitted radio waves with a wavelength of 21 cm, the hyperfine transition of hydrogen. The expansion of the Universe causes this radiation to be observable today at wavelengths of 2 to 20 meters, and a number of low-frequency radio telescopes are currently being built to search for it. One of the most advanced is the Low Frequency Array (LOFAR) in the Netherlands, a project in which the Max Planck Institute for Astrophysics is taking a significant role, together with a number of other German institutions. A bit further off is the even more ambitious Square Kilometer Array (SKA) which will have higher resolution and sensitivity.

In the pregalactic hydrogen are structures of all sizes which are the precursors of galaxies, and there are up to 1000 of these structures at different distances along every line of sight. A radio telescope can separate these because structures at different distances give signals at different observed wavelengths. As a result many statistically independent maps of the hydrogen at different distances can be made. The gravitational distortions of these maps will be coherent since they are caused by the same objects in the foreground. By combining many maps of the hydrogen a three dimensional map of the foreground density distribution can be constructed. This map would contain all the matter, both dark and light.

Figures 2.14 and 2.15 show one measure of how well two proposed radio telescopes will be able to measure the foreground mass distribution. In these plots are the power spectra of fluctuations in the

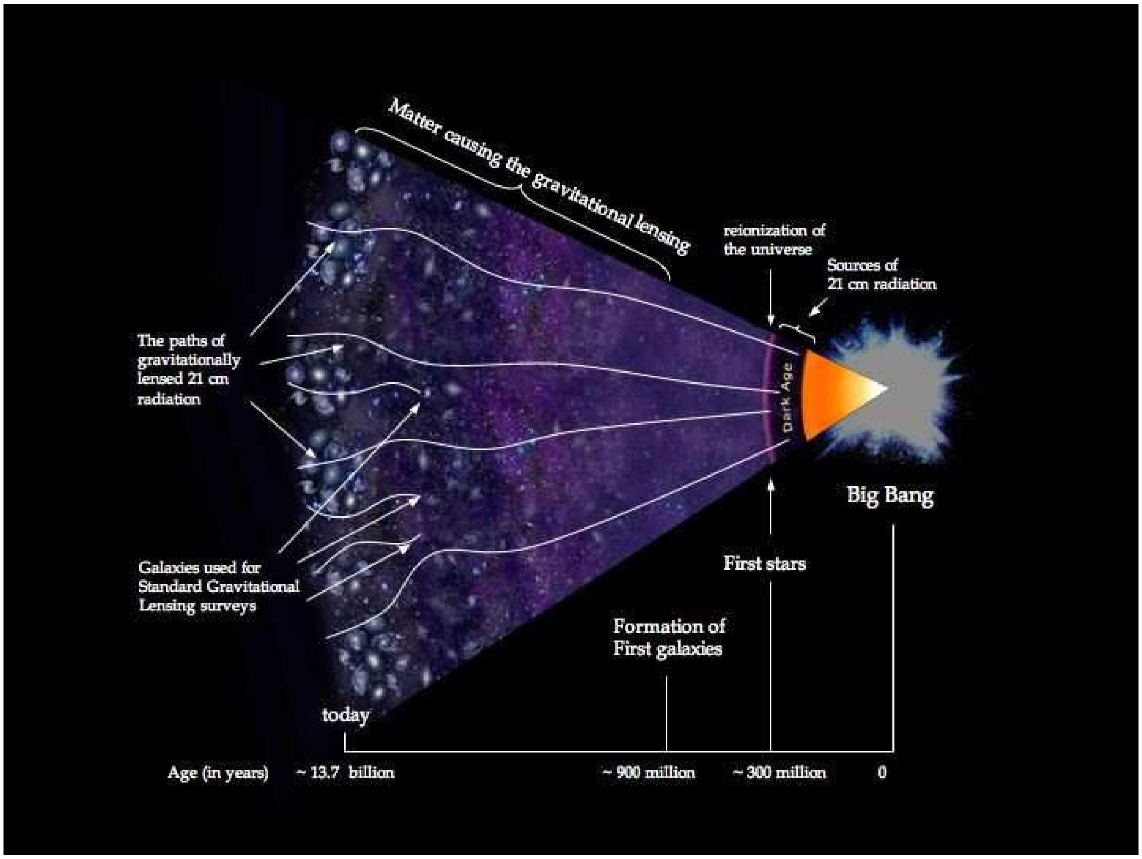


Figure 2.13: Radio telescopes will be able to observe hydrogen gas clouds just a few 100 million years after the Big Bang, before they turned into galaxies. Optical telescopes can observe galaxies as far back as a few billion years after the Big Bang. Measurements of the distortion of these images by the gravity of foreground matter allow telescopes of both types to measure the mass and even to image everything that gravitates.

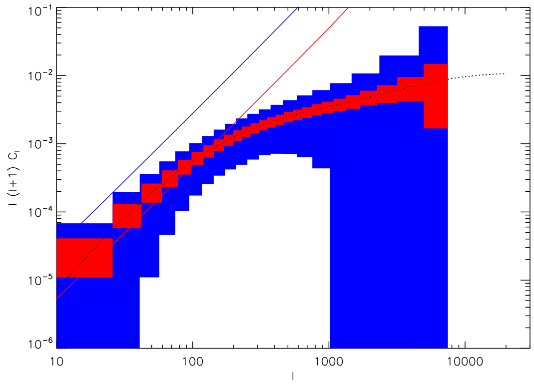


Figure 2.14: Forecasts of the 1σ uncertainties in estimates of the matter surface density power spectrum for LOFAR after 30 days of integration (blue) and after 90 days of integration (red). The dotted curve is the expected power spectrum. The surface density is in units of the critical density. The x-axis is the multipole on the sky ($l \sim 1,000$ corresponds to fluctuations on 10 arcminute scales and $l \sim 10,000$ corresponds to fluctuations on 1 arcminute scales.) We have assumed that 10% of the sky has been observed (the noise scales as (sky fraction)$^{-1/2}$). The band powers are for bins in ℓ chosen arbitrarily for display purposes. Wider bins would have smaller noise, but less resolution in l. The solid straight lines give the noise in each mode. These lines do not fall significantly below the expected signal signifying that individual modes will not be measured with signal-to-noise greater than one, but it can be seen that their statistical distribution can be well characterized.

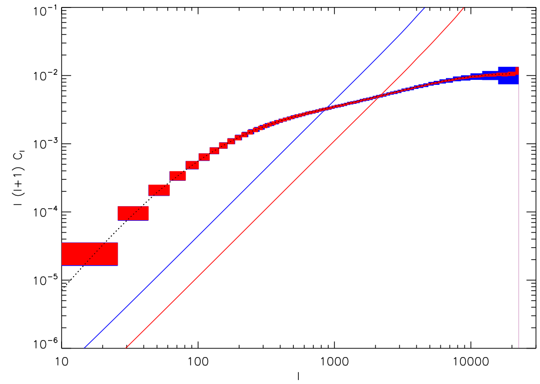


Figure 2.15: Same as in Figure 2.14 except for the SKA. The noise per mode is well below the expected signal in this case signifying that high-fidelity images of the dark matter should be possible.

surface density of mass along the line of sight and their forecasted errors. The surface density is measured in units of the "critical density" which is a function only of the average mass and energy density of the universe. LOFAR should be able to measure gravitational lensing and measure the power spectrum of density fluctuations with high signal-to-noise. SKA will have significantly higher sensitivity. The normalization and shape of the power spectrum is set by the physics of the very early Universe. In this way theories such as *inflation*, which purports to explain why the Universe is so homogeneous and how the primordial density fluctuation were seeded, can be tested precisely.

SKA should not only be able to measure the power spectrum and other statistics of the density fluctuations very accurately, but also to make high-fidelity images of the dark matter distribution with a resolution of several arcminutes. Figure 2.16 shows a simulated map of what should be possible with SKA resolution. This map was made by running light rays through the Millennium Simulation, the largest computer simulation of cosmic structure formation ever carried out. Even small fluctuations in the density are visible with high signal-to-noise. Since structure formation on these angular scales did not begin till well after the reionization epoch this represent a map of essentially all the structure that exists along this line of sight.

These measurements would also be able to measure the evolution in the expansion rate of the Universe. The expansion rate is determined by the average energy and mass density in the Universe and its evolution in time. Dark energy is a substance whose energy density diminish is less rapidly with the expansion of the Universe than that of ordinary matter. Combining SKA data with planned galaxy lensing surveys (to increase the radial resolution) would make possible more precise measurements of dark energy than any other method yet proposed. The precision with standard dark energy parameters are determined would increase by factors of 100s over present-day values.

If a really BIG radio telescope were made, an array densely covering a region about 100 km across, an object similar in mass to our own Milky Way could be detected all the way back to the time when the Universe was only 5% its present age. This telescope would be 100 times the size planned for densely covered central part of LOFAR, and about 20 times bigger than densely covered core of the Square Kilometer Array (SKA) the biggest such facility currently under discussion. Such a giant telescope could map the entire gravitating mass distribution of the Universe, providing the ultimate comparison map for images produced by other telescopes which highlight only the tiny fraction of the mass which emits radiation they can detect. This telescope could make a picture of everything that

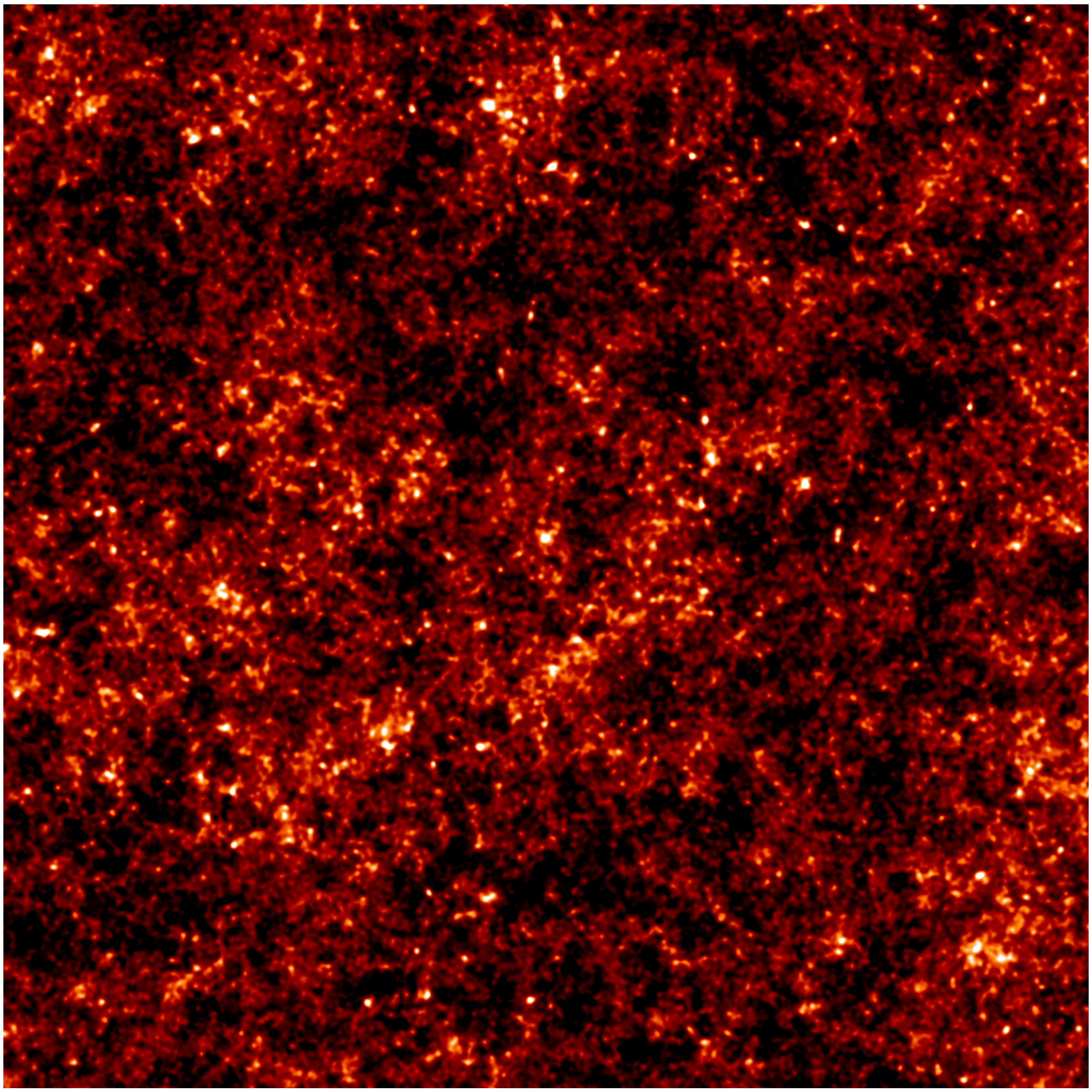


Figure 2.16: A simulated surface density map from gravitational lensing of the pregalactic 21 cm radiation. The field is 5 degrees by 5 degrees with a resolution of 1 arcminute, approximately the resolution of the core array of the proposed radio telescope SKA. The visible structures are the dark matter surrounding galaxies and galaxy clusters. This image was made by PhD student Stefan Hilbert using the Millennium Simulation.

gravitates which would rival the pictures made by optical telescopes of everything that shines. (Ben Metcalf)

2.7 The role of magnetic fields in gamma-ray burst flows

Gamma-ray bursts (GRBs) are flashes of gamma-rays distributed isotropically on the sky. There is about one burst taking place per day; it lasts for a few seconds and is followed by emission in softer energy bands, the so-called afterglow. GRBs are believed to come from catastrophic stellar events that result in the formation of stellar-mass black holes. The mechanism that powers the GRB flow remains debated 40 years after their discovery. Through previous work at MPA, however, it has become clear that their puzzling phenomenology is easier to understand if GRBs are essentially magnetically driven flows.

The afterglow emission of GRBs allows for their accurate localization in the sky, identification of the galaxies where the bursts take place and the determination of their redshift. With their large distances (typical redshifts of $\sim 2-3$), GRBs are extremely powerful cosmic explosions. During the last decade, a strong observational connection of supernovae and long-duration (lasting a few tens of seconds) GRBs has been established. Studies of the host galaxies provide further compelling evidence for the connection of long duration GRBs with the end-point of evolution 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. Both kinds of catastrophic event are believed to give birth to a black hole that is surrounded by a massive accretion disk. The black-hole-disk system is, likely, the central engine that powers these explosions.

The mechanisms responsible for the formation and the acceleration of the GRB flow remain debated. So are the dissipative and radiative mechanisms that lead to the observed radiation. If the disk is hot enough, it emits copious neutrinos. Neutrino-antineutrino annihilation in the polar region of the disk may be the dominant process that leads to the formation of a fireball, i.e. a flow initially dominated by its thermal energy. Alternatively, if powerful enough, magnetic fields can efficiently extract the rotational energy from the disk (or the black hole) launching a magnetically dominated flow. The burst of gamma rays then results from internal dissipation of energy in the flow. The energy dissipation may take place because of internal collisions of faster and slower parts of the flow (in the so-called “internal shock” picture) or dissipation of magnetic energy (in a strongly magnetized flow).

Internal shocks in unsteady flows lead to dissipation of energy at the location where the flows collide. The resulting emission depends on the location of the collision and on details of particle acceleration in the shocks. Dissipation of magnetic energy carried in the flow has a rather different effect; it leads to a more gradual energy release over a wide range of distances from the source. Dissipation of magnetic energy can take place either directly through reconnection in a flow that contains small scale field reversals or through MHD instabilities in axisymmetric flows. In the magnetic dissipation picture, the radiating particles can be continuously heated and their energy is determined by balancing heating and (radiative or adiabatic) cooling rates.

Recently, Giannios and Spruit have explored in detail the spectrum from such magnetic dissipation models with both analytical tools and radiative transfer (Monte Carlo) simulations. For typical inferred GRB parameters, dissipation takes place in both Thomson thick and Thomson thin parts of the flow. Photons that are advected with the flow are upscattered by hot electrons in the region of moderate optical depth with respect to Thomson scattering leading to powerful emission that peaks in the ~ 1 MeV energy range. Synchrotron-self-absorbed emission becomes more important at larger distance from the source and dominates in soft X-rays and softer bands. Synchrotron self absorption provides an efficient channel for energy exchange among electrons. As a result the electrons thermalize effectively (relax to a Maxwell distribution). This reduces the dependence of the model on the poorly understood mechanisms of particle acceleration that operate in the regions where magnetic energy is dissipated. The model has just a few parameters and makes rather robust predictions for the emitted spectrum. Those predictions have to be confronted with multi-frequency observations of the prompt emission that range from optical to ~ 1 MeV gamma-rays. The resulting spectrum agrees well with that of the typical GRB (Fig.2.17). The figure shows that the model predicts a large flux in the GeV range. The *GLAST* satellite, expected to be launched this Summer, will be sensitive enough to probe the $\sim$ GeV emission of the bursts and

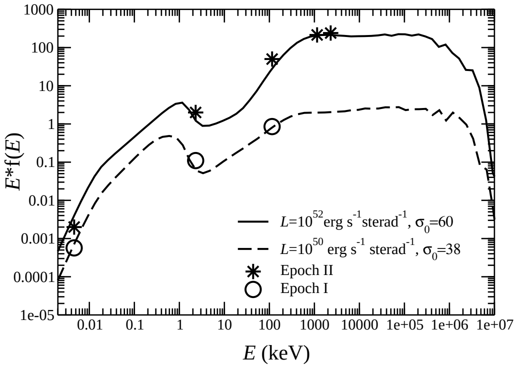


Figure 2.17: Applying the model to multi frequency observations of the prompt emission of GRB 061121. The circles stand for the observations of epoch I (just before the main pulse of the burst) and the stars for those of epoch II (during the pulse). The solid and dashed curves show spectra for two different sets of the parameters of the flow illustrating that the model can account for the broad-band prompt emission spectra.

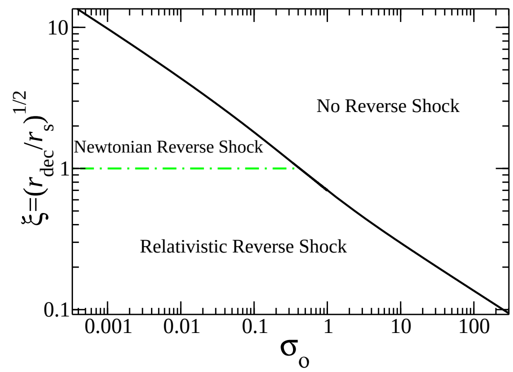


Figure 2.18: Regime of existence of a reverse shock in magnetic outflows propagating into a constant density external medium. The ξ parameterizes the strength of the reverse shock that would form in unmagnetized ejecta; its value for typical GRB parameters is $\sim$1. σ_0 stands for the Poynting-to-kinetic flux ratio of the flow at the onset of the afterglow. The lower left part with respect to the black line shows the regime where a reverse shock forms. For $\sigma_0 \gtrsim 1$ there is no reverse shock forming for a large parameter space that describes the properties of the GRB ejecta. The observed absence of emission coming from a reverse shock in the large majority of gamma-ray bursts is expected in strongly magnetized flows.

provide further tests of the model.

Additional information for the strength of the magnetic fields in the GRB flow (and, hence, hints for the mechanism responsible for the formation of the flow) can come from the study of the afterglow emission. After the acceleration and GRB emission phases, the GRB flow interacts with the external medium and slows down. This interaction is believed to give rise to the afterglow emission. The various afterglow phases have been observationally studied in detail and can probe properties of both the GRB flow and of the external (circumburst) medium.

The dynamics of the deceleration of weakly magnetized ejecta (as predicted by the fireball model) has been rather well understood. The interaction of the GRB flow with the external medium leads to the formation of a forward shock in the external medium and of a reverse shock into the ejecta. The reverse shock crosses the ejecta on a short timescale leading to a brief powerful emission episode expected in the optical band (the so-called optical flash). After the reverse crossing, the forward shock dominates the afterglow emission. Despite the extensive observations over the last decade, there is evidence for such reverse shock emission in just a few bursts. This has become a important problem for the fireball model.

In contrast to fireball models, MHD models for GRBs predict ejecta with dynamically important magnetic fields in the afterglow phases. The study of the deceleration phase of strongly magnetized ejecta is far from complete. Recently, Giannios in collaboration with Mimica and Aloy (University of Valencia) derived an analytic condition for the existence of a reverse shock and showed that even moderate magnetization can suppress it, for typical GRB parameters (see Fig.2.18). This possibly explains the observed paucity of optical flashes-signatures of a reverse shock.

We are currently working on relativistic MHD simulations to study the complete deceleration dynamics. Once the dynamics are understood, we plan to proceed by including radiative transfer in the simulations. This can be done by, for example, assuming particle acceleration at shock fronts and calculating the resulting synchrotron and inverse Compton emission. The target is to calculate afterglow lightcurves in order to quantify the observational effects of magnetization in the afterglow. (Dimitrios Giannios)

2.8 What can we learn from the cosmological recombination spectrum

Roughly 260,000 years after the Big Bang the initially fully-ionized plasma became sufficiently cold to allow the existence of neutral hydrogen atoms. By that time the temperature of the nearly isotropic Cosmic Microwave Background (CMB) blackbody radiation, which is filling the expanding Universe, had dropped to about 3800 K. The process of recombination is associated with the emission of ~ 5 photons per hydrogen atom by electrons cascading from upper levels of the hydrogen atom to its ground state. For 40 years the kinetics of cosmological hydrogen recombination has been known to be extremely unusual: due to the very small expansion rate of the Universe the escape of photons from the Lyman-α resonance was extremely inefficient. This strongly enhanced the role of the very improbable two-photon decay of the metastable 2s level to the 1s state. About 57% of all electrons in recombined hydrogen atoms reached the ground state via the 2s-1s two-photon transition. As a result, the kinetics of recombination cannot be described by the formulae for Saha-equilibrium in cooling plasmas, and recombination was strongly delayed. In addition, because of the extremely high entropy of the Universe (with about 2×10^9 photons per baryon), the primordial plasma is dominated by radiation. Therefore, unlike in stellar atmospheres, collisions of atoms with electrons and ions played a negligible role, and the populations of highly excited levels were completely defined by radiative processes, including stimulated recombination and induced emission.

Detailed computations have allowed us in collaboration with J.A. Rubiño-Martín from the Instituto de Astrofisica de Canarias (IAC) to calculate the spectrum of the recombinational radiation arising from all possible atomic transitions of hydrogen among levels with principal quantum numbers up to 100 (see Fig. 2.19). Due to the expansion of the Universe this signal is redshifted more than 1000 times, so that ultraviolet photons reach the observer in the sub-mm band today. Transitions among highly excited levels lead to photons that nowadays should appear at radio frequencies, where experimental techniques developed for the extremely successful investigations of CMB angular fluctuations have achieved unprecedented sensitivity.

For experimentalists the ratio of the com-

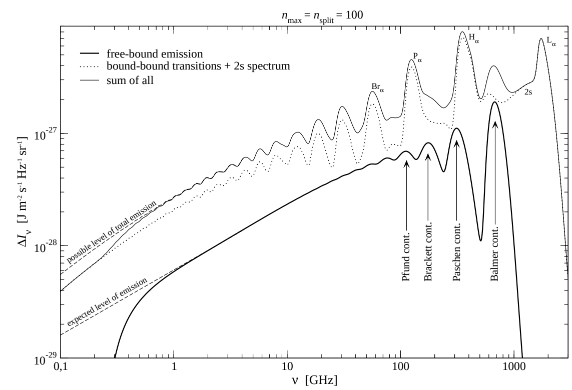


Figure 2.19: CMB spectral distortions due to cosmological hydrogen recombination. At high frequencies one can clearly see the features connected to the Lyman, Balmer, Paschen and Brackett series. At low frequencies the lines due to α-transitions among highly excited states overlap strongly. The contribution due to the 2s two-photon decay is also accounted for. The dashed lines indicate the expected level of emission when including more shells.

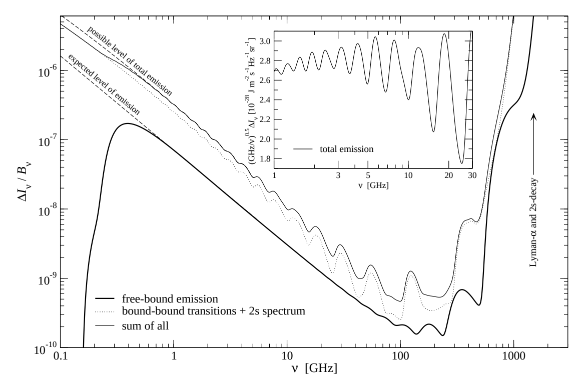


Figure 2.20: CMB spectral distortion due to hydrogen recombination relative to the CMB blackbody spectrum. The strongest distortion appears in the Wien part of the CMB blackbody spectrum and is due with the Lyman-α and 2s-1s two photon transition. At low frequencies the relative distortion exceeds the level of 10^{-7}. The inlay plot illustrates the modulation of the total emission spectrum for $1\,\mathrm{GHz} \leq \nu \leq 30\,\mathrm{GHz}$ in convenient coordinates.

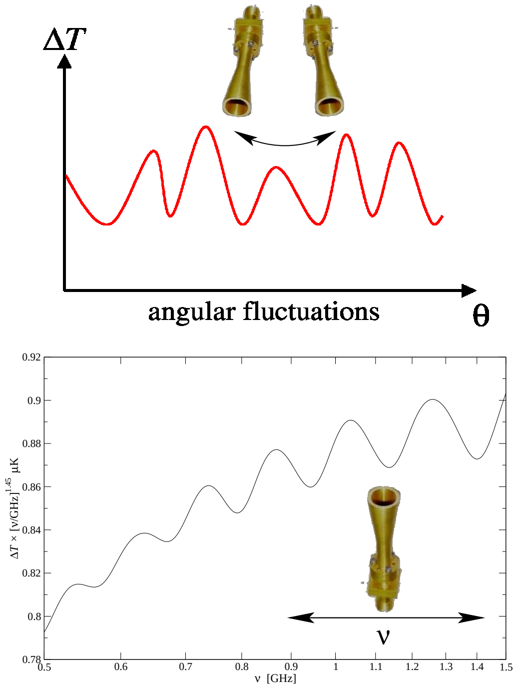


Figure 2.21: Comparison of observing strategies: top panel – observations of the CMB angular fluctuations. Here one is scanning the sky at fixed frequency in different directions. lower panel – proposed strategy for the signal from cosmological recombination. For this one may fix the observing direction, choosing a large, least contaminated part of the sky, and scan along the frequency axis instead.

puted signal relative to the intensity of the CMB blackbody radiation is more representative (see Fig. 2.20). Most likely it will be easiest to search for the distortions under discussion in the low frequency domain, just above 1.4 GHz. This is because there the contributions from the lines of distant galaxies, especially due to the 21 cm line of neutral hydrogen, is minimal. The insert of Figure 2.20 illustrates the detailed frequency dependence of the features produced during cosmological hydrogen recombination. These have a unique "pattern" which has nothing in common with other widely discussed and well-known foregrounds, or spurious instrumental signals. Using the computed "template" observers may have a chance to separate the recombinational signal from possible sources of noise.

We have recently proposed a new type of CMB experiment (see Fig. 2.21 for illustration): instead of scanning the sky at given frequency and searching for tiny angular fluctuations of the CMB temperature, one should observe a large area of the sky, scanning its radiation over frequency, and looking for the predicted characteristic spectral variability.

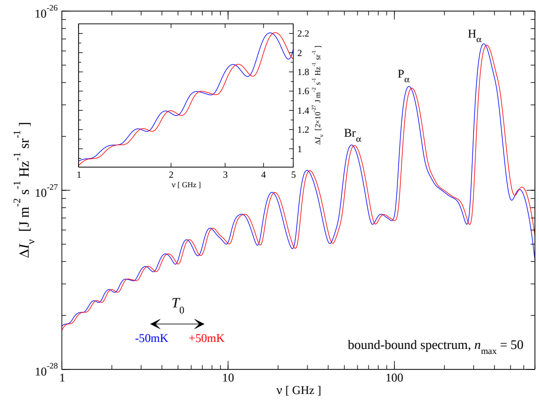


Figure 2.22: The dependence of the bound-bound hydrogen recombination spectrum on the value of T_0.

Experiments under construction in the USA to observe the CMB angular fluctuations will have sensitivities on the level of 10 nK. The spectral features under discussion have amplitudes between 30 and 50 nK. It is very important to mention that the recombinational signal should be practically the same in any direction on the sky.

The position of the spectral features on the frequency axis strongly depends on the exact value of the CMB temperature (see Fig. 2.22 for illustration). The best and only existing precise measurement of this value, as performed by the COBE/FIRAS experiment, was awarded the Nobel Prize in Physics, 2006. It is very interesting that there is a new independent method to determine the CMB monopole, and the computations carried out at MPA might offer such an opportunity. Furthermore, the intensity of the features depends on the total amount of hydrogen nuclei in our Universe, and is practically independent of the values of the other key cosmological parameters. An observation of these spectral distortions will therefore provide an additional way to measure the specific entropy of the Universe. In principle it should also be possible to reconstruct the detailed ionization history.

It is worth mentioning that the photons forming these small CMB spectral distortions were emitted mainly between redshifts $z \sim 1300$ and 1400, i.e. before recombination made the Universe transparent, defining the last scattering surface around $z \sim 1100$, at which the observed CMB angular fluctuations were formed. Therefore, a detection of the recombinational lines in the CMB spectrum will yield the final proof that hydrogen recombination has occurred as we think it has.

Turning to the contributions of helium to the

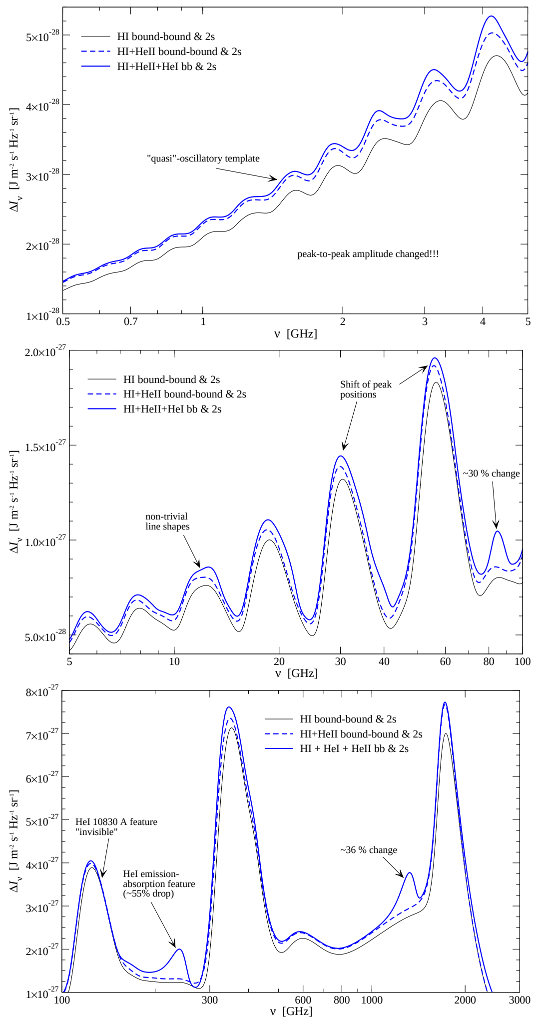


Figure 2.23: H I and He II (bound-bound) recombination spectra in different frequency bands. In the figures we also point out some of the most significant additions to the pure hydrogen recombination spectrum, which are only because of the presence of pre-stellar helium in the primordial plasma.

total cosmological recombination spectrum, we present the sum of the bound-bound emission from He II, He I and hydrogen in Fig. 2.23. The computation on neutral helium were also carried out in collaboration with J.A. Rubiño-Martín. It is important to mention that the lines from neutral helium appeared at $z \sim 2000$, while the photons from He II were released even earlier, at $z \sim 6000$.

Although the abundance of helium nuclei is only $\sim 8\%$ relative to the number of hydrogen, one can clearly see that some strong additional features appear because of the presence of helium in the early Universe. This is possible due to several reasons. First, there are two epochs of helium recombination. Then both He II and He I recombination occurs faster than hydrogen recombination, such that photons are distributed over a more narrow frequency range. And finally, neutral helium has a much more complicated spectrum, where even negative features connected with fine-structure transitions appear. All this leads to a non-trivial superposition of spectral signatures, so that the presence of neutral helium leaves distinct traces in the CMB spectrum.

Observing these signatures therefore may allow us to directly measure the primordial helium abundance well before the first appearance of stars. (J. Chluba and R.A. Sunyaev).

2.9 Dynamical formation of low-mass X-ray binaries in the bulge of Andromeda galaxy

It has been long known that the ratio of the number of low mass X-ray binaries (LMXBs) to stellar mass is $\sim$ two orders of magnitude higher in globular clusters than in the Galactic disc. With the advent of *Chandra* and *XMM-Newton*, studies of X-ray point sources in external galaxies have become possible, and have shown that also there globular clusters are especially abundant in LMXBs. This is attributed to dynamical processes, through which LMXBs are formed in close encounters of compact objects with normal stars. The most well-known of these is tidal capture of a main sequence star by a neutron star or a black hole. Collisions of compact objects with red giants and exchange reactions in the course of binary-single interactions are also important. Due to the ρ_*^2 dependence of two-body encounters on the stellar density (ρ_*) they are fre-

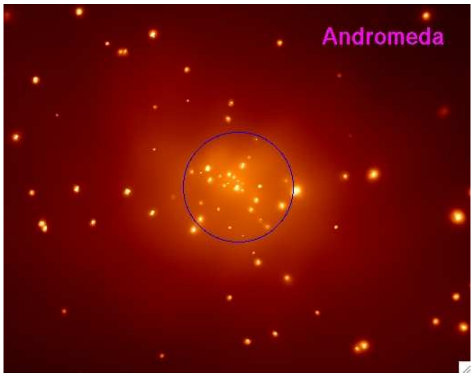


Figure 2.24: X-ray image of the inner bulge of the Andromeda galaxy in the 0.5-2 keV band obtained by Chandra. The majority of sources inside the dark blue circle (radius of 60″) are formed via tidal captures of low-mass stars by black holes and neutron stars and via collisions of the latter with red giants.

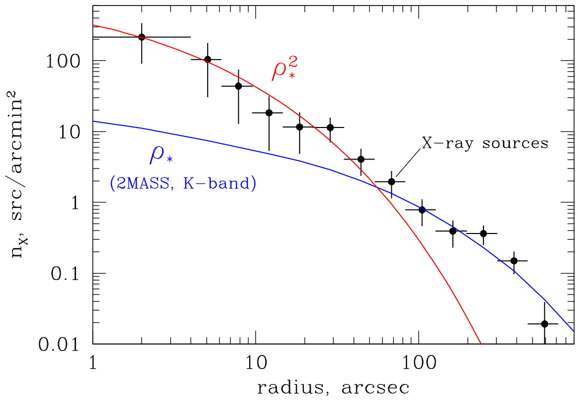


Figure 2.25: The radial distribution of compact X-ray sources in M31. Two smooth solid lines show projected distributions of stellar mass ρ_* and its square ρ_*^2.

quent in globular clusters and are negligible in the field. For example, in massive ellipticals which are usually characterized by rich globular cluster systems, as much as $\sim 2/3$ of X-ray binaries may be located in globular clusters.

In the central parts of massive galaxies, the stellar densities can reach $\sim 10^3 - 10^4$ pc^{-3}. This is still somewhat lower than the densities found in the most luminous globular clusters, where the LMXBs are preferentially found. However, the large volume compensates for the smaller density and LMXBs can be created near the galactic centers in two-body encounters in significant numbers. Due to the large stellar mass contained in the central region of a galaxy, a number of primordial LMXBs formed through the standard evolutionary path exist there too. Although these can not be easily distinguished from binaries resulting from two-body encounters, a statistical argument can be employed which has been used previously for the discovery of dynamical formation of binaries in globular clusters. The volume density of the primordial LMXBs follows the distribution of the stellar mass in a galaxy whereas the spatial distribution of the dynamically formed binaries is expected to obey the ρ_*^2/v law. Hence the latter should be expected to be much more concentrated towards the center of the host galaxy and reveal themselves as a population of "surplus" sources near its center.

M31 is the closest "full-size" spiral galaxy. At a distance of 780 kpc X-ray sources can be easily resolved with *Chandra*, even near the center of the galaxy (Fig.2.24). It has been extensively explored with Chandra. Using these data we find a significant increase of the specific frequency of X-ray sources, per unit stellar mass, within 1 arcmin from the center of the galaxy. The radial distribution of surplus sources in this region follows the ρ_*^2 law (Fig.2.25), suggesting that they are low-mass X-ray binaries formed dynamically in the dense stellar environment of the inner bulge.

While dynamical interactions in globular clusters have been investigated in the 70-ies and 80-ies, the parameter range typical of galactic centers remains unexplored. Velocities of stars are an order of magnitude higher in the bulge, changing the character of the dynamical interactions and, hence, the role of different formation channels. We have investigated dynamical formation of binaries and their further evolution to the X-ray active phase in the high stellar velocity regime. We find that X-ray binaries are formed in the bulge of a typical spiral galaxy at a rate of $\sim 50 - 100$ per Gyr. The calculations suggest that the majority of the surplus sources result from tidal captures of black holes by main sequence stars of low mass, $M_* < 0.3 M_\odot$, with some contribution of neutron star systems of same type. Because of large stellar velocities in the bulge, very compact and bright binary systems will be created, with X-ray luminosity $\log L_X > 37$ and orbital periods $\sim 1 - 2$ hours and shorter. Due to the small size of the accretion discs in such systems a large fraction of black holes may be persistent X-ray sources, in contrast to the population of mostly transient primordial black hole binaries in the Galactic disk. Some of sources will be ultra-compact X-ray binaries with helium star/white dwarf companions formed in the collisions of compact objects with red giants. We also predict a large number of faint transients within $\sim$ 1 arcmin from the M31 galactic center, both BH and NS systems. The latter may be progenitors of the accreting millisecond pulsars, similar to the famous SAX J1808.4-3658 discovered in our Galaxy ten years ago. (Marat Gilfanov & Rasmus Voss)

3 Research Activities

3.1 Stellar Physics

Stellar astrophysics continued to be a very active field of research at MPA. This includs work in the field of solar physics, the modelling of stellar interiors and atmospheres and of stellar evolution from the main sequence all the way to core-collapse and supernova explosions, both for single stars and for binaries.

Using almost ten years of data provided by GOLF, helioseismic instrument aboard the SoHO spacecraft, R. A. Garcia [CEA, Saclay] and several co-workers including J. Ballot have claimed the detection of an oscillation pattern fully compatible with solar gravity modes. Solar gravity modes are the subject of an extensive research for more than 20 years, since they are a very accurate probe of the deep solar core. The detected signal seems favor solar models with a core spining 3–5 faster than the surrounding radiative zone.

F. Kupka continued his studies on the modelling of p-mode oscillations in the Sun and in solar-like stars as part of his collaboration with K. Belkacem, M.-J. Goupil, R. Samadi [Obs. de Paris-Meudon]. They could show that the previously developed model for the excitation rates of so far p-modes, which accounts for the flow topology and fluctuations of both turbulent pressure and entropy, recovers also the observed excitation rates of α Cen A to within measurement accuracy. Also in the field of solar physics U. Anzer continued his collaboration with M. Bárta, F. Fárník, S. Gunár and P. Heinzel (all at the Astron. Inst. in Ondřejov, Czech Republic) on solar prominences. They studied the Lyman lines and continuum of hydrogen to construct models of the prominence-corona transition region and applied their modelling of prominences on the limb where both line absorption and blocking is present to new data which were obtained by the Japanese Hinode satellite. U. Anzer and P. Heinzel also addressed the question of how much the magnetic fields in prominences deviate from the state of force-free configurations.

R. Collet, R. Trampedach (ANU), and M. Asplund carried out realistic, ab initio, 3D, hydrodynamical simulations of convection at the surface of red giant stars with varying effective temperatures and metallicities ranging from solar down to [Fe/H] $= -3$. They used the simulations as time-dependent hydrodynamical model atmospheres to study the formation of spectral lines from various ions and molecules under the assumption of local thermodynamic equilibrium (LTE). The low surface temperatures encountered in 3D model atmospheres of very metal-poor giants cause spectral lines from neutral species and molecules to appear stronger than in 1D. As a consequence, elemental abundances derived from these lines using 3D models are significantly lower than predicted by 1D analyses. More specifically, Collet et al. (2007) found large negative 3D$-$1D LTE abundance corrections (typically -0.5 to -1 dex) for weak low-excitation lines from molecules and neutral species in the very low metallicity cases. G. M. De Silva (ANU), K. C. Freeman (ANU), M. Asplund, J. Bland-Hawthorn (AAO), M. S. Bessell (ANU), and R. Collet derived abundances of several key elements (Na, Mg, Si, Ca, Mn, Fe, Ni, Zr, and Ba) in a sample of twelve red giant stars belonging to the old open cluster Collinder 261 based on VLT-UVES spectra. They found that the intrinsic star-to-star abundance scatter to be very low, namely less than 0.05 dex, which allows to establish a high degree of chemical homogeneity among cluster members. This indicates that the chemical information laid down at birth has been preserved over the time evolution of this old open cluster and can therefore be used as a true tracer of star formation history in the Galactic disk.

A. J. Korn (Uppsala), F. Grundahl (Aarhus), O. Richard (Montpellier), L. Mashonkina (Russian Academy of Science, Moscow), P. S. Barklem (Uppsala), R. Collet, B. Gustafsson (Uppsala), and N. Piskunov (Uppsala) analysed a sample of 18 stars along the evolutionary sequence of the metal-poor globular cluster NGC 6397 from the main-sequence turnoff point to red giants below the bump. The spectroscopic abundance analysis revealed, for the first time, systematic trends of iron abundance with evolutionary stage. Iron is found to be 30% less abundant in the turnoff stars than in the red giants, and an abundance difference in lithium is seen between the turnoff and warm subgiant stars.

They compared the trends for various elements (Li, Mg, Ca, Ti, and Fe) with stellar structure models including the effects of atomic diffusion and radiative acceleration: such models reproduce the observed element-specific trends well, if extra +(turbulent) mixing just below the convection zone is introduced. They concluded that atomic diffusion and turbulent mixing are largely responsible for the sub-primordial stellar lithium abundances of warm halo stars.

The development of tools for asteroseismology analysis has been continued. J. Ballot has analyzed with R. A. Garcia [CEA, Saclay] methods like the backward difference filter used to remove unwanted long-term trend in seismic data. In the context of new asteroseismic missions like Kepler or current ones like CoRoT, a new international collaboration, AsteroFLAG, has been created and has been granted by the ISSI (Bern). In this new team, leaded by W. J. Chaplin [Univ. of Birmingham], J. Ballot has involved in "Hare and Hounds" exercises aiming in deriving the so-called large separation, an asteroseismic parameter especially useful to constrain the radius of a star.

A. Weiss, A. Serenelli (IAS, Princeton), M. Salaris (JMU, Liverpool), and M. Miller Bertolami (La Plata University) reinvestigated the initial–final mass relation of stars. Emphasis lay on the systematic uncertainties due to the stellar evolution models and where investigated by means of Monte Carlo simulations using various sets of models with different input physics. The results also shed light on questions like the mass loss history of low and intermediate mass stars and the amount of convective overshooting in different evolutionary stages.

Core helium flashes and their consequences were also investigated. M. Mocak, in a PhD project advised jointly by E. Müller and A. Weiss, used state of the art numerical techniques implemented in the Herakles code to study the hydrodynamic evolution of the core helium flash at its peak. He performed a set of 1D and 2D simulations in order to check whether the star can maintain the quasi-hydrostatic equilibrium, which is usually assumed in stellar evolutionary calculations. The simulations show that when allowing for energy transport by multidimensional flow a thermonuclear runaway is not encountered and that the star is not disrupted by an explosion. In order to check the validity of this finding when no symmetry assumptions are imposed 3D simulations are presently performed. V. Silva (Santiago de Chile) followed under the supervision of A. Weiss low-mass stellar models through the core helium flash, a dynamical phase is the life of stars which only few codes can follow. After the flash the stars evolve on a timescale of 1 Million years from the top of the Red Giant to the Horizontal Branch, crossing the RR Lyrae strip of pulsational instability. Though the timescale is short, some of these non-canonical RR Lyrae variables might be found in large surveys and the period changes caused by the rapid evolution might be used to test the post-flash models.

The long-term population synthesis project with P. Coelho, S. Charlot (both IAP, Paris) and G. Bruzual (Merida, Venezuela) was continued by A. Weiss with an extension of the stellar library by models with α-element enhancement and subsolar total metallicity. In addition, P. Jofré worked on estimating the age of the Milky Way halo stars. For this purpose is necessary to break the age-metallicity degeneracy and it is important to have an independent method to estimate their metallicity. SDSS data provide a large sample of low resolution stellar spectra that can be analyzed by comparing them with a grid of synthetic spectra. In collaboration with B. Panter (Royal Observatory, Edinburgh) she is developing a code based on the MOPED tool which allows an extremely fast estimation of stellar parameter for large data sets.

Compact binaries, 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. Also, 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), 8 releases (the latest as of 1 July 2007) of this catalogue have so far been issued (with the next release due 1 January 2008). Additional work on compact stars was concerned with the physics of neutron stars. R. Birkl, in a PhD project advised by E. Müller and in close collaboration with N. Stergioulas (Univ. Thessaloniki, Greece), has finished the theoretical preparation required for the numerical analysis of the influence of meridional fluid motions in stationary, axisymmetric neutron stars.

Both, observations and models of all kinds of supernovae continued to be part of MPA's activities in the past year. In the course of his PhD work, supervised by W. Hillebrandt, S. Taubenberger studied the properties of Type Ia and stripped-envelope core-collapse (CC-) supernovae. He completed the analysis of the underluminous Type Ia SN 2005bl, which differs from similar objects by the presence of conspicuous C II lines in the earliest spectra, about 6 days prior to maximum brightness. Modelling of four early-time spectra, carried out in collaboration with S. Hachinger and P. Mazzali, indicates a carbon abundance at the photosphere of several percent at the earliest phases, and in general a large amount of unburned material. Together with the low content of NSE elements, this suggests very incomplete burning, revising in parts the current picture of underluminous Type Ia SNe, and lending some support to progenitor systems or explosion mechanisms different from ordinary SNe Ia.

Following the completion of the EU RTN on "The Physics of Type Ia Supernova Explosions" P. Mazzali, F.K. Röpke, S. Benetti (INAF-OAPD, Italy) and W. Hillebrandt used the very extensive data set collected over the previous 4 years, complemented by earlier data, to extract basic information about SNe Ia and the physics of their explosion. In particular, modelling a large number of nebular-phase spectra and combining with observations obtained near the peak of the light curve, they could map the distribution of elements in the ejecta. While they confirmed the well-known relation between the mass of radioactive ^{56}Ni and the light curve decline rate, which lies at the basis of the calibration of the luminosity of SNe Ia, they showed that regardless of the amount of ^{56}Ni produced, all SNe Ia seem to synthesize a roughly constant amount of stable Fe-group elements. Interestingly, they found that a better correlation is obtained between the light curve decline rate and the total mass of nuclear statistical equilibrium (NSE) material than between the light curve decline rate and the ^{56}Ni mass alone, indicating that it is the former quantity that determines the opacity and hence the lightcurve shape. Additionally, the amount of lighter, intermediate-mass elements produced in incomplete burning is inversely proportional to the amount of NSE, suggesting that a roughly constant fraction of the star is nuclearly processed. The most straightforward explanation for these results is that all, or most SNe Ia progenitors have the same mass, likely the Chandrasekhar mass, and that the explosion probably takes the form of a delayed detonation.

The possible detection of Circum Stellar Material (CSM) near the type Ia supernova 2006X, with implications on the nature of the progenitor, was published in Science. This work, led by F. Patat (ESO), involved MPA scientists including P. Mazzali, N. Elias-Rosa and W. Hillebrandt. Also, N. Elias-Rosa, in collaboration of J.E. Beckman (IAC, Spain), S. Benetti, M. Turatto, E. Cappellaro (INAF-OAPD, Italy) and other members of the *European Supernovae Collaboration*, studied the highly extinguished type Ia supernovae 2002cv and 2006X. Both supernovae seem to obey a non-canonical extinction law, with lower values of R_V. Whether only high extinction objects behave like this is not clear yet. In addition, the average size of the dust grains along the lines-of-sight towards these supernovae was determined.

S. Hachinger finished his diploma thesis, supervised by P. A. Mazzali and W. Hillebrandt, modelling spectral properties of differently luminous SNe Ia. The most systematic changes in line strengths within a "luminosity sequence" occur in the SiII λ5972 feature. Although not theoretically understood as yet, $\mathcal{R}$(SiII), the ratio of the features at λ5972 and λ6355, has long been known as a luminosity indicator. In collaboration with M. Tanaka (Univ. Tokyo), the physics behind the spectral changes could be clarified. The increased strength of the λ5972 line at low luminosities is due to changes in ionization, while the λ6355 line is largely saturated and constant in strength.

D. Sauer in collaboration with P. Mazzali worked on the interpretation of observed supernova spectra using a fast Monte Carlo spectral synthesis code which is suitable for providing estimates of explosion parameters soon after observation. For one specific object, the type Ia supernova 2004eo which was observed by the Research Training Network on the physics of type Ia supernovae, a detailed analysis of the composition structure of the ejecta was carried out using a series of early time spectra, a nebular spectrum and the light curve. In another project the formation of the UV flux in type Ia supernovae was studied using a series of spectral models. The spectrum in the UV wavelength bands is particularly sensitive to the density structure and composition in the outer layers of the expanding ejecta and could therefore provide evidence for different explosion scenarios. Understanding this part of the spectrum can help to determine differences between nearby and distant SNIa that may affect the accuracy of cosmological distance measurements employing those objects.

S.A. Sim continued to work on the application of Monte Carlo (MC) radiative transfer methods to the study of multi-dimensional models of Type

Ia supernovae (SN Ia). Together with D.N. Sauer, F.K. Röpke and W. Hillebrandt, he studied orientation effects in supernova models where the primary products of nuclear burning are produced off-centre, as motivated by recent hydrodynamical explosion models. It was shown that viewing-angle effects in such models could lead to significant differences in light curve properties which may have ramifications for understanding aspects of the observed diversity in the SN Ia population. S.A. Sim and P.A. Mazzali studied the effect of explosion geometry on theoretical γ-ray spectra for a wide range of SN Ia toy models, including aspherical models. They showed that, in principle, the γ-ray spectrum and light curve are sensitive to the explosion geometry and that future γ-ray observations may therefore provide useful constraints. M. Kromer and S.A. Sim have began to extend their existing SN Ia MC radiative transfer code to treat three-dimensional, non-grey, non-LTE spectral synthesis in the infrared to ultraviolet wavebands. When completed, the code will allow studies of band-limited light curves and spectra for realistic explosion scenarios which will complement the existing work on bolometric light curves and γ-ray spectra.

Not only thermonuclear but also core-collapse (CC) supernovae were analysed in some detail by MPA scientists. S. Taubenberger focussed on nebular spectra of stripped-envelope CC-SNe. In collaboration with S. Valenti (ESO), he examined the profiles and Doppler shifts of the [O I] $\lambda\lambda6300, 6364$ emission lines in a sample of about 100 spectra, taken more than 100 d after the explosion when the ejecta are mostly transparent. At those phases the line profiles probe the geometry of the inner SN ejecta, providing information on the degree of asphericity of the explosion. Far more than 50% of all stripped-envelope CC-SNe exhibit significant deviations from spherical symmetry, and many of them show signs of clumpiness or one-sided explosions.

P. Mazzali continued his work on the properties of SNe Ic and their connection with GRBs, with papers on the nebular spectra of SNe 2002ap and 2006aj and on the properties of SNe 2003jd, with graduate student S. Valenti (U. Ferrara/ESO). The possible coincidence of an LBV outburst with a subsequent SN Ib explosion was reported in Nature magazine in a paper led by A. Pastorello (Belfast) and including MPA scientists (P. Mazzali). The same team offered an alternative, supernova interpretation for a burst observed in M85. This work was also published in Nature. P. Mazzali's collaboration with the Swift SN group on the X-ray and UV properties of CC SNe continued, as did his work with the Univ. of Tokyo group led by K. Nomoto, and in particular graduate student M. Tanaka, on the theoretical aspects of SNe. A 3D spectrum synthesis code is now fully developed and has been tested on exemplary cases.

On the modelling side, L. Scheck in collaboration with H.-Th. Janka and T. Foglizzo (CEA Saclay, France) has performed hydrodynamical simulations of stellar core collapse with simplified neutrino physics for studying systematically the effects of convection and the standing accretion shock instability (SASI) in the supernova core. The results show that the SASI triggers strong secondary convection supporting neutrino-driven explosions, and are consistent with an explanation of the SASI phenomenon as a consequence of an amplifying advective-acoustic cycle in the cavity between shock and neutron star. B. Müller in a PhD project, supervised by H.-Th. Janka, has continued previous work done by F.-S. Kitaura on the core-collapse and explosion of stars with O-Ne-Mg cores in spherical symmetry and two dimensions. The results of his explosion simulations with the Vertex-Prometheus code have been used as input to neutrino oscillation and nucleosynthesis studies. A. Marek and H.-Th. Janka have performed core-collapse simulations in two dimensions with sophisticated energy-dependent neutrino transport, using the Vertex-Prometheus code, and found that neutrino heating, supported by convection and the SASI, can lead to strongly aspherical explosions several hundred milliseconds second after core bounce, not only for 11 solar mass stars, but also to 15 solar mass stars.

3.2 Nuclear and Neutrino Astrophysics

Research activities included the implementation of improved inelastic neutrino-nuclei scattering rates for supernova matter, the nucleosynthesis and neutrino oscillation effects in 8–10 $M_\odot$ stars with O-Ne-Mg cores, and neutrino-antineutrino annihilation in the vicinity of black-hole/accretion-torus systems.

B. Müller, supervised in his PhD project by H.-Th. Janka, performed hydrodynamic simulations of stellar core collapse with sophisticated, energy-dependent neutrino transport, using a new, improved description of inelastic neutrino-nuclei scattering rates for supernova matter, which was provided by K. Langanke and G. Martínez-Pinedo (GSI Darmstadt, Germany). The simulations showed that the high-energy tail of the neutrino spectra emitted during the shock-breakout burst is significantly suppressed, an effect which reduces by up to 60% the detection rates of the burst neutrinos for detector materials with a high threshold energy for neutrino absorption.

H.-Th. Janka and B. Müller have analyzed the shock dynamics in O-Ne-Mg core supernovae with respect to the conditions for r-process nucleosynthesis. Their detailed explosion models fail to produce the conditions needed for the formation of high-mass r-process elements in a new scenario recently proposed by Ning, Qian, and Meyer. The shock expands too slowly to produce the high entropies and short expansion timescales assumed by them. R. Hoffman (LLNL, USA) performed nucleosynthesis calculations using data from supernova explosion models generated by the Garching group (R. Buras, B. Müller, H.-Th. Janka). In particular, he analyzed O-Ne-Mg core supernovae for their nucleosynthesis potential and demonstrated that r-process elements are not produced, also challenging the scenario proposed by Ning, Qian, and Meyer. G. Lunardini (Arizona State Univ., Tempe, USA) in collaboration with B. Müller and H.-Th. Janka, conducted an analysis of neutrino oscillation effects in O-Ne-Mg core supernovae, using explosion models from the Garching group. She demonstrated that the extremely steep density gradient that bounds the O-Ne-Mg core of stars with 8–10 solar masses leads to characteristic differences in the oscillation-modified neutrino emission compared to supernovae of more massive progenitor stars.

Finally, R. Birkl in collaboration with E. Müller and H.-Th. Janka has extended the annihilation code developed during his diploma work, which treats the annihilation of neutrinos and antineutrinos around accreting stellar black holes. The improved code is no longer limited to a collective neutrinosphere, but computes individual neutrinospheres for each neutrino by integrating the opacity along the neutrino trajectory.

3.3 Numerical Hydrodynamics

The activities of the stellar hydrodynamics group at MPA in 2007 have focussed on simulations of core collapse and thermonuclear supernovae, on studies of general relativistic collapse, on studies of magnetic flows, and on simulations of solar/stellar convection (see also the sections on Stellar Physics and on Nuclear & 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, radiation-hydrodynamics code, by extending his implicit hydrodynamics solver from two to three spatial dimensions. Together with Xin Bian, a computer science student of the Technical University of Munich staying for an internship at MPA, they have furthermore started to work on a Poisson solver to enable the solution of self-gravitating flow problems on the non-orthogonal curvilinear meshes employed by the hydrodynamics scheme. In the diploma thesis work of Fabian Miczek, which is jointly supervised by F. Roepke and K. Kifonidis, the same implicit hydrodynamics algorithm is being extended to accurately handle both compressible and incompressible flow. Low Mach-number preconditioning techniques for steady and unsteady flows are investigated for this purpose.

Within his PhD project supervised by E. Müller, N.J. Hammer began an investigation of the propagation of the shock wave formed in a core collapse supernova through the stellar envelope using three dimensional hydrodynamic simulations. Of particular interest are the developing dynamical flow structures and the resulting mixing of hydrogen and heavier elements, e.g. oxygen, nickel, etc., which are synthesized during the progenitor's thermonuclear evolution and during the explosion itself. This work extends previous studies by Kifonidis et al which were restricted to axisymmetric models.

The modeling of *thermonuclear supernova explosions* (SNe Ia) continued to be a major part of the activities of the group.

M. Fink has begun a PhD project supervised jointly by F. Röpke and W. Hillebrandt and continued his work on sub-Chandrasekhar mass SNe Ia. The robustness of these explosions comes from the geometrical amplification of the converging shock entering the WD core due to the He shell detonation. An analysis of the observable predictions showed that these models are not good candidates for normal or sub-luminous SNe Ia, as significant amounts of ^{56}Ni are found in the outer layers at high expansion velocities. This is inconsistent with near-maximum spectra.

F. Röpke (in collaboration with W. Hillebrandt, S.E. Woosley [Univ. of California, Santa Cruz], P. Mazzali, J. Niemeyer [Univ. Würzburg, Germany], W. Schmidt [Univ. Würzburg, Germany], S. Blinnikov [ITEP Moscow, Russia], S. Sim, and D. Sauer) pursued the theoretical modeling of SNe Ia, and tried to determine whether theoretical models agree with observations. This was studied in large three-dimensional simulations of the explosion process. In combination with earlier simulations, a highly resolved full-star model of the thermonuclear explosion in the turbulent deflagration model confirmed that this scenario may indeed account for observed features of weaker examples of normal SNe Ia. The unprecedented high resolution achieved in the simulation led to a self-consistent description of the propagation of the turbulent deflagration flame through the exploding white dwarf star. Shortcomings of the model in reproducing brighter and more energetic SNe Ia, however, indicate that an extension of the model is necessary in order to account for the full range of observations. A possibility is a transition from the subsonic deflagration flame propagation to a supersonic detonation in late stages of the explosion. A physically motivated hypothesis on how the transition may occur was proposed. Three dimensional simulations of the delayed detonation model incorporating this hypothetical transition showed that such a scenario is a promising candidate for explaining SNe Ia.

Several projects were concerned with the study of the *effects of relativistic gravity in core collapse*.

T. Maedler, in a PhD project jointly advised by E. Müller, J.A. Font (Univ. of Valencia, Spain) and L. Lehner (Louisina State Univ., Baton Rouge, USA), and in collaboration with J. Winicour (Univ. of Pittsburgh, USA) investigated general relativistic axisymmetric rotational core collapse using a null foliation of spacetime. This so-called characteristic approach should allow for a more accurate and numerically less noisy determination of the resulting gravitational waves (to be 'read off' at future null infinity) than by studies relying on the widely used 3+1 foliation of spacetime. He finished a spherical symmetric numerical implementation of the characteristic method including an ideal gas equation of state and a high resolution shock capturing scheme for solving the general relativistic equations of hydrodynamics. Presently he develops a full relativistic 2D of code which will be capable to solve the Einstein equations together with the relativistic hydrodynamic equations for a rotating collapsing stellar object in axisymmetry.

P. Cerdá-Durán, J.A. Font (Univ. of Valencia, Spain) and H. Dimmelmeier (Aristotle Univ. Thessaloniki, Greece) developed a new code to solve the general relativistic magneto-hydrodynamics equations in axisymmetric dynamical spacetimes. The code use the conformal flatness approximation for the spacetime, a microphysical description of matter including deleptonization effects, and state-of-the-art stellar evolution models. As a first step towards simulations of the magneto-rotational collapse of stellar cores to neutron stars, simulations in the passive magnetic field approximation were performed. These simulations demonstrate the difficulty of forming a highly magnetized proto-neutron star on a dynamic timescale, if progenitors with an astrophysically plausible (weak) magnetic field are considered. The only possibility to amplify such an initial magnetic field to a dynamically important strength on the collapse timescale is the magneto-rotational instability. A version of the code without the passive field approximation is currently being tested.

P. Cerdá-Durán is developing new techniques to extract accurate gravitational wave signatures from general relativistic core collapse simulations using two new approaches. In collaboration with G. Faye (Institut d'Astrophysique de Paris, France) a first post-Newtonian accurate quadrupole formula has been developed. Preliminary results show that the new formalism can provide very accurate signals in the case of core collapse supernovae. In ongoing work with I. Cordero-Carrión and J.M. Ibañez (both at the Univ. of Valencia, Spain) the Meudon formalism of the Einstein equations is being applied to extract waveforms from hydrodynamic simulations.

Using the well-tested and accurate 2D/3D general relativistic hydrodynamics code CoCoNuT which utilizes the conformal flatness approximation of spacetime, H. Dimmelmeier together with C. Ott (MPI für Gravitationsphysik, Golm, Germany), A. Marek, H.-T. Janka, and E. Müller studied the dynamics and the gravitational wave signal of collapsing rotating stellar cores in supernova events. Using a microphysical equation of state and an approximate description of the deleptonization they show that for a wide range of initial rotation rates and angular momentum distributions, the gravitational wave burst signals from core bounce are generic (known as Type I). They identify and quantify the influence of rotation, of the equation of state, and of the deleptonization on this result. The generic nature of the gravitational wave signal produced by rotational core collapse will facilitate a more efficient search in current and future gravitational wave detectors of interferometric and resonant type.

Studies of magnetic flows were concerned with the growth of the magneto-rotational instability (MRI), the influence of magnetic fields on the evolution of the Kelvin-Helmholtz instability, the launch of astrophysical jets, and magnetohydrodynamic phenomena in the Sun.

Using their newly developed Newtonian MHD code, M. Obergaulinger and P. Cerdá-Durán started an investigation of the growth of the MRI in post-collapse cores of core collapse supernovae by means of three dimensional local box simulations. This technique is applied widely in studies of the MRI in accretion disks to demonstrate that the MRI is able to account for the turbulence and the enhanced transport of angular momentum required for efficient accretion. Recently, on grounds of analytic estimates, the MRI has gained much attention also in supernova cores. Additionally, two dimensional global simulations emphasize this possibility. However, confirmation by well resolved 3D simulations is still lacking. Preliminary results from these simulations indicate the possibility of MRI-driven field amplification and turbulence in a subset of supernova models.

M. Obergaulinger, in a PhD project supervised jointly by M.A. Aloy and E. Müller, studied the influence of magnetic fields on the evolution of the hydromagnetic Kelvin-Helmholtz instability in neutron star mergers. Using local simulations (shear disk approach), they were able to verify the claims by Price & Rosswog, based on global SPH simulations, that the magnetic field strength can be amplified to local equipartition with the kinetic energy, corresponding to magnetic field strengths of about 10^{16} Gauss.

Magnetic fields and rotation are thought to be crucial ingredients in the process of launching astrophysical jets which are observed in objects ranging from proto-stars to quasars. Such jets, which typically extend over many orders of magnitude in length scale, are studied by means of three dimensional Newtonian MHD simulations in the PhD project of R. Moll supervised H. Spruit.

With advances in computation power and numerical methods complex magneto-hydrodynamic phenomena like those seen in sunspots are becoming accessible to realistic three dimensional MHD simulations. T. Heinemann (DAMPT, Cambridge, England), A. Nordlund (Niels Bohr Inst., Copenhagen, Denmark), G. Scharmer (Inst. for Solar Physics, Stockholm, Sweden) and H. Spruit published simulations of a small sunspot reproducing most of the observed time-dependent structure of observed spots. The results confirm a theoretical picture developed earlier by the authors (see highlight in Annual Report 2005).

Numerical simulations of *solar surface convection* have been performed with the Antares simulation code at ultra-high resolution for both the two and the three dimensional case. Due to the advanced numerics it has been possible to resolve the shear-driven turbulence in the flow underneath the smoothly looking observable surface of the solar convection zone. Acoustic energy is generated at the shearing interface between strong up- and downflows in the three dimensional case, similar to the two-dimensional one. However, the pulses and pressure fronts generated this way look clearly different. This work is performed by F. Kupka in collaboration with H. Muthsam and his co-workers [Univ. of Vienna, Austria]. A DEISA proposal has been granted to this project which provides supercomputing resources for performing simulations of solar convection at yet even higher resolution. The colleagues at the Univ. of Vienna have also shown that the numerical scheme is crucial to observe the onset of turbulence at lower resolution in two dimensions by performing an extended resolution study with different numerical methods. In three dimensions the simulations have just reached this transition region. During a visit at MPA by C. Obertscheider [Univ. of Vienna, Austria] work on accelerating the simulation code and on enhancing its portability to various types of massively parallel machines has been performed. This work preceded the high resolution simulations of solar convection in three dimensions. In collaboration with J. Ballot, changes to the microphysical input and other parts of the simulation code have been made to prepare for simulations of stars other than the Sun.

A project with interdisciplinary collaboration was granted by the German Research Foundation to F. Kupka and M. Losch (AWI Bremerhaven, Germany), which aims at simulations of diffusive and double-diffusive convection (semi-convection, thermohaline convection). F. Zaussinger, in a PhD project supervised by F. Kupka, began his work on these topics, which first requires further developments and optimizations of the Antares simulation code (in co-operation with H. Muthsam [Univ. of Vienna, Austria] and his team).

J. Ballot with A.S. Brun and S. Turck-Chieze (both at CEA, Saclay, France) continued the simulations of convective envelopes of young solar-type stars by computing models with even higher turbulence levels. Such models spinning five times faster than the Sun exhibit peculiar vacillating and localized convection. This study has shown a weak dependence of the differential rotation contrast on the rotation rate which, however, weakens noticeably the intensity of the meridional circulation.

3.4 High Energy Astrophysics

The cosmic X-ray background (CXB) is believed to be a superposition of active galactic nuclei (AGN), since at energies below several keV most of the CXB has been resolved into individual AGN. However, the peak of the CXB luminosity is around 30 keV, where 99% of the background emission remains unresolved. It remained to be demonstrated that the sum of the hard X-ray (between ten and several hundred keV) spectra of all AGN residing in a given volume of Universe is indeed compatible with the measured CXB spectrum. This has now been achieved by S. Sazonov, M. Revnivtsev, E. Churazov, R. Sunyaev and R. Krivonos using the all-sky hard X-ray surveys made with the RXTE and INTEGRAL observatories. They calculated the cumulative spectrum of the local ($z < 0.1$) AGN population in the broad energy band 3–300 keV and demonstrated that it is consistent with that of the CXB if the strong "cosmic downsizing" of AGN between redshifts z 1 and z=0 known from deep X-ray surveys happened without significant changes in the average hard X-ray spectral shape of AGN. This proves that the popular concept of the CXB being a superposition of AGN is probably correct.

A. Watts and LMU Diploma student I. Maurer developed phenomenological models of the X-ray burst process on accreting neutron stars, in order to study the factors affecting the shape of burst lightcurves. They found that simple measures of burst morphology (such as the curvature of the bolometric lightcurve) can be a robust diagnostic of ignition latitude and burning regime. The study showed that these two factors may also explain variations in the detectability of burst oscillations, brightness asymmetries seen during X-ray bursts that are often used to infer neutron star spin.

Galaxies

The X-ray telescope *eROSITA* is being developed by MPE as a part of the future Spectrum-X mission. One of the main objectives of this mission is an all-sky survey in which eROSITA will be the primary instrument. I. Prokopenko (Space Research Institute, Moscow) and M. Gilfanov investigated statistical properties of the sample of normal galaxies which will be detected in this survey. Based on the radio and K-band luminosity functions of galaxies they predicted X-ray logN-logS curves for early and late type galaxies and compared them with source counts in Chandra deep fields. Based on these curves they predicted the numbers of galaxies which will be detected in the eROSITA all-sky survey, their distribution over morphological type and distance. They also estimated numbers of ultra-luminous X-ray sources which will be detected in the survey.

Low-mass X-ray binaries form efficiently in high stellar density environment of globular clusters and galactic bulges. Close encounters of stars with compact objects naturally lead to formation of tight binaries of high X-ray luminosity, therefore a deficit of faint sources among dynamically formed LMXBs may be expected. A study of the population of X-ray sources in the inner bulge of Andromeda galaxy by R. Voss (MPE) and M. Gilfanov suggested that this may indeed be the case. Now Rasmus Voss, Zhongly Zhang (Jiao Tong University, Shanghai) and M. Gilfanov are investigating this phenomenon in more detail based on the ultra-deep (700 ksec) Chandra observation of the Centaurus A galaxy and archival data of Chandra and XMM-Newton observations of other nearby galaxies.

The spiral structure of a galaxy is a wave pattern traveling around the galaxy, and different phases of the wave are seen at optical, radio and X-ray wavelengths P. Shtykovskiy and M. Gilfanov studied manifestations of spiral structure in the X-ray band. Due to the time delay between star-formation and the peak in the population of high-mass X-ray binaries they predict an offset between spiral structure observed in the distribution of bright X-ray sources and in conventional star-formation indicators, such as H_α emission. The magnitude of this offset increases with the distance from the corotation radius, thus presenting an opportunity to study kinematics of the spiral structure in galaxies by combining X-ray, optical and FIR and UV data. They also predicted longitudinal distribution of HMXBs in the Milky Way and demonstrated that it can qualitatively explain results of the INTEGRAL observatory.

With the X-ray telescopes Chandra and XMM -Newton nearby galaxies can now be studied at a level of detail that was previously possible only for our own galaxy. In one such study, A. Bogdan and M. Gilfanov investigated the properties and origin of the unresolved X-ray emission from the bulge of M31. Using archival Chandra and XMM-Newton observations they showed that it is defined by three components: (i) Broad-band emission from a large number of faint sources – mainly accreting white dwarfs and active binaries associated with the old stellar population, similar to the Galactic Ridge X-ray emission of the Milky Way. (ii) Soft emission from ionized gas with a temperature of ~ 300 eV. The gas is significantly extended along the minor axis of the galaxy. Its morphology and physical parameters suggest that it may be outflowing in the direction perpendicular to the disk of the galaxy. (iii) Hard extended emission from spiral arms, most likely associated with young stellar objects and young stars located in the star-forming regions.

Dissipation of turbulent gas motions is a likely mechanism for the observed heating of the intracluster medium (ICM) in the cores of clusters and groups of galaxies. P. Rebusco, E. Churazov, R. Sunyaev, H. Böhringer (MPE) and W. Forman (CfA) calculated the expected width of the X-ray emission lines in galaxy clusters due to such turbulent gas motions. In the Perseus cluster the turbulent velocity required to balance radiative cooling (as derived by Rebusco et al. 2006), would imply a width of the 6.7 keV Fe line of 10-20 eV, while the pure thermal broadening contrbutes 4 eV. The radial dependence of the linewidth is sensitive to i) the radial dependence of the velocity amplitude and ii) the "directionality" of the stochastic motions (e.g. isotropic turbulence or predominantly radial gas motions). Line broadening of this magnetitude can be easily detected with the new generation of X-ray micro-calorimeters, such as the Spektr-RG calorimeter (SXC).

In a study of the complex cluster of galaxies Abell 3128, N. Werner, E. Churazov with colleagues from MPE, CfA, IKI, SRON discovered a distant cluster behind it. Their detailed study of the X-ray properties of Abell 3128 (at a redshift z = 0.06) is based on a deep (100 ks) observation with XMM-Newton. The most obvious feature of the X-ray morphology of A3128 is the presence of two X-ray peaks separated by 12'. By detecting the redshifted Fe K line, they found that the Northeast (NE) X-ray peak observed toward A3128 is a distant luminous cluster of galaxies at redshift z = 0.44. Subsequent optical spectroscopic observation of a distant radio bright galaxy in the centre of the NE X-ray peak with the Magellan telescope also revealed a redshift of z = 0.44, confirming the association of the galaxy (seems to be a cD galaxy) with the cluster seen in X-rays. The properties of the Southwest X-ray peak suggest that it is the core of a group merging with A3128 along our line of sight. The unrelaxed nature of A3128 can be attributed to its location in the high density environment of the Horologium-Reticulum supercluster.

Gamma-ray bursts

Despite the recent progress achieved in constraining the progenitors of GRBs, the physical processes and radiative mechanisms responsible for the prompt emission are poorly understood. D. Giannios and H. Spruit have used analytical tools and radiative transfer (Monte Carlo) simulations the spectrum expected from GRBs that are powered by magnetic dissipation rather than the usual hydrodynamic ('internal shock') models. For typical inferred GRB parameters, dissipation proceeds gradually, with a substantial contribution around the Thomson photosphere of the flow. Photons that are advected with the flow are upscatered by hot electrons in this region, leading to powerful emission that peaks in the observed energy range (~ 1 MeV). Synchrotron-self-absorbed emission becomes more important in the optically thin outer region of the flow; it produces radiation in soft X-rays and softer bands. The resulting spectrum agrees well with the prompt emission of a typical GRB. Overall, the model contains only few parameters. It makes rather robust predictions which can be confronted with multi-frequency observations of the prompt emission currently (or soon to be) available thanks to *Swift*, robotic telescopes and *GLAST*.

Dynamically important magnetic fields in GRB ejecta can affect the early afterglow phases in several ways. The question whether a reverse shock can form in a GRB outflow if it contains a strong magnetic field has been controversial. With P. Mimica and M. A. Aloy [both at Department of Astronomy and Astrophysics, University of Valencia] D. Giannios has revisited this question with detailed analytical and numerical calculations. The results show conclusively that even a moderately strong magnetic field can suppress the reverse shock (the shock wave traveling backwards into the GRB ejecta when it hits the interstellar environment). The reverse shock figures prominently in the standard, nonmagnetic, theories of GRBs. This theory predicts that the reverse shock produces an optical flash, which are seen only rarely, however. This points to a magnetic origin of GRBs.

The GRB central engine is expected to be neutron rich and so may be the GRB outflow. A substantial neutron component can affect the flow dynamics in a number of ways. H. Koers [University of Amsterdam] and D. Giannios calculated the high γ and neutrino emission expected from inelastic neutron-proton collisions in magnetic and nonmagnetic models for GRB flows. An important finding of the study is that in a hydrodynamic GRB outflow (a 'fireball'), the γ-rays produced lead to pair cascades with possibly observable ~GeV emission. In strongly magnetized flows, on the other hand, the first generation of pairs produced cool via synchrotron emission emitted in the ~MeV energy range. This difference might be used to discriminate between fireballs and MHD models.

Many long GRBs are observed to have faint 'precursors', short bursts of softer X-rays before the main burst, separated by quiescent period of a minute or less. Their origin is still uncertain, but they are likely to be important for understanding the nature of GRBs since precursors must be produced by a process closer to the central engine than the main burst. L.-X. Li has investigated a model in which a precursor arises from the thermal radiation which is initially trapped in the fireball and leaks out when the fireball becomes optically thin. The model can interpret the lightcurve and the spectrum of some observed precursors, and constrain the Lorentz factor of the fireball.

Because of the limited number of GRBs with available redshifts and spectra, all current investigations on the correlation among GRB variables (such as the so-called Amati relation) use burst samples spanning a large range in distance (redshift). Selection effects and possible evolution of burst properties with cosmic time can have an important influence on such results. L.-X. Li investigated this by dividing the 48 long-duration GRBs studied by Amati into four redshift groups. The result shows that the parameters in the Amati relation (between burst energy $E_{\rm iso}$ and characteristic photon energy $E_{\rm peak}$) evolve with redshift systematically and significantly. Monte Carlo simulations show that there is only a ~ 4 per cent chance that this variation is caused by the selection effect arising from the fluence limit. The conclusion is that GRB properties may evolve strongly with cosmological redshift.

The prompt emission of gamma-ray bursts is thought to be produced in internal shocks of relativistic shells emitted by the progenitor at different times, whereas the late afterglow is interpreted as the synchrotron emission of electrons swept up by the fireball expanding through the surrounding interstellar medium. The short timescale variability observed in flares superimposed on the X-ray/optical afterglow of several bursts has been interpreted as evidence for prolonged activity of the inner engine through internal shocks. Yet, it is not clear whether this applies to all the observed bursts and, in particular, whether the bursts exhibiting single gamma-ray pulses with no short timescale variability at late times should also be entirely interpreted as external shocks. C. Guidorzi (University of Milan), S.D. Vergani (Dunsink Observatory), S. Sazonov and collaborators analyzed prompt gamma-ray, early near-infrared/optical, late optical and X-ray observations of the peculiar GRB 070311 discovered by INTEGRAL. The results support a common origin for both prompt and late X-ray/optical afterglow rebrightening of GRB 070311 within the external shock scenario. The main fireball would be responsible for the prompt emission, while a second shell would produce the rebrightening when it impacts the leading blast wave in a refreshed shock.

3.5 Accretion

The origin of the hard ($\sim$ 100 keV) X-ray flux from accreting black holes is a subject of continuing debate. One of the existing models proposes that this radiation is produced at a point where the accretion flow changes its nature as it approaches the hole: from a cool, optically thick disk to a very hot, optically thin ion-supported flow (this is the so-called truncated disk model). This idea provides a coherent explanation for many observations, but has recently been challenged by the detection of an excess energy flux at about 0.5 keV, interpreted as evidence for a cool disk extending all the way to the hole. In collaboration with D. Giannios, H. Spruit and C. Dullemond, C. D'Angelo showed that, instead of proving that a cool disk extends all the way to the black hole, a soft X-ray component is in fact an intrinsic property of the truncated disk configuration. It originates in the region of overlap between the cool outer disk and the ion-supported flow. The predicted spectrum of this component fits the soft X-ray observations better than an extended cool disk model.

Recent observations of black hole binaries, particularly GX 339-4 and Swift J1753.5–0127, indicate the presence of cool matter in the close vicinity of the central object during the low hard spectral state. This seems to contradict the commonly accepted picture of the accretion geometry during phases of low accretion, a truncated outer disk and an advection-dominated hot flow in the inner region. The existence of a weak condensation-fed inner cool disk allows to understand the new observations. F. Meyer, E. Meyer-Hofmeister, B.F. Liu (National Astronomical Observatories, CAS, Kunming, China), and R.E. Taam (Northwestern University, Evanston, USA) derived estimates for the mass flow rates for which condensation can occur, in agreement with the luminosities observed. Compton cooling is an important ingredient of the condensation process.

F. Meyer, E. Meyer-Hofmeister, in collaboration with V. Burwitz (MPE) and F.K. Liu (Peking University, China), determined the structure of the thermal boundary layer between accreting coronal gas and the surface of the white dwarf in VW Hydri using a model description worked out earlier. A comparison of computed spectra with the now available XMM-Newton EPIC spectra lead to the surprising conclusion that heat conduction in this layer is very low. This points to isolating magnetic fields as the cause of the low conductivity and might indicate the formation of magnetically supported cooling filaments and spots.

The galaxy contains a few binaries consisting of two neutron stars orbiting each other. Their orbit shrinks by the emission of gravitational waves, as predicted by general relativity. The final coalescence of the stars through this process is one of the most promising candidates for gravitational waves detectable in the near future, as well as the leading candidate for the 'short' class of Gamma-ray bursts. R. Oechslin and H.-Th. Janka performed relativistic simulations of such mergers and discovered that the gravitational-wave signature from the merger and early post-merging phases can be characterized by three measurable parameters, whose values correlate strongly with the still incompletely known properties of the neutron star equation of state. This finding shows new perspectives how future gravitational-wave detections from neutron star mergers could help to constrain the nuclear physics at extreme conditions.

A. Watts, B. Krishnan (MPG/AEI Golm), B.F. Schutz (MPG/AEI Golm) and L. Bildsten (KITP/UCSB) completed a comprehensive assessment of the prospects for detecting gravitational waves from accreting neutron stars. Many neutron stars in binaries spin more slowly might be expected from naive estimates of accretion-induced spin-up, and angular momentum losses due to gravitational wave emission had been suggested as one means of limiting spin. Initial estimates of detectability looked promising for the current generation of detectors such as LIGO and GEO. The new assessment, which takes into account the effects of parameter uncertainty, shows that detection is likely to be extremely challenging even under optimistic assumptions. The study outlines the key developments necessary to improve these prospects.

3.6 Interaction of radiation with matter

Numerous physical problems require a detailed understanding of the radiative transfer of photons into different environments, ranging from intergalactic and interstellar medium to stellar or planetary atmospheres. The full solution of the seven dimensional radiative transfer equation is still beyond our computational capabilities. For this reason, an increasing effort has been devoted to the development of radiative transfer codes. An on-going effort by A. Maselli and B. Ciardi is further developing the radiative transfer code CRASH. Lately, an implementation of scattering of Ly_α photons (M. Pierleoni, A. Maselli, B. Ciardi) and of molecular hydrogen physics (A. Maselli, B. Ciardi, A. Kanekar, India) has been added.

X. Sun (MPIfR), W. Reich(MPIfR), A. Waelkens and T. Enßlin confronted synchrotron observations of the Galactic magnetic field with simulations done using the Hammurabi code developed at MPA. The existing models of Galactic magnetic fields available in the literature are usually tuned to fit only one type of observational data (e.g. the WMAP polarization data). In this project they were confronted with other types of observations which also trace the Galactic magnetic field (e.g. Faraday rotation), and shown to be unable to reproduce such data. Therefore, a new model for the Galactic magnetic fields was developed, using physical insight to fix the model parameters. This model is simultaneously consistent with many of the different available data sets spanning radio-synchrotron polarimetric data to extra-galactic Faraday rotation maps.

In related work using a blind but more systematic parameter space search method, Ronnie Jansson (NYU), Glennys Farrar (NYU), Andre Waelkens and Torsten Ensslin performed a parameter study for known Galactic magnetic field models, finding a high degree of degeneracy when estimating parameters.

3.7 Galaxy formation and Intergalactic Medium

G. Kauffmann, T. Heckman (JHU, Baltimore) and P. Best (Edinburgh) studied the subset of radio AGN with emission lines in the Sloan Digital Sky Survey. The majority of nearby radio galaxies are found in giant elliptical galaxies with old stellar populations and harbour black holes that are not strongly accreting. At high redshifts, however, the radio galaxy population is very different: their host galaxies are disturbed, contain young stars and are accreting at rates close to Eddington. Those nearby radio AGN which have actively accreting black holes can help clarify why the nature of radio galaxies changes with epoch. The main conclusion of the study is that nearby radio galaxies with active black holes are located in galaxies with young stellar populations that reside in denser-than-average environments. They thus may be triggered by simultaneous accretion of both cold and hot gas. These conditions are likely to be more common at higher redshifts.

R. Overzier (JHU,Baltimore), T. Heckman (JHU, Baltimore) and G. Kauffmann studied the HST morphologies of local analogues of Lyman Break Galaxies observed at high redshifts. The work used quantitative tests to demonstrate that the morphologies of the nearby systems are very similar to those of their high-z cousins. Faint tidal features or companions were found in all of the rest-frame optical images, suggesting that the starbursts in these systems are the result of a merger or interaction. The UV/optical light is dominated by unresolved (100-300 pc) super starburst regions. The small-scale structural features revealed by the new HST images are not detectable in images of high redshift LBGs, except in a few cases where they are magnified by gravitational lensing. These local systems thus provide detailed insight into the nature of the interstellar medium in high redshift galaxies and the physical processes responsible for triggering their star formation.

L. Wang, C. Li, G. Kauffman and G. De Lucia extended their previous physically based halo occupation distribution models to include the dependence of clustering on the spectral energy distributions of galaxies. The high-resolution Millennium Simulation was used to specify the positions and the velocities of the model galaxies. The stellar mass of a galaxy is assumed to depend only on the halo mass when the galaxy was last the central dominant object of its halo. Star formation histories were parametrized using the formation time of the galaxy and the time when it first becomes a satellite. By fitting these models to Sloan Digital Sky Survey data, constraints on the star formation history as a function of galaxy stellar mass were obtained. Central galaxies with large stellar masses have ceased forming stars. At low stellar masses, central galaxies display a wide range of different star formation histories, with a significant fraction experiencing recent starbursts. Satellite galaxies of all masses have declining star formation rates, with e-folding times ~ 2.5 Gyr.

D. Sijacki, as part of her PhD work supervised by V. Springel, implemented new cosmological hydrodynamical simulations of structure formation that self-consistently follow the build up of galaxies and their supermassive black holes. The model tracks the growth of initial seed black holes at the centers of galaxies by gas accretion and mergers with other black holes. For black holes that are active, two distinct modes of feedback are implemented, depending on the black hole accretion rate. Black holes that accrete at high rates are assumed to be in a 'quasar regime' and provide local thermal feedback with low efficiency. For black holes with low accretion rates, the model conjectures that most of the feedback occurs in an efficient mechanical form, corresponding to the activity of radio galaxies. This is implemented through the injection of AGN-driven bubbles. In a collaboration with T. Di Matteo (Carnegie-Mellon University) and L. Hernquist (Harvard-CfA), D. Sijacki and V. Springel applied the model to 'zoom' simulations of the formation of clusters of galaxies, and to cosmological boxes. They found that the model matches observational constraints on the black hole and stellar mass densities. AGN feedback significantly influences the evolution of galaxies by changing their star formation histories, their colours and the amount of cold gas they contain. Clusters of galaxies show shallower metallicity and entropy profiles, and much reduced or absent cooling flows. This supports the conjecture that AGN at the centers of clusters are critical for understanding the thermodynamic structure of the intracluster medium.

In the new 'Aquarius' project of the Virgo consortium, V. Springel, S.D.M. White, in collaboration with A. Jenkins, C.S. Frenk (Durham), J. Navarro (U. of Massachusetts) and A. Helmi (Groningen), have carried out new ultra-highly resolved simulations of Milky Way sized dark matter halos. A small sample of target halos was studied with a variety of different numerical resolutions using the new code GADGET-3. The largest simulation improves on previously published simulations by a factor of 15 in resolution. This work will allow development of new strategies for exploring the formation of our Galaxy, for searching for signals from dark matter annihilation, and for designing experiments for direct detection of dark matter. Current results demonstrate better convergence for the properties of dark matter substructures than previously reported in the literature. Also, for the first time, the central dark matter density cusp is reliably probed into a regime where the local logarithmic slope becomes shallower than -1.

J.S Bolton and M.G. Haehnelt (IoA) used detailed simulations of the intergalactic medium (IGM) to examine the implications of the observed Lyman-alpha forest opacity at $z \geq 5$ for the nature and duration of the hydrogen reionisation epoch. The main conclusion was that the completion of reionisation at or before z=6 requires an ionising emissivity which rises towards higher redshifts or one which remains constant but is dominated by sources with a rather hard spectral index.

J.S Bolton and M.G. Haehnelt (IoA) also used a cosmological radiative transfer implementation combined with IGM density distributions drawn from hydrodynamical structure formation simulations to model the spectra of quasars at $z > 6$. These high redshift quasar spectra exhibit 'highly ionised near-zones' – regions of transmission immediately blueward of the quasar emission redshift – which are thought to correspond to a region of enhanced ionisation in the IGM surrounding the quasar. Using a future sample of several tens of high resolution quasar spectra, the ratio of the Lyman-alpha to Lyman-beta near-zone sizes could be used to distinguish between an IGM which has a volume weighted neutral hydrogen fraction greater or less than 10 per cent.

J.S Bolton, with J.S.B. Wyithe (Melbourne) and M.G. Haehnelt (IoA), used a semi-analytical model combined with numerical radiative transfer simulations to predict the evolution of the ionisation state of the IGM in the dense, biased regions around high redshift quasars as well as more typical regions in the IGM. The model simultaneously reproduces the observed Lyman-alpha forest opacity at $4 < z < 6$, the ionising photon mean free path at $z \sim 4$ and the rapid evolution of highly ionised near-zone sizes around high redshift quasars at $5.8 < z < 6.4$.

J.S. Bolton, with T.-S. Kim (Potsdam), M. Viel (Trieste), M.G. Haehnelt (IoA) and R.F Carswell (IoA) presented new measurements of the Lyman-alpha forest flux probability distribution function (PDF) at $1.8 < z < 3.2$ from a sample of 18 high resolution, high signal-to-noise quasar spectra obtained with VLT/UVES. The metal contamination, continuum placement and noise properties of the spectra were carefully analysed, enabling an improved measurement of the flux PDF to be made. The measurements will be extremely useful for constraining the various cosmological and astrophysical parameters responsible for producing the observed flux distribution of the Lyman-alpha forest. The data has been made publicly available for this purpose.

J.S. Bolton, M. Viel (Trieste), T.-S. Kim (Potsdam), M.G. Haehnelt (IoA) and R.F. Carswell (IoA) also compared the new measurements of the Lyman-alpha forest flux PDF to a large suite of hydrodynamical simulations of the Lyman-alpha forest with different cosmological parameters and thermal histories. The simulations are in good agreement with the observational data if the voids in the IGM are hotter than is usually assumed. The thermal state of the low density IGM at $z \sim 3$ may therefore be significantly more complex than previously thought. Radiative transfer effects which alter the spectral shape of ionising radiation during the epoch of helium reionisation provide a possible physical mechanism for producing this additional heating.

S. Bonoli (under supervision of V. Springel and S. White) studied the co-evolution of galaxies and their central supermassive black holes (SMBHs) using semi-analytic models of galaxy formation applied to the outputs of the Millennium Simulation. A model for the build-up of SMBHs by accretion and galaxy mergers, similar to those implemented in previous semi-analytic models of galaxy formation, was implemented and different theoretical models for the quasar lightcurve of individual accretion events, and for the dependence of the lifetime on black hole mass were investigated. The models were used to predict the observed luminosity function of active galactic nuclei as a function of redshift. S. Bonoli, V. Springel, in collaboration with F. Marulli (University of Bologna), found that this standard model for quasar growth is in broad agreement with observations, but has difficulty to explain the number density of luminous AGN observed at high redshifts.

D. Schiminovich (Columbia), B. Catinella, G. Kauffmann and other collaborators at various institutions planned and proposed the GALEX Arecibo SDSS Survey (GASS). This survey, to be carried out with the Arecibo radio telescope, is designed to measure the neutral hydrogen content of a representative sample of massive, *green valley* galaxies, uniformly selected from the SDSS spectroscopic and GALEX imaging surveys. It is well known that galaxies appear to divide into two distinct families, red and old elliptical galaxies and bluer and star-forming spirals. This bimodality is best seen in color-magnitude diagrams when UV-to-optical colors are used. However, the transition from the blue cloud to the red sequence (i.e., the *green valley*) is less understood. In fact, detailed information about a crucial ingredient in this picture, i.e. the HI content of transition objects, is largely missing from current studies. GASS will produce the first statistically significant sample of massive transition galaxies with homogeneously measured stellar masses, star formation rates and gas properties. The proposal for GASS was submitted in June 2007 and approved three months later. The Arecibo observations are expected to start in early 2008. More information (including the complete list of collaborators) can be found on the GASS web site (*http://www.mpa-garching.mpg.de/GASS*).

In collaboration with D. Zaritsky (University of Arizona), D. Christlein has continued a multi-year project studying the kinematics, surface brightness, and metallicities of the outer disks of nearby disk galaxies using deep optical spectroscopy. Kinematics are disk-like with no break in the rotation curve or increase in the velocity dispersion, but in individual cases, interesting kinematic anomalies, such as gas on non-circular orbits and a kinematically hot second disk component, were found. This may tentatively be interpreted as indications of interactions of the outer disk with material of external origin.

In collaboration with Eric Gawiser (Rutgers), Danilo Marchesini (Yale) and Nelson Padilla (Pontifícia Universidad Católica de Chile), D. Christlein continued to develop the *Photometric Maximum Likelihood Method*, a method for recovering galaxy luminosity functions from multi-band photometric surveys that does not require the calculation of photometric redshifts. This method is being applied to the MUSYC survey to constrain the faint end of the field LF at low redshift, and preliminary results point to a faint-end excess of dwarf galaxies over the extrapolation of the bright-end Schechter function.

The role of very massive, metal-free stars in the first stages of reionization is a highly controversial issue.. B. Ciardi, in collaboration with R. Schneider (Florence, Italy), used numerical simulations with the code PINOCCHIO to study 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 and studied the impact of this transition on reionization. U. Maio, B. Ciardi, K. Dolag and L. Tornatore (Trieste, Italy) are now studying the same transition using GADGET simulations of the early stages of galaxy formation, when very low mass objects, whose formation depends on the presence of molecular hydrogen and deuterium, become important.

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, in collaboration with R. Salvaterra (Milano, Italy), has studied the conditions for IGM heating by Lyα to be effective in rendering the 21 cm line visible in emission, finding that this is possible at $z < 15$. B. Ciardi is also collaborating with the LOFAR Epoch of Reionization Team (Netherlands) to model quantities that will be observed in the next decade by telescopes presently under construction in the Netherlands and other European countries including Germany.

D. Docenko and R.A. Sunyaev studied the hyperfine structure line of the hydrogen-like ion of nitrogen and demonstrated that it is strong enough to probe the warm-hot intergalactic medium. The line probes regions of this medium having temperatures about 10^6 K, that are at present impossible to study by any other means. Detection of this absorption line will open a new way to investigate the elusive warm-hot intergalactic medium.

E. Donoso, G. Kauffmann and P. Best (Royal Observatory Edinburgh, UK) compiled a sample of radio-loud AGN at intermediate redshifts ($0.4 < z < 0.8$) using a large catalog of luminous red galaxies (LRGs) selected from the Sloan Digital Sky Survey. These galaxies were cross-correlated with the Faint Images of the Radio Sky at Twenty-Centimeters (FIRST) and the NRAO VLA Sky Survey (NVSS). New techniques were developed for extending the cross-correlation algorithm to FIRST detections that are below the nominal 1 mJy S/N limit of the catalogued sources. The matching criteria were tested and refined using Monte-Carlo simulations, estimating an overall reliability of ∼98.3%. The resulting sample of 14,635 radio-loud AGN with median redshift $z = 0.55$ will be used to study the properties of radio AGN and their host galaxies.

D. Gadotti finished a series of tests on parametric decomposition of galaxy images, suggesting that bars can make a significant contribution to the stellar mass budget in the local universe. These tests also indicate to what extent one can rely on such technique in the study of both local and more distant galaxies.

Galaxy growth in the concordance ΛCDM cosmology

Q. Guo and S. White used galaxy and dark halo data from the public database of the Millennium Simulation to study the growth of galaxies. The stellar masses of galaxies increases through three processes: major mergers, the accretion of smaller satellite systems, and star formation. It was found that the relative importance of these three modes is a strong function of stellar mass and a weak function of redshift. For galaxies significantly less massive than the Milky Way, star formation dominates the growth at all epochs, but for more massive galaxies, growth through mergers is the dominant process at all epochs. At all stellar masses, the growth rates through star formation increase rapidly with increasing redshift.

C. Li, G. Kauffmann, T. Heckman (JHU, Baltimore), S. White and Y. P. Jing (SHAO, Shanghai) explored the connection between galaxy interactions and enhanced star formation by applying a variety of statistics to a complete sample of 10^5 star-forming galaxies drawn from the SDSS. It was shown that specific star formation rates of galaxies are higher if they have close companions. This was interpreted as the signature of enhanced star formation induced by tidal interactions that were confirmed to be the dominant trigger of enhanced star formation in the most strongly star-forming systems. The group has extended this study by applying exactly the same techniques to AGN in the survey, and showed that close companions are not associated with any similar enhancement of nuclear activity. Star formation is enhanced in AGN with close neighbours in exactly the same way as in inactive galaxies, but the accretion rate onto the black hole is not influenced by the presence or absence of companion. It was concluded that star formation induced by a close companion and star formation associated with black hole accretion are distinct events. These events may be part of the same physical process, for example a merger, provided they are separated in time. In this case, accretion onto the black hole and its associated star formation would occur only after the two interacting galaxies have merged.

A. Maselli, S. Gallerani (SISSA, Trieste), A.Ferrara (SISSA, Trieste) and T. R. Choudhury (IoA, Cambridge) investigated the possibility of constraining the mean neutral hydrogen fraction of the IGM from quasar spectra characterized by a detected Gunn-Peterson trough. Combined SPH and radiative transfer simulations were performed to study the properties of high-redshift quasar HII regions at $z \approx 6$ in a partially ionized intergalactic medium. The impact of the quasar ionizing flux on its absorption spectrum was estimated by extractin, synthetic Lyman-α absorption spectra from the simulation outputs and comparing these with observational data. The extent of spectral region with transmitted flux detected between the quasar redshift and the onset of the GP trough was found to underestimate the actual extent of the quasar HII region. These results agree with an independent study by Bolton and Haenhelt. The conclusion of the study resides is that the transmitted flux close to the quasar redshift in $z \approx 6$ cannot be used as a measure of the ionization state of the intergalactic medium, as was suggested in previous studies. A novel approach for the data analysis is required.

V. Wild and G. Kauffmann (in collaboration with T. Heckman [JHU]), used new optical spectral indices applied to local galaxies in the Sloan Digital Sky Survey to study the recent star formation history of bulges hosting Active Galactic Nuclei. They concluded that galaxy bulges which are undergoing or have recently undergone a starburst host black holes with higher mean accretion rates. However, the majority of black hole growth in the local Universe occurs in galaxies with bulges showing unspectacular recent star formation histories.

V. Wild (in collaboration with P. Hewett [IoA, Cambridge]) investigated the host galaxy properties of CaII absorption line systems at z 1. They used K-band imaging of 30 QSO fields to show that the CaII absorber host galaxies are relatively luminous and at large impact parameters (tens of kpc) from the absorbing gas itself. This is in conflict with suggestions that these dusty, metal rich absorbers are caused by galaxy disks.

C. Scannapieco, P.B. Tissera (Institute for Astronomy and Space Physics, Buenos Aires), S.D.M. White and V. Springel used numerical cosmological simulations to study the effects of supernova feedback on the formation of galactic disks. The injection of energy into the interstellar medium strongly affects the evolution of the galaxies, generating a self-regulated cycle for the star formation activity and triggering important mass-loaded galactic winds. As a result, the galaxies are able to form young stellar disk-like components under rotational support, in addition to old spheroids dominated by velocity dispersion. Small galaxies are more strongly affected by supernova feedback, lose most of their gas content in winds and are unable to form large stellar systems.

K. Dolag, together with S. Borgani and D. Fabjan (Dip. Astro. Trieste) and L. Tornatore (SISSA, Trieste) studied the process of metal enrichment of the intra-cluster medium. Metal release from Type II supernovae (SNII), Type Ia supernovae (SNIa) and asymptotic giant branch (AGB) stars was tracked by properly accounting for the lifetimes of stars of different mass. The effects of changing the stellar initial mass function (IMF), the lifetime function and the stellar yields were investigated. It was found that the distribution of metals produced by SNII is more clumpy than for the products of low-mass stars because A standard Salpeter IMF produces a radial profile of iron out to half the virial radius that is in fairly good agreement with observations.

3.8 Large scale structure, Dark Matter and Gravitational Lensing

J.S. Bolton, with M.Viel (Trieste) G.D. Becker (Caltech), M.G. Haehnelt (IoA), M. Rauch (Carnegie) and W.L.W. Sargent (Caltech), used simulations of the Lyman-alpha forest combined with 55 high resolution Lyman-alpha forest spectra at $2 < z < 6.4$ obtained with Keck/HIRES to place lower limits on the mass of candidate warm dark matter particles. From the HIRES data, lower limits of $m_{\rm WDM} \geq 1.2$ keV and $m_{\rm WDM} \geq 5.6$ keV were obtained if the warm dark matter consists of early decoupled thermal relics or sterile neutrinos, respectively. This result improves previous constraints by a factor of two. The small scale matter power spectrum probed by the high resolution, high redshift HIRES data was instrumental for this improvement.

J. Wang, G. De Lucia, M. Kitzbichler, and S. White have combined N-body simulations of the structure growth with semi-analytic models of galaxy formation in order to study how the shift in best-fit cosmological parametres between the first and third-year results from the Wilkinson Microwave Anisotropy Probe affects the quantities predicted by the models. The study shows that structure formation is significantly delayed in the WMAP3 cosmology, because the initial matter fluctuation amplitude is lower on the relevant scales. The decrease in dark matter clustering however, is almost entirely offset by an increase in halo bias, so predictions for galaxy clustering are barely altered. In both cosmologies, several combinations of physical parameters can reproduce the observed properties of low redshift galaxies, while model predictions diverge more dramatically at high redshift. Better observational data at high redshifts will better constrain galaxy formation models.

The control and characterization of stochastic and systematic effects is neceesary in order to serive accurate cosmological information from large galaxy surveys. Francisco S. Kitaura and Torsten Enßlin developed an accurate and high-performance reconstruction technique, called **A**lgorithm for the **R**econstruction of the **G**alaxy-traced **O**verdensities (ARGO), to translate galaxy catalogs into reconstructed dark matter density fields ARGO allows one to efficiently create many maps of the underlying dark matter density field and to sample the joint probability of the density field, the power spectrum and the cosmological parameters. Jens Jasche and Francisco S. Kitaura have used ARGO to estimate the joint probability of the cosmic matter field and its power spectrum.

M. Grossi and V. Springel investigated the formation of dark matter halos in a class of early dark energy cosmologies recently proposed by Wetterich. They carried out a set of high-resolution cosmological simulations with a modified version of the GADGET code in order to follow the evolution of structures in the non-linear regime in a number of different dark energy cosmologies. The new simulation set allowed them to carry out precise measurements of fundamental statistical quantities that characterize the distribution of dark matter, such as halo mass function, mass power spectrum, and structural properties of halos such as concentration and substructure content. Interestingly, they found that the Sheth and Tormen formalism to estimate the abundance of dark matter halos continues to work very well in early dark energy cosmologies without modifications of the assumed viriral overdensity or linear density collapse threshold, in disagreement with recent theoretical suggestions.

M. Grossi, K. Dolag, E. Branchini (University of Roma TRE), S. Matarrese (University of Padova, INFN) and L. Moscardini (University of Bologna, INFN) performed high-resolution cosmological N-body simulations of a concordance

ΛCDM model to study the evolution of virialized dark matter haloes in the presence of primordial non-Gaussianity. The non-Gaussianity was quantified through a dimensionless non-linearity strength parameter $f_{\rm NL}$. They find that the halo mass function and its redshift evolution closely follow the analytic predictions of Matarrese, Verde and Jimenez in such cosmologies.

J. Donnert and K. Dolag performed several constrained cosmological simulations with full ideal magneto hydrodynamics to investigate the possibility of magnetic field seeding by outflows from primordial, starbursting galaxies. The field is assumed to originate from an extended bubble containing an initial magnetic energy, fed at a constant rate with magnetic energy from the galactic disc during the time scale of the starburst. The analysis demonstrated that observed field strengths in galaxy clusters are reproduced for a wide range of parameters describing the wind models. The modeling of the outflow geometry does not have a strong influence on the magnetic field strength and structure. All reproduce the shape of the observed, radial profile of rotation measures in galaxy clusters very well, making galactic outflows an attractive mechanism to seed magnetic fields in galaxy clusters.

R. Ben Metcalf and S.D.M. White investigated what cosmological information could be extracted from future observations of the 21-cm radiation coming from the neutral atomic hydrogen that filled the universe before the reionization epoch. They found that the gravitational lensing of this radiation should be detectable with planned telescopes and that it could be used to put stronger constraints on many of the cosmological parameters than will be possible with other proposed methods.

S. Hilbert, R.B. Metcalf, and S.D.M. White investigated the the capabilities of future radio telescopes for imaging the cosmic matter distribution. They used the Millennium Simulation to simulate large-area maps of the lensing convergence with the noise, resolution and redshift-weighting achievable bt a variety of future observational programmes. It was demonstrated that by observing lensing of 21-cm emission during reionization with the planned Square Kilometre Array (SKA), mass imaging with comparable resolution, but much higher signal-to-noise than that obtainable by galaxy lensing will be possible.

S. Hilbert, S.D.M. White, Jan Hartlap (AIfA Bonn), and P. Schneider (AIfA Bonn) studied gravitational lensing by ray-tracing through the Millennium Simulation. Strong-lensing probabilities as function of source redshift were calculated. It was shown that strong-lensing events are almost always caused by a single dominant lensing object. The mass and redshift distribution of these primary lenses was studied. The effect of material in front of or behind the primary lens was investigated. Although strong-lensing lines-of-sight are indeed biased towards higher than average mean densities, the additional matter typically contributes only a few percent of the total mass along the light path. The influence of stellar mass in galaxies on strong lensing was investigated by comparing the results obtained for lensing by dark matter alone to those obtained by also including the stellar mass components predicted from galaxy-formation models. It was found that the stellar mass strongly enhances the probability for strong lensing, in particular for small image splittings.

Weak collisional interactions between dark matter and baryonic matter is a possible solution of the 'cooling flow' problem. Using available X-ray observations of several 'cooling flow' clusters, J. Hu and Y.-Q, Lu (Tsinghua University) derived an upper limit on the heavy dark matter particle-proton cross-section . Based on a simple stability analysis of the thermal energy balance equation, it was demonstrated that that this mechanism is unlikely to be a stable non-gravitational heating source of the intracluster medium in the inner core regions of 'cooling flow' galaxy clusters.

M. Vogelsberger and S.D.M. White developed a new numerical technique to access the fine-grained phase-space structure of Dark Matter halos. Current N-body simulations cannot access the scales that might be relevant for direct and indirect searches of Dark Matter in the Galactic halo. The new method is based on evaluation of the geodesic deviation equation of each Dark Matter simulation particle. The method allows small scale features like streams and caustics in the Dark Matter fluid to be resolved. The scheme was implemented in the most recent version of the GADGET code and tested with various static and time-dependent N-body models. First tests showed that it works and can resolve caustics very reliably.

Y. Wang (Shanghai Astronomical Observatory SHAO), X. Yang(SHAO), F. van den Bosch (MPIA Heidelberg), S. Weinmann and Y. Chu(SHAO) have investigated how the clustering strength of galaxy groups in the SDSS DR4 depends on their masses and colours. It was found that groups with red central galaxies are more strongly clustered than groups of the same mass but with blue central galaxies.

M. Baldi, S.D.M. White and V. Springel modified the cosmological N-body code GADGET-2 to include interactions in the dark sector, namely a direct coupling between the dark matter and the dark energy components. This new physics in the dark sector leads to non-standard gravitational interaction of dark matter particles. The analysis by means of an N-body code will investigate whether there are possible distinctive features in the non-linear regime of structure growth, and will further constrain the coupling constants.

M. Baldi, L. Amendola (INAF - Osservatorio Astronomico di Roma) and C. Wetterich (Institut für Theoretische Physik - Heidelberg) investigated the possibility of a direct interaction between the dark energy scalar field and cosmological massive neutrinos, as a possibility to solve the "Coincidence Problem". The interaction naturally realizes the exit from the scaling regime of a scalar field with an exponential self interaction potential, and leads to a final scaling attractor between dark energy and neutrinos. The most remarkable feature of this model is that it naturally relates the properties of dark energy on the final attractor (energy density and equation of state) to the average neutrino mass measured in laboratory experiments.

3.9 Cosmic Microwave Background Studies

A.J. Banday has continued studies of the nature of the anisotropy data collected by NASA's *WMAP* satellite, with particular emphasis on the development of a Bayesian framework for the estimation of the CMB anisotropy power spectrum with simultaneous determination and removal of the Galactic foreground components. Much of this work has been undertaken with a core group of collaborators including F.K. Hansen, H.K.E. Eriksen and P.B. Lilje (Oslo, Norway), C. Dickinson, C. Lawrence and K.M. Górski (JPL, USA). In particular, foreground uncertainties can now be rigorously propagated through to CMB power spectrum estimation and cosmological parameter inference. The method has been applied to both the *WMAP* three-year temperature and polarisation data (the latter at low angular resolution).

Bayesian methods have also been applied to continue the investigation of the presence of a power asymmetry in the *WMAP* data between the northern and southern hemispheres in a frame closely aligned with the ecliptic. By parameterising the asymmetry with a dipolar modulation of the underlying temperature anisotropy, it was found that such a description of the observations is preferred to a purely isotropic model at the $\sim 99\%$ confidence level.

A component separation technique based on Independent Component Analysis (ICA) has been devloped in collaboration with D. Maino and S. Donzelli (U. Milan, Italy) and F. Stivoli and C.Baccigalupi (SISSA, Italy). 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. In collaboration with M.-P. Bottino, this method was extended to allow foreground template fitting to the *WMAP* data on a frequency by frequency basis, and the subsequent 'iterative' application of the ICA algorithm to the cleaned maps. This latter step allows the final output CMB component to be cleaned from foregrounds that are not well described by existing templates, or indeed to determine the presence of previously unknown components.

In collaboration with C. Raeth and P. Schuecker† (MPE), novel statistical tools have reinforced previous claims concerning the presence of non-Gaussian signals in the *WMAP* data, and specifically the presence of the power asymmetry. In particular, the scaling index method has been, for the first time, applied to the case of spatial data on the sphere.

A. Waelkens, M. Maturi and T. Ensslin concluded studies about the Galactic kinetic Sunyaev-Zeldovich effect, demonstrating that it can safely be ignored as a CMB foreground for total and polarized emission.

M. Frommert and T. Ensslin worked on an adaptive grid-based algorithm for representing and projecting functions in higher dimensional spaces. The algorithm was used to represent the WMAP likelihood surface with the aim to provide a fast evaluation of the likelihood function. This can significantly speed up sampling of the posterior distribution for cosmological parameter estimation. In future, Grid-technology will allow the process of building up the interpolation to be heavily parallelized.

C. Carbone (SISSA) and V. Springel, in collaboration with C. Baccigalupi (SISSA), M. Bartelmann (ITA Heidelberg) and S. Matarrese (Padova) used the Millennium Simulation to construct the first all-sky maps of the gravitational lensing potential and the deflection angle due to foreground large-scale structures in front of the CMB. The method exploits the Born approximation and is based on direct ray-tracing through the evolving gravitational potential of the Millennium Simulation. A novel randomization scheme allows the construction of continuous all-sky maps with arcminute angular resolution, while at the same time a repetition of structures along the line of sight is avoided when the periodic simulation box is stacked to cover the backwards lightcone. The angular power spectra of the projected lensing potential and the deflection-angle modulus agree well with semi-analytic estimates on scales between a few arcminutes and about one degree, but there is a small excess in the deflection-angle power on small scales, which the team interprets as being due to non-linear clustering effects that are difficult to describe with alternative techniques. The new map-making procedure is well suited for studying weak lensing of CMB anisotropies, for analyzing cross-correlations with foreground structures, or other secondary CMB anisotropies such as the Rees-Sciama effect.

M. Righi, in collaboration with C. Hernández-Monteagudo and R. Sunyaev, developed a model based upon the merging of haloes in order to study whether a population of dusty star-forming galaxies can contribute to the small-scale CMB foreground at high frequencies. They found that the signal due to the clustering of such sources will be significant for forthcoming CMB experiments like PLANCK, the Atacama Cosmology Telescope (ACT) and the South Pole Telescope (SPT). They also showed that the detection of such a signal could provide very useful information about the physical nature of these sources, in particular about the dust properties of star-forming galaxies at high redshift.

Observations of the Cosmic Microwave Background (CMB) have revealed an unexpected quadrupole-octopole alignment along a preferred axis pointing toward the Virgo cluster. M. Maturi (ITA, Heidelberg), together with K. Dolag and T. Ensslin, investigated whether this feature could be explained by secondary anisotropies produced by the non-linear evolution of the gravitational potential, the so-called Rees-Sciama (RS) effect. The analysis focused on the effect caused by the local supercluster. This was estimatede using a constrained high-resolution hydrodynamical simulation, based on the IRAS 1.2-Jy all-sky galaxy redshift survey. The simulation reproduces the main structures of our Universe out to a distance of 110 Mpc from our Galaxy. The resulting RS effect peaks at low multipoles and has a minimum/maximum amplitude of -6.6 μK/ 1.9 μK. Even though its quadrupole is well aligned with the measured one its amplitude does not match observations. To produce a large enough effect, photons traversing the local cosmic structures would need to experience a five/ten times larger gravitational redshift.

J. Chluba and R.A. Sunyaev extended their studies of the detailed physics operating during the epoch of cosmological hydrogen recombination. The effects of two-photon transitions from excited s- and d-states in hydrogen to the ground state were examined, showing that previous work overestimated the relevance of this process. The importance of line feedback within the Lyman-series was considered in detail. Chluba and Sunyaev also investigated possiblities for using the recombination spectrum to measure cosmological parameters, such as the specific entropy of the Universe and the CMB monopole temperature. In collaboration with J.A. Rubino-Martin (IAC Tenerife/Spain), Chluba and Sunyaev have computed the helium recombination spectrum, taking into account the relevant fine-structure transitions in neutral helium and the effect of photoabsorption in the hydrogen continuum at redshifts $z \sim 2500$. These computations have shown that helium leaves distinct traces in the cosmological recombination spectrum, which might be observable in the future. Measuring these features allows one to determine the primordial helium abundance, well before the appearance of the first stars.

3.10 Quantum mechanics of atoms and molecules, astrochemistry

The energy spectra and wave functions of two and three electrons confined by a quasi-one-dimensional Gaussian potential have been calculated and analyzed for three regimes of the strength of confinement ω_z, namely, large ($\omega_z = 5.0$), medium ($\omega_z = 1.0$) and small ($\omega_z = 0.1$) by using the full configuration interaction method. For large and medium ω_z the energy spectrum shows a band structure which is characterized by the polyad quantum number v_p while for small ω_z it is characterized by the extended polyad quantum number v_p^*. In case of two electrons the energy levels for small ω_z form doublet pairs each of which consists of a pair of singlet and triplet states. The nodal pattern of their wave functions are almost identical to each other except for their phases. The energy spectra for the strongly anharmonic Gaussian potential look quite similar to those of the nearly harmonic case except that an irregular level structure appears in the high energy region for $\omega_z = 0.1$. The wave functions of the corresponding states have curved nodal lines which aline along a pair of bent *nodal coordinates*. Two types of pairs of bent nodal coordinates have been identified, namely, those passing through the valleys of the confining potential and the others passing along the summit. It is shown that the wave functions with these nodal coordinates correspond to new types of classical *local-mode* motions of electrons. In the case of three electrons the wave functions of the quartet states have been assigned uniquely by counting the number of *nodal planes* for the three normal modes, namely, the center-of-mass, permutation and breathing modes. The energy levels for small ω_z form nearly degenerate triplets each of which consists of two doublet states and one quartet state. The nodal pattern of their wave functions in this small ω_z regime are almost identical to each other except for their phases. The origin of the tripling of energy levels and the similarity of the wave functions for different spin states has been rationalized by using the projection of one- and two-electron potentials onto the *internal plane*. Effects of anharmonicity in the confining potential on the energy spectra and wave functions have been also examined. (Tokuei Sako and Geerd H.F. Diercksen)

Part of the research performed in this group is concerned with quantummechanical studies of exothermic binary reactions such as radiative association, electron-ion dissociative recombination, or photo-dissociation which are basic processes of potential astrophysical relevance. For a couple of weakly bound diatomic and triatomic systems extensive calculations have been performed providing a detailed understanding of these processes. In these weakly bound systems the number of bound and low-lying quasi-bound vibration-rotational levels is relatively small which allows a detailed state-to-state analysis of the reaction process. The calculations have demonstrated the fundamental importance of so-called resonance states for the reaction performance. Resonance states are quasi-bound vibration-rotation levels lying above the relevant dissociation threshold of the molecular system and are stabilized by rotational centrifugal barriers. They are intermediately populated in the reaction process and depending on their life times they either redissociate to the reactants 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. Extensions of these studies to strongly bound systems are impossible because in these systems the number of bound vibrational levels and and low-lying quasi-bound resonance states becomes excessively large and characterizations of the highly excited states by distinct quantum numbers are meaningless. In such a case of complex quantum dynamics with high a density of states it can be helpful to study the statistical properties of the quantum spectrum. These properties often show an universal behavior depending only on some general features of the system. As a first attempt to apply a statistical description to the complex dynamics of a molecular system, studies of the isomerization reaction in HN_2^+ and for $HCO^+ \leftrightharpoons COH^+$ were undertaken. The nearest-neighbor level spacing distribution (NNSD) is one of the simplest quantities used for the local statistical analysis when fitted to different distribution forms. Calculations were performed to study the effect of tunnelling states connected with the isomerization process on the NNSD representation. A future aspect of these studies will be to develope a connection between statistical properties of the quantum spectrum of a reaction complex and the temperature dependent macroscopic properties for the reaction such as for example reaction cross sections or rate constants (W. Krämer).

4 Publications and Invited Talks

4.1 Publications in Journals

4.1.1 Publications that appeared in 2007 (193)

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4.2.1 Publications in proceedings appeared in 2007 (43)

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4.2.2 Publications available as electronic file only

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Arp, H.: Quasars and the Hubble Relation. arXiv:0711.2607 (http://de.arxiv.org/) 2007

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`http://www.iop.org/EJ/article/1742-6596/78/1/012071/jpconf7-78-012071.pdf`

4.3 Books and popular articles

Bouche N., M. Murphy et al. (incl. V. Wild): Are strong Mg II absorbers the signature of outflows? 2007, NewAR, **51**, 131–134 (2007).

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Janka, H.-Th.: Asymmetrische supernova-explosies en voortsnellende neutronensterren. Zenit, **34/02**, 56–60 (2007).

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4.4 Invited review talks at international meetings

P. Cerdá-Durán:
France, 3.09)
– "Matter at extreme densities and gravitational waves from compact objects" workshop, (ECT*, Trento, Italy, 10.9-14.9)

D. Christlein:
– "At the Outer Banks of the Island Universes - A Spectroscopic Perspective" Vatican Observatory Symposium "Formation and Evolution of Disk Galaxies", Rome, Italy, Oct 2nd, 2007

E. Churazov:
– Joint Astronomical Conference VAK 2007, (Kazan, Russia, 17.09.-22.09)
– Helmholtz International Summer School on Modern Mathematical Physics (Dubna, Russia, 22.07-30.07)

B. Ciardi:
– "First Stars III" (Santa Fe, New Mexico, USA, 16.7–20.7)
– "HI Survival through Cosmic Times" (Sarteano, Italy, 11.6–15.6)
– "XCIII National Congress of the Italian Society of Physics" (Pisa, Italy, 24.9–29.9)

G. De Lucia:
– "Tracing Cosmic Evolution with Clusters of Galaxies: Six Years Later" (Sesto Puesteria, Italy, 25.06 - 29.06)

T. Enßlin:
– Invited Talk, "The large scale magnetic field of the Milky Way" Workshop, (Princeton, USA, April 30.04-02.05)

D.A. Gadotti:
– Invited Review at Chaos in Astronomy 2007, Research Center for Astronomy, Academy of Athens, Athens, Greece, September, 2007

D. Giannios:
– Invited Review Talk, “Workshop in Short Gamma Ray Bursts: Observations and Physics” (Ringberg, Germany, 26.03.–30.03.)

M.Gilfanov:
– “Workshop on Microquasars and AGN” (Crete, Greece, 4.06–8.06)
– “Astrophysics of Neutron Stars” (Istanbul, Turkey, 2.07-6.07)
– “X-rays from Nearby Galaxies” (Villafranca del Castillo, Spain, 5.09–7.09)
– Invited Plenary Talk, Russian Astronomy Meeting (Kazan, Russia, 17.09–22.09)
– “HEA-2007” (Moscow, Russia, 24.12–26.12)

W. Hillebrandt:
– Paths to Exploding Stars: Accretion and Eruption (KITP, Santa Barbara, USA, 19. 3. – 23. 3.)
– ScicomP13 (Garching, 16.7. – 20.7.)
– Nuclear Astrophysics: Beyond the first Fifty Years (Caltech, Pasadena, USA, 23. 7. – 27 7.)

H.-Th. Janka:
– “Supernova 1987A: 20 Years After. Supernovae and Gamma-Ray Bursters” International Conference (Aspen, Colorado, 19.2.–23.2.)
– “Twenty Years After SN 1987A” International Conference (Hawaii, 23.2.–25.2.)
– “XIXth Rencontres de Blois: Matter and Energy in the Universe: from Nucleosynthesis to Cosmology” Workshop (Blois, France, 20.5.–26.5.)
– “40 Years of Pulsars: Millisecond Pulsars, Magnetars, and More” Conference (Montreal, Canada, 12.8.–17.8.)
– “Cosmic Matter” Astronomische Gesellschaft and KAT Conference (Würzburg, 24.9.–29.9.)
– “Supernovae: Lights in the Darkness” Conference (Menorca, Spain, 3.10.–5.10.)

G.Kauffmann:
– “Structure formation on the Universe: Galaxies, Stars, Planets” (Chamonix, France , 27.5.)
– “Spectroscopy in Cosmology and Galaxy Evolution 2005-2015” (Granada, Spain, 3.10.)

P. Mazzali:
– “Supernovae and Gamma-ray Bursts” at the meeting “SN1987a: 20 years after”, (Aspen, CO, USA, 19.2.-23.2.)
– “Hypernovae and Gamma-ray Bursts” at the meeting “Accretion and Explosion” KITP, (Santa Barbara, CA, USA, 20.3.-24.3.)
– “The SN-GRB connection” at the meeting ”Cosmology: Energetic events in the Universe” (Marseille, France, 25.6.–27.6.)
– “H-depleted Supernovae” at the meeting “H-depleted Stars” (Tübingen, 17.9.–21.9.)

H. Ritter:
– “Jean-Pierre Lasota, X-ray binaries, accretion disks and compact stars” conference at the occasion of Jean-Pierre Lasota’s 65th birthday (Trzebieszowice castle, Poland, 7.10-13.10.)

F. Röpke:
– The XXIII Trobades Científiques de la Mediterránia “Supernovae: light in the darkness”, (Maó, Menorca, Spain, 3.10.-5.10.)

V. Springel:
– “The Impact of AGN Feedback on Galaxy Formation” (Ringberg Castle, 20.-26.5.)
– ESO Conference on “Obscured AGN Across Cosmic Time” (Seeon, 5.-8.6.)
– “Next generation of computational models of baryonic physics in galaxy formation: from protostellar cores to disk galaxies” (Zurich, Switzerland, 17.-21.9.)

Spruit, H.C.:
– Invited review, “40 years of Pulsars” Symposium, McGill University (Montreal, Canada 15.8.)

S. White: – IUCAA Workshop, Pune,
– ESF Meeting on The Origin of Galaxies, Obergurgl, Austria
– Zeus Science Meeting, London, 2007
– The Hunt for Dark Matter, Fermilab, Batavia, USA,
– Structure formation in the Universe, Chamonix, France
– IAP Colloquium No. 23 From Giant Arcs to CMB Lensing, Paris, France
– From IRAS to HERSCHEL/PLANCK, London, UK,
– Dynamics of Galaxies, St. Petersburg, Russia
– Gas Accretion and Star Formation in Galaxies, Garching, Germany
– Spectroscopy in Cosmology and Galaxy Evolution, Granada, Spain

4.4.1 Public talks

G. Börner: Humboldt Sriftung München (16.7.)

D. Docenko: Institute of Astronomy, University of Latvia (25.04)

M. Frommert: "Ein Blick zurück bis fast zum Urknall" (Girl's Day, 26.4.)

W. Hillebrandt: "Wo sind die Aliens?" (Lange Nacht der Wissenschaften, 13.10.)

H.-Th. Janka: Vortragsreihe Physik Modern, LMU München (14.6.)

P. Jofre-Pfeil: "Sternenzoo" (Girl's Day, 26.4.)

W. Müller: "Gravitationswellen: Erschütterungen der Raumzeit" (Lange Nacht der Wissenschaften, 13.10.)

P. Rebusco: "Das Hochenergie Universum" (Girl's Day, 26.4.)

T. Sawala: "Die Welt der Galaxien" (Lange Nacht der Wissenschaften, 13.10.)

V. Springel: Volkssternwarte Trebur (15.6.)
– Taus-Gymnasium Backnang (19.11.)
– Physik Modern, LMU München (12.12.)

Spruit, H.C.: "Wie sieht ein schwarzes Loch aus?" (Lange Nacht der Wissenschaften, 13.10.)

M. Vogelsberger: "Simulating the Universe on Supercomputers" (27.12. Chaos Communication Congress, Berlin)

A. Weiss: "Die Vermessung der (ganzen) Welt" (Lange Nacht der Wissenschaften, 13.10.)

S. White: "Alles aus Nichts" (Lange Nacht der Wissenschaften, 13.10.)

V. Wild: "Das Leben der Galaxien" (Girl's Day, 26.4.)

5 Personnel

5.1 Scientific staff members

Directors

M. Asplund (since 1.9.), 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

A.J. Banday, J. Ballot, J. Blaizot (till 31.8.), G. Börner (till 30.4.), J. Bolton, M. Boylan-Kolchin (since 15.10.), B. Catinella (since 1.8.), P. Cerda-Duran, J. Chluba, B. Ciardi, D. Christlein (since 11.9.) E. Churazov, R. Collet, G. De Lucia, N. De la Rosa, K. Dolag, T. Enßlin, A. Faltenbacher (since 1.11.) D. Gadotti, D. Giannios, M. Gilfanov, E. Hayashi (till 30.9.), C. Hernandez-Monteagudo (since 15.10.), J. Hu (since 1.9.) H.–T. Janka, G. Kauffmann, K. Kifonidis, F. Kupka, Ch. Li (since 1.9.), L.-X. Li, A. Marek (since 1.2.), A. Maselli, P. Mazzali, B. Metcalf, A. Merloni (till 28.2.), O. Möller (till 31.8.), E. Müller, R. Oechslin (till 31.7.), E. Olsson (till 31.8.), R. Overzier (since 15.11.), E. Puchwein (since 1.10.), M. Reinecke, M. Revnivtsev, H. Ritter, F. Röpke, M. Ruszkowski (till 31.8.) H. Sandvik (till 30.6.), D. Sauer, S. Sazonov, C. Scannapieco, S. Sim, V. Springel, H.C. Spruit, A. Watts (till 31.12.), S. Weinmann (since 1.11.) A. Weiss, V. Wild, X.-G. Zhang (since 1.12.)

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.

Alexander von Humboldt Awardees

D. Bond (1.10.–31.12.), M. Davis (1.9.–31.12), C. Hogan (since 15.3), P. Madau (till 31.8.), S. Mao (1.4.–1.9.), J. Navarro (1.5.–31.7.), A. Szalay (12.3.–31.7.)

Ph.D. Students

[1] M. Alves-Cruz* (since 1.9.), A. Arcones* (till 12.4.), M. Baldi*, A. Bauswein, R. Birkl, A. Bogdan*, S. Bonoli*, M.-P. Bottino* (since 23.4.) M.A. Campisi*, M. Carrasco-Kind*, C. D'Angelo*, E. Donoso*, D. Docenko*, F. Elsner (since 1.5.), M. Fink (since 1.1.), M. Frommert, M. Grossi*, Q. Guo*, S. Hachinger (since 1.10), N. Hammer, S. Hess (since 1.5.), S. Hilbert, J. Jasche, P. Jofre-Pfeil*, F. Kitaura* (till 31.12.), A. Kitsikis* (till 31.12.), M. Kitzbichler*, M. Kromer, T. Mädler, U. Maio*, A. Marek* (till 31.1.), S. Mineo* (since 1.9.), M. Mocak*, R. Moll, B. Müller, M. Obergaulinger, R. Pakmor (since

[1] *IMPRS Ph.D. Students

1.2.) M. Petkova*, M. Pierleoni*, P. Rebusco* (till 4.5.), M. Righi*, S. Sazmaz* (since 1.9.), T. Sawala* (since 1.9.), D. Sijacki* (till 30.9.), F. Stasyszyn* (since 1.9.), S. Taubenberger, M. Vogelsberger, A. von der Linden* (till 31.12.), R. Voss* (till 4.5.), A. Waelkens, L. Wang, J. Wang*, A. Wongwathanarat* (since 1.9.), F. Xiang*, F. Zaussinger (since 1.9.).

Diploma students

J. Donnert (till 1.10.), S. Hachinger (till 1.3.), I. Maurer (till 1.9.), B. Möbis (till 30.11.).

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 (till 31.12.).

Staff news

N. Grüner: received a special award called "white camel" for his special commitment in the OpenSource Community (PERL)

G. Kauffmann received the "Gottfried Wilhelm Leibniz Prize", (the highest German prize in support of research) for her work on the connection between the evolution of galaxies and their central supermassive black holes.

F. Kupka: Habilitation thesis submitted at Faculty of Physics, Technische Universität München.

F. Röpke: accepted to the Emmy Noether Programme of the German Research Foundation (DFG)

R. Sunyaev: Member of American Philosophical Society (2007).

S. White: Gold Medal, Royal Astronomical Society (2007).

S. White: Honorary doctorate (D.Sc.) Durham University, 2007

S. White: Foreign Associate of the USA National Academy of Sciences, 2007

Ph.D. theses 2007

Almudena Arcones: On nucleosynthesis-relevant conditions in neutrino-driven supernova outflows. Technische Universität München.

Martin Jubelgas: Cosmological hydrodynamics: thermal conduction and cosmic rays. Ludwig-Maximilians-Universität München.

Francisco Kitaura: Cosmic Cartography: Bayesian reconstruction of the cosmological large-scale structure with ARGO- an Algorithm for the Reconstruction of Galaxy-traced Over-densities. Ludwig-Maximilians-Universität München.

Andreas Marek: Multi-dimensional simulations of core collapse supernovae with different equations of state for hot proto-neutron stars. Technische Universität München.

Paola Rebusco: Impact of supermassive black holes on galaxy clusters. Ludwig-Maximilians-Universität München.

Debora Sijacki: Non gravitational heating mechanisms in galaxy clusters. Ludwig-Maximilians-Universität München.

Anja von der Linden: Galaxy evolution from the SDSS and EDisCS surveys. Ludwig-Maximilians-Universität München.

Rasmus Voss: Populations of low mass X-ray binaries in the galaxies Centaurus A and Andromeda. Ludwig-Maximilians-Universität München.

Diploma theses 2007

Julius Donnert: A numerical study on the origin of cluster magnetic fields. Technische Universität München.

Stephan Hachinger: Quantitative analysis of spectra of type Ia supernovae. Technische Universität München.

Immanuel Maurer: Morphology of Type-I X-ray Bursts. Ludwig-Maximilians-Universität München.

5.2 Visiting scientists

Name	home institution	Duration of stay at MPA
Marek Abramowicz	(Chalmers Univ. Schweden)	15.5.–31.5.
Miguel Aloy	(Univ. of Valencia)	21.3.–4.4.
Pia Amigo	(Univ. Catolica, Chile)	13.2.–12.6.
Charmaine Armitage	(Univ. of Illinois, USA)	11.6.–1.7.
Isabelle Baraffe	(Univ. of Lyon)	22.10.–21.12.
Miroslav Barta	(Astron. Inst. Ondrejov, Czech Rep.)	19.3.–16.4.
Rahul Biswas	(Univ. of of Illinois, USA)	1.2.–31.7.
Sergey Blinnikov	(ITEP Moscow)	1.8.–15.9.
Richard Bond	(CITA, Toronto)	1.10.–31.12.
Matthieu Brassart	(Obs. de Paris, France)	since 1.12.
Tamas Budavari	(Johns Hopkins University)	1.7–31.7.
Gilles Chabrier	(Univ. of Lyon)	22.10.–21.12.
Phil Chang	(UC Berkeley)	7.8 - 22.8.
Ruixiang Chang	(Shanghai Obs. China)	till 28.2.
Yan-Mei Chen	(Inst. of HE Phys. Beijing)	since 10.10.
Paula Coelho	(Univ. Sao Paulo, Brazil)	till 26.5.
Isabel Cordero	(Carrion Valencia, Spain)	26.4.–21.5.
Rodolfo Costa	(Sao Paulo, Brazil)	12.6.–11.9.
Marc Davis	(Univ. of California)	1.9.–31.12.
Celine Eminian	(Univ. of Sussex, U.K.)	7.1.–30.4.
Chad Fendt	(Univ. of Illinois)	13.5.–24.6.
Ekaterina Filippova	(HE Astr. Dept. Moscow)	4.2.–3.5.
		1.11.-9.12.
Sergio Flores	(Univ. Catolica, Santiago, Chile)	25.5.–25.7.
Liping Fu	(IAP Paris, France)	1.4.–30.6.
Konstantinos Gourgouliatos	(Cambridge, England)	17.4.–16.7.
Sergey Grebenev	(HE Astr. Dept. Moscow)	22.11.–22.12.
Gustavo Guerrero	(Sao Paulo, Brazil)	22.2.–8.33
Melanie Guittet	(Univ. Bourgogne, Dijon)	16.07. to 31.08.
Stanislav Gunar	(Ondrejov, Czech. Rep.)	15.1.–14.4.
Kevin Heng	(Univ. of Colorado)	25.7.–24.10.
Craig Hogan	(Univ. of Washington)	since 26.6.
Jiri Horak	(Univ. Köln) 15.5.–31.5.	
Zhen Hou	(CAS, Beijing China)	since 17.10.
Nail Inogamov	(Landau Inst., Moscow)	30.1.–7.4.
Chunyan Jiang	(SHAO, Shanghai, China)	since 1.9.
Chanda Jog	(IISC, Bangalore, Indien)	19.9.–11.10.
Anjor Kanekar	(Pune, India)	8.5.–23.7.
Wolfgang Kerzendorf	(MS Obs. Australien)	8.1.–7.2.
Rishi Khatri	(Univ. of Illinois)	15.5.–15.7.
Kei Kotake	(Nat. Astron. Obs, Japan)	01.04-31.12.
Roman Krivonos	(HE Astr. Moscow)	11.5.–9.8.
Michael Kuhlen	(Princeton Univ. USA) 31.5.–15.6.	
Jounghun Lee	(Astro, SNU, Korea)	1.8.–31.8.
Yang-Shyang Li	(Univ. Groningen)	29.10.–15.12.
Fukun Liu	(Beijing Univ.)	10.1.–10.2.
Patryk Mach	(Cracow University, Poland)	until 31.07.
R.E. Garcia Machado	(Sao Paulo, Brazil)	till 8.3.
Michal Maciejewski	(IAP France)	19.3.–18.6.
Kei'ichi Maeda	(Univ. of Tokyo, Japan)	till 14.12.

Name	home institution	Duration of stay at MPA
Gian Mario Manca	(Univ. di Parma, Italy)	1.2.–30.9.
Samir Mandal	(CSP, Kolkata, India)	6.3.–15.5.
Shude Mao	(Univ. of Manchester, UK)	1.4.–1.9.
Federico Marulli	(Astron. Bologna, Italy)	1.2.–30.4.
Brice Menard	(Univ. of Toronto, Canada)	29.8.–12.10.
Jorge Melendez	(ANU, Weston, Australia)	18.11.–1.12.
Petar Mimica	(Univ. of Valencia)	11.6.–10.7.
Antonio Montero Dorta	(Inst. Astr. Andalusia, Spain)	24.2.–11.3.
Dimitrij Nadyozhin	(ITEP, Moscow)	22.3.–21.5.
Daniel Neumann	(Univ. Würzburg)	15.2.–31.3.
Caroline Nunez Santilices	(PUC Chile)	8.9.–7.12.
Sebastian Nuza	(Inst. for Astron., Buenos Aires)	1.9.–30.11.
Christof Obertscheider	(Univ. of Vienna, Austria)	20.5. – 15.6.
Igor Panov	(ITEP, Moscow)	1.3.–30.4.
Ben Panter	(IfA Edinburgh, UK)	5.2.–16.2.
Santiago Patiri	(IAC Tenerife, Spain)	11.1.–10.4.
Dante Paz	(Univ. Buenos Aires, AR)	16.7.–15.10.
Maria Josefa Perez	(O.N. de la Plata, Argentina)	26.7.–27.9.
Christoph Pfrommer	(CITA, Toronto, Canada)	30.09–20.10
Igor Prokopenko	(HE Astr. Dept. Moscow)	1.4.–30.4.
Andreas T. Reisenegger	(Univ. Santiago de Chile)	2.2.–20.7.
Elena Rossi	(Univ. of Colorado, USA)	12.6.–11.7.
Maurizio Salaris	(Liverpool, John Moores Univ., U.K.)	1.10.–13.10.
Samui Saumyadip	(IUCAA, Pune, India)	1.11.–16.11.
Alexandro Saro	(Liverpool, John Moores Univ.)	till 30.4.
Arman Shafieloo	(IUCAA, Pune, India)	15.5.–14.7.
Nikolai Shakura	(Sternberg Inst. Moscow)	1.9.–30.9.
Ken Shen	(UC Santa Barbara, USA)	28.5.–27.8.
Shiyin Shen	(Shanghai Obs. China)	till 15.2.
Pavel Shtykovskyi	(Space Research Institute, Moscow)	15.4.–15.6.
		7.10.–7.11.
Debora Sijacki	(Cambridge, UK)	30.9.–16.10.
Victor Silva	(Pont. Univ. Catolica, Santiago de Chile)	1.4.–31.5.
Jan-Hendrik Spille	(Univ. Würzburg)	15.2.–31.3.
Kohsuke Sumiyoshi	(Shizuoka, Japan)	7.8.–22.8.
Alex Sandor Szalay	(Johns Hopkins University, USA)	12.3.–31.7.
Federico Stasyszyn	(Univ. of Cordoba, Argentina)	1.5.–30.6.
Manuchehr Taghizadeh	(Johns Hopkins University)	10.04 – 10.07
Luca Tonatore	(Astr. Obs. Trieste, Italy)	9.7.–21.7.
Sergey Tsygankov	(HEA Dept. Moscow)	22.5.–21.8.
Victor Utrobin	(ITEP, Moscow)	1.10.–30.11.
Franco Vazza	(Radio Astron. Bologna, Italy)	28.10.–10.11.
Benjamin Wandelt	(Univ. of Illinois, USA)	6.1.–1.8.
Norbert Werner	(Utrecht, NL)	1.1.–31.8.
Dandan Xu	(Univ. of Manchester)	23.6.–7.7.
Amit Yadav	(Univ. of Illinois, USA)	15.3.–15.5.
Ching-Wa Yip	(Johns Hopkins University)	20.5.–11.6.
Zhongli Zhang	(Shanghai Jiao Tong University)	15.4.–14.8.