Max-Planck-Institut
für
Astrophysik

Annual Report 2008

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 more than a decade. The Managing Directorship rotates every three years, with Simon White in post for the period 2006-2008 and Wolfgang Hillebrandt for 2009-2011. A major event in 2007 was the arrival of Martin Asplund as a new director who will replace Wolfgang Hillebrandt on his retirement in 2012. The institute also has three external Scientific Members: Riccardo Giacconi, Rolf Kudritski 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 an emphasis on 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 our Milky Way and other 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 results in a close and productive working relationship 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 23000 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 publications. This catalogue and the corresponding catalogues of other MPI libraries on the Garching campus and elsewhere are accessible online via the internet from the library and from every office terminal or PC. Internet access to other bibliographical services, including electronic journals and the SCI, is also provided.

Additional technical services such as several PCs and terminals in the library area, copy machines, a microfiche reader/printer, a 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 (e.g. ca. 900 publications in 2007). 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. Blank (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 Computer Centre (the RZG) and the Leibniz Computer Centre of the state of Bavaria (the LRZ).

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 Computer Center Garching (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 524 processors, 1088 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 required of users

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

In addition to the desktop systems, most of which are less than 5 years old, and which (in 2008) amount to more than 170 fully equipped working places, users have access to central number crunchers (about 15 machines, all 64-bit architecture; with up to 16 processor cores and 64 GB memory), mainly through a batch system. The total on-line data capacity is beyond 300 Terabyte, individual user disk space ranges from a mere GB to several TB, according to scientific need.

All MPA scientists and PhD students may also get a personal laptop for the duration of their stay 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 also possible.

The basic operating system relies on OpenSource software and developments. One MPA system manager is actively participating in the OpenSource 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 concentrate fully 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 2008 at the MPA

The new director settles in

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 identify an early replacement for one of the two who would then be able to participate fully in selecting the second replacement. This effort culminated in the recruitment of Martin Asplund, a stellar astrophysicist specialising in stellar atmosphere modelling aimed towards the precise element abundance determinations needed to clarify cosmic and Galactic chemical evolution. Martin arrived in September 2007 and throughout 2008 he was active in establishing new activities at the MPA and in building up a group of young scientists, both observers and theoreticians, working in his areas of interest. By the end of 2008 this expansion was almost complete, leading to a substantial and stimulating broadening of the MPA's science, as well as to further pressure on its office space. From a scientific point of view, Martin will effectively replace Wolfgang Hillebrandt, when the latter retires, so the MPA will need to start thinking soon about finding successor for Rashid Sunyaev in order to ensure a smooth transition in his part of the institute's activities also.

Figure 1.1: The LOFAR low frequency antenna field

The MPA's Radio Observatory takes shape

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 is under construction on 2 hectares of agricultural land in a rural area about 50km north of Garching (see Fig. 1.1. This will be one of at least five such stations in Germany and will almost double the north-south resolution of the interferometer. A full set of 96 Low Frequency antennas was delivered and assembled in 2008, the 96 High-Frequency antennas should follow in 2009. The electronics of the LBAs is complete and is connected to Garching, further connection to Juelich and then to the main LOFAR processing centre in the Netherlands should become active during 2009. The MPA scientist in charge is Benedetta Ciardi, who also chairs the Science Working Group of German LOFAR participants.

Biermann lectures on supernova physics

2008 was the twelfth year of the Biermann Lecture series at MPA. This year's lecturer was Stan Woosley, a well-known American astrophysicist who works at the University of California, Santa Cruz. Stan has been a frequent visitor to MPA in the past and has many interests in common with the MPA's own supernova theorists. Indeed, his connections go deeper than just science, since he met his (German) wife during one of his previous visits to the Institute where she was working as one of the administrative staff. The arrival of the Woosleys for the Biermann lectures was thus a reunion of old friends as well as a chance to spur existing collaborations and to learn about the physics of supernovae from one of the acknowledged experts in the field. As always the lectures themselves were very well attended, and they gave everyone at the institute a very clear introduction to many of the major questions which underlie the research of our own supernova theorists.

The MPA's first half century

This year marked the fiftieth anniversary of the MPA's founding by Ludwig Biermann as a sub-institute within the Heisenberg's Max-Planck Institute for Physics and Astrophysics, which had

Figure 1.2: Part of Auditorium during the 50th anniversary of MPA.

Figure 1.3: Rudolf Kippenhahn and Simon White cutting the *Special birthday cake* for the 50th anniversary of MPA

just moved from Goettingen to Munich. This anniversary provided a wonderful opportunity for a party to celebrate what has been accomplished, to invite previous members to return to the Institute and see how it has evolved, and to allow current members to learn about the history of their institution. Remarkably, a number of scientists who were at the MPA when it was founded or very soon thereafter were able to take part in the event. The formal programme consisted of greetings from the MPA Managing Director and representatives of the two Munich universities and the town of Garching, followed by an interesting and entertaining speech from Peter Gruss, the current MPG president, and talks from Rudolf Kippenhahn (one of the MPA's original scientists and the successor to Ludwig Biermann as its Director) on "Das Institut von 1958 bis 1991" and from Scott Tremaine (Institute for Advanced Study, Princeton, and a recent Humboldt Prize winner at MPA) on "Wo viel Licht ist, ist starker Schatten: black holes, dark matter and dark energy". The proceedings were framed by music from the Carcente String Quartet with the MPA's own Martin Reinecke playing one of the violin parts, and were followed by a less formal but very friendly buffet and party in the MPA building itself. (As with all major MPA events, the formal celebration could not be held at the institute itself for lack of a large enough assembly room. It took place next door in the MPE's large seminar room. Because of this and other space problems, a request to build an extension to MPA was submitted to the Max Planck Society in 2008. A final decision on whether this will be possible is expected in 2009.)

International Activities

In addition to expanding involvement in LOFAR, the MPA took on another major observational project in 2008 by becoming a full institutional partner in the third phase of the Sloan Digital Sky Survey. This primarily US-led project is using a dedicated telescope in New Mexico to survey the northern sky. SDSS-III is now fully funded and has begun operation. It will spend six years carrying out spectroscopic surveys of distant galaxies, of the Milky Way's stellar populations, and of nearby stars which may potentially have detectable planets. The MPA's scientific participation is led by Martin Asplund and Guinevere Kauffmann, and the cost of participation was carried half by the institute and half by Guinevere Kauffmann's 2007 Leibniz Prize.

The institute's international exchange programmes have also continued to be very active. The principal channels are to China, where there is an active MPA partner group at the Shanghai observatory, and to the Canadian Institute for Theoretical Astrophysics (Toronto), the Kavli Institute for Theoretical Physics (Santa Barbara) and the Harvard-Smithsonian Center for Astrophysics (Cambridge, Massachussetts) with all of whom we have a formal bilateral agreement for exchange of postdocs.

Public Outreach

As part of an MPG-wide initiative to intensify public outreach and to increase the professionalism of institute PR activities, a new position for a joint PR coordinator for the MPA and the MPE was created at the end of 2007, with the intention both of supporting public outreach activity by the individual scientifc groups, and of initiating new PR projects. This should involve a diversification of the target group for the PR work of the two institutes: in particular, press releases and other scientific PR material are now targeted not only at the specialist "quality" press but also at the mass media. Public outreach work should no longer just respond to pre-existing interest, but should also arouse interest among those who have had little previous contact with astrophysics or with science in general.

Because science communication in such cases is not effective if viewed simply as traditional information transmission, at the end of 2008 and on the occasion of the International Year of Astronomy (IYA) in 2009, new media were introduced into the institute's PR palette, which are able to address people emotionally: Video podcasts and astronomy comics on the internet aim to engage by young people through the preferred media of their spare time, and to arouse their enthusiasm for astrophysics. Knowledge transfer is of secondary importance in this first step.

The last months of 2008 were marked by preparation of additional projects for the upcoming Year of Astronomy . At Simon White's suggestion the MPA, together with the MPE, the MPP, ESO and the Excellence Cluster Universe, initiated construction of a cosmology exhibition for the Deutsche Museum in Munich. The exhibition, which is supposed to open in Fall 2009, will take visitors on a journey through time from the Big Bang up to the present, and will forecast what may happen to our Universe in the future. This journey through time will showcase recent discoveries in astrophysics and particle physics and show the deep conections between them. Further IYA projects, for which the course was set in 2008 include a series of posters with astronomical motives in central Munich underground stations, and a series of articles showcasing Max Planck research in the journal Sterne und Weltraum. This will eventually be supplemented by didactic material and assembled into a booklet for the public outreach work in schools.

In addition to these special events and to the experiments with new means of communication, MPA scientists continued in 2008 the public outreach activities of previous years, presenting talks in schools and in public fora, supervising students and interns, and guiding visitors through the institute. As in 2007, the MPA also participated in this year's Girl's Day, which for the first time was organised jointly with the MPE (see Fig.1.4). The intensification of press relations has increased direct contacts between MPA scientists and the media, resulting in many interviews for the press and for TV. In this context, a prominent role was played by preparing journalists for the 2009 start of the Planck satellite, for which the MPA has spent ten years developing software.

Figure 1.4: Girls aged between 14-16 watching a 3D movie of *Cosmic Cinema* during the Girls Day, April 24, 2008

2 Scientific Highlights

2.1 Progenitor systems of SN Ia

Supernovae are some of the brightest objects in the universe. For a few weeks they can be nearly as bright as their host galaxy. In addition, a particular subgroup of supernovae, the so-called supernovae of type Ia (SNe Ia), look remarkably homogenoues. For SNe Ia there exists an empirical relation between their brightness and the rate at which they fade. This relation can be used to calibrate their peak luminosity. With that SN Ia can be used as cosmological distance indicators. Following this, they provide a unique option to study the expansion history of our universe which led to the discovery of its accelerating expansion.

However, to do precision cosmology, i.e. to measure the time-dependend expansion history of the universe, it is necessary to understand in detail how the explosion mechanism of SN Ia works and how their properties depend on their environment.

There is general agreement that SN Ia are thermonuclear explosions of CO white dwarfs (WDs). The modelling of the explosion phase has made significant progress over the last few years. These models start from a Chandrasekhar mass ($M_{\mathrm{CH}} \simeq 1.4 M_{\odot}$) WD and ignite one or more thermonuclear flames near the center of the WD. The flames propagate as deflagrations and may turn into detonations. Models of this kind are now able to reproduce most observed properties of normal SN Ia such as their lightcurves and spectral properties.

However all models of the explosion phase have in common that they start from a M_{CH} WD assuming those WDs reached the Chandrasekhar mass somehow. Yet typical WDs have a mass of only $0.7 M_{\odot}$ when they are born from a star that ejects its envelope after helium burning and is too light to reach the central temperatures required for carbon burning. Therefore the WD has to accrete material from a companion star to grow to the Chandrasehkar mass. There are basically two progenitor scenarios that differ in the nature of the companion star. The *single degenerate scenario* assumes a main sequence or red giant companion star. This star at some point of its evolution transfers material to the WD either by Roche-lobe overflow or stellar winds. At the surface of the WD the accreted material is burned to carbon and the WD grows until reaching M_{CH}. We concentrate on progenitor systems with main sequence companion stars and hydrogen accretion by Roche-lobe overflow, which is the most favourable scenario. The *double degenerate scenario* assumes a binary system of two WDs, that looses angular momentum due to gravitational wave emission and finally merges. This merger may produce a SN Ia either directly or form a single massive WD first that eventually explodes after heating up its center.

The explosion itself will look quite similar in both cases, however, there are some side-effects that can be used to put constraints also on the progenitor systems.

One property of SN Ia that can be used in this way is the complete absence of hydrogen in SN Ia ejecta to the current detection limits. Upper limits on its amount derived from models of nebular spectra are as low as $0.01 M_{\odot}$.

At this point single and double degenerate scenarios make significantly different predictions. A double degenerate progenitor system contains no hydrogen at all, so the amount of hydrogen in the ejecta is essentially zero.

In the single degenerate scenario, however, at least the envelope of the companion star is made of hydrogen. So when the SN ejecta hit the companion star, they will strip material (mostly hydrogen) from it, that is subsequently mixed into the ejecta.

Previous studies that modelled the interaction of the SN ejecta with the companion star found that about $0.1 M_{\odot}$ of material is stripped, which is in contradiction to the observational constraints. However, these studies used a very simplified model of the progenitor system that did not include any effects of the previous binary evolution on the companion star.

We carried out a similar study, but used a sample of more realistic progenitor models with main sequence companion stars obtained from binary evolution calculations. We simulated the impact of a SN Ia, represented by the commonly used W7 supernova model, using a version of the smoothed particle hydrodynamics code GAD-

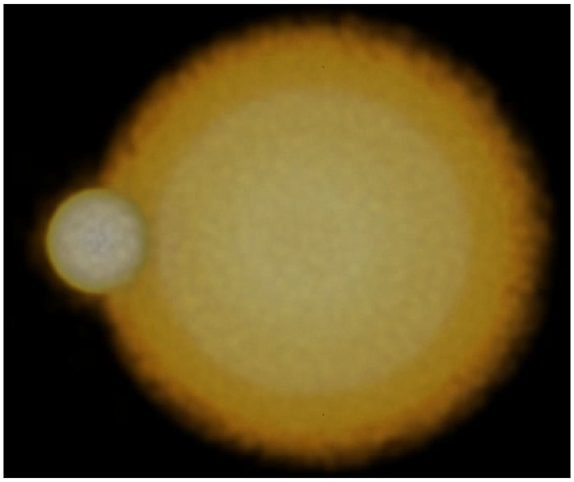

Figure 2.1: Volume rendered temperature of the supernova (right) and the companion star (left) shortly after the supernova blast wave hit the star.

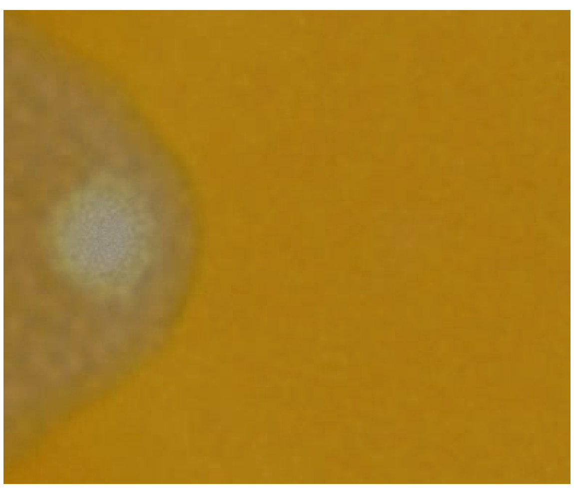

Figure 2.2: Volume rendered temperature of the supernova and the companion star after the shock wave passed the star. It is clearly visible how the star, which is an obstacle for the supernova blast, forms a conical hole in the ejecta.

GET3 with some modification to apply it to stellar objects.

The impact of the SN ejecta on the companion star triggers a shockwave that passes through the star and, in addition, heats up its envelope. We followed the simulation for a few dynamical timescales of the companion after the impact. After that we determined how much material was still bound to the star and how much was stripped and mixed into the SN ejecta. Two snapshots of one of these simulations are shown in figures 2.1 and 2.2.

We found that the amount of stripped material ranges from $0.01M_{\odot}$ to $0.06M_{\odot}$ which, within their errors, is not in contradiction to the observational limits.

The main difference to previous studies originates from the effects of binary evolution. During the accretion phase the companion star steadily looses mass from its envelope. As the timescale of the mass transfer is about an order of magnitude smaller than the Kelvin-Helmholtz timescale of the main sequence companion star, it is not able to relax and to adjust its density profile to its new mass. Therefore the star is significantly more compact at the time of the explosion than a similar isolated star of the same mass and composition. This leads to a considerable reduction of the amount of mass that is stripped by the supernova blast wave.

Our results also indicate that future observations, if they are at least $5-10$ times more sensitive to the amount of hydrogen in the SN ejecta, should be able to confirm or reject the single degenerate scenario as a possible progenitor system of supernovae of type Ia. (Rüdiger Pakmor, Fritz Röpke and Wolfgang Hillebrandt)

2.2 A close look at solar granulation

How would the surface of our Sun look like, if we had telescopes which have a resolution ten times that one of present instruments? Would the Sun look any different further inside? In an international collaboration scientists at the University of Vienna, Austria, and the Max Planck Institute for Astrophysics have used numerical simulations on high performance computers to answer this question. They found a highly turbulent flow showing ever more details hidden underneath the smooth looking surface which we know from images of our Sun in visual light.

Observations of the surface of our Sun reveal a

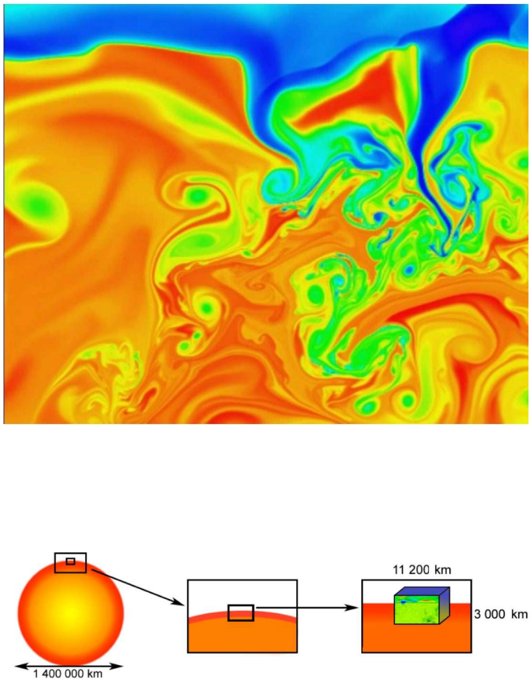

Figure 2.3: The figure shows a region 2600 km wide and 2000 km deep. Horizontal and vertical resolution are 3 km and 2 km, respectively. The region is embedded in a domain 11200 km wide and 3000 km deep simulated at a resolution of 12 km by 8 km. The upper panel shows the simulated region, the lower panel illustrates the scales. The quantity displayed is entropy. It is tightly related to temperature and allows tracing the origin of the gas. High entropy gas is colored in red and originates from further inside. Low entropy gas is colored in blue and has been cooled at the surface layers. Intermediate values are shown in green and yellow. The latter are also found at the transition between the visible layers (near the top) and the hidden layers underneath as a sharp, but smooth boundary within the uppermost part of the figure ([1]).

pattern of visually bright structures (the granules) embedded in a network of gas with a much lower visual brightness. On average such granules are about 1200 km wide. Within the granules gas is hotter than its environment. It moves upwards at some 2 km/s until radiation into space provides sufficient cooling. Pushed sidewards the cold and dense gas sinks downwards in a network surrounding the granules. The best instruments available for taking images of the solar surface can detect details as small as 70 km ([2][3][4]). At that resolution the granules appear remarkably smooth. This has also been found in numerical simulations of solar granulation at similar resolution. What if we looked at these layers, but were able to spot details as small as a few km? Since each granule is influenced also by its environment, numerical simulations of this process have to be performed for a much larger domain, more than 10000 km wide and 3000 km deep. Even on supercomputers a smaller region of interest has to be selected to predict the dynamical behavior of such tiny structures. This smaller region contains only a few granules. Its surroundings are simulated at lower resolution. Fig. 2.3 shows such a simulation, which has been performed taking into account only one horizontal direction. The solar surface is clearly visible as a vertically narrow and highly corrugated region which is thus located at various geometrical depths. Most small scale details are related to a few fronts moving upwards within the visible solar atmosphere. This picture agrees with images of the solar surface and physical explanations given for it in the literature, but here we look at that phenomenon at a much higher resolution. The region underneath the surface looks completely different: the longer the gas has had time to sink into the interior, the more details appear. The small scale structures mostly originate from shear stresses between the regions of upwards and downwards flowing gas.

Such small scale structures do not appear unless a minimum amount of resolution and advanced numerical methods are used for the simulations. This has been double-checked both with simulations at lower resolution and by using various numerical methods. The results just described are corroborated by the finding that once the resolution is high enough different numerical methods yield more and more similar results. Since the highly turbulent flow structures in Fig. 2.3 are hidden by layers of opaque gas (the visible solar surface), one has to look for indirect observational consequences. One possibility are oscillations and waves generated by the flow. The Sun is known to pulsate and these pulsations are the best "probe" available for the structure of the solar interior. They are (standing) sound waves trapped in the solar envelope. Most of the energy is transferred into these waves in the layers right underneath the solar surface, just where all the small scale structures appear (Fig. 2.3). An analysis of the simulations reveals numerous "acoustic events", pulses which are generated near regions where up- and downflows create large shearing forces and where regions of lower density are suddenly compressed. Fig. 2.4 shows an illustration of these pulses as black lines connecting locations which have identical differences between local and horizontally averaged pressure. These pressure fluctuations often travel non-aligned to the actual flow. The pulses cross each other, get damped or amplified, and some make their way up to the visible surface. How are they related to the

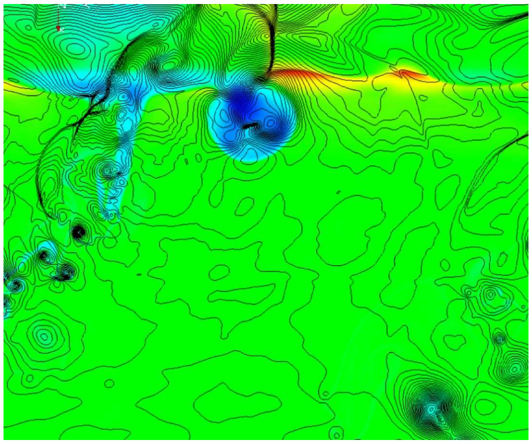

Figure 2.4: The figure shows the development of temperature in the same region for the same simulation as in Fig. 2.4, but at an earlier instant in time. The quantity shown is the difference between local temperature and horizontally averaged temperature (both on a logarithmic scale). Regions hotter than average appear in red, regions colder than average in blue, regions close to the average in green. Narrow black lines connect locations with identical difference of pressure to its horizontal average, a bit similar to a chart in a weather forecast. But note that here the vertical direction (X) indeed corresponds to the vertical direction in the simulation (Y is the horizontal direction, indicated by arrows near the top) and in a forecast chart isolines would connect locations of identical local pressure ([1]).

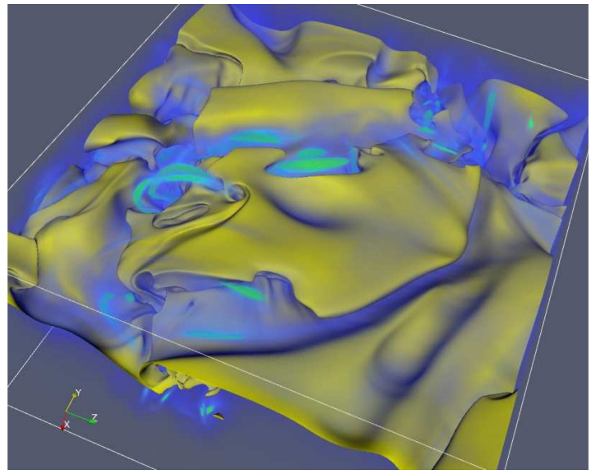

Figure 2.5: The figure shows a region 4000 km wide in each horizontal direction (Y, Z) and 2000 km deep (X). Horizontal and vertical resolution are 10 km and 7 km, respectively. The region is embedded in a domain 11200 km wide and 3000 km deep simulated at a resolution of 40 km horizontally and 28 km vertically. The dark yellow surface connects all points with a temperature of 8000 K. Volume rendering is used to visualize regions with large pressure gradients. The physical quantity chosen for this purpose is the norm (size) of the gradient of differences between local pressure and its horizontal average (both taken in logarithmic units). This way locations with strong local changes in pressure are shown in red. Moderate changes are in blue, while green and bright yellow denote values in between.

observed oscillations, which in fact take place at length scales of at least a few granules and larger?

To answer this question requires more realistic simulations which account for both horizontal directions. The restriction to two dimensions creates features which are not expected (nor observed) for real solar convection, such as the stable whirls notable in both Fig. 2.3 and Fig. 2.4 (which do not reach the surface). The computational requirements for such a three-dimensional simulation are considerable and to achieve the same resolution as in Fig. 2.4 means to push the top supercomputers of today to their very limits. Fig. 2.5 shows results from a first series of such simulations, at roughly one third of the resolution achieved in the case of two dimensions. The increase in complexity in the flow is evident by following the development from the initial stage (at a resolution which is effectively comparable to that one achieved in images of the solar surface by the most advanced instruments) to its final one. The smooth surface denotes a temperature region just underneath the visible layers of the Sun and its temporal development illustrates, how upflows decay (and reappear) in time and how their boundaries to downflow regions become disrupted by shearing. In time, fronts of strong pressure differences (yellow-red) appear particularly at the boundary regions of upflows (the interior part of the granules) and they move further upwards. The appearance of these phenomena and the drastic increase in complexity within the regions of strong downflows motivates simulations similar in resolution to those in Fig. 2.4 to clarify the role of shear stresses in the generation of sound waves in the Sun. These are now conducted as part of a computing project within the framework of DEISA and as part of another project at the Leibniz-Rechenzentrum (LRZ). However, already now it is clearly perceivable that what looks smooth from the outside at currently achievable observational resolution appears quite different, if studied with methods that can look underneath the solar surface at high resolution. (Friedrich Kupka and Florian Zaussinger)

2.3 Present-day cosmic abundance standard

The formation and evolution of galaxies, stars, interstellar gas and dust, planets, planetary systems, and even life are tightly related to the origin and evolution of the chemical elements and the cosmic cycle of matter. The principal reference for the chemical composition of cosmic matter has traditionally been established as that of our Sun because of the wealth of information that our star provides. Its chemical composition can be constrained by spectroscopic analysis of the photosphere, measurement of solar wind and energetic particles. Solar nebula abundances can be determined from primitive meteorites, so-called CI chondrites, which are unaltered since the formation of the solar system. Solar photospheric analyses are, however, challenging because of its complex convective nature. Recent 3D hydrodynamical simulations permit theory to be pushed to the present limits, providing the most precise solar values so far (e.g. Asplund and co-workers). Although helioseismic constraints and photospheric abundances remain to be reconciled, the solar abundances from the independent sources are in good agreement.

We may however ask whether a 4.6×10^9 yr old star formed far from its current location is indeed representative of the cosmic matter in the solar neighbourhood at present. Alternatively, unevolved stars of spectral types O9 to B2 are highly valuable as tracers for chemical abundances, providing simultaneously temporal (present-day) and local (birth place) information. They are young ($\sim 10^6$-10^7 yr), massive ($\sim$8-20 solar masses) and luminous ($\sim 10^4$-10^5 solar luminosities). In contrast to the Sun they are so short lived that they have no time to leave their birth place. A major advantage is their relatively simple photospheric physics - complications such as clumped stellar winds or convection are not an issue. Their atmospheres are represented well by classical hydrostatic plane-parallel 1D-models in radiative and local thermodynamic equilibrium. Moreover, they are unaffected by atomic diffusion that gives rise to peculiarities of metal abundances in many cooler stars. Slowly rotating stars are preferred as their photospheres should be essentially unaffected by mixing of nuclear processed material, such as CNO-cycled products.

As a consequence, early B-stars in the solar neighbourhood were subject to several studies in the past decades. Overall, a contradictory wide range of abundances by a factor 10 was found, about the range bridged by smooth Galactochemical evolution in the past $\sim$13 Gyr, when comparing with predictions from Chiappini and co-workers. The average metallicity was unexpectedly low, much lower than the then prevailing understanding of the solar chemical composition. Because of the expected chemical enrichment over the past 4.6 Gyr this was both surprising and difficult to explain. Hence, the impression arose that the solar neighbourhood is chemically highly heterogeneous and the Sun anomalously metal-rich compared to young stars – the latter was partially remedied by the new solar abundances from Asplund and co-workers. The previous findings are problematic in terms of Galactic chemical evolution. Dispersal of stellar nucleosynthesis products increases the metallicity over time and hydrodynamic mixing tends to homogenise the interstellar medium (ISM) locally. Characteristic timescales for homogenisation are short, ranging from 10^6-10^8 yr on scales of 100-1000 pc. In contrast to the young stars the interstellar gas shows a high degree of chemical homogeneity in the solar neighbourhood, with the scatter of mean abundances being 10%. However, the ISM gas phase is not suitable as a tracer for cosmic abundances because of selective depletion of elements onto dust grains.

Since a few years ago (in collaboration with N. Przybilla, Remeis Observatory Bamberg, University of Erlangen-Nuremberg) great efforts were made in order to improve the spectral modelling and the quantitative analysis of early B-type stars. Investigation of several potential sources of systematic errors was decisive in order to improve the accuracy of stellar parameters and chemical abundances. State-of-the-art model atoms for non-local thermodynamic equilibrium (non-LTE) line-formation calculations of several elements have been constructed based on recently computed radiative and collisional cross-sections for atomic transitions (in collaboration with K. Butler, Munich Observatory, LMU). The model calculations utilise a robust and at the same time versatile non-LTE approach based on line-blanketed LTE model atmospheres and non-LTE line-formation calculations.

Using the FEROS spectrograph on the 2.2-m Max-Planck-ESO telescope at La Silla very high-quality spectra at signal-to-noise ratio $\sim$500-800 and resolving power 48 000 were taken. A representative sample of six unevolved early B-type stars located in nearby OB associations and the field were

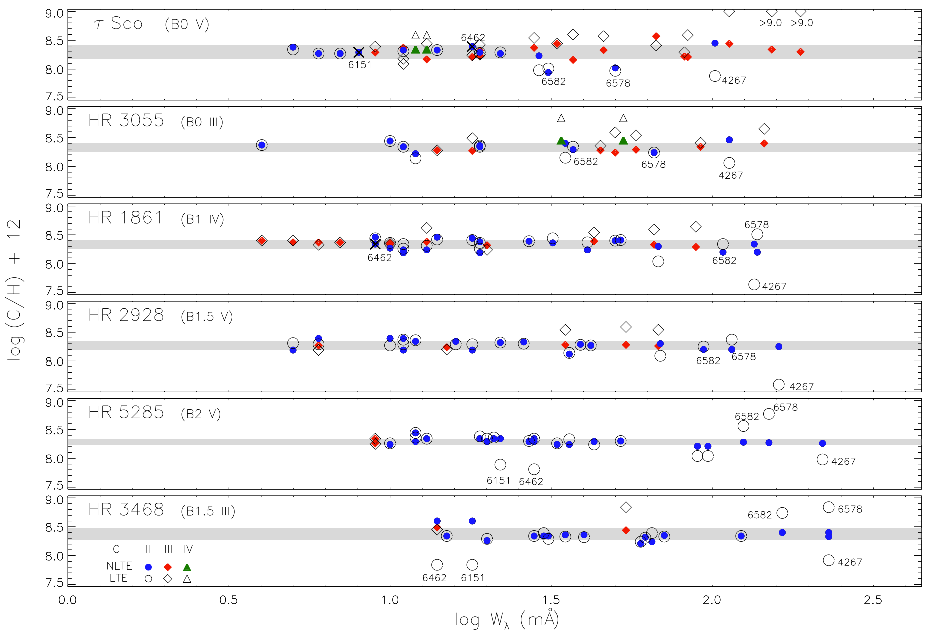

Figure 2.6: Non-LTE and LTE carbon abundances derived from line profile fits vs. equivalenth width of individual lines from 3 ionization stages. The grey rectangles correspond to the 1σ-uncertainties of C abundance from the line-to-line scatter. The average carbon abundance from the six stars is displayed in Fig.2.7 for comparison with other work.

analysed, covering temperatures from ∼21 000 to 32 000 K. A self-consistent iterative spectral analysis technique was implemented, using multiple independent spectroscopic indicators for a robust determination of the atmospheric parameters, effective temperature and surface gravity: all Stark-broadened Balmer lines and ionization equilibria of He I/II, C II/III/IV, O I/II, Ne I/II, Si II/III/IV, Fe II/III. Results from the analysis of carbon lines are displayed in Fig. 2.6.

For the first time the quantitative analysis of the optical to near-IR spectra of this kind of star gives consistent results at high precision, reproducing all modelled lines of several elements in different ionization stages simultaneously. Essential in this is the elimination of systematic errors, e.g. by the critical choice of input atomic data and a self-consistent temperature determination via multiple ionization equilibria, among 10 other non-negligible sources of systematics. The self-consistent analysis provides atmospheric parameters and chemical abundances with unprecedented accuracy, with uncertainties as low as ∼1% in effective temperature, ∼10% in surface gravity and ∼20% in abundance, with reduced systematic error. This improves significantly on results from previous studies, which typically give uncertainties of 5-10%, ∼25% and a factor ∼2-3, respectively.

The resulting chemical composition is found to be more metal-rich and much more homogeneous than indicated by previous work (Fig. 2.7). A rms scatter of ∼10% in abundances found for the six stars, which is confirmed by six evolved stars with similar masses (BA-supergiants) by Firnstein & Przybilla (2006), agrees with that reported for the ISM gas-phase. Good agreement with solar photospheric abundances from 3D radiative-hydrodynamical simulations carried out by Asplund and collaborators of the solar atmosphere is obtained. Our oxygen abundance is supported by a new independent study of early B-type stars in the Orion association by Simon-Diaz (in prep.).

The derived abundances are useful to constrain the composition of the ISM dust-phase. The amount of material incorporated into dust grains is determined by the difference between our B-star abundances and the ISM gas-phase abundances. The latter were determined by several groups, as traced by resonance lines in UV spectra of different stars. Accordingly, a composition poor in carbonaceous material but rich in oxygen and refractory elements that compose silicates is found.

We further combine our B-star abundances with data for S, Cl and Ar from the analysis of the Orion nebula (Esteban et al. 2004) and solar meteoritic values for other abundant refractory ele-

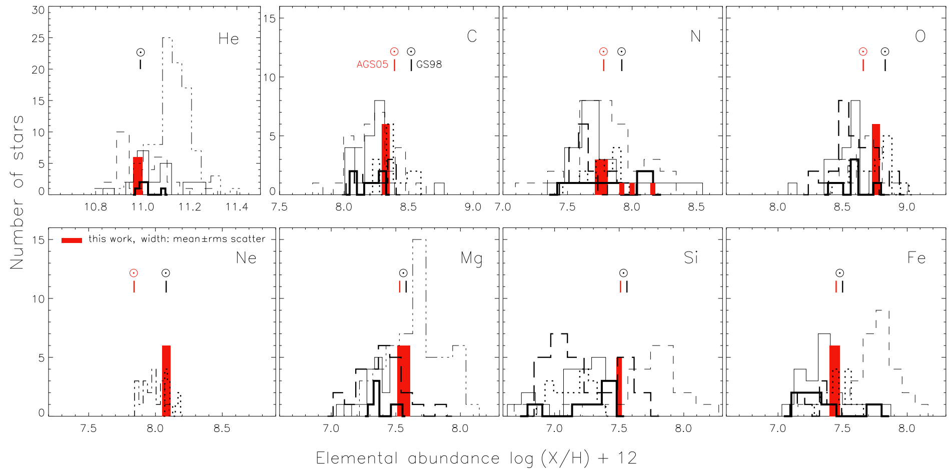

Figure 2.7: Comparison of chemical abundances of unevolved early-B stars in the solar neighbourhood from our work (red bars) and previous work (black histograms) for different elements. Solar abundances (without correction by diffusion: +0.04 dex) ⊙: Asplund, Grevesse & Sauval (2005) in red and Grevesse & Sauval (1998) in black.

ments to derive mass fractions for hydrogen, helium and the heavier elements: X = 0.715, Y = 0.271 and Z = 0.014. A cosmic abundance standard for the present-day solar neighbourhood is proposed. These abundances are our recommended values for a wide range of applications requiring an accurate knowledge of the chemical composition at present (e.g. for opacity calculations), examples being models of star and planet formation, stellar evolution of massive stars or the empirical calibration of Galactochemical evolution models. (Fernanda Nieva and Martin Asplund)

2.4 Hydrodynamic simulations on a moving mesh with the AREPO code

When only dark matter is considered, the current generation of cosmological codes has reached a high-degree of accuracy, allowing an impressive dynamic range in high-resolution studies of dark matter clustering and galaxy formation. This constitutes important progress, which is in part due to the fact that there is little doubt about what is required to achieve high accuracy in collisionless simulations; this is simply an accurate gravitational force calculation, accurate time integration, and use of a large number of particles.

However, the situation is different for hydrodynamic cosmological simulations. Here a variety of fundamentally quite different numerical methods are in use, the most prominent ones are Lagrangian smoothed particle hydrodynamics (SPH) and Eulerian mesh-based hydrodynamics with adaptive mesh refinement (AMR). An issue of great concern is that these methods sometimes yield conflicting results even for basic calculations that only consider non-radiative hydrodynamics. Perhaps the most famous example is the Santa Barbara cluster comparison project, and the systematic offsets in the core entropy that are apparently produced between SPH and AMR codes. This uncertainty compromises the trust one would like to have in the predictive power of ab-initio hydrodynamical cosmological simulation, especially when applied to the full problem of galaxy formation, where additional processes such as radiative cooling, star formation and feedback must be included. The latter bring about significant additional complexity, and further extend the dynamic range that needs to be addressed.

It has become clear over recent years that both SPH and AMR suffer from fundamental problems that make them inaccurate in certain regimes. SPH codes have comparatively poor shock resolution, and offer only low-order accuracy for the treatment of contact discontinuities. Worse, they appear to suppress fluid instabilities under certain conditions, as a result of a spurious surface tension and inaccurate gradient estimates across density jumps. While is is possible to alleviate these effects by introducing artificial heat conduction or mixing terms, it is still unclear whether any of these fixes provides a universal solution that gener-

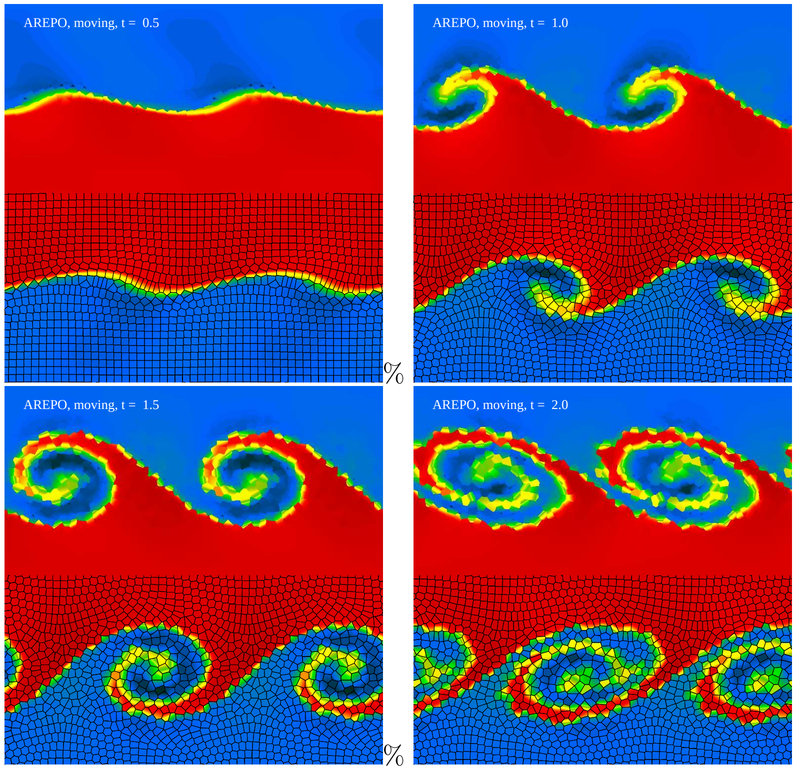

Figure 2.8: The four panels show the time evolution of a Kelvin-Helmholtz instability in a low resolution (50×50 cells) test calculation with the moving-mesh method. The central strip of gas moves to the right with velocity $v_x = 0.5$ and is twice as dense as the rest of the gas, which moves to the left with $v_x = -0.5$. Each panel gives the density field at different times (at $t = 0.5$, 1.0, 1.5 and 2.0), with the Voronoi mesh overlaid in black in the lower half of the box. It is nicely seen that the mesh geometry stays regular and does not suffer from mesh twisting, despite the strong shear present in this problem.

ally improves the results without introducing significant problems in other situations.

Eulerian methods are the traditional method to solve the system of hyperbolic partial differential equations that constitute ideal hydrodynamics. There are decades of experience with these methods in computational fluid dynamics, and accurate Godunov schemes exist which offer high-order spatial accuracy, have negligible postshock oscillations, and low numerical diffusivity. However, fundamental problems remain with these methods as well. Perhaps the most serious one is their lack of Galilean-invariance, making the results sensitive to the presence of bulk velocities. This is a source of substantial concern in simulations of galaxy formation, where galaxies move with large speeds relative to each other, speeds that are often orders of magnitude larger than the sound speed of the dense interstellar medium that one wants to follow hydrodynamically. Similarly, it is also challenging with AMR to follow a highly refined region that moves with large velocity relative to the reference frame adopted for the calculation as a whole, because refinement criteria that correctly 'anticipate' the motion of a system across a grid are difficult to construct. Eulerian methods have also problems to properly resolve flows where the kinetic energy is much larger than the thermal energy and both the pre- and postshock gas move supersonically with respect to the grid. This situation is ubiquitous in cosmological applications.

In order to overcome these problems in the two prevailing hydrodynamic methods used in cosmology, we have developed a novel formulation of numerical hydrodynamics, based on an *unstructured mesh* that is allowed to *move with the flow*. In this approach, the mesh is defined as the Voronoi tessellation of a set of discrete mesh-generating points, which are in principle allowed to move freely. Using the Voronoi cells as principle control volumes, a finite-volume volume discretization of the Euler equations can be consistently defined. Most importantly, due to the mathematical properties of the Voronoi tessellation, the mesh contin-

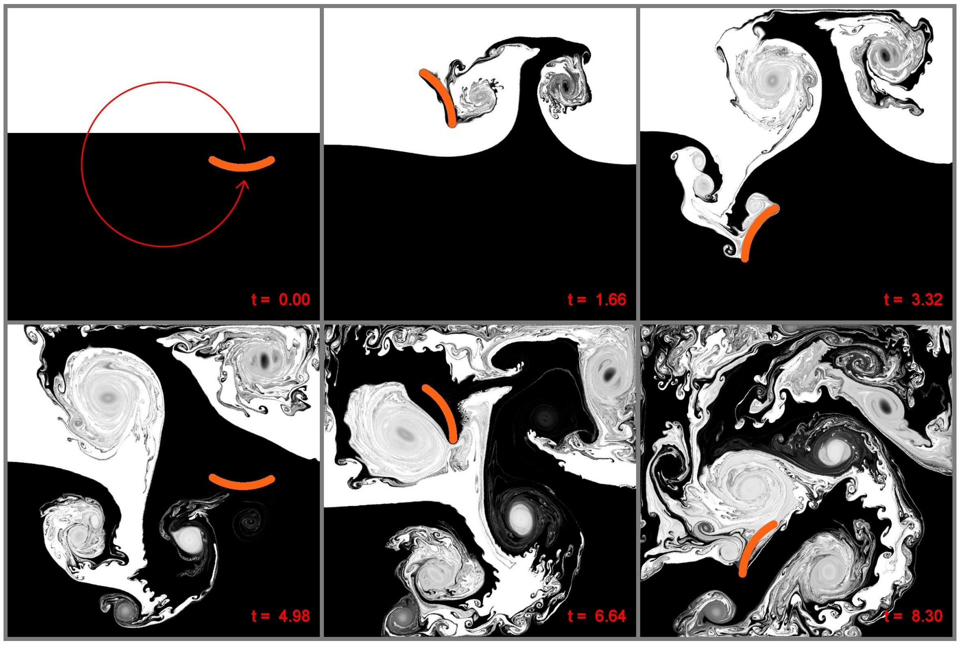

Figure 2.9: Time evolution of the mixing of two fluids induced by the motion of a solid object. This test illustrates the ability of AREPO to cope with arbitrarily curved, moving boundary conditions. As illustrated, the orange 'spoon' is moved on a circular path, through a two-phase gaseous medium that is initially at rest. The mixing is shown in terms of a tracer dye that is advected with the flow, and which was given an initial value of 1 (white) in the lower-density top phase, and a value of 0 (black) in the higher-density lower phase. Each frame shows the value of the dye in grey-scale, at different times as labeled. The square domain was initially populated with a 768×768 mesh-generating points on a Cartesian grid, and has reflective boundary conditions at the outer walls.

uously deforms and changes its topology when the points move, without ever leading to the dreaded mesh-tangling effects that are the curse of previous moving-mesh methods.

Our new method therefore retains the principal advantage of the mesh-free SPH approach: It offers an unrestricted and continuous adjustment of its resolution to local clustering. In addition, the new method is Galilean-invariant when the mesh is moved along with the flow. There are no preferred directions in it, unlike in Cartesian grids. Thanks to its Lagrangian nature, mesh refinement is normally not needed when one wants to maintain roughly constant mass resolution, but if desired, the Voronoi mesh may also be adaptively refined or derefined. With these properties, the moving-mesh approach represents a compromise between SPH and AMR. It inherits the automatic adaptivity, geometric flexibility and Galilean-invariance of SPH, while it shares the high-accuracy treatment of shocks, shear waves, and fluid instabilities, as well as the low noise and the absence of artificial viscosity, with AMR.

This novel approach for hydrodynamics has been realized in the new cosmological simulation code "AREPO" developed at MPA. In Figure 2.8, we show an example calculation with this code, the formation of Kelvin-Helmholtz instabilities at the interface between two phases of a gas that are in pressure equilibrium and stream past each other. Such a shear flow is known to be unstable to the development of wave-like Kelvin-Helmholtz billows that start to mix the fluids. We note that the growth of this fluid instability is suppressed in SPH for numerical reasons, due to a spurious surface tension that develops across contact discontinuities with large density jumps. However, the AREPO code does not suffer from this problem.

A further advantage of the new moving-mesh method lies in its ability to easily handle boundary conditions at curved surfaces that can be stationary, move with the flow, or are governed by a prescribed velocity field. An example is shown in Figure 2.9, where we show the time evolution of the gas motions that develop when a solid object is moved through a two-phase fluid that is initially at rest. This is akin to stirring a mug of coffee and cream with a spoon.

Besides hydrodynamics, the AREPO code offers a high-resolution gravitational solver (a TreePM scheme) that can adjust its resolution continuously to the clustering occurring in cosmic structure formation. The code is fully parallelized for distributed memory architectures, and allows the use of individual timesteps. Due to this combination of features, the AREPO code is an interesting and competitive tool for future applications in cosmology, as well as in related fields. (Volker Springel)

2.5 Dark Matter Astronomy

In the 75 years since Zwicky first pointed out the need for substantial amounts of unseen material in the Coma cluster, the case for a gravitationally dominant component of non-baryonic dark matter has become overwhelmingly strong. Particle physics has suggested many possible Cold Dark Matter (CDM) particles beyond the standard model. Two promising candidates are WIMPs (weakly interacting massive particles), and axions. Among the WIMPs, the lightest supersymmetric particle, the neutralino, is currently favoured as the most likely CDM particle, and the case will be enormously strengthened if the LHC confirms supersymmetry. However, ultimate confirmation of the CDM paradigm can only come through the direct detection of the CDM particles themselves.

Event rates in direct detection experiments are determined by the local DM phase-space distribution at the Earth's position. The relevant scales are those of the apparatus and so are extremely small from an astronomical point of view. As a result, interpreting null results as excluding specific regions of candidate parameter space must rely on (strong) assumptions about the fine-scale structure of phase-space in the inner Galaxy. In most analyses the dark matter has been assumed to be smoothly and spherically distributed about the Galactic Centre with an isotropic Maxwellian velocity distribution or a multivariate Gaussian distribution. The theoretical justification for these assumptions is weak, and when numerical simulations of halo formation reached sufficiently high resolution, it became clear that the phase-space of CDM halos contains considerable substructure, both gravitationally bound subhalos and unbound streams. In principle, this could have substantial consequences for the ability of direct detection experiments to constrain particle properties.

Until very recently, simulation studies were unable to resolve any substructure in regions as close to the Galactic Centre as the Sun. This prevented realistic evaluation of the likelihood that massive

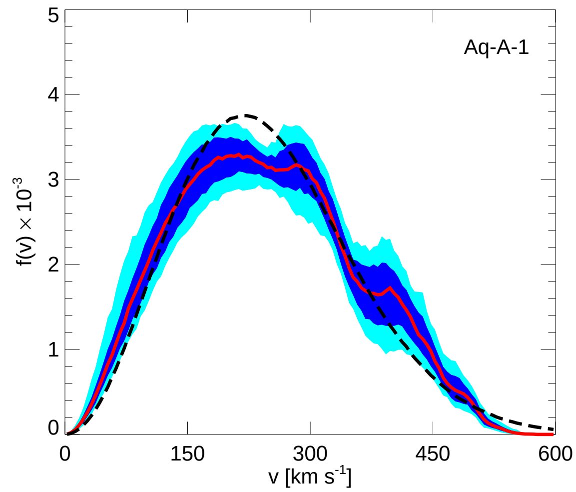

Figure 2.10: Velocity modulus distributions for dark matter particles in 2 kpc boxes at different positions at the Solar circle centred between 7 and 9 kpc from the centre of a simulated halo. At each velocity a thick red line gives the median of all the measured distributions, while a dashed black line gives the median of all the fitted multivariate Gaussians. The dark and light blue contours enclose 68% and 95% of all the measured distributions at each velocity. The bumps seen in the distribution for a single box are clearly present with similar amplitude in all boxes, and so also in the median curve.

streams, clumps or holes in the dark matter distribution could affect event rates in Earth-bound detectors, and so weakened the particle physics conclusions that could be drawn from null detections.

Scientists from MPA and from other institutions of the Virgo Consortium have now performed very high resolution simulations of Milky Way-like dark matter halos in order to get more insight into the expected detector signals. This so-called Aquarius Project provides the first reliable characterisation of the dark matter phase-space distribution near the Sun and so of the detector signals to be expected in WIMP and axion searches.

The group began by looking for small-scale structure in the density distribution of dark matter. For all of their simulations the densities at Galactic radii similar to that of the Sun are very well fit by a smooth model where density falls as a power of radius and is constant on ellipsoidal isodensity surfaces. From the quality of the fits one can infer with 99.9% confidence that the local density near the Sun differs from the mean over its ellipsoidal shell by less than 15% In other words, the dark matter distribution near the Sun is very smooth. The chance that a dark matter detector will be hit by a subhalo is well below 0.01%. Thus it is safe for experimentalists to neglect small-scale density structure when modelling the signals to be seen in their detectors.

Another important ingredient in predicting detector rates is the dark matter velocity distribution. Analysis of the simulations showed that this distribution is also predicted to be very smooth, with no sign of massive streams or significant contributions from subhalos. The standard assumption of a Maxwellian velocity distribution is not a good fit to the simulated halos, because their velocity distribution is clearly anisotropic. The velocity ellipsoid at each point aligns very well with the shape of the halo. The simulations are better fit by a multivariate Gaussian, but even this description does not reproduce the numerical data perfectly. In particular, the magnitude of the velocity vector shows marked deviations from such smooth model predictions, and its distribution differs from a multivariate Gaussian model in a similar way in all the simulated halos. The most interesting feature is that the velocity distributions shows features ("bumps") which are stable in time and are reproduced from place to place within a given halo, but which differ between different halos. This is illustrated in Fig. 2.10 for one of the Aquarius halos is shown. The red line shows the median of the distributions found at a variety of different locations all at roughly the solar distance from the centre, while the blue contours represent the 68% and 95% scatter among these distributions. The black line is the median of the best-fit multivariate Gaussian representations of these local velocity distributions. Bumps and dips are clearly visible and are reproduced at different locations.

It turns out that these features are related to the detailed formation history of each individual halo. This can be demonstrated explicitly by computing a mean phase-space density distribution as a function of energy f(E) and splitting it up into contributions from particles that first became part of the halo at different times. The left panel of Fig. 2.11 shows results for a halo with a very "quiet" merger history. Material accreted at different times is arranged in a very orderly way in energy space. All the most strongly bound particles were accreted before redshift 5, and material accreted at successively later times forms a series of "shells" in energy space. The most weakly bound wiggles are due entirely to the most recently accreted material, and progressively more bound bumps can be identified with material accreted at earlier and earlier times. In contrast, the right panel shows a different halo that had a very "active" recent history, with a major merger between z=0.75 and z=0.68. The correspondence between binding energy and epoch of accretion is much less regular in this case, and much of the most bound material actually comes from the massive object which fell in near z=0.7. It is also striking that many of the wiggles in this object are present in material that accreted at widely separated times, suggesting that they may be non-steady coherent oscillations rather than stable structures in energy space. In both cases, features in the phase-space density distribution can be identified with particles accreted at certain epochs, and in both cases the most weakly bound particles were added only very recently. The phase-space density of this material is very low, so it contributes negligibly to the overall local dark matter density.

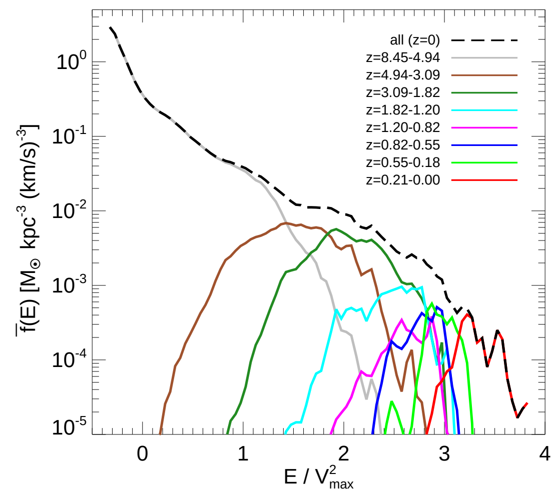

Figure 2.11: Contributions to the present-day mean phase-space density distribution from particles accreted at different epochs (indicated by different colours). The plot shows the build-up of the mean phase-space density distribution for a halo with a quiescent formation history and no recent mergers. It is clear that material accreted at specific times is responsible for some of the bumps seen in the present-day mean phase-space density distribution.

It is interesting to ask whether the features in the velocity and energy distributions could be observed with Earth-bound detection experiments. If the simulations are used to predict detector signals for WIMP and axion searches, they predict that WIMP recoil spectra will deviate by about 10% from predictions based on the best-fit multivariate Gaussian model. The energy dependence of these deviations looks similar in all six halos; especially at higher binding energies. Axion detectors may also see interesting structure. The spec-

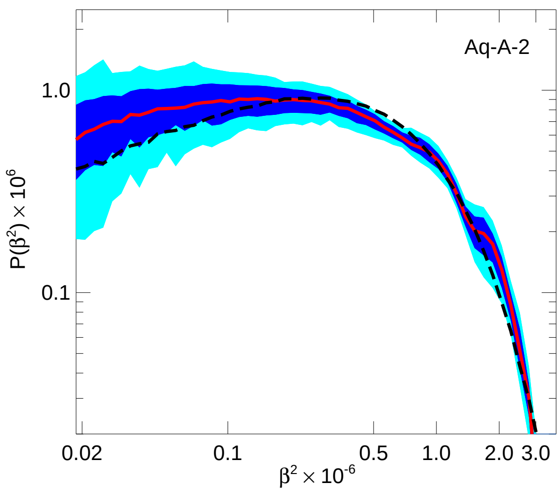

Figure 2.12: Predicted axion spectra at the same set of locations for which the velocity distributions were shown in Fig. 1. The x-axis is proportional to axion energy and to the frequency of the tuned microwave detection cavity while the y-axis is proportional to the power P developed in the detector cavity. This is the kind of frequency spectrum predicted for an axion search experiment like ADMX. This spectrum is moderately well reproduced by a multivariate Gaussian model, but significant differences remain. The maximum in the power is at lower frequencies in the simulation than in the model, and the bumps already seen in the velocity and energy distributions are clearly visible in the spectrum as well. The lines and contours correspond to those of Fig. 2.10.

tra are predicted to be smooth without any sign of massive streams, but they show characteristic deviations from those predicted by a multivariate Gaussian model. The power at low and high frequencies is greater than predicted, and the bumps from the phase space energy distribution also show up quite clearly in the axion spectra (see Fig. 2.12). These effects are all driven by long-lived structure in the energy distributions of particles; individual subhalos or streams have no measurable effect in any of the six Aquarius halos. Nevertheless, the bumps should be easily detectable once direct DM detection has become routine. This would allow astronomers to study the dark matter assembly history of the Milky Way directly. A new field, "dark matter astronomy", will then emerge. (Mark Vogelsberger, Amina Helmi, Simon White and Volker Springel)

2.6 Constraints on How Black Holes Grow in Nearby Galaxies

Large surveys of active galactic nuclei (AGN) are able to teach us a great deal about the growth of super-massive black holes in galaxies as a function of cosmic time. The majority of work in the field has focused on the evolution of the quasar population. Quasars are the most luminous AGN in the Universe, outshining their host galaxies by many orders of magnitude in luminosity. By comparing quasar counts at different redshifts to the mass and number densities of black holes in the present-day Universe, one can derive constraints on the radiative efficiencies and lifetimes of these systems. There is now general consensus that optically luminous quasars are radiating close to their Eddington limit, have short($\sim 10^7$ yr) lifetimes, and in total account for a sizeable fraction of the total mass density in black holes at the present day.

By number, however, quasars only account for a small fraction of the total AGN population. Much effort at the MPA has gone into studies of complete samples of AGN in the local Universe. These studies have taught us that the fraction of AGN in massive galaxies with $> 10^{10.5} M_\odot$ galaxies is very high (> 50 %) and that the AGN population as a whole spans a large range in Eddington ratios. In lower-luminosity AGN, the active nucleus does not outshine the underlying host galaxy, so one can carry out joint analyses of the accretion rate as a function of the physical properties of the host, and attempt to figure out which processes may be involved in triggering accretion onto the central black hole. Such studies have demonstrated that black hole growth is generally more rapid in low-redshift galaxies with younger stellar populations. The average ratio between the mass stars forming in the bulge and the mass being accreted by the black hole is ~ 1000, which is very similar to the ratio between bulge mass and black hole mass in present-day inactive elliptical galaxies and bulges. This provides important confirmation that bulge formation and black hole growth are indeed connected, at least in an average sense.

It is important to try and pinpoint which physical mechanisms are responsible for the link between back hole growth and star formation in the host galaxy. One idea that has gained considerable popularity in recent years is that black hole growth and star formation are both triggered during interactions between two or more galaxies. The idea is

Figure 2.13: This artist's illustration shows two young galaxies in the process of merging. This picture illustrates the popular theoretical notion that the merger has triggered a prodigious burst of star formation and is providing fuel for the growth of the galaxies' central supermassive black holes.

that gravitational torques that arise during galaxy-galaxy mergers or interactions drive gas into the nuclear regions of galaxies, where it is able to fuel a central starburst and also accrete onto the black hole. It is possible to model these processes in considerable detail using numerical simulations. In more recent simulations, some of the energy of the accreting black holes couples to the surrounding gas, and black hole growth eventually shuts down when the feedback energy is sufficient to unbind the reservoir of gas and blow it out of the galaxy entirely. In this picture, growth of the black hole is responsible for the eventual death of its galactic host.

Observationally, there is still considerable debate as to whether any link exists between mergers/interactions and accretion onto the black hole. The best constraints again come from studies of large samples of low redshift AGN. Scientists from the MPA and JHU have been exploiting the sheer statistical power of these large samples to pinpoint whether there is any significant boost in the accretion rate onto the central black hole when two galaxies come into close contact. On scales less than 100 kpc, it was found that the amplitude of the two-point correlation function exhibits a strong dependence on the specific star formation rate of the galaxy, but there was no similar dependence on the black hole accretion rate (see Figure 2.14). A variety of additional statistical tests confirmed the basic conclusion that whereas the presence of a close companion is associated with enhanced star formation, there is no evidence that black hole growth is boosted by a near neighbour.

In collaboration with scientists at JHU, , "lopsidedness" in the stellar light distribution was also explored as a signpost of interactions and mergers. Large-scale asymmetries in the stellar mass distribution in galaxies are believed to trace non-equilibrium situations in the luminous and/or dark matter component of galaxies. The MPA/JHU team used the m=1 azimuthal Fourier mode of the light distribution to probe the link between interactions and AGN activity. Once again a clear link between lopsidedness and star formation was found. However, it could be demonstrated that if AGN and non-AGN samples are matched to have the same stellar masses, structural properties and central stellar populations, there is no difference in the lopsidedness of the light distribution between the active and non-active galaxies.

In summary, therefore, mergers and interactions are clearly not instrumental in fueling accretion onto the central black holes of nearby galaxies. Other mechanisms must be at work in fuelling black hole growth in the local Universe. Motivated by these results, MPA scientists have recently taken a more careful look at the distribution of accretion rates in nearby black holes and have discovered that there appear to be two distinct regimes of black hole growth in nearby galaxies (see Figure 2.15).

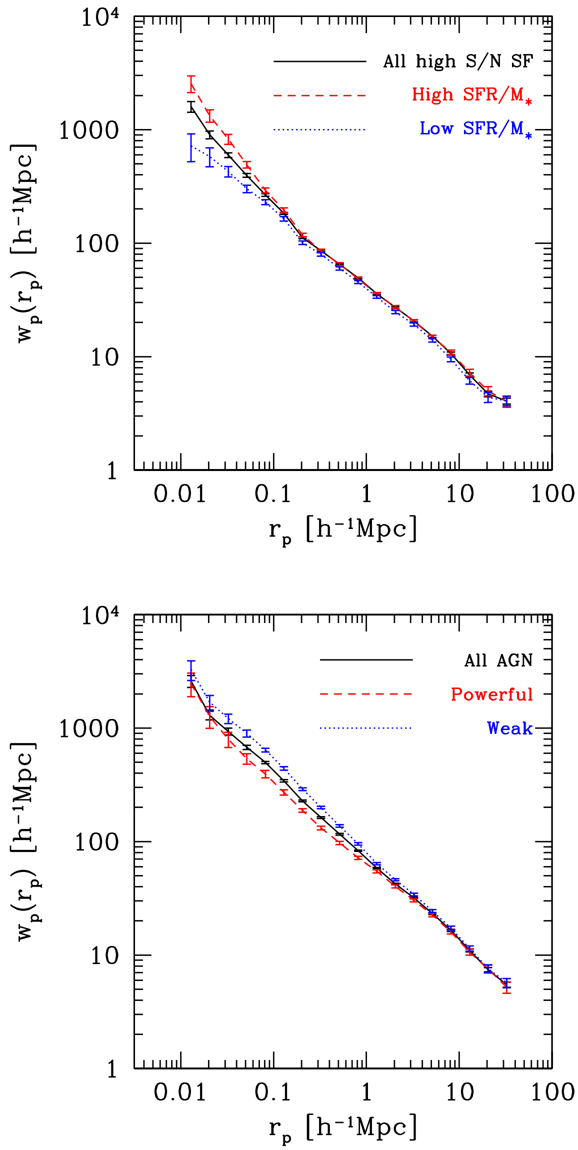

Figure 2.14: *Upper:* The two-point correlation function of galaxies split according to their specific star formation rate, showing that more strongly star-forming galaxies are more strongly clustered on scales less than 100 kpc. *Lower:* The two-point correlation function of galaxies split according to accretion rate onto the central black hole, showing that galaxies with more strongly accreting black holes are slightly more weakly clustered.

One mode was associated with galaxy bulges that are undergoing significant star-formation. More quantitatively, these are bulges in which the present stellar mass can be formed at the current star-formation rate on a timescale of-order the Hubble time. For these black holes, the distribution of the Eddington-ratio (L/L_{Edd}) takes a log-normal form that is universal with respect to both the mass of the black hole and the current star formation rate. This regime dominates the growth of black holes with present-day masses less than $\sim 10^8$ $M_\odot$. The other mode is associated with galaxy bulges with little or no on-going star-formation. In these systems, the formation of the stars in the bulge occurred long ago. For this population of black holes, the distribution of the Eddington-ratio is a power-law with a universal slope, but with a normalization that depends on the age of the stellar population. It could be shown that the slope and age-dependence of the normalization are predicted by a simple model in which the black hole accretes on-average ~ 0.3 to 1% of the mass lost by evolved bulge stars. This regime dominates the growth of the more massive black holes ($> 10^8$ $M_\odot$), the population with an insignificant present-day growth rate.

It was also argued that the log-normal Eddington ratio distribution functions for young galaxies are inconsistent with catastrophic feedback from the black hole that operates on the scale of the whole galaxy (or even of the bulge). Instead, it is likely that the log-normal distribution of the Eddington ratio is set by a long-running competition between the sporadic supply of cold gas from the bulge to the black hole and subsequent feedback that operates locally (speculatively, within the sphere of influence of the black hole $r < GM_{BH}/\sigma^2_{bulge}$). In the log-normal regime, accretion onto the black hole is apparently not limited by the global supply of gas in the galaxy. This result helps us to understand why there is no connection between mergers/interactions and black hole accretion rate in AGN in the local Universe. Galaxy-galaxy interactions drive gas from the outer disk into the central kiloparsec of the galaxy, where it can fuel a starburst. However, this increase in gas supply on kiloparsec scales has no significant impact on the accretion onto the central black hole. Once the gas runs out entirely, then the black hole growth appears to be regulated by the rate at which evolved stars lose their mass.

The picture that appears to emerge from these results is thus very much a "passive" one, seemingly at odds with theoretical models where violent processes – interactions, mergers and explosive feedback – regulate the growth of galaxies and their central supermassive black holes. It remains to be seen to what extent the lessons we have learned about nearby AGN will still apply at higher redshifts. So far, very large and complete samples of accreting black holes can only be studied at low redshifts, but as instrumentation and telescopes improve, so too will our knowledge of how galaxies and black holes have co-evolved across cosmic time. (Guinevere Kauffmann and Cheng Li)

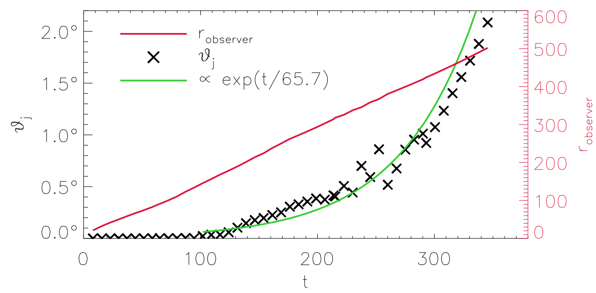

Figure 2.17: Amplitude of the perturbations as seen by an observer moving with the flow, just behind the jet front. The instability grows exponentially with the growth time being of the order of the time needed by an Alfvén wave to cross the jet.

2.7 Kink instabilities in magnetically driven jets

Collimated outflows of plasma, also known as jets, exist in a variety of astronomical objects: at the birth of a star, when the protostar grows from the gas cloud in which it was formed, at the end of the life of a very large star, when its core collapses to a black hole and emits flashes of gamma rays, and at the center of galaxies, where supermassive black holes devour nearby matter. All these phenomena are associated with rotating objects (stars, black holes, accretion disks) which possibly harbor magnetic fields within themselves and/or their environment. The rotation can drive an outflow by twisting the magnetic field. The magnetic field thus acts as an agent by which the rotational energy of the "central engine" is made available for the propulsion of jet.

The huge range of physical length scales involved in the evolution of astrophysical jets, from their launching up to where they emit light, makes their simulation a daunting task, especially so if the problem is to be treated realistically by taking all

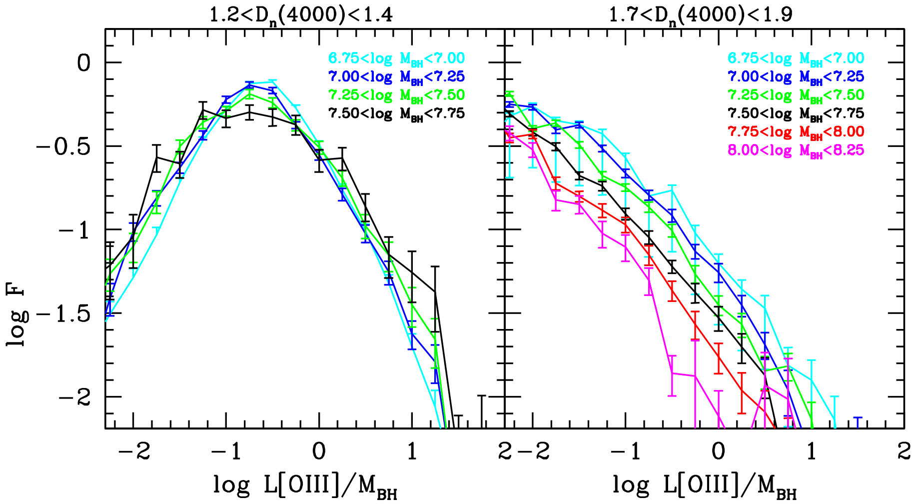

Figure 2.15: The two regimes of black hole growth in nearby galaxies: (a) the log-normal regime (left), where the Eddington ratio distribution is peaked at a few percent of Eddington and is independent of both black hole mass and the age of the stellar population, (b) the power-law regime, where the Eddington ratio distribution has a universal slope, but an amplitude that depends on the age of the stellar population.

three dimensions into account. For optimum computational efficiency, R. Moll (with H. C. Spruit and M. Obergaulinger) invented a numerical grid adapted to the problem (a spherical, logarithmically expanding grid). In this way, simulations of magnetically driven jets could be done which cover about three orders of magnitude in physical scales, with the jet expanding about two orders of magnitude in lateral direction. The simulations show the acceleration phase as well as the evolution past the so-called Alfvén surface. The resulting magnetic field has a high twist, see Fig. 2.16.

The high twist in the magnetic field makes the jet unstable against kink-like perturbations. This is akin to an overtwisted rubber band that finally snaps aside, thereby releasing part of the accumulated energy. The kinks grow while moving with the flow (Fig. 2.17) and the jet becomes helically deformed. The degree of instability was found to be dependent on the variation of the twist with distance from the central axis, with a uniform twist being especially unstable, and to the variation of the opening angle of the jet with distance from the launching site (which is predetermined by the shape of the initial magnetic field), with a "collimating" jet (one in which the opening angle decreases with distance) being more prone to instabilities.

The simulations also demonstrate how the instabilities lead to the dissipation of the twisted component of the magnetic field, i.e. the component which is responsible for the instabilities. The free energy stored in the twist gets released in the process, heating the plasma and disturbing the path of the jet, see Fig. 2.18. This may explain the structures found in observations of real jets, e.g. the knots and wiggles seen in jets from protostars. The results also improve our understanding of the non-visible region close to the central jet engine, where magnetic dissipation can change the jet's dynamical properties (Reiner Moll).
Animated plots can be found at *http://www.mpa-garching.mpg.de/∼ rmo/jb08/index.html*

2.8 Measuring the non-thermal pressure in early type galaxy atmospheres

Giant elliptical galaxies, consisting of up to a trillion (10^{12}) stars, have all the characteristics of old objects in the Universe, which have not changed much during the last few billion years. The stars in these galaxies are very red (old) and almost perfectly spherical appearance of galaxies in optical images suggests that we are dealing with steady systems and a mighty machinery of classic mechanics is ideally suited to describe the motion of stars in them. In particular, if we know the velocity

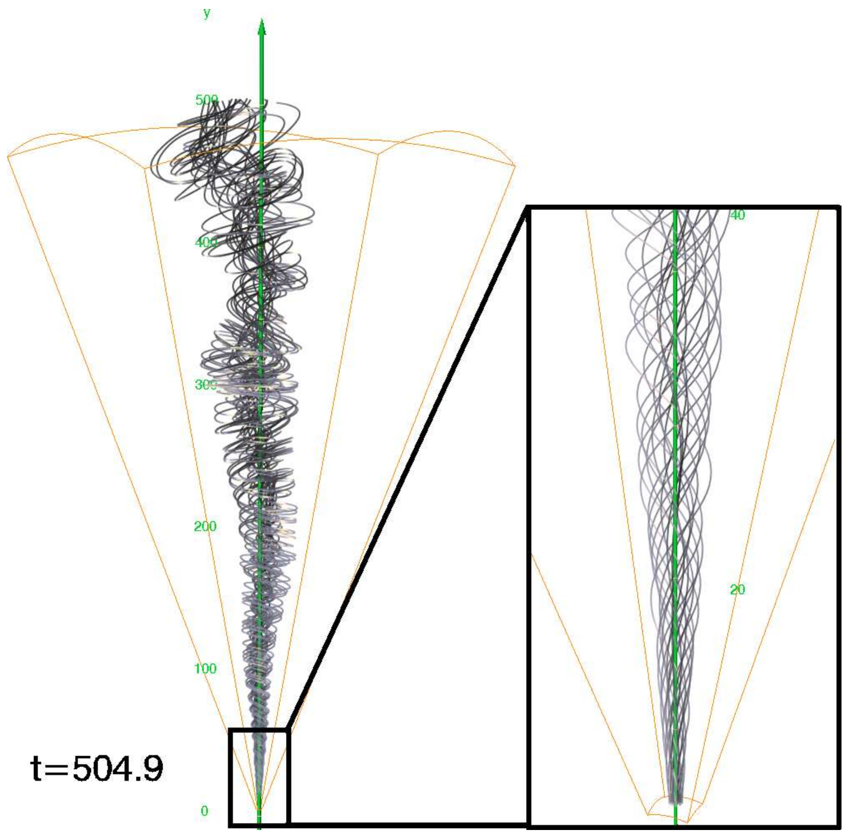

Figure 2.16: Snapshot of selected magnetic field lines in a jet. The magnetic field, which is initially straight, gets twisted by rotation applied at the bottom boundary. Shown here is the state after about 53 rotations. Instabilities cause kink-like deformations in the magnetic field structure. Length is measured in units of the lower jet diameter (which is at bottom of the blow-up at the right-hand side).

dispersion of stars and the size of the galaxy we can immediately estimate the mass of the galaxy, which is determined not only by stars themselves, but also by the dark matter.

However, this is not the only way to measure the galaxy mass. Massive elliptical galaxies often posses hot gaseous atmospheres, which are powerful sources of X-ray emission. If the gas is in hydrostatic equilibrium - the galaxy's gravity is balanced by the pressure of the gas, then we can use the gas to make an independent estimate of the galaxy mass. Both approaches (optical and X-ray based) should give the same answer, unless we miss important ingredients in our modeling. Thus the comparison of optical and X-ray data for nearby elliptical galaxies can be a useful tool to search of such ingredients.

To measure the galaxy mass from the hydrostatic equilibrium equation one needs to measure accurately the gas temperature and its spatial distribution. With the launch of the Chandra X-ray observatory, having angular resolution of order of 0.5 arc second, the quality of X-ray images is comparable to ground based optical data (Fig.2.19), and therefore the mass of the galaxy can be equally well determined by each method on all spatial scales.

Any disagreement between the two methods is a valuable tool to determine the characteristics of the gas. For instance, it has been suggested that relativistic protons - an elusive constituent of cosmic rays - are often mixed with the thermal plasma that we see in X-rays. Due to their large mass, the protons, unlike electrons, do not produce much radiation and we cannot easily detect their presence in the gas. However, if relativistic protons make a substantial contribution to the gas pressure, then the gas spatial distribution will be broadened. The net result would be an error in the mass determination - X-ray analysis is expected to give a lower mass, compared to the mass determined from the optical data. This comparison was made for a few well-studied elliptical galaxies. To make the com-

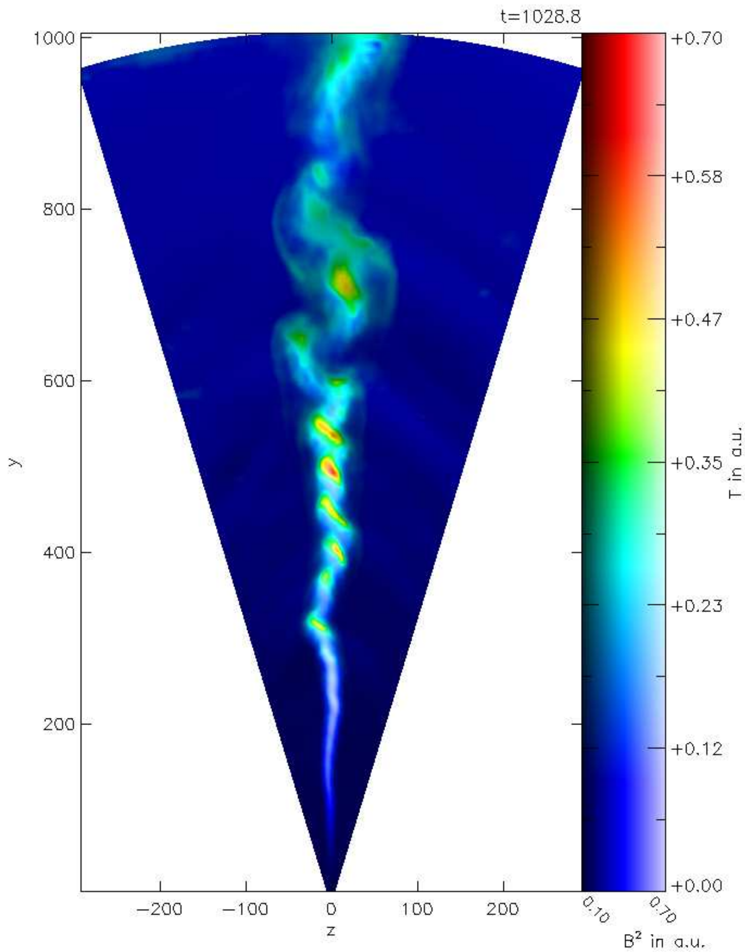

Figure 2.18: Volume rendering of an unstable jet, with color representing temperature and brightness representing the magnetic field strength. The instabilities cause dissipation of magnetic fields, converting magnetic field energy into heat (red, hot regions).

parison less sensitive to observational noise, the gravitational potential, rather than the mass itself, has been calculated and compared as shown in Fig.2.20.

The potentials derived from X-ray and optical data came up remarkably close to each other with the discrepancy amounting to less than 10-20%. This immediately translates into a similarly small upper limit on the contribution of cosmic rays to the gas pressure. Moreover, this 10-20% limit is perhaps applicable to other hard to detect effects including departures from hydrostatic equilibrium, gas motions, substantial magnetic fields or incorrect modeling of stellar kinematics. Of course it is possible that different effects have larger amplitudes, but opposite signs so that they cancel each other. However, it would be a remarkable coincidence that the residual discrepancy is so small. The conclusion reached so far is that in the most round and well-behaved systems the gas hydrostatic equilibrium is a good approximation and the contribution of cosmic rays and micro-turbulence to the gas pressure is small.

On the other hand it is unlikely that the contribution of non-thermal components to the gas pressure is much smaller than these 10-20%. In-

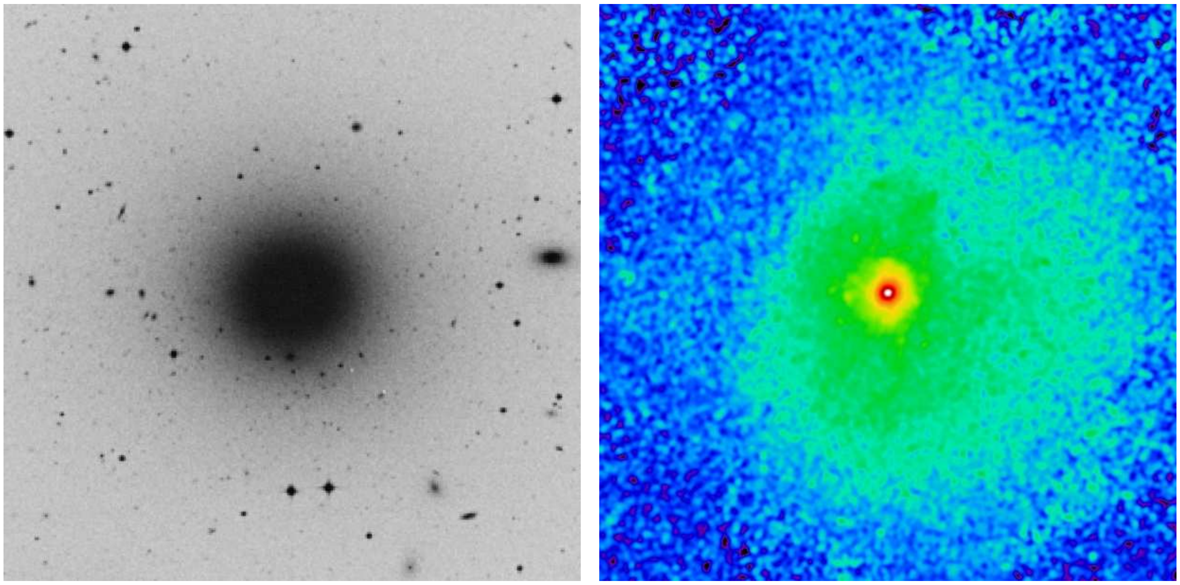

Figure 2.19: Central $10' \times 10'$ ($10' = 58$ kpc) region of the optical (Digital Sky Survey, right) and X-ray Chandra 0.6–2 keV (left) image of NGC1399. The galaxy appearance is very regular in the optical band, while the X-ray image is moderately disturbed.

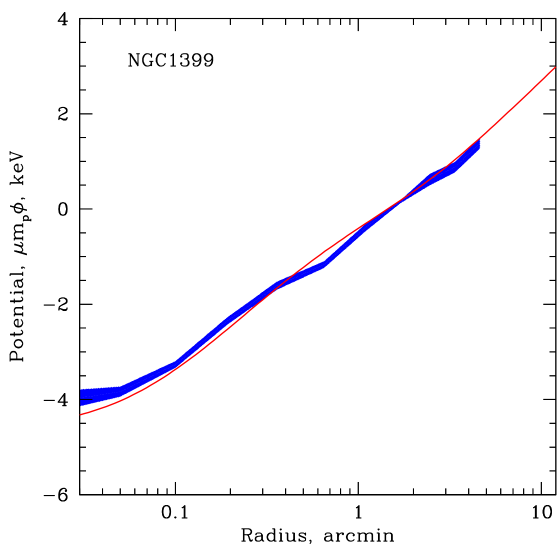

Figure 2.20: Gravitational potential of NGC 1399 derived from X-ray data. The thick red solid line shows the potential derived from optical data. The good agreement of the curves suggests that the fraction of non-thermal pressure is low.

deed, we often see clear signes that billions solar masses black holes, lurking in the centers of elliptical galaxies, disturb the surrounding gas. For instance, we routinely observe bubbles of relativistic plasma produces by these black holes in a good fraction of massive elliptical galaxies (as radio bright regions and as ‘cavities’ in X-rays). In fact we believe that in this process supermassive black holes provides vast amount of energy to the gas, needed to prevent its cooling. A natural prediction is that stirring of the gas by black holes makes the X-ray appearance of the galaxy visibly disturbed - see Fig.2.19. Order of magnitude estimates suggest that 10% deviations from hydrostatic equilibrium are almost inevitable.

The next step will be to look at systems that are more complicated and use the X-ray observations to study the characteristics of their stellar populations, which are difficult to measure by other means (Eugene Churazov).

2.9 On the kSZ Effect in ACT Galaxy Clusters

Performing Tomography of the Reionization Epoch with CO Radio Observations

When the Universe was $\sim 380,000$ years old, most of the protons recombined the electrons to form hydrogen, and matter remained practically neutral until the first sources of ionizing radia-

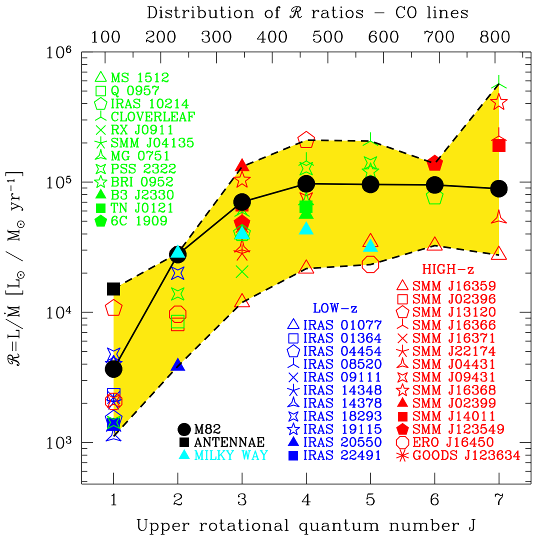

Figure 2.21: The distribution of the $\mathcal{R} = L/\dot{M}$ ratios as a function of the upper rotational quantum number of the CO transitions (the corresponding frequency is shown in the upper axis in GHz). The black solid line is SED for M82, for which there exists data for the full set of lines. Dashed lines represent the upper and lower limits for $\mathcal{R}$ in the sample.

tion appeared in the Universe. This period of time is known as the *Dark Ages*, and it came to an end when the UV radiation emitted by the first stars propagated through the Inter Galactic Medium (IGM). There is strong observational evidence that the Universe was already ionized at redshift $z \sim 6$, and that by that time there was a significant amount of synthesized species heavier than helium in overdense regions.

However, there is a lot to be learnt about the reionization epoch. Currently, a huge observational effort aims to observe how the first ionizing bubbles grew at the expense of the neutral medium by looking at the redshifted HI 21 cm transition. The heating of the neutral gas outside the bubbles increases spin temperature of neutral hydrogen above the Cosmic Microwave Background (CMB) temperature and leads to emission in the 21 cm line. The growth of ionized bubbles modifies the spatial emission pattern of the HI 21 cm transition and ongoing radio experiments are hoping to distinguish this signal from intervening foregrounds.

At the same time, the CMB offers another view of this cosmological episode. As electrons flow free in the IGM after reionization, they scatter again CMB photons, introducing new intensity and polarization anisotropies in the CMB. These new fluctuations are frequency independent, and therefore do not provide information of the redshift where they were generated. The main goal of CMB spacecrafts like WMAP and PLANCK and numerous ground based experiments like the Atacama Cosmology Telescope, South Pole Telescope and others is to observe the primordial intensity and polarization angular fluctuations of the CMB, generated at the epoch of cosmological recombination. Nevertheless, the sensitivity of experiments is becoming so high that they should also detect foreground angular fluctuations, which arise at lower redshifts. These, however, constitute an obstacle when interpreting the intrinsic angular anisotropies. In any case, the detection of these foreground fluctuations will provide extremely interesting information about the physics of a more evolved Universe, including properties of star forming galaxies in the epoch of reionization and/or intense Star Formation in the Universe.

Researchers at MPA have been intensely studying the impact of the presence of the first metals and molecules on the CMB. Among other processes, collision induced emission of fine structure lines of metal species like CII, NII, OIII, OI, etc, introduce intensity fluctuations that do depend on the frequency: the observing frequency is just the redshifted resonant frequency of the line under study. By tuning the observing frequency, one probes different redshifts with a given line, and therefore one can perform *tomography* of the reionization epoch, not only in an analogue way to HI 21 cm observations, but also complementary (since one would be looking at the ionized, metal enriched regions, as opposed to neutral ones). Particular emphasis has been paid to the study of the rotational lines of the CO molecule.

The very bright emission in the rotational lines of CO molecules in the frequency range 115 – 807 GHz has been found in star forming galaxies in the local and high redshift Universe. MPA scientists have been compiling the observed data of Star Formation Rate (SFR) in star forming galaxies and studied its connection to CO luminosities in the different rotational lines. They proposed a simple linear law of the type $L_{\rm CO\ line} = \mathcal{R} \cdot \dot{M}_\star$ relating the luminosity of the CO line with the SFR ($\dot{M}_\star$) in a given galaxy. In this study, three samples of galaxies are used, one corresponding to IRAS low redshift galaxies, one to high redshift submillimeter galaxies, and the third one to high redshift QSOs and radio-galaxies: the resulting estimates for the proportionality constant relating SFR with CO luminosity ($1/\mathcal{R}$) for each CO transition are given in Fig. 2.21. It was found that the data for M82 (black circles in Fig.2.21) are fair descriptors of the average linear relation, and that the dispersion of the other data around this average (shaded region in this figure) encode the complicated physics and chemistry of molecular clouds and radiative transfer and emission processes in the CO lines. This dispersion must therefore be understood as the intrinsic model uncertainty.

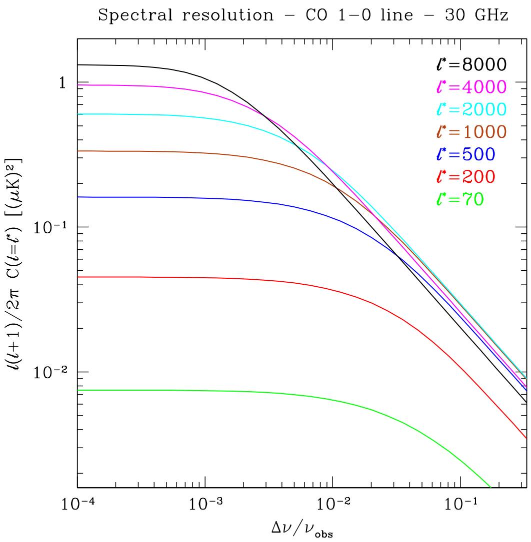

Figure 2.22: The dependence of the amplitude of the signal associated to the clustering of star forming galaxies on the spectral resolution of the observing instruments, for the CO (1-0) line at 30 GHz and for several values of the multipole index l.

The star forming activity in the Universe is known to be linked to the merging history of halos throughout cosmic history. With the aid of the extended Press-Schechter (ePS) formalism that describes the mergers of the halo population at different epochs, it is possible to build a model for the Star Formation history of the merging objects in the Universe. This model provides an estimate of the SFR in each halo of a given mass at a given redshift, which, via the linear $L_{\rm CO\ line} - \dot{M}_\star$ relation, can be inverted into the CO luminosity in each of the rotational lines for each of such halos. This produces a model for the CO emission at any cosmological time, and in particular, during the epoch of reionization. This model also enables the computation of the angular power spectrum of the angular anisotropy field that the CO emission introduces in the CMB. Since star forming galaxies tend to cluster in overdense regions that later will give rise to clusters and super-clusters of galaxies, there are two types of anisotropy introduced by the CO lines. One accounts for the actual clustering of star forming galaxies, and corresponds to a typical linear (comoving) size of a proto-cluster (~ 20 h^{-1}Mpc). The second one describes the Poissonian nature of the actual star forming galaxy number density, and is more important at very small angular scales.

Given the emission pattern associated to a particular line, each observing frequency channel of a CMB experiment will be probing a shell centered at a corresponding redshift. Furthermore, the thickness of this shell is proportional to the observing frequency bandwidth. It is found that the actual amplitude of the angular intensity fluctuations that CO lines introduce *grows* with increasing angular resolution, since more *definition* of the emitting shell is achieved. For the anisotropy associated to the clustering of the star forming galaxies, the anisotropy level will increase until the thickness of the observed shell is comparable to the size of the proto-cluster containing star forming galaxies, or the frequency resolution is of the order of the ratio of the CO clouds peculiar velocities to the speed of light. Such strong dependence of the angular anisotropy level with respect to the observing spectral resolution is *unique*, and can be used to subtract all other potential contaminants (such as radio, dust, intrinsic CMB anisotropies, etc), which show practically no dependence upon spectral resolution.

Fig. 2.22 displays the growth of the amount of angular anisotropy per unit solid angle $(l(l+1)C_l/(\pi))$ with respect to spectral resolution for different angular scales (corresponding to different multipoles $l \simeq \pi/\theta$). It is found that, for decreasing band widths, the anisotropy associated to the bulk of star forming galaxies in each of the proto-clusters increases until it reaches a *plateau* at $\Delta\nu/\nu \sim 10^{-3}$. It is also very relevant that the actual amplitude of the CO emission at high spectral resolution renders this mechanism as the most important extragalactic foreground for the CMB in the frequency range $\nu \in [30, 70]$ GHz, as shown in Fig. 2.23. Its amplitude and its particular dependence on the observing spectral resolution make CO observations a novel and very promising tool to conduct tomography of the epoch of reionization. At lower frequencies (i.e. 20 GHz), practically only the first CO rotational transition contributes to the foreground signal. Therefore, this line is only probing one slice of the Universe at redshifts close to 5. For higher observing frequencies, two slices are observed simultaneously, one radiating in the first line, the another in the second, and at even higher frequencies observations are probing more than two narrow slices simultaneously. Furthermore, no other molecule or ion contributes in the same frequency range with an amplitude comparable with CO (they are down by at least one order of magnitude).

Unfortunately, PLANCK and most sensitive ground based CMB experiments are currently using broad frequency bands and lack good spectral sensitivity. To perform CO observations a new type of experimental facilities is required, like those already present in VLA, Green Bank, or Effelsberg. (Mattia Righi, Carlos Hernández-Monteagudo and Rashid Sunyaev)

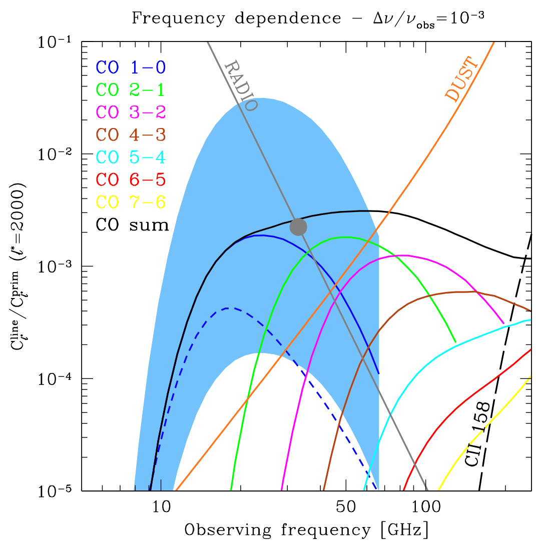

Figure 2.23: The ratio of the correlation signal from CO emission to the primordial CMB signal at $l = 2000$ as a function of frequency and for a spectral resolution $\Delta\nu/\nu_{\rm obs} = 10^{-3}$. The black solid line is the sum of the correlation from the first seven CO lines, computed by assuming the $\mathcal{R}$ ratio for M82. The blue short-dashed line is obtained with the model based on simple Press-Schechter distribution. The contribution from dust emission in merging galaxies is shown with the orange line. The gray point is the Poisson at 33 GHz from radio sources, estimated by the model of de Zotti et al. (2005). The shaded region around the curve for the first CO line represents the range of uncertainties in the correlation signal, according to the different values of $\mathcal{R}$ for the sample of objects in Fig. 2.21.

3 Research Activities

3.1 Solar Physics

Together with Å. Nordlund (Copenhagen) and R.F. Stein (Michigan State University), M. Asplund have investigated the physics of solar surface convection, including the effects of magnetic fields. Current generations of supercomputer simulations including a detailed treatment of radiative transfer and realistic microphysics (opacities, equation-of-state) are highly successful in reproducing key observational diagnostics, including granulation topology (e.g. length- and time-scales, velocities, intensity brightness contrast), center-to-limb variation and spectral line shapes, shifts and asymmetries. This allows robust conclusions to be drawn from analysis of the model properties. At larger spatial scales the properties of the convective velocity field at the solar surface are strongly influenced by constraints from mass conservation, with amplitudes of larger scale horizontal motions decreasing roughly in inverse proportion to the scale of the motion. To a large extent, the apparent presence of distinct (meso- and supergranulation) scales is a result of the folding of this spectrum with the effective "filters" corresponding to various observational techniques. Convective motions on successively larger scales advect patterns created by convection on smaller scales; this includes patterns of magnetic field, which thus have an approximately self-similar structure at scales larger than granulation. Convection in the solar surface layers is also of great importance for helioseismology since excitation of the wave spectrum occurs primarily in these layers, and convection influences the size of global wave cavity and, hence, the mode frequencies.

The solar chemical composition is an important ingredient in our understanding of the formation, structure and evolution of both the Sun and our solar system. Furthermore, it is an essential reference standard against which the elemental contents of other astronomical objects are compared. M. Asplund in collaboration with N. Grevesse (Liege), A.J. Sauval (Brussels) and P. Scott (Stockholm) have undertaken a complete re-determination of the solar chemical composition with a new highly realistic 3D hydrodynamical model of the solar atmosphere as the theoretical foundation. Non-equilibrium spectral line formation has been accounted for whenever possible and particular care has been exercised in employing the best possible atomic/molecular input data and avoiding problematic lines due to e.g. blends. The end result is a comprehensive and homogeneous compilation of the solar elemental abundances, which will appear in an extensive review article in ARAA in 2009 as well as in a series of A&A articles detailing the actual analyses. Particularly noteworthy findings are significantly lower abundances of carbon, nitrogen, oxygen and neon compared with the widely-used values of a decade ago. The new solar chemical composition is supported by a high degree of internal consistency between available abundance indicators, and by agreement with values obtained in the solar neighborhood and from the most pristine meteorites. There is, however, a stark conflict with standard models of the solar interior according to helioseismology, a discrepancy that has yet to find a satisfactory resolution.

Standard solar models (SSM) are a corner stone of stellar astrophysics. Among the most important ingredients needed to model the solar structure and evolution is the solar chemical composition. Most recent and sophisticated solar atmosphere models predice solar chemical abundances that lead to a degraded agreement between SSM predictions and detailed measurements of solar structure using solar oscillations. The situation is such that best SSM and best solar atmosphere models seem to be incompatible. In order to help understand the situation better and provide additional constraints on solar composition, C. Peña-Garay (IFIC, University of Valencia) & A. Serenelli have included the most up-to-date microphysics in new calculations of SSMs and have studied the possibility of constraining the solar composition by using present and future measurements of solar neutrino fluxes. The conclusion reached is that current neutrino measurements are not accurate enough to yield a determination of the solar core composition, but onging neutrino experiments should allow in 2 or 3 years time to achieve the necessary accuracy for solar neutrinos to become an important observational tool to probe the solar core. In a parallel effort, S. Basu (Yale University), W. Chaplin, Y. Elswort (University of Birmingham), R. New (Sheffield Hallom University) and A. Serenelli have used frequencies of low-degree solar oscillation modes obtained with the Birminghan Solar Oscillation Network (BiSON) to improve observational constraints on the solar structure. Better agreement between solar and SSM density profiles are found with the new helioseismology data, as well as reduced uncertainties in the determinations of the density and sound speed profiles.

Recent observations from space with the SUMER instrument on board of the SOHO satellite have provided very detailed profiles of the hydrogen Lyman lines emitted from the sun. In solar prominences observed on the limb these lines show very pronounced asymmetries. Radiative transfer calculations for these lines based upon multithread models with randomly distributed line-of-sight velocities have been performed by U. Anzer, S. Gunár and P. Heinzel (Astron. Inst. Ondřejov, Czech Rep.). We demonstrated that rather modest velocities around 10 km/s are sufficient to produce the observed asymmetries. U. Anzer together with F. Fárník and P. Heinzel (Astron. Inst. Ondřejov) has also suggested new methods to analyse prominence observations in EUV lines and in X-rays which are presently carried out with the new Japanese satellite Hinode. U. Anzer developed a simple model for prominence oscillations which allows one to relate the observed periods of the oscillations to the magnetic field which supports the prominence. These models can contribute to the field of 'prominence seismology'.

The origin of the complex structure of sunspots has become a topic of intense debate over the past few years, fueled by high-resolution observations made with the Swedish 1-m Solar Telescope (SST), the Hinode satellite, and by recent numerical MHD simulations. One of the discoveries of the SST are the moving 'striations' observed in bright penumbral filaments. H. Spruit (with M. Löfdahl and G. Scharmer of the Institute for Solar Physics, Stockholm) showed how the properties of this striation provide key evidence for understanding the bright filaments as a form of overturning convection in nearly field-free gaps below the observed surface. This is strengthens the (still strongly contested) interpretation proposed by Scharmer and Spruit in 2006.

3.2 Stellar physics

The light we observe from stars is emitted by a relatively thin region at the stellar surface known as the stellar atmosphere. The distribution of photons at the different wavelengths in the emitted stellar radiation depends on the physical structure and chemical composition of these surface layers: model stellar atmospheres are therefore necessary in order to quantitatively interpret observed stellar spectra. While classical model atmospheres of solar- and late- type stars (spectral classes F,G, and K) usually assume a simplified 1D geometry, in recent years it has become possible to produce 3D hydrodynamical simulations of the gas flows in the surface layers of stars including the effects of radiation. The atmospheric temperature stratifications predicted by such 3D simulations differ in general from the ones predicted by classical 1D models. In particular, at very low metallicities, 3D models show much cooler temperature stratifications in the upper photosphere than their 1D counterparts, which translates to different elemental abundances being derived. Together with Anna Frebel (UT Austin), R. Collet have recently applied one such 3D model atmosphere of very metal-poor star to the analysis of a high-resolution UVES spectrum of the extremely iron- poor halo star HE1327-2326. In particular, the fit of CH, OH and NH molecular bands is greatly improved when the 3D model is taken into account in the spectral line formation calculations, which strongly indicates that the 3D simulations are indeed more accurate than 1D models in reproducing temperature gradients in stellar atmospheres.

For 3D hydrodynamical simulations of stellar surface convection and atmospheres, the treatment of the energy exchange between the gas and the radiation field is critical as it determines the temperature stratification and is ultimately what drives the convective motion. Due to the computationally demanding nature of such simulations, simplifications have to be made for the radiative transfer treatment compared with classical 1D model atmospheres and even then the solution of the radiative transfer in 3D completely dominates the computational time. One assumption that has been made until now is to ignore scattering and to assume pure absorption, which is a reasonable approximation for for example the solar atmosphere but is expected to be poor for red giant stars, especially at low metallicity. PhD student W. Hayek under the supervision of M. Asplund have together with M. Carlsson, B. Gudiksen and V. Hansteen

(Oslo) designed a new efficient solution for the radiative transfer when including scattering. The new scheme has been implemented in the BIFROST magneto-radiative-hydrodynamical code and has been tested for different stellar parameters. With scattering the resulting atmospheric structure is cooler due to less efficient radiative heating.

Low mass stars retain in their atmospheres a fossil record of the chemical elements in the interstellar medium at the time of their formation and therefore they provide the best tool in deconstructing the formation and evolution of our Galaxy, the Milky Way.

To achieve such a goal, and to make full use of ongoing and future large astronomical surveys (e.g. SDSS3, GAIA) an improved determination of fundamental stellar parameters is required. The effective temperature of a star is one of the parameters most notoriously affected by systematic uncertainties, which are still of order 100 Kelvin. L. Casagrande, I. Ramírez, M. Asplund and J. Meléndez (CAUP, Portugal) are currently working in determining a both precise and accurate temperature scale for low mass stars. This is now possible to achieve using solar twins –stars with physical parameters identical to the Sun– which for the first time will allow to pin down systematic uncertainties to within a few degrees.

Reliable and homogeneously determined effective temperatures will be also crucial for studying yet largely unexplored territories of the HR diagram, such as metal-poor low-mass stars. To this purpose, two observing proposals for obtaining high quality spectra of a large sample of M dwarfs (including metal poor candidates) have been approved on the Very Large Telescope (VLT) and Telescopio Nazionale Galileo (TNG).

In stars like the Sun, the convection zone reaches up to the visible surface, which gives rise to granulation: a continuously evolving pattern of warm ascending gas and cold downflowing material. Granulation is easily observed on the Sun but can not be directly seen on stars for which the surface can not be resolved in sufficient detail. The convective motions imprint, however, characteristic fingerprints in the detailed line shapes, which for stars like the Sun result in typical C-shape bisectors. For the first time, I. Ramírez, M. Asplund and collaborators have investigated the observed line asymmetries in cooler stars to infer the granulation properties using extremely high-quality McDonald spectra of a sample of nine K dwarfs. Because of the cooler temperatures and higher densities, the convective velocities are smaller than for the Sun, which means that the resulting line shifts are smaller and more difficult to detect. The predicted line shapes from a 3D hydrodynamical model atmosphere agree very well with the observations, implying that the 3D models are realistic representation of the real atmospheres also for these cooler stars, as have previously been demonstrated for F and G dwarfs. The 3D models can thus be used for more reliable elemental abundance determinations. In particular the molecular lines are much better reproduced with the 3D models compared with classical 1D models.

Massive stars with masses between roughly 10 and 25 $M_\odot$ spend some time as red supergiants (RSG) being the largest stars in the universe. They have effective temperature ($T_{\rm eff}$) ranging from 3450 to 4100K, luminosities of 20000 to 300000 $L_\odot$, and radii up to 1500 $R_\odot$. Their luminosities place them among the brightest stars, visible to very long distances. There is however a number of open issues: (i) they shed large amounts of mass back to the interstellar medium, but their mass-loss mechanism is unidentified; (ii) their chemical composition is largely unknown due to difficulties in analysing their spectra with broad, asymmetric lines with variations suspected to stem from a convection pattern consisting of large granules and (super)-sonic velocities.
In recent years, hydrodynamical modeling of convection in RSGs has lagged behind that of solar type stars due to the necessity to include the whole star in the simulation box. A. Chiavassa together with B. Plez, E. Josselin (GRAAL, Montpellier, France) and B. Freytag (CRAL, Lyon, France) have constructed 3D hydrodynamical simulations of such stars and studied the granulation pattern at different wavelengths. In addition, the signatures of convection on different interferometric observables (e.g. visibility curves and closure phases) have been predicted to establish a benchmark for future measurements of the granulation pattern. These predictions are already on the way to be confirmed with the VLTI-Amber observations reduced in collaboration with the infrared astronomy group lead by G. Weigelt (Max Planck Institute for Radioastronomy, Bonn, Germany).

It has long been known that abundances of iron group elements (Mn, Co, Cr) in the atmospheres of old low-mass Galactic stars correlate in some way with stellar metallicity, or abundance of iron. This resulted in a number of theories explaining synthesis of these elements in the Milky Way. One of them is that Mn and Co are created in supernova (SN) explosions and depend on the initial metallicity of SN progenitor stars. However, the stellar abundances are not error-free, because they are derived by fitting spectral lines calculated using models of radiation transfer in a plasma to observed spectra of stars. Up to now, abundances of Mn and Co have only been calculated using a local thermodynamic equilibrium (LTE) assumption for a plasma state, which was shown to be far from reality for many elements. Using a physically accurate non-local thermodynamic equilibrium (NLTE) approach, M. Bergemann supervised by T. Gehren (University Observatory Munich) showed that the LTE assumption is inadequate to describe excitation- ionization equilibrium of Mn and Co in stellar atmospheres and, as a result, leads to large errors in elemental abundances. The NLTE abundance trends of Mn and Co in the Galaxy are radically different from those calculated using the LTE approach, and interpretation of the trends suggests metallicity-independent production of Mn and Co during SN explosions. However, relative yields of these elements are proposed to be different in supernovae of different types (SN II, Ia) and masses.

Stellar and Galactochemical evolution models predict homogeneous and enriched chemical composition of normal young B-type stars. In contrast, results from spectral analyses in the past decades showed highly inhomogeneous and sub-solar chemical abundances in the solar vicinity. New spectral modelling and analysis developed by M.F. Nieva and N. Przybilla (Bamberg Observatory) showed that stars in the solar neighbourhood are chemically homogeneous on the 10% level in accordance with the interstellar medium (ISM) gas-phase. The new abundances agree with data from the Orion nebula and newest solar values by Asplund et al. A present-day cosmic abundance standard was proposed allowing the dust-phase composition of the local ISM to be constrained (N. Przybilla; K. Butler, Munich Observatory). Chemical analyses of hyper-velocity stars were also performed finding a chemical peculiar (magnetic) star and a hyper-runaway star ejected by a super-/hypernova in a binary system.(N. Przybilla, U. Heber, A. Tillich, Bamberg Observatory; K. Butler; W. Brown, Harvard, CfA)

F. Kupka collaborated with J.D. Landstreet [Univ. of Western Ontario] on the analysis of spectra of a large sample of B-F type main sequence stars and supergiants observed in previous years. They confirmed for their sample that the classical microturbulence parameter used in spectroscopic analyses always indicates non-zero velocity fields for the photosphere of A-type main sequence stars, with a maximum around an effective temperature of 8000 K and systematically larger values for metallic line stars. Provided that the projected rotational velocity is small enough, these velocity fields where shown to become visible as asymmetrically broadened spectral line profiles. This property was established for a sample three times larger than previously available and for the first time allowed an analysis of line broadening properties as a function of effective temperature and metallicity in this part of the HR diagram. The observed line broadening was demonstrated to originate from photospheric velocity fields and to follow similar functional dependencies as the microturbulence parameter previously used as a proxy to detect photospheric velocity fields. Pulsation appears excluded from the primary cause of line broadening in these stars. Presently, contrary to solar-like stars, hydrodynamical simulations are unable to explain the profiles of strong lines in these objects in which neither large global magnetic fields are present nor large rotational broadening that would mask the photospheric velocity fields. Pronounced spectral line broadening due to photospheric velocity fields was also found in the supergiants contained in the observational sample, although in their case the origin of the line broadening could well be different, particularly, since the profiles themselves appear quite symmetric for effective temperatures associated with spectral type A in contrast with their main sequence counterparts.

Work in stellar evolution theory revolves around stars of low and intermediate mass (up to $\approx 8M_\odot$), their internal evolution, their ages, and final fate. With regard to the latter issue M. Salaris (Liverpool, UK), A. Serenelli (Princeton, USA), M. Miller Bertolami (La Plata, Argentina) and A Weiss had a new look at the initial-final mass relation, which is used to determine the connection between observed white dwarfs and the initial mass of their progenitors. This relation depends substantially on the theory of stellar evolution, and therefore its uncertainty is dominated by systematic errors, which arise, for example, from assumptions about convective mixing in the progenitor stars. For the first time such systematic errors where investigated. Among other results it could be shown that age and mass of the white dwarf remnant depends mostly on observational errors, while the error in the initial mass is dominated by stellar model uncertainties.

The initial-final mass relation itself can be predicted directly by stellar theory. For this the mass loss history of intermediate mass stars during their evolution on the Asymptotic Giant Branch is decisive. A. Kitsikis has produced the first grid of such models, which completely consistently takes into account the effect of carbon dredge-up during this phase. The enrichment of the envelope by carbon leads to an increase of the molecular opacities. These were specifically calculated by J. Ferguson (Wichita, USA) for this PhD project led by A. Weiss. The increased opacities lead to a strong decrease of surface temperature and thus to an increase in dust-driven mass loss from carbon-rich atmospheres. The grid comprises a large range of metallicities, from about 1/200 to more than twice the solar abundance. It is the largest grid of such model ever produced, and the only one with completely up-to-date and consistent physical input.

M. Mocak, in a PhD project supervised 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 to check whether the star can maintain the quasi-hydrostatic equilibrium, which is usually assumed in stellar evolutionary calculations. Both 2D and 3D hydrodynamic simulations do not show any explosive behavior, although the energy generation rate in the 3D models is 10% higher than in the 2D ones. The convective flow patterns developing in the 3D models are structurally different from those of the corresponding 2D ones, and the typical convective velocities are higher than those found in their 2D counterparts. 3D models also tend to agree better with the predictions of mixing length theory. The hydrodynamic simulations show the presence of turbulent entrainment that results in a growth of the convection zone on a dynamic time scale. Contrary to mixing length theory, the outer part of the convection zone is characterized by a sub-adiabatic temperature gradient, the radius of the transition from the super-adiabatic to the sub-adiabatic regime being determined by the location where the work done by buoyancy becomes negative.

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), 10 releases (the latest as of 1 July 2008) of this catalogue have so far been issued (with the next release due 1 January 2009).

3.3 Supernovae

The magnetic fields of the progenitor of a core-collapse supernova are, according to latest stellar-evolution models, probably too weak to have a strong influence on the explosion dynamics unless they are amplified strongly. Hydromagnetic instabilities possibly operating in the post-bounce core, in particular the magneto-rotational instability (MRI), have been proposed as an efficient amplification mechanism. M. Obergauliger, P. Cerdá-Durán, E. Müller and M.A. Aloy (Universitat de València) have investigated the growth and saturation of the MRI in simplified models of supernova cores. These systems differ from the more traditional cases of MRI-unstable systems, viz. accretion discs, by the importance of a thermal stratification. Analysing the dispersion relation of MRI-unstable modes in the presence of positive or negative entropy gradients, they identified different instability regimes possibly important in supernovae. The properties of these regimes were confirmed by semi-global numerical simulations. Furthermore, they identified the mechanism responsible for the onset of saturation in these simulations and established scaling laws relating the saturation level of the instability to physical and numerical parameters of the models. Under the conditions investigated in the simulations, the MRI may lead to rapid (within a few tens of milliseconds) amplification of weak pre-collapse fields to a dynamically important strength. Possible implications of these fields on the explosion dynamics have to be studied in subsequent global simulations including additional physics.

Supernovae are among the strongest and most frequent sources of gravitational waves. Previous relativistic models of stellar core collapse and bounce used only crude approximations of the equation of state and effects of neutrino losses. In contrast to these older simulations, relativistic calculations with microphysical equations of state and a deleptonization scheme predict a generic type of gravitational-wave burst signal from the moment of core bounce for a wide range of core rotation rates and profiles, including also the conditions expected from stellar evolution models at the onset of core collapse. This result was first obtained by H. Dimmelmeier, C.D. Ott (AEI, Golm), H.-Th. Janka, A. Marek and E. Müller, and it was recently demonstrated by this collaboration to hold also for a large set of supernova progenitors and for different nuclear equations of state. A. Marek, H.-Th. Janka and E. Müller extended the analysis to the later post-bounce evolution of the collapsing stellar core by using two-dimensional hydrodynamic simulations with a sophisticated treatment of the neutrino transport. They found that non-radial fluid instabilities (convection and the standing accretion shock instability) impose characteristic quasi-periodic modulations on the neutrino emission and cause a gravitational-wave signal that by far dominates the core-bounce signal for rotation rates typically expected for supernova progenitors.

The progenitor mass of type IIP supernova can be determined from either hydrodynamic modeling of the event or pre-explosion observations. To compare these approaches, V. P. Utrobin (also ITEP, Moscow) in collaboration with N. N. Chugai (IARAS, Moscow) determined parameters of the sub-luminous supernova 2005cs and estimate its progenitor mass. They computed the hydrodynamic models of the supernova to describe its light curves and expansion velocity data. They estimated a pre-supernova mass of $17.3 \pm 1\ M_{\odot}$, an explosion energy of $(4.1 \pm 0.3) \times 10^{50}$ erg, a pre-supernova radius of $600 \pm 140\ R_{\odot}$, and a radioactive ^{56}Ni mass of $0.0082 \pm 0.0016\ M_{\odot}$. The derived progenitor mass of SN 2005cs is $18.2 \pm 1\ M_{\odot}$ is in-between those of low-luminosity and normal type IIP supernovae. The obtained progenitor mass of SN 2005cs is higher than derived from pre-explosion images. The masses of four type IIP supernovae were estimated by means of hydrodynamic modeling and turned out to be systematically higher than the average progenitor mass expected to be in the $+9 - 25\ M_{\odot}$ mass range. This result, if confirmed for a larger sample, would imply that a serious revision of the present-day view on the progenitors of type IIP supernovae is required.

Out of the Hubble Space Telescope observations of SN 1987A over the past 20 years the hot spots in the inner circumstellar ring are one of the most fascinating features. In 2000 some new brightening spots appeared that now have developed into a chain of about 30 spots around the circumference of the inner ring. F. Meyer shows how this pattern of alternating mass distribution was caused by Rayleigh-Taylor instabilities already some 8000 years ago on the formation of the inner ring. The pattern now becomes visible by shock heating through the impact of the ejecta of SN 1987A on this structure.

For core-collapse SNe, attention focused on SNe Ibc, in particular because of their connection with Gamma-ray Bursts. Arguably the SN of the year was 2008D. This type Ib (H-poor, He-rich) SN was discovered thanks to the detection of an X-ray burst by the Swift satellite. A paper in Nature suggested that the X-ray signal was the result of the breakout from the stellar surface of the explosion shock. P. Mazzali, D. Sauer, N. Elias-Rosa, S. Taubenberger and collaborators, using VLT data, showed that SN2008D was significantly over-energetic (a so-called "hypernova", HN), which suggests that it hosted a collapsar event like in GRB/SNe, which are usually of type Ic (no H, no He), hence coming from more stripped progenitors. In a paper published in Science they suggested that the X-ray signal was indeed the breakout of a GRB-type jet, which was however "choked" while penetrating the massive He envelope, so that it did not give rise to a full-fledge GRB but only to an XRB.

The direct signature of the HN in a GRB (GRB 060904B) was potentially discovered in a work led by the Italian Swift team (INAF Milan): an emission line identified as the Ni K-shell line was observed within hours of a GRB: the likely origin is the ^{56}Ni freshly made in a GRB-SN. The impact of HN ejecta on metal-poor star abundances was studied by P.Mazzali in collaboration with R. Smiljanic, F. Primas and L. Pasquini (ESO), D. Galli (INAF, Triest), and G. Valle (INAF, Florence): HN abundances may be directly detected in some very metal-poor stars.

Late-phase observations of supernovae (SNe) are technically challenging and time-consuming, but provide invaluable insight into basic properties of the explosions. From the light-curve tail the amount of radioactive ^{56}Ni can be estimated, and the profiles of emission lines in nebular spectra probe the geometry of the SN ejecta, providing information on the degree of asphericity of the explosion. Such a geometry study has been conducted by S. Taubenberger, S. Valenti (Belfast) and collaborators. They examined the profiles and Doppler shifts of forbidden oxygen and magnesium emission lines in a sample of 34 late-phase stripped-envelope core-collapse SNe. They found that the majority of these objects showed significant deviations from spherical symmetry and evidence of bipolar or even strongly one-sided outflows, in agreement with modern 3D hydrodynamic explosion simulations. Similarly, collecting data of many SNe Ibc at VLT, Subaru and Keck, P. Mazzali, S. Taubenberger, and collaborators showed in a paper published in Science (Maeda et al., 2008) that asphericity is a common feature in the inner ejecta of envelope-stripped SNe, although it may be more pronounced at the higher masses and energies. es are consistent with observed neutron-star kick velocities of several 100 $\mathrm{km\,s^{-1}}$.

As part of his PhD thesis, supervised by F. Röpke and W. Hillebrandt, and in collaboration with M. F. Nieva and N. Przybilla (Sternwarte Bamberg), R. Pakmor has studied the effect of the explosion of a massive star undergoing core collapse on a companion star in a binary system in a similar scenario. Such an event has been suggested to be the origin of the runaway B star HD 271791. In a second project R. Pakmor is analysing possible progenitor systems of type Ia supernova explosions. The effect of such an explosion on the companion star is investigated for different proposed progenitor systems of the standard single degenerate Chandrasekhar mass scenario. A first set of simulations performed for main-sequence binary companion models computed by A. Weiss showed that, in contrast to previous results, the mass of hydrogen ablated can be sufficiently low to meet current observational constraints.

Thermonuclear supernovae (SNe Ia) are used to determine cosmic distances which led to the detection of an accelerated expansion of the Universe. The measurements are based on an empirical calibration of the maximum luminosity of the supernova with properties of its light curve. For corroborating and improving the determination of cosmic parameters with SNe Ia, a better theoretical understanding of these events is desirable. This is the goal of the Emmy Noether research group "Comprehensive Modeling of Type Ia Supernova Explosions" (funded by the German Science Foundation, DFG) that has been established at MPA and is led by Fritz Röpke. Its main focus is the numerical simulation of the explosion process. In a recent joint project with D. Kasen and S. Woosley (UC Santa Cruz), a large number of two-dimensional models was computed and synthetic observables were derived. It could be shown that the underlying astrophysical model reproduces properties of a large part of the observed SN Ia sample well. This allows to draw conclusions on the origin of the diversity of these events. Moreover, the empirically established relation between light curve and maximum brightness could be obtained from these theoretical models marking a first important step towards a theoretical foundation of the use of SNe Ia in observational cosmology.

Many of the currently viable explosion models for Type Ia supernovae include detonations as a necessary ingredient to achieve at least qualitative agreement with observations. Ivo Seitenzahl and his collaborators from the University of Chicago, derived a new set of critical detonation conditions from high resolution reactive hydrodynamics simulations that extend previous work to include hitherto unexplored crucial dependences on geometry, composition, and functional form of the temperature profile of the hot spot leading to the runaway. To determine whether hitherto observed in situ detonations occurring in the gravitationally confined detonation model are an artifact low resolution, they performed a resolution study focusing on the details of the initiation mechanism. They showed that higher resolution appears to inhibit the initiation of a detonation since temperature gradients that were artificially extended as an artifact of low resolution become steeper and higher resolution and sub-critical. However, shear induced instabilities, which are suppressed at low resolution, create a turbulently mixed region, where with the aid of a compression wave the transition to detonation may occur after all.

In the deflagration model of type Ia supernovae explosions, the laminar burning front is affected by several instabilities. These instabilities wrinkle and deform the flame, its velocity being determined by turbulent velocity fluctuations. To analyze these fluctuations, kinetic energy spectra and velocity correlation functions have been computed in spherical coordinates by F. Ciaraldi-Schoolmann (in collaboration with W. Hillebrandt and F. Röpke, and J. C. Niemeyer and W. Schmidt (U. Würzburg)) with data from a highly resolved type Ia supernova simulation. It was shown that turbulence is isotropic on small length scales obeying Kolmogorov scaling. However, in the radial direction, the Rayleigh-Taylor instability dominates on larger length scales. Therefore turbulence becomes anisotropic in the direction of gravity.

M. Kromer and S. A. Sim continued to work on the application of Monte Carlo radiative transfer methods to the study of multi-dimensional models of type Ia supernovae. Development of their three-dimensional, non-grey, non-LTE spectral synthesis is nearing completion and it has already been used to perform test calculations for standard supernova models and to make a preliminary study of optical light curves for off-center explosion models, results from which have been presented at an international conference. Work has now begun using the radiative transfer code to compute astronomical observables for state-of-the-art hydrodynamical supernova explosion models, as required to validate such models.

The MPA group continued the investigation of the properties of various types of Supernovae through the analysis of observational data. For type Ia supernovae Ia, a second paper on the tomography of an RTN supernova was published in MNRAS by P.Mazzali, D. Sauer, and W. Hillebrandt in collaboration with A. Pastorello (U. Belfast) and S. Benetti (INAF, Padua). This supernova, SN 2004eo, was at the dim end of the distribution of normal SNe. Not only less ^{56}Ni was produced in the explosion, but also the Si and intermediate-mass element zone is more extended, confirming general results that all explosions involve the same mass and produce about the same kinetic energy, which favors delayed detonations as a mechanism.

The data reduction and the analysis of the spectra and lightcurves of type Ia supernovae observed by the European Supernova Collaboration (ESC) is coming to an end. Spectra of several targets were published that did not fulfill the criteria for a full monitoring campaign (P. Pfahler, S. Taubenberger, N. Elias-Rosa, W. Hillebrandt and collaborators from the ESC). A fast expanding SN Ia (SN 2002dj) was analyzed in detail (P. Mazzali, M. Stehle, W. Hillebrandt and other ESC members), as well as an under-luminous SN Ia (SN 2005bl; S. Taubenberger, S. Hachinger, S. Mazzali, N. Elias-Rosa, W. Hillebrandt, and collaborators). Finally, extinction and reddening laws for type Ia supernovae were investigated, and the VRIJHK photometry and optical and near-infrared spectroscopy of a heavily extinguished supernova (SN 2002cv, located in NGC 3190) was published (N. Elias-Rosa, W. Hillebrandt, and collaborators from the ESC and UC Berkely).

As part of his PhD thesis, supervised by P. Mazzali, S. Hachinger, used observed spectra of type Ia supernovae to explore correlations between spectral features and the supernova's luminosity. In particular, a physical reason for the observed behaviour of the ratio of two Si II lines was established and published (S. Hachinger, P. Mazzali, M. Tanaka (U. Tokyo), W. Hillebrandt, S. Benetti (INAF, Padua)).

D. Sauer, P. Mazzali, M. Stehle and collaborators from UC Berkeley and Harvard/CfA modeled the UV spectra of SNe Ia observed by the HST, and could show that the dependence of the UV flux on metallicity is not as simple as previously suggested, but rather depends in a very complex way on metal content, stratification of composition, age and luminosity.

In collaboration with M. Tanaka and K. Nomoto (U. Tokyo), S. Benetti (INAF, Padua), R. Kotak (U. Belfast), G. Pignata (U. Santiago) and V. Stanishev (U. Stockholm), P. Mazzali, N. Elias-Rosa and S. Hachinger studied the properties of the outer ejecta of SNe Ia from early spectroscopy, showing that "delayed detonation" models are more consistent with the observations as they place more material at high velocities, but also that the presence of a low-density CSM may explain how some of the observed high-velocity absorptions form. This may be useful for the determination of the nature of the progenitors. Also in collaboration with D.K. Sahu (IIA, Bangalore) and members of the U. Tokyo group, P. Mazzali performed an analysis of the peculiar SN Ia 2005hk, suggesting that a pure deflagration of a CO WD may be consistent with the observations.

S. Sim and P. Mazzali used a newly developed multidimension, time-dependent Monte Carlo code is used to compute sample γ-ray spectra to explore whether unambiguous constraints could be obtained from γ-ray observations of Type Ia supernovae. The could show that moderate departures from sphericity can produce viewing-angle effects that are at least as significant as those caused by the variation of key parameters in 1D models. Thus, γ-ray data could, in principle, carry some geometrical information, and caution should be applied when discussing the value of γ-ray data based only on 1D explosion models.

S. Taubenberger, W. Hillebrandt and P.A. Mazzali also obtained late-phase spectrophotometry of a peculiar thermonuclear (Type Ia) SN, which had been reported to be overluminous by a factor ~ 2 compared to normal SNe Ia at peak. They use these observations to distinguish between different scenarios for the high early-phase luminosity: an enhanced mass of radioactive ^{56}Ni (probably in company with a total ejecta mass exceeding the 1.4 $M_\odot$ limit for non-rotating white dwarfs) would manifest itself in bright late-phase light curves, whereas a boosted early-time emission due to an off-center distribution of ^{56}Ni would result in normal late-time brightness, but a Doppler shift of Fe emission lines in the nebular spectrum.

Within his PhD project supervised by E. Müller, Nicolay Hammer investigated the propagation of the shock wave formed in a core collapse supernova through the stellar envelope using three dimensional hydrodynamic simulations. Of particular interest is the mixing of elements due to Rayleigh-Taylor and Richtmyer-Meshkov instabilities. This work extends previous studies which were restricted to axisymmetric models.

3.4 Black holes and compact objects

Four years of all-sky observations by the IBIS/ISGRI soft gamma-ray imager aboard ESA's INTEGRAL observatory have provided a sample of more than a hundred nearby active galactic nuclei (AGN) selected in the hard X-ray (17–60 keV) band. This practically unbiased sample for the first time permits a statistical investigation of the local AGN population. Several tens of INTEGRAL sources remained unidentified, with most of them located near the Galactic plane ($|b| < 5$ deg) and in the Galactic Center region. S. Sazonov, M. Revnivtsev, R. Sunyaev and E. Churazov, R. Burenin (Space Research Institute, Moscow), I. Bikmaev (Kazan State University), W. Forman and S. Murray (Harvard-Smithsonian Center for Astrophysics) used the Chandra X-ray Observatory and the Russian-Turkish 1.5-meter Telescope to refine the positions, measure the spectra, and establish the nature of unidentified INTEGRAL sources. Several objects were found to have a Galactic origin, being magnetic cataclysmic variables or high-mass X-ray binaries. The majority of sources proved to be nearby (at redshifts from 0.025 to 0.25) AGN with significant X-ray absorption along the line of sight, including two Compton-thick objects. With the newly-identified sources, the number of (nearly) Compton-thick AGN detected by INTEGRAL has increased to 10. Therefore, such objects constitute 10–15% of hard X-ray bright, non-blazar AGN in the local Universe.

On June 10 of 2007 the Burst Alert Telescope aboard Swift triggered on GRB 070610, an unusual long-duration X-ray transient presumably of Galactic origin. The INTEGRAL observatory conducts regular scans of the Galactic plane and, in addition, performed several long pointed observations of the field around GRB 070610. R. Krivonos, S. Grebenev and R. Sunyaev reanalyzed the archival data of INTEGRAL and found no activity of GRB 070610 in the past with putting strong upper limits for source detection.

A. Bogdan and M. Gilfanov continued to investigate the unresolved X-ray emission in M31 using archival data of Chandra and XMM-Newton. Their study was extended to the entire galaxy, with the emphasis on similarities and differences between the bulge and the disk. Based on spectral properties of unresolved emission and X-ray to K-band ratios observed in the disk and bulge they demonstrated that unresolved X-ray emission has the same origin in the bulge and disk of M31, namely it originates from the same type of faint X-ray sources - accreting white dwarfs and active binaries associated with the old stellar population. It was also shown that there is excess emission from spiral arms which is primarily due to young stellar objects and young stars located in the star-forming regions. The accurate measurement of X-ray to K-band ratios also allowed them to constrain the mass of the white dwarf and accretion rate in progenitors of Classical Novae.

R. Voss (Excellence Cluster Universe), M. Gilfanov, G. Sivakoff (University of Virginia) and Ralph Kraft (CfA) studied population of compact X-ray sources in the nearby early-type galaxy Centaurus A. Based on the data of 800 ksec long Chandra observation they found that the luminosity distributions of X-ray binaries located in globular clusters and in the field are different, demonstrating that the samples are drawn from distinct populations. This confirms that dynamical processes taking place in globular clusters can not be responsible for formation of the entire population of X-ray binaries in early-type galaxies and primordial binaries do make a sizable contribution.

M. Revnivtsev and his colleagues S. Sazonov, E. Churazov, M. Gilfanov and H. Ritter have continued studying various populations of Galactic X-ray sources. Their main efforts were directed toward the identification of newly discovered sources from the INTEGRAL all-sky survey and to the investigation of statistical properties of low-mass X-ray binaries and accreting white dwarfs. Using ultra-deep observations of the Galactic bulge region with the INTEGRAL observatory, the luminosity function of low-mass X-ray binaries was continued down to luminosities as low as 1e35 erg/s, where it was found to flatten with respect to the previously known high-luminosity part. This probably indicates a change in the mechanism responsible for the binary system angular momentum removal, e.g. from magnetic stellar wind to gravitational wave radiation. This study also revealed that the spatial distribution of low-mass X-ray binaries in the Galactic bulge closely traces that of stellar mass. A similar study of the luminosity function and spatial distribution of accreting white dwarf binaries demonstrated that the hard X-ray emission of the so-called galactic ridge can be the superposition of the radiation from the huge number of cataclysmic variables distributed over the Galaxy.

M. Revnivtsev and E. Filippova (Space Research Institute, Moscow) have developed a model of propagation of a shock wave into a stellar wind with the aim to explain an unusual X-ray outburst of the Galactic source CI Cam. They demonstrated that a thermonuclear (X-ray nova) explosion on the white dwarf surface can produce ejecta forming a shock wave with parameters consistent with the data from X-ray telescopes. The adopted 1D approach to the problem, however, does not fully correspond to the real situation in the binary system CI Cam, since the optical companion is a B[e] star whose stellar wind is likely disk-like rather than spherically symmetric. In order to investigate the effect of such a disk-like structure on the results, E. Fillipova has started to implement a 2D computational scheme.

M. Revnivtsev have completed a series of works on study of populations of Galactic X-ray sources. In particular, part of the work was devoted to identification of newly discovered sources from INTEGRAL all sky survey catalog and in another part M.Revnivtsev in collaboration with S. Sazonov, E. Churazov, M. Gilfanov, H. Ritter used complete all sky survey INTEGRAL catalog in order to study statistical properties of populations of galactic low mass X-ray binaries and accreting white dwarfs. For the first time in our Galaxy it became possible to continue luminosity function of Galactic low mass X-ray binaries down to luminosities as low as 1e35 erg/sec. It was made with the help of series of ulta deep observations of the Galactic bulge region with INTEGRAL observatory. It was demonstrated that the luminosity function of low mass X-ray binaries in the limit of low luminosities flattens with respect to its high luminosity end. This might indicate the change of the mechanism responsible for the binary system angular momentum removal (e.g. from magnetic stellar wind to gravitational waves radiation). As a part of the same work it was shown that the spatial distribution of low mass X-ray binaries in the Galactic bulge region very well traces the distribution of the stellar mass in the Galaxy. Using results of INTEGRAL all sky survey a luminosity function of accreting white dwarf binaries and parameters of their distribution over the sky were constructed. For the first time a cumulative X-ray emissivity of hard X-ray emitting cataclysmic variables was measured. It was shown that the value of the cumulative emissivity is appropriate for explanation of the Galactic ridge hard X-ray emission as summed contribution of huge number of cataclysmic variables distributed within the Galaxy.

The phenomenon of Soft Gamma Repeaters (SGRs) may allow us in the near future to determine fundamental properties of strongly magnetized, compact stars. The analysis of the decay of the flares reveals several quasi-periodic oscillations (QPOs). One attempt to explain those involves the excitation of Alfvén oscillations. P. Cerdá-Durán, N. Stergioulas (Univ. of Thessaloniki) and J.A. Font (Univ. of Valencia) performed numerical MHD simulations of torsional Alfvén oscillations in the core of neutron stars confirming the presence of a continuum spectrum that relaxes to form QPOs. During his PhD project, supervised jointly by E. Müller and P. Cerdá-Durán, Michael Gabler will extend this model to include the effects of a solid crust.

3.5 Accretion

The generation of jets: narrow outflows of material such as observed from protostars and Gamma-ray bursts, is still one of the most intensively studied fields in high-energy astrophysics. A magnetic model has become the standard explanation for most observed jets: the rotation of a magnetized compact object is the source of energy powering a collimated outflow. The large amount of magnetic energy carried by such a jet tends to become unstable by internal (kink) instabilities. This process has been studied in detail with 3-D MHD simulations by R. Moll (with H. Spruit and M. Obergaulinger). The results show for the first time that instabilities cause the toroidal field in the jet to decay with distance. This was made possible by using a grid extending over a factor 1000 in distance from the rotating source.

A major still controversial problem in X-ray astronomy is the nature of the accretion flow that produces the energetic X-rays in the so-called ‘hard state’ in mass-accreting black holes. Observational and theoretical lines of evidence suggest that close to the hole the cool ($\sim$ 1 keV) accretion disk can jump to a different, very hot, state producing hard ($\sim$ 100 keV) X-rays, in the process truncating the inner regions of the cool disk. This has been challenged by the observation that an excess of soft X-rays (<1 keV) is often present together with the hard radiation. This has been interpreted as evidence that truncation of the inner disk does not occur. As part of her thesis, C. D'Angelo (with H. Spruit) has shown that a soft excess is naturally produced by the interaction of a hot accretion flow with the cool disk. Artefacts of the fitting process used for interpreting the X-ray spectra also contribute to the inferred soft excesses.

When an accretion disk feeds mass onto a strongly magnetic star (protostar, white dwarf or neutron star), the inner regions of the disk are disrupted by the magnetic field ('magnetospheric accretion'). In a traditional view, the accreting mass is expelled from the system ('propellering') if the star rotates faster than the edge of truncated disk. Instead, it is more likely that friction of the magnetosphere against the disk edge only causes a slow outward expansion of the disk. C. D'Angelo has studied this process by numerical simulation, and finds that the interaction between disk and magnetosphere can become unstable, producing a cyclic alternation between accreting and non-accreting states. The process is relevant to certain forms of cyclic behavior observed in neutron stars and protostars.

In the last few years, there has been growing speculation about the possible role of outflows from accretion discs in explaining a variety of properties of the X-ray spectra of active galactic nuclei (AGN). In order to quantify the spectroscopic influence of such outflows, S.A. Sim, K.S. Long (STScI), L. Miller (Oxford) and T.J. Turner (NASA/GSFC) have make a study of X-ray spectral formation for a range of outflow conditions using Monte Carlo radiative transfer calculations. They have found that accretion disk winds could imprint a wide range of spectroscopic signatures including both absorption and emission features as have previously been seen in observations. They also showed that electron scattering in such flows may lead to extended red wings in emission lines including the well-known Fe K feature detected in many AGN spectra.

Low-mass X-ray binaries show a variety of outburst behaviour, and during the outburst cycles an evolution from a low-luminosity hard spectral state to a high-luminosity soft spectral state and back. The different spectra result from different accretion modes in the inner region around the accreting neutron star or black hole. For low accretion rates an outer accretion disk is truncated and a geometrically thick but optically thin hot flow ("advection-dominant accretion flow") fills the inner region. But recent observations of black hole binaries indicate the possible presence of cool matter in the close vicinity of the central object (see above, however), which seems to put doubts on the commonly accepted model. F. Meyer, E. Meyer-Hofmeister, B.F. Liu (National Astronomical Observatories, CAS, Kunming, China), and R.E. Taam (Northwestern University, Evanston, USA) investigated whether re-condensation of gas from the hot flow to an inner disk can occur. Cooling processes, both, thermal conduction and Compton cooling are important. The model allows to understand the observations of cool matter in the innermost central regions of systems like GX 339-4 and Swift J1753. In another X-ray binary, LMC X-3, a sequence of hard and soft spectral states not yet noticed before is observed. During the soft state a hard state component appears, but only while the soft radiation is decreasing, not when it rises. F. Meyer studied whether advection of magnetic flux in the accretion disk may be responsible for these features.

3.6 Milky Way

The evolutionary history of the Milky Way bulge and its relationship with the other Galactic populations is still poorly understood. The Galactic bulge has been suggested to be either a merger-driven classical bulge or the product of a dynamical instability of the inner disk. In an attempt to probe the star formation history, the initial mass function and stellar nucleosynthesis of the bulge, a group led by J. Meléndez (CAUP, Portugal) and M. Asplund has performed an elemental abundance analysis of bulge red giant stars as well as an identical study of local thin and thick disk and halo giants to establish the chemical differences and similarities between the various populations. For the purpose high-resolution infrared spectra of 19 bulge giants and 49 comparison giants in the solar neighborhood were acquired with Gemini/Phoenix. The study confirms the well-established differences for [O/Fe] at a given metallicity between the local thin and thick disks. No chemical distinction between the bulge and the local thick disk was found, which imply that the bulge and local thick disk have experienced a similar, but not necessarily shared, chemical evolution history. This conclusion is in stark contrast to previous studies relying on literature values for disk dwarf stars in the solar neighborhood, which was shown to introduce systematic errors. The formation time-scales, star formation rates and initial mass functions of Galactic bulge and thick disk must therefore have been similar.

The Galactic halo contains the oldest stars known in the Universe and thus contain critical clues to the formation and evolution of galaxies like the Milky Way. The nature of the first generations of stars is still poorly understood although on theoretical grounds one expects them to have been predominantly much more massive than stars today. One way to shed light on this is to determine the chemical compositions of the oldest remaining stars, which should show the nucleosynthetic fingerprints of the first stars. A team led by PhD student D. Fabbian (ANU, Australia) and M. Asplund, have determined the carbon and oxygen abundances in some of the most metal-poor stars known in the Galaxy using high-quality observations obtained over several nights with ESO's Very Large Telescope. The analysis was carried out by means of new, detailed non-local thermodynamical equilibrium calculations for the spectral line formation for both elements. While oxygen is produced predominantly in the supernova explosions of massive ($> 8\,\mathrm{M}_\odot$) stars, carbon was thought to originate in solar-type stars. Since their lifetimes is much longer, one would expect that the carbon abundance to be low during the early epochs of the Milky Way before those low-mass stars have enriched the interstellar medium with their nuclear-processed gas. In contrast, the group found that these very old stars contained large amounts of carbon while at the same time less oxygen than previous studies had claimed. The new analysis provides support for recent theoretical calculations of the evolution of the first stars, which imply that even very massive stars containing initially only hydrogen and helium can produce the large amounts of carbon observed. The new observations may therefore reveal the tell-tale nuclear signature of the elusive first stars.

Concerning the age of metal-poor field stars, P. Jofre, together with B. Panter (Edinburgh, UK) and A. Weiss, developed during her PhD a fast and efficient tool to determine metallicities of many thousands of stars automatically from low-resolution spectra. The method, which can be applied to any stellar spectrum, accelerates a likelihood analysis by performing an appropriate form of data compression. She has tested the code on turn-off metal-poor stars by using the low resolution spectra from SDSS DR6 and the high resolution spectra from VLT UVES. Together with color information or the effective temperature determined simultaneously, the bluest stars in the sample of any given metallicity will provide a lower limit to the age of the dominating sub-population of the galactic halo, whose age and age-metallicity related can thus be derived.

3.7 Galaxy structure and evolution

Using the 305m Arecibo radiotelescope, B. Catinella and her collaborators at Cornell University (M.P. Haynes, R. Giovanelli) and University of Washington (J.P. Gardner and A.J. Connolly) have successfully carried out a pilot survey that has obtained the highest-redshift detections of HI emission from individual galaxies to date ($z = 0.25$). Their sample comprises non-interacting disk galaxies in relatively isolated fields, selected from the optical Sloan Digital Sky Survey (SDSS). The objects detected are massive disk galaxies in the redshift interval 0.17−0.25 (i.e. 2−3 Gyr look-back time), with HI masses of $3{-}8\times10^{10}\,M_\odot$ and high gas mass fractions (HI -to-stellar mass ratios $\sim 10\% - 30\%$), which appear to be rare in the local universe.

Future extension of this pilot program, together with complementary HI synthesis mapping programs of cluster galaxies at similar redshifts carried by other groups, will allow the group to explore the evolution of the HI content of disk galaxies over the last several Gyr for a statistically complete sample.

D. Schiminovich (Columbia), B. Catinella, G. Kauffmann and other collaborators at various institutions are carrying out the GALEX Arecibo SDSS Survey (GASS), an ambitious program designed to measure the neutral hydrogen content of ~ 1000 nearby, massive 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. Recent work based on the SDSS shows that galaxies with stellar masses $M_{\rm star} > 3 \times 10^{10}\ M_\odot$ generally fall on the red sequence, whereas lower mass galaxies are typically blue and star-forming. Interestingly, this mass scale may correspond to the transition between two regimes of gas accretion, a clumpy, filamentary "cold accretion" mode and a quasi-spherical, smooth "hot accretion mode". It remains a challenge to test this hypothesis, because information on the gas content of galaxies is still largely missing in studies with SDSS. GASS will produce the first statistically significant sample of massive transition galaxies with homogeneously measured stellar masses, star formation rates and gas properties, thus providing new insight into the physical mechanisms that regulate the transition between the blue and red sequences.

The survey started in March 2008 and is ongoing. All the Arecibo observations have been carried out remotely from the MPA by B. Catinella, joined by S. Fabello in late 2008. More information (including the complete list of collaborators) can be found on the GASS web site (*http://www.mpa-garching.mpg.de/GASS*).

W. Zhang (NAOC, Beijing), C. Li, G. Kauffmann and collaborators have estimated the H I gas mass for 10^5 emission-line galaxies in the SDSS DR4. For this a new photometric estimator of H I-to-stellar mass ratio for nearby galaxies was calibrated using a sample of 800 galaxies with H I mass measurements from the HyperLeda catalogue and optical photometry from SDSS. Using these data the group has derived an estimate of the H I mass function, which is in excellent agreement with recent results from H I blind surveys. The group has also re-examined the well-known relation between gas-phase metallicity and stellar mass, and found that gas-poor galaxies are more metal rich at fixed stellar mass.

Several mechanisms have been proposed to explain the formation of bulges in disc galaxies, as well as the formation of elliptical galaxies, such as disc instabilities and the merger of smaller units. Each mechanism is expected to produce stellar systems with specific characteristics, concerning their structure and stellar content. Using images from the Sloan Digital Sky Survey, D. Gadotti has obtained estimates of several structural parameters of bulges, discs, bars and elliptical galaxies, in a sample of 1000 local galaxies, providing a detailed characterization of the structural properties of such stellar systems, which can be compared with theoretical predictions. The results suggest that, at the low mass end of the bulge mass distribution, a different formation process is dominant, as compared to the high mass end. However, there are also indications that in many cases different formation processes are at play simultaneously. Using these results, D. Gadotti and G. Kauffmann have estimated how the mass in central black holes is distributed amongst elliptical galaxies and bulges in the local universe.

C. Li, D. Gadotti, S. Mao (Manchester) and G. Kauffmann have studied, for the first time, the clustering properties of barred galaxies using data from the SDSS. The clustering of barred and unbarred galaxies of similar stellar mass was found to be indistinguishable over all the scales probed (∼20 kpc–30 Mpc). This result also holds even if the sample is restricted to bars with bluer $g-i$ colours (and hence younger ages). The only property of bars that appears to be influenced by environment is ellipticity. More elliptical bars are more strongly clustered than less elliptical bars, on scales > 1 Mpc. There appears to be no significant evidence that bars are a product of mergers or interactions. The stronger clustering of the more elliptical bars was tentatively interpreted as evidence that they are located in older galaxies, which reside in more massive halos.

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.

It is well known that the properties of galaxies depend on environment. Galaxies residing in denser regions form on average fewer stars and more often have elliptical morphologies. S. Weinmann, G. Kauffmann, F. van den Bosch (MPIA Heidelberg), A Pasquali (MPIA Heidelberg), D. McIntosh (University of Kansas), H.J. Mo (UMass), X. Yang (Shanghai Observatory) and Y.Guo (UMass) have studied the properties of galaxies in a group catalogue based on the SDSS, specifically concentrating on galaxy morphology and radial profiles. They have found evidence that a decreased star formation rate of galaxies in denser regions is indeed caused by an environmental effect (which they claim is "starvation", i.e. the removal of the hot gas halo around galaxies in dense regions). On the other hand, no evidence was found that environmental effects transform disk galaxies into ellipticals. Rather, the higher prevalence of elliptical galaxies in dense regions is due to the higher average stellar mass in those regions.

Although it is relatively simple to derive physical properties like star formation rate for nearby galaxies, things get much harder at higher redshifts, because the data quality is often much poorer and key emission lines are missing from the available spectra. Yan-Mei Chen (MPA and IHEP,Beijing), V. Wild and G. Kauffmann studied the evolution of star formation in galaxies out to z=1. Spectra of 600-1000 galaxies with similar stellar masses were combined and the strength of the hydrogen Balmer absorption-line series in the rest-frame wavelength range 3750-4150 Å was used to constrain the average specific star formation rate of the stacked population. This method, unlike other ways of estimating star formation rates, can be applied in a consistent way to spectra drawn from local galaxy surveys and from surveys at z∼ 1. The results suggested that star formation reales at z∼ 1 have been systematically overestimated in previous work.

The galaxy luminosity function (LF) both in the high-redshift universe and in the local universe at very faint luminosities, is currently subject of great interest. Large spectroscopic surveys of such faint samples are expensive, and often only multi-band photometric information is available. The Photometric Maximum Likelihood method developed by D. Christlein in collaboration with N. Padilla (Pontificia Universidad Católica Chile), E. Gawiser (Rutgers University), and D. Marchesini (Yale University) is a rigorous Bayesian algorithm developed specifically for analyzing the LF and its evolution in such samples without resorting to photometric redshifts. Work throughout 2008 focused on refining the results obtained from the E-CDFS sample by the MUSYC project, and on extending the method by adding the capability of analyzing multiple samples simultaneously as well as using synthetic templates in order to access the high-redshift universe. In collaboration with S. Miekse (ESO) and L. Infante (PUC), we have also begun to apply this algorithm to a sample of galaxy clusters surveyed with the ACS with the aim of determining the faint end shape of the LF both in the field and in clusters.

The last few decades have seen a remarkable development in the observational study of high-redshift galaxies. Using a semi-analytic approach, Q. Guo and S. White investigated observationally defined subsets of the galaxy population, and investigated how they evolve with time. Three populations were studied: Lyman break galaxies at z ∼ 3 (LBG), star forming galaxies at z ∼ 2 (BX) and distant red galaxies at z ∼ 2(DRG). They showed that current galaxy formation models can simultaneously reproduce the abundances, redshift distributions and clustering of all three observed populations. The star formation rates (SFRs) of model LBGs and BXs are lower than those quoted for the real samples, reflecting differing initial mass functions and scatter in model dust properties. About 85% of model galaxies selected as DRGs are star-forming, with SFRs in the range 1 to $\sim 100 M_\odot$/yr. Model LBGs, BXs and DRGs together account for less than half of all star formation over the range $1.5 < z < 3.2$; many massive, star-forming galaxies are predicted to be too heavily obscured to appear in any of these populations. Half of all LBG descendants at $z \sim 2$ would be identified as BXs, but very few as DRGs. Model LBGs and DRGs end up as red ellipticals, while BXs have a more varied fate. Clustering increases with decreasing redshift for descendants of the three populations and becomes stronger than that of L^* galaxies by $z = 0$. Around 30% of massive galaxies are identified as LBGs and BXs at their corresponding redshift, but about 65% as DRGs. Matching the observed properties of these high redshift galaxies required the introduction of a new dust model, thus providing clues to evolution in the relation between dust and other galaxy properties.

Several teams have used deep observations to search for the existence of faint companion galaxies of QSOs at z ∼ 6, which are naturally expected if the QSOs form in the densest regions at high redshift. R. Overzier, Q. Guo, G. Kauffmann, G. De Lucia, R. Bouwens (UCSC) and G. Lemson (MPE) have used the Millennium Run cosmological simulations to construct a large mock survey of star-forming galaxies at z∼ 6 and make predictions for the distribution of i-dropouts and Lya-emitters, and their relation to the most massive halos and protocluster regions at z∼ 6. They predict significant variations in surface density across the sky with voids and filaments extending over scales of 1 degree, much larger than is probed by current surveys. Two structures of galaxies found in random fields with the Subaru Telescope are shown to be related to massive galaxy clusters in formation. In contrast, when comparing the counts of star-forming galaxies in the simulations with those observed towards six QSOs at $z = 6$, the widely used assumption that QSOs are associated with the most massive high redshift halos could not be confirmed. However, neither can it be ruled out based on the currently available data.

3.8 Galaxies and their AGN

One of the major themes of studies of nearby galaxies by MPA researchers has been to understand how galaxies and their central supermassive black hole co-evolve across cosmic time.

G. Kauffmann and T. Heckman (JHU, Baltimore) analyzed the observed distribution of Eddington ratios as a function of supermassive black hole mass for a large sample of nearby galaxies drawn from the Sloan Digital Sky Survey. They demonstrated that there are two distinct regimes of black hole growth in nearby galaxies. The first is associated with galaxies with significant star formation in their central kiloparsec regions, and is characterized by a broad log-normal distribution of accretion rates peaked at about one percent of the Eddington limit. The second regime is associated with galaxies with old central stellar populations, and is characterized by a power-law distribution of Eddington ratios. In this regime, the time-averaged mass accretion rate onto black holes is proportional to the mass of stars in the galaxy bulge, with a constant of proportionality that depends on the mean stellar age of the stars. It was also shown that both the slope of the power-law and the decrease in the accretion rate onto black holes in old galaxies are consistent with population synthesis model predictions for the decline in stellar mass loss rates as a function of mean stellar age. These results lead to a very simple picture of black hole growth in the local Universe. If the supply of cold gas in a galaxy bulge is plentiful, the black hole regulates its own growth at a rate that does not further depend on the properties of the interstellar medium. Once the gas runs out, black hole growth is regulated by the rate at which evolved stars lose their mass.

PhD student E. Donoso and G. Kauffmann constructed a catalogue of 14,000 radio-loud AGN from cross-correlating the MegaZ-luminous red galaxy catalogue from Sloan Digital Sky Survey imaging data with the FIRST and NVSS radio surveys. A new determination of the luminosity function of radio AGN at $z \sim 0.55$ was made and this was compared to the luminosity function of nearby ($z \sim 0.1$) radio sources from the Sloan Digital Sky Survey main survey. The comoving number density of radio AGN with luminosities less than 10^{25} W Hz^{-1} increases by a factor of 1.5 between $z = 0.1$ and 0.55. At higher luminosities, this factor increases sharply, reaching values of more than 10 at radio luminosities larger than 10^{26} W Hz^{-1}. The redshift evolution of the relation between radio AGN and their host galaxies was also studied. The main conclusion is that the fraction of radio-loud AGN increases towards higher redshift in all massive galaxies, but the evolution is particularly strong for the lower mass galaxies in the sample.

Another topic of much current study is how "feedback" from radio jets may heat and otherwise perturb the gas in massive dark matter halos. Shiyin Shen (Shanghai Observatory), G.Kauffmann, A. von der Linden, S. White and P. Best (Edinburgh) studied the X-ray properties of a sample of 625 groups and clusters of galaxies selected from the Sloan Digital Sky Survey. Clusters with similar velocity dispersions were stacked to investigate whether their average X-ray luminosities and surface brightness profiles vary with the radio activity level of their central galaxies. At a given velocity dispersion, clusters with a central radio active galactic nucleus (AGN) have more concentrated X-ray surface brightness profiles, larger central galaxy masses and higher X-ray luminosities than clusters with radio-quiet central galaxies.

SMBHs appear to be ubiquitous in the centers of elliptical galaxies and bulges, and their masses are tightly correlated with physical properties of their host galaxies. This suggests that the processes that form spheroids also trigger black hole growth and quasar activity, and that galaxies and their SMBHs may influence each other during their evolution. 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. In collaboration with F. Marulli (University of Bologna) the group tested a model for accretion and evolution of SMBHs based on galaxy mergers, and tested different models for quasar lightcurves by comparing the clustering of simulated quasars with the clustering properties of observed objects. They found that a lightcurve model that includes a quiescent phase can describe the behaviour of faint active galactic nuclei. Moreover, the observed spatial distribution of quasars is well predicted by a model in which nuclear activity is triggered by galaxy mergers, thus lending support to the conjecture that mergers could indeed be the main physical process responsible for triggering efficient black hole accretion and bright quasar activity.

R. Mandelbaum (IAS, Princeton), C. Li, G. Kauffmann and S. White have computed two-point correlation functions and measured the shear signal due to galaxy-galaxy lensing for AGN samples constructed from the SDSS. Halo occupation models were used to estimate halo masses and satellite fractions for optical and radio-loud AGN. Halo masses deduced from clustering and from lensing were found to agree satisfactorily. Radio AGN are found in more massive halos than optical AGN: in the samples being studied their mean halo masses are 1.6×10^{13} and 8×10^{11} M_{sun}/h, respectively. Optical AGN follow the same relation between stellar mass and halo mass as galaxies selected without regard to nuclear properties, but the dark matter halos of radio-loud AGN are about twice as massive as those of control galaxies of the same stellar mass. This leads the group to conclude that the large-scale gaseous environment of the galaxy clearly plays a crucial role in producing observable radio emission.

There is compelling evidence that black holes (BHs) vigorously interact with their surroundings in the central regions of galaxy clusters, indicating that any realistic model of cluster formation needs to account for these astrophysical processes. In particular, it is believed that the lack of accounting for BH physics in previous hydrodynamical simulations has been responsible for the severe difficulties to explain the halo gas fractions and the X–ray luminosity temperature scaling relation of galaxy clusters and groups. E. Puchwein, D. Sijacki (Institute of Astronomy, Cambridge, UK), and V. Springel performed high-resolution cosmological simulations of a large galaxy cluster and group sample to study how BHs affect their host systems. They demonstrated that including BH feedback into the simulations brings both halo gas fractions and the X–ray luminosity temperature scaling relation in excellent agreement with observations, while at the same time yielding more realistic stellar mass fractions. This shows that feedback from BHs can indeed account for the discrepancies between observed and simulated X–ray properties of galaxy clusters and groups.

3.9 Reionisation and the intergalactic medium

A very debated issue is the role of very massive, metal-free stars in the first stages of reionization. B. Ciardi, in collaboration with R. Schneider (Florence, Italy), has extended, using numerical simulations with the code PINOCCHIO, a previous analytical study of the physics of the transition from an early epoch dominated by massive Pop III stars to a later epoch dominated by familiar low-mass Pop II/I stars and their impact on reionization. U. Maio, B. Ciardi, K. Dolag and L. Tornatore (Trieste, Italy) are now studying the same transition by means of numerical simulations with the code GADGET that focus the attention on the early stages of galaxy formation, when very small mass objects (whose formation relies on the presence of molecular hydrogen and deuterium) are formed.

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) and T. Di Matteo (Pittsburgh, USA), has studied the conditions for IGM heating by Lyα and x-ray photons to be effective in rendering the 21 cm line visible in emission, finding that this is typically possible at $z < 15$. B. Ciardi and A. Maselli are collaborating with the LOFAR Epoch of Reionization Team (Netherlands) to model quantities that will be observed by this telescope, presently under construction in the Netherlands and other European countries including Germany, in the next decade.

Early structure formation is one of the fundamental problem in Astrophysics. U. Maio in collaboration with B. Ciardi, K. Dolag, L. Tornatore (SISSA) and N. Yoshida (IPMU) has studied this process and the subsequent metal-enrichment history finding that primordial, massive, metal-free (pop III) star formation regime is generally negligeble, as first stars rapidly pollute the surrounding medium, and the following generation is formed with a mass-spectrum similar to the one observed today. These results are discussed in U. Maio's Ph.D. thesis.

The Lyman-alpha forest of absorption lines observed in the spectra of high redshift quasars provides a unique and powerful probe of the intergalactic medium (IGM). The comparison of detailed hydrodynamical simulations of structure formation to high quality observations of the Lyman-alpha forest provides important constraints on the structure of the IGM at small scales, and enables detailed investigation of the temperature and ionisation state of the IGM. J.S. Bolton, in collaboration with M. Viel (Trieste), T.-S. Kim (Potsdam), M.G. Haehnelt (IoA, Cambridge) and R.F. Carswell (IoA, Cambridge) performed such a comparison to establish that the observed flux distribution of the Lyman-alpha forest requires voids in the IGM to be hotter than is typically assumed around two billion years after the Big Bang. They suggest that this result may be associated with the impact of radiative transfer effects during HeII reionisation.

Current observations indicate the epoch of HeII reionisation (the transition when most of the helium in the IGM is converted from being singly ionised to doubly ionised) completes around two billion years after the Big Bang. The ionising sources which drive HeII reionisation are expected to be quasars, which are one of the few sources able to provide the energetic photons needed to complete HeII reioniation. J.S. Bolton, in collaboration with S.P. Oh (UCSB) and S.R. Furlanetto (UCLA) investigated the temperature evolution of the IGM during HeII reionisation in a series of two papers. In the first paper, it was found that photo-heating during HeII reionisation will result in a more gradual increase in IGM temperature than conventionally assumed. The second paper extended this study by exploring the implications of this result for the observed Lyman-alpha forest opacity. It was highlighted that current observational constraints are inconsistent with the intepretation that a period of strong, rapid heating occurred during HeII reionisation, and a complex relationship between temperature and density in the IGM is expected.

3.10 Galaxy formation

While being only one galaxy among many, our own Galaxy - the Milky Way - is the one we can study in unique detail. For the Milky Way, and for a number of the brightest members of the Local Group, a wealth of observational data is now available about the ages and chemical abundances of their stars. Much more data will become available over the next decade, providing important tests for current models of galaxy formation and evolution. G. De Lucia (at MPA), in collaboration with A. Helmi (Kapteyn Astronomical Institute) have studied the formation and evolution of a 'Milky-Way'-like galaxy using a combination of high-resolution N-body simulations and semi-analytic models of galaxy formation. The analysis shows that the stellar halo of our Galaxy (which contains only a tiny fraction of the total stellar mass) is mainly formed from a few massive satellites accreted early on during the galaxy's lifetime. The stars in the halo do not exhibit any metallicity gradient, but higher metallicity stars are more centrally concentrated than stars of lower abundances. This is due to the fact that the most massive satellites contributing to the stellar halo are also more metal rich, and dynamical friction drags them closer to the inner regions of the host halo.

C. Scannapieco, S.D.M. White and V. Springel, in collaboration with P. Tissera (Institute for Astronomy and Space Physics, Buenos Aires), used numerical hydrodynamical simulations to study the formation and evolution of galaxy disks in a Lambda-CDM Universe. They showed that realistic disks can be formed from cosmological initial conditions when multiphase gas and supernova feedback models are included in the simulations. They simulated the formation of eight isolated halos similar in mass to the Milky Way, extracted from a large cosmological simulation without restriction on spin parameter or merger history. The simulated galaxies were found to have different morphologies at the present time: four of them have well-formed disk components (with disk-to-total mass ratios of the order of 0.2), three have dominant spheroids and very small disks, and one is a spheroidal galaxy with no disk at all. They found that neither the existence of a disk at $z = 0$ nor the final disk-to-total mass ratio seems to depend on the spin parameter of the halo. Most simulated galaxies, except for one, were found to have significant disks at $z > 2$, regardless of their $z = 0$ morphologies. Both major mergers and instabilities produced when accreting cold gas is misaligned with the stellar disk trigger a transfer of mass from the disks to the spheroids. In some cases, the disks are destroyed; while in others, they survive or re-form. These results suggest that the survival probability of disks depends on the particular formation history of each galaxy.

In collaboration with M. Ruszkowski (now at U. of Michigan), V. Springel studied the role of dissipationless "dry mergers" for the formation and evolution of brightest cluster galaxies. To this end, a rich cluster of galaxies was selected from the Millennium Simulation and resimulated with significantly higher resolution. At redshift $z = 3$, a large number of the progenitor halos of the cluster were identified and replaced with compound galaxy models consisting of dark halos and stellar spheroids. Continuing the simulation forward in time then allowed a study of the merger events between cluster galaxies, and in particular, what impact this has on the galaxy scaling relations, such as the Kormendy and Faber-Jackson relations. The self-consistent treatment of the coupled dark matter and stellar fluids also allowed an analysis of the differential mixing between dark matter and stars. Interestingly, Ruszkowski and Springel found that the brightest cluster galaxy (BCG) evolves away from the Kormendy relation, while only a weak distortion in the Faber-Jackson relation develops. At the same time, the total mass-to-light ratio of BCGs becomes significantly higher than in typical elliptical galaxies.

3.11 Cosmic Microwave Background

M. Frommert and T. Enßlin in collaboration with F. Kitaura have developed optimal methods to detect the integrated Sachs-Wolfe (ISW) effect in the cosmic microwave background (CMB). The integrated Sachs-Wolfe effect is a secondary effect on the CMB temperature anisotropies, created when the background radiation passes through time-varying gravitational potentials of the large-scale-structure (LSS). The ISW can be detected by using the cross-correlation between CMB and the large scale structure (LSS). These scientists have improved existing cross-correlation methods by working conditional on the LSS data, i.e. by using the specific realization of the LSS in our Universe in the analysis, instead of an average over all possible LSS realizations. This enhances the signal-to-noise ratio by about 7 per cent for a galaxy survey that covers all the volume where the ISW effect is created. The method was then further improved by using not only temperature data from the CMB, but also polarization data. The polarization data are correlated with the primordial temperature fluctuations of the CMB, and can thus be used to work conditional on that part of the temperature fluctuations which is known from polarization data. This enhances the signal-to-noise by another 16 per cent for noiseless polarization data, so that the improvement of the signal-to-noise is in total 23 per cent.

The mapping and analysis of the cosmic microwave background temperature fluctuations, as well as the cosmic matter field faces the generic problem of how to reconstruct a signal from noisy, incomplete data, where non-linearities and signal-noise coupling can complicate any signal inference. T. Enßlin and M. Frommert have developed information field theory (IFT), a generic Bayesian framework to tackle non-linear inference problems rigorously by mapping them onto statistical field theories. The usage of a field theoretical language permits to employ many known methods like diagrammatic perturbation series and renormalization techniques to signal inference problems. IFT could be shown to easily allow the construction of optimal estimators for non-Gaussianities in the cosmic microwave background, which are of higher order than previously published estimates. Furthermore, an IFT algorithm to reconstruct log-normal distributed density fields, subject to incompleteness and Poissonian noise was developed in collaboration with F. Kitaura for Cosmography applications. Reassuringly, IFT in the linear regime reproduces the well-known Wiener filter theory, and therefore provides a natural framework to construct and optimise the existing data processing techniques for large-scale structure reconstruction.

Together with C. Carbone (Trieste), M. Bartelmann (U. of Heidelberg), C. Baccigalupi and S. Mattarese (both Trieste), V. Springel constructed full-sky gravitational lensing deflection maps from the Millennium Simulation. To this end the team developed a new map-making procedure based on direct ray tracing through the gravitational potential of the Millennium Simulation. The employed randomization procedure avoids the repetition of structures along the line of sight, but simultaneously produces seamless and continuous maps on the sky. Compared to analytic estimates, the constructed weak lensing maps of the CMB show a small excess of power on small scales, which is interpreted as being due to the non-linear clustering captured in the numerical simulation. The study also shows how non-linear lensing power in the polarized CMB is transferred to large angular scales by suitably misaligned modes in the CMB and the lensing potential.

Radiation from the Cosmic Microwave Background (CMB) is generally regarded as one of the cleanest probes of cosmological information available. However, at the wavelengths at which observations are usually made, foregrounds due to physical emission from our own Galaxy and external ones are significant and can bias the determination of cosmological parameters. The precision measurement of the CMB angular power spectrum requires the subtraction of both diffuse foregrounds and a contribution due to unresolved point-source power.

A.J. Banday has collaborated with a group of colleagues comprising H.K. Eriksen, F.K. Hansen

(Oslo), C. Dickinson, K.M. Huffenberger, J.B. Jewell, K.M. Górski and C. Lawrence (JPL) to implement an exact, flexible, and computationally efficient algorithm for joint component separation and CMB power spectrum estimation, building on a Gibbs sampling framework. Given a parametric model of the foreground signals, the exact joint foreground-CMB posterior distribution can be estimated both efficiently and accurately. To verify the method, the large-scale CMB and foreground posteriors of the 3 yr WMAP temperature data was computed. The parametric data model includes the cosmological CMB signal and instrumental noise, a single power law foreground component with free amplitude and spectral index for each pixel, a thermal dust template with a single free overall amplitude, and free monopoles and dipoles at each frequency. This simple model yields a good fit to the data over the full frequency range from 23 to 94 GHz. We obtain a new estimate of the CMB sky signal in substantial agreement with that derived by the WMAP team, and a new foreground model, including a measurement of the effective spectral index over the high-latitude sky. The corresponding cosmological parameters are also virtually unchanged.

Mapping the Galactic magnetized plasma is of importance for understanding the turbulent mechanisms which amplify and maintain the observed Galactic magnetic field. This field may regulate star formation and molecular cloud collapse. Furthermore, the magnetized inter stellar medium is an important foreground emitter to be understood in detail for cosmic microwave background studies. Understanding galactic magnetic fields is also equivalent to disentangling the origin of ultra-high energy cosmic rays (UHECR). A. Waelkens, T. Jaffe (Jordrell Bank Centre for Astrophysics), M. Reinecke, F.S. Kitaura and T.A. Enßlin developed a now publicly available software tool, `Hammurabi`, for simulating a number of observational signatures of Galactic magnetism. These range from polarized and unpolarized synchrotron emission, Faraday rotation, UHECR deflection and dispersion measure. X.H. Sun (MPIfR), Wolfgang Reich (MPIfR), A. Waelkens and T. Enßlin confronted radio data of our Galaxy with Mock observations generated with the Hammurabi code. Besides a construction of a novel and the currently most precise model of galactic magnetic field structure, this work suggested that the scale height of the galactic thermal electrons is about two kpc instead of one, as previously thought. This finding was independently confirmed by some recent reanalysis of pulsar data.

If the Universe has undergone a recent epoch of accelerated expansion, then large scale gravitational potential wells must have become shallower, and the CMB photons crossing them must have consequently gained energy (this is the so-called Integrated Sachs-Wolfe effect, [ISW]). In order to distinguish the contribution of the ISW from all other CMB temperature anisotropies, Carlos Hernández-Monteagudo has implemented an optimal cross-correlation method in Fourier space that searches for similarities in the large angle CMB temperature pattern and the galaxy distribution (which should probe the potential wells). This method has been applied on real CMB and radio galaxy data, and is part of an algorithm proposed in collaboration with B.Barreiro, P.Vielva and E.Martinez-Gonzalez (from IFCA in Spain) that actually separates the ISW map from the other CMB anisotropies generated at earlier times. Likewise, C. Hernández-Monteagudo is studying, in collaboration with R.E. Smith (Univ.of Zurich) the impact of galaxy bias in ISW - density cross correlation analyses.

At least half of the baryons in the local Universe remain undetected. Under the assumption that these baryons are sharing their peculiar motion with the most massive, nearby (distance $<$ 20-40 Mpc/h) halos, C.Hernández-Monteagudo and R.A.Sunyaev have demonstrated that the signature of these *missing baryons* can be unveiled if future observations of the kinetic Sunyaev-Zeldovich (kSZ) effect in halos can be combined with E-mode polarization measurements of the CMB. Furthermore, in collaboration with S.Ho (Univ.of Berkeley), C.Hernández-Monteagudo has shown that if future kSZ/LSS observations provide accurate templates of the local peculiar velocity field, the signature of the missing baryons can be indepedently probed by looking at the velocity field template – CMB map cross-correlation. These two analyses would provide unique tests both for the presence of the missing baryons and for the validity of theoretical predictions of peculiar velocities in the present Universe.

M. Righi, in collaboration with C. Hernández-Monteagudo and R.A. Sunyaev, has computed the impact of collisionally induced emission of several CO transitions on the CMB. After both building a theoretical description for the CO emission mechanism and calibrating this model with observations, he has shown that, in the frequency range from 30 to 70 GHz, the CO emission is the largest CMB foreground, giving rise to a signal that shows a characteristic dependence with respect to the observing frequency resolution. This particular frequency dependence is very different from any other potential source of contamination, and makes the CO emission a promising tool to explore the high redshift, star-forming universe with future CMB multi-frequency observations.

In preparation for the launch of the Planck satellite mission, K. Dolag prepared hydrodynamical simulations which are used to as template to estimate the possibility to measure the SZ effect from the diffuse signal of the large scale structure, which is one of the main tasks of WG5-project "Diffuse and kinetic SZ signals".

3.12 Dark matter and dark energy

In the new 'Aquarius' project by the Virgo Consortium, V. Springel, S. White, M. Vogelsberger, J. Wang, C. Frenk, A. Jenkins (both Durham), J. Navarro, A. Ludlow (both U. of Victoria), and A. Helmi (Groningen) calculated high resolution simulations of Milky-Way sized dark matter halos. The project's simulation suite studies 6 randomly selected halos in total, which were simulated with at least several hundred million particles in the final virialized regions. For each halo, extensive convergence tests were carried out, culminating in the best-resolved realization with well above 1.5 billion particles in the virial radius. This allowed the identification of about 300,000 gravitationally bound substructures that still orbit in the halo, providing exquisite resolution for probing the structure of the central dark matter cusp. For the first time, the simulations directly demonstrated that the dark matter profile indeed develops a profile with a logarithmic index shallower than -1, which has important implications for our understanding of the non-linear structure formation process.

Using the Aquarius simulations, the Virgo team studied the dark matter annihilation signal expected from supersymmetric dark matter particle candidates in our own Galaxy. They showed that the best chances for detection of the gamma ray radiation expected from self-annihilation of these Majorana fermions lie in the use of optimum filters that help to discriminate the signal against the bright background. The analysis of the team clarified that the highest signal-to-noise is expected for the signal from the main halo of the Galaxy. While substructures boost the overall luminosity significantly due to their large abundance, they typically lie in the outskirts of the Galaxy and yield a much lower signal-to-noise for detection than the smooth component. The Fermi telescope that is now in orbit may have a chance to detect the faint glow of the dark matter in the Galaxy if the backgrounds can be accurately modelled, and the parameters of the supersymmetric particle model are not too unfavorable.

The team around V. Springel also provided accurate measurements for the spatial distribution and abundance of subhalos in dark matter halos, as well as the first convergence study for the internal density profiles of dark matter subhalos. Interestingly, there is evidence that the subhalos show a similar behaviour of their density profiles to main halos, with profiles that become gradually shallower towards smaller radii. Extrapolating the accurately measured substructure mass functions to the thermal limit of dark matter (which is expected to lie around one Earth mass), the simulations showed that the local dark matter density at the Solar circle is expected to be surprisingly smooth, despite the large abundance of dark matter subclumps. The mass fraction of substructures within the Solar Circle is predicted to be well below 0.1%, and within 100 kpc to be still below 3%.

M. Vogelsberger, A. Helmi (Groningen), V. Springel, S. White and other members of the Virgo Consortium used the Aquarius simulations to analyse the dark matter phase-space structure at the Sun's position. Understanding this structure is important for interpreting currently running and planned direct detection dark matter search experiments. The authors found that the spatial distribution near the Sun should be very smooth. Experimentalists can therefore use smooth models to analyse their results. Contrary to numerous published suggestions, the simulation do not predict any massive dark matter streams near the Sun. The velocity and energy distributions show clear features, however in form of bumps and dips that can be related to the formation history of the halo. The authors explicitly show how these imprints influence detectors signal for WIMP and axion searches. They conclude, that once dark matter detection has become routine, these features will allow 'dark matter astronomy' to disentangle the formation history of our halo.

S. White and M. Vogelsberger developed a general analytic treatment of dark matter caustics and their influence on annihilation radiation. Caustics are expected to populate the dark matter distribution in the CDM scenario. Due to their high density they can contribute significantly to the dark matter annihilation radiation. This effect depends on the exact density of the caustic. Based on the phase-space evolution and the symplectic structure of Hamiltonian flows the authors derived expressions for stream densities inside and outside of caustic points. Furthermore, they propose a way to calculate the annihilation radiation of caustics in N-body simulations by integrating the stream density along the trajectory of individual dark matter particles. They show how this integration can be done analytically when the particle passes through a caustic, recovering the well-known logarithmic divergence that is regularised by the finite velocity dispersion of dark matter particles.

The nature of dark matter is one of the most fascinating mysteries of physics today. Neutralinos arise as natural candidates in supersymmetric extensions of the standard model of particle physics and may well be the major component of dark matter in the Universe. Interestingly, their properties as Majorana fermions (they are their own antiparticle) make their detection feasible through non-gravitational effects. One particularly exciting prospect for their detection lies in observing the gamma-ray radiation created in pair annihilations of neutralino dark matter particles. This radiation is expected to contribute significantly to the so-called cosmic gamma-ray background radiation. J. Zavala and V. Springel are using state-of-the-art cosmological N-body simulations to produce the first full sky-maps of the expected radiation coming from the extragalactic dark matter structures. The total gamma-ray luminosity for all haloes and their sub-haloes is taken into account to produce such maps, and corrections for unresolved components of the emission and an extrapolation to the thermal limit of the neutralinos is included. This limit is expected to introduce a low-mass cut-off in the spectrum of dark matter structures at around one Earth mass. The new simulated maps allow a study of the angular power spectrum of the gamma-ray background from dark matter annihilation, which has distinctive features associated with the nature of the annihilation process and may be detectable in forthcoming observations with satellites like the recently launched Fermi Gamma-ray Space Telescope.

The nature of dark energy and dark matter are two of the most important puzzles in modern astrophysics, from both theoretical and observational perspectives. The presence of dark energy is especially difficult to understand, as the observed small value today invokes serious fine-tuning and 'cosmic coincidence' problems in the standard framework of particle field theory. However, a number of theoretical conjectures for new types of scalar fields, such as quintessence, can work around some of these difficulties. Interestingly, such models also predict possible interactions between the dark matter and dark energy components, and may modify the growth of cosmic structures in the linear and non-linear regimes. This class of interacting dark energy models has been investigated by M. Baldi, in collaboration with V. Pettorino (ITP, Heidelberg), G. Robbers (ITP, Heidelberg), and V. Springel. They developed a suitably modified N-body code to study the impact of Coupled Quintessence models on structure formation and their observational signatures. As a result of this investigation it has been found that the interaction imprints characteristic features both in the linear and non-linear regimes of cosmic structure formation. In particular, it lowers the mean halo concentrations and baryon fractions, and produces a large-scale bias between the baryon and cold dark matter distributions. These effects tend to alleviate tensions between the standard cosmological model and observations of cosmic structures on small scales.

The physical origin of dark energy represents a major puzzle for theoretical physics and cosmology. The hope is that accurate observational determinations of the expansion history of the Universe can provide important clues on the nature of dark energy. However, in order to reach the required precision, an accurate understanding of non-linear structure formation in different dark energy cosmologies is required. Margherita Grossi and Volker Springel have carried out high-resolution N-body simulations of so called Early Dark Energy (EDE) cosmologies in order to quantify the differences with respect to a standard ΛCDM model. Analytic modeling of this class of dark energy scenarios has previously suggested that substantial changes in the mass function would result, due a modification of the virial overdensity and collapse threshold. In contrast to these expectations, the simulations have shown that the ordinary formalism to calculate the mass function in cold dark matter models continues to hold for EDE cosmologies. Only the different history of the linear growth factor in these cosmologies has to be taken properly into account. The presence of EDE could be directly tested in observations by counting groups as a function of the line-of-sight velocity dispersion. Using dark matter substructures as a proxy for member galaxies, Grossi and Springel demonstrate that even with 3-5 members, sufficiently accurate measurements of the halo velocity dispersion function are possible.

With a complementary set of hydrodynamical simulations, Margherita Grossi and Volker Springel studied the thermal and kinetic Sunyaev-Zeldovich (SZ) effect in Early Dark Energy (EDE) cosmologies. They show that the earlier formation of clusters in EDE scenarios and the enhanced cluster count at high redshift lead to a substantially increased SZ fluctuation power in the Cosmic Microwave Background. This could in principle also explain the recent observational evidence that suggests an earlier evolution of clusters of galaxies than predicted in the standard LCDM model, especially when a low value for the power spectrum normalization is assumed.

The statistical nature of the initial primordial perturbations in the Universe is of fundamental importance. Even very small deviations from the perfect Gaussianity assumed in the standard model, if detected, would provide crucial information about the physics of the early Universe. M. Grossi and K. Dolag together with E. Branchini [TRE, Roma], S. Matarrese [INFN, Padova] and L. Moscardini [INFN, Bologna] used numerical N-body simulations to study the imprints of weak primordial non-Gaussianity on cosmic structure formation. They found that the non-Gaussianity is well preserved in the negative tail of the probability density distribution during the evolution of the density perturbation. The effect is already noticeable at redshifts as large as 4 and can be detected up to the present epoch. This result suggests that dedicated void-based statistics may provide a powerful method to spot primordial non-Gaussianity even at low redshifts. To further investigate this idea they have studied the statistical properties of the regions with high Lyman-alpha flux transmittivity, in the first high-resolution hydrodynamical simulations of non-Gaussian models performed so far, together with M.Viel [INAF, Trieste]. They conclude that, although challenging, a detection of non-Gaussianities could be possible with future datasets. Within a larger collaboration, including F. Iannuzzi, L. Verde [IEEC, Barcelona] and C. Carbone [IEEC, Barcelona], we also calibrated theoretical predictions for the abundance and clustering of halos within such models for primordial non-Gaussianity using large scale N-body simulations. They demonstrate that correcting the analytical predictions to account for the non-spherical collapse dynamics yields excellent agreement with the numerical results. They also confirm that the non-Gaussian halo bias offers a robust and highly competitive test for primordial non-Gaussianity.

Mapping the detailed large scale structure of the Universe is an important task for precision cosmology. F. Kitaura, J. Jasche, C. Li in collaboration with T. Enßlin, B. Metcalf, B. Wandelt (University of Illinois), G. Lemson (ARI Heidelberg), and S. White performed a high resolution Wiener reconstruction of the large scale structure based on the Sloan Digital Sky Survey (SDSS) data release 6.

The Wiener filter is especially suited for analyzing data, which is subject to a variety of systematic effects. In the specific case of the SDSS data these systematic effects are due to incomplete sky coverage (see figure 3.2) or selection effects. In addition the Wiener filter corrects for the shot noise due to the discrete sampling of the density field by galaxies. The main problem in Wiener reconstruction methods arises from the requirement of solving huge systems of equations, which in a brute force approach requires both enormous amounts of memory and very long computational times. High resolution brute-force reconstructions of large volumes therefore are numerically prohibitive.

To overcome this limitation, the ARGO code (Algorithm for the Reconstruction of Galaxy traced Overdensities) was developed by F. Kitaura and J. Jasche. ARGO is a high performance implementation of the Wiener filter, based on Krylov space inversion methods. It now embraces digital signal processing techniques, such as a novel super-sampling method, which greatly reduces signal aliasing which may have affected previous work in this field. These developments enabled the cosmography team at MPA to perform the most detailed reconstruction of the large-scale structure of the Universe so far (see figure 3.2). The reconstruction reaches a resolution of about a Mpc within a reconstructed volume of ($500\,\mathrm{Mpc}^3$). The resulting 3-d map can now be used for follow up investigations of the cosmic matter field such as an analysis of the cosmic power spectrum to constrain cosmological parameters.

A. Faltenbacher, C. Li and W. White studied how the orientation of galaxies is related to large-scale structure. They found that an alignment of elliptical galaxies with surrounding structure can be detected out to beyond 50 Mpc in SDSS data. They found a qualitatively similar but stronger signal in the Millennium Simulation between the orientations of dark halos and the surrounding large-scale structure. Correlations of this kind pose a serious problem for precision cosmology studies using gravitational lensing.

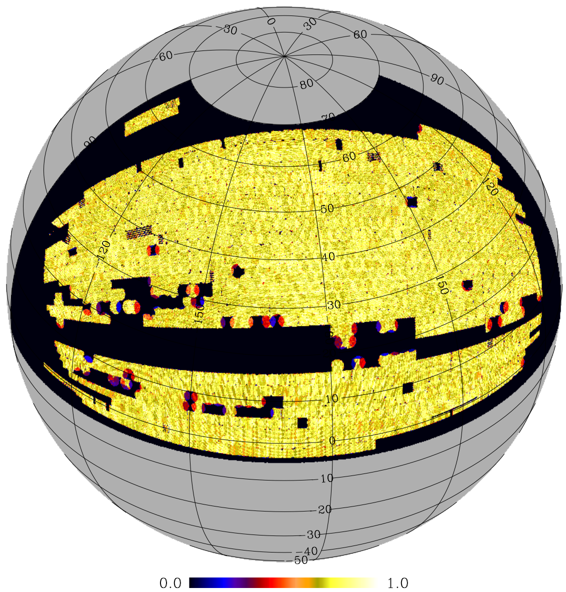

Figure 3.1: Sky mask of the SDSS data release 6 galaxy catalog. Black regions correspond to unobserved areas.

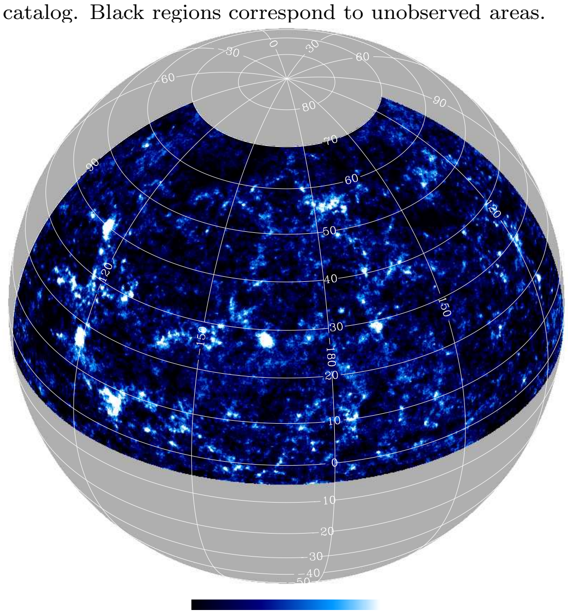

Figure 3.2: View on the 3-d reconstruction of the large scale structure with the ARGO code. Note that the reconstruction provides extrapolations of the matter field into the unobserved regions visible in figure 3.1.

We know that the universe is almost entirely ionized today. We also know that there was an epoch in the early universe when all the hydrogen and helium was in neutral, atomic or molecular, form. Neutral hydrogen emits radiation at a wavelength of 21cm due to the hyperfine splitting of its ground state. There has been a great deal of interest in observing this epoch by detecting this radiation with very large radio telescopes. R. Metcalf and S. White have been investigating what constraints these observations could put on cosmological and particle physics parameters such as the equation of state of dark energy and the mass and number of neutrino species. These constraints come mostly from studying the gravitational lensing of 21 cm sky maps. Neutrino properties are degenerate with dark energy properties in cosmological constraints from the cosmic microwave background (CMB) and from constraints at low redshift ($z < 1$). These 21 cm lensing measurements will remove this degeneracy, making our constraints on massive neutrinos and dark energy much more precise.

E. Neistein and A. Maccio (MPIA Heidelberg) investigated the scaling properties of dark-matter merger-trees for different cosmological models. By using a set of N-body simulations with different power-spectrum shapes and matter densities they found the scaling laws which allow a universal description of merger-trees. They suggested a method to transform merger-trees extracted using a specific cosmological model into a different one. The accuracy of this methodology when applied to different halo masses was examined, as a tool for increasing the resolution of a given merger-tree.

The origin of magnetic fields within galaxy clusters and the large scale structure of the universe is still one of the remaining, open questions in our understanding of the diffuse medium filling the space between galaxies. The strength and structure of such magnetic field is important to understand the origin of the non-thermal emission of galaxy clusters as well as for the propagation of ultra high energy cosmic rays from their extragalactic origin to the observer. Using cosmological, magneto-hydrodynamical simulations of structure formation K. Dolag together with F. Stasyszyn demonstrated that the structure of the magnetic field observed in galaxy clusters can be explained due to the turbulent velocity field within their atmosphere. By, performing extremely large simulations, it was possible for the first time to resolve velocity and magnetic field structures as small as the observed ones. The same numerical method was used by J. Donnert and K. Dolag to verify the possibility that the observed magnetic field in galaxy clusters could be originating from galactic outflows. Performing various model calculations adapting different descriptions for such galactic outflows they showed that reasonable magnetic fields in galaxy clusters are obtained for a broad spectrum of model parameters, compensating for the actual uncertainties in the observations of galactic outflows. Such models for the magnetic field in galaxy clusters were also used to investigate the origin of the observed, cluster-wide diffuse radio emission. In a project together with R. Cassano and G. Brunetti [IRA, Bologna] they were able to put tight constrain on the presence of relativistic protons in galaxy clusters, below the values where such a component could play a dynamical role in the intracluster medium.

An interesting, recent observational finding has been the measured, anisotropic arrival directions of ultra-high energy cosmic rays as observed by AUGER. Such arrival directions seem to be linked to the large-scale matter distribution in the close-by universe, which must therefore host the as yet unidentified sources of these high energy particles. However, such particles were not observed towards all close-by matter concentrations. Together with M. Kachelriess [NTNU, Trondheim] and D.V. Semikoz [APC, Paris] the simulated magnetic field configurations in galaxy clusters were used to demonstrate the effect of magnetic lensing on the propagation of these ultra high energy cosmic rays. Such magnetic lensing leads to an anisotropic emission pattern in the case that the sources of these particles are located within galaxy clusters. This magnetic lensing effect could well explain why AUGER has so far not detected any such particles from the Virgo cluster, the most prominent, close-by matter concentration.

3.13 Numerical methods

Concerning *cosmological hydrodynamics* Volker Springel proposed a novel numerical scheme based on an unstructured moving mesh. The grid is defined as the Voronoi tessellation of a set of mesh-generating points that can be moved with the local flow. A finite-volume discretization of continuum hydrodynamics is constructed on this mesh, using second-order accurate spatial reconstruction and an exact Riemann solver for flux calculations. Unlike ordinary Eulerian codes, the scheme is fully Galilean-invariant. It also inherits many of the principal advantages of smoothed particle hydrodynamics (SPH), in particular its automatic spatial adaptivity and the relative ease with which self-gravity in the presence of an additional collisionless component can be treated. The scheme has been implemented in the new cosmological hydrodynamic simulation code AREPO, which is fully parallelized and offers similar capabilities as the SPH-code GADGET, except that it treats the hydrodynamics completely differently. This opens up new possibilities for improving the accuracy of hydrodynamic cosmological simulations, and should allow progress in understanding the origin of differences reported in the literature between the results of SPH and Eulerian calculations.

Observations suggest that the Universe has been reionised somewhere between redshifts $z = 6$ and perhaps $z \sim 12$, but how this important transition in the state of the intergalactic medium took place in detail is still unclear. In order to study the *reionisation process* with self-consistent hydrodynamic simulations of galaxy formation, Margarita Petkova and Volker Springel have developed a novel numerical implementation of radiative transfer in the cosmological smoothed particle hydrodynamics simulation code GADGET. It is based on a fast, robust and photon-conserving integration scheme where the radiation transport problem is approximated in terms of moments of the transfer equation and a variable Eddington tensor is used as a closure relation, following the 'OTVET'-suggestion of Gnedin & Abel. Tests of the method, performed to check the accuracy and performance of the method, show promising results. Unlike most other radiative transfer codes presently in use for studying reionisation, the new code of Petkova & Springel can be used on-the-fly during dynamical cosmological simulations, allowing a simultaneous treatment of galaxy formation and the reionisation process of the Universe. Also, the calculational speed of the new method is insensitive to the number of sources, a particularly useful property in light of the high number density of star-forming galaxies that contribute to cosmic reionisation.

Numerical simulations of *solar surface convection* with the Antares code at ultra-high resolution and for the 3D case have continued as part of the DEISA project SOLEX that had been granted to H.J. Muthsam (Univ. of Vienna) as a PI and Friedrich Kupka as a co-I. The simulations are expected to clarify how shear driven turbulence is generated and how turbulence manifests itself by means of pairs of vortex tubes and other phenomena. Using resources also at the Univ. of Vienna the case of an exploding granule could be considered at resolutions of better than 5 km and 10 km, respectively, and research on the case of ordinary granulation has begun. Additional 2D simulations were used to demonstrate that the simulation results most likely converge at resolutions around 1 km in the sense that no new phenomena appear and all functions of interest such as the radiative cooling rate and phenomena such as shock fronts are fully resolved. In collaboration with Jerome Ballot the Antares code has also been used to perform numerical simulations of A-type stars, first for the 2D case. These simulations are the first step in a project aiming at understanding line profile formation as well as pulsation driving in A to F-type stars.

F. Kupka has also commenced a systematic comparison between different numerical simulation codes used in the community for simulating solar convection to quantify the effects of boundary conditions, numerical methods, resolution and simulation size, treatment of radiative transfer, and other properties, on the ensemble averaged, statistical properties of the numerical simulations. This work aims at quantifying the uncertainties introduced when using numerical simulations as a test bed for convection modeling.

Within a DFG project on *diffusive and double-diffusive convection* (semi-convection, thermohaline convection) co-led by F. Kupka and performed as an interdisciplinary collaboration with M. Losch and T. Zweigle (AWI Bremerhaven) within the DFG Schwerpunktsprogramm MetStröm (SPP 1276), F. Zaussinger continued his work on numerical simulations of these physical processes. To achieve a higher computational speed a hybrid version (MPI and OpenMP) of the Antares simulation code has been developed by him. The code can now use up to 1024 CPUs in appropriate simulations and its scaling properties can be optimized for different computational architectures. In co-operation with M. Losch and T. Zweigle stellar and oceanic double diffusion scenarios have been analyzed. For a better understanding of semi-convection zones, long time simulations have been started, first in 2D, which will be followed later on by 3D simulations.

The modeling of *convection dominated flows* requires to solve the hydrodynamic equations in the low Mach number regime. In the context of a diploma thesis supervised by F. Röpke, Fabian Miczek explored suitable spatial and temporal discretization techniques. For improved accuracy in the low Mach number regime, he used flux-preconditioned Godunov schemes, whereas computational efficiency requires one to use an implicit time stepping method. The analysis and improvement of the numerical solver for the resulting non-linear algebraic equations is part of the ongoing research of his F. Miczek's PhD thesis.

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.

Core collapse supernova simulations in two or three dimensions including neutrino transport have been done so far either with Newtonian gravity or with an approximate treatment of relativistic gravity by employing an effective potential as suggested by A. Marek, H. Dimmelmeier, H.-Th. Janka, E. Müller and R. Buras. In order to investigate stellar core collapse and explosion and the associated emission of neutrinos and gravitational waves with two dimensional, fully general relativistic models, Bernhard Müller, supervised during his PhD work by H.-Th. Janka, has constructed a new code, coupling H. Dimmelmeier's COCONUT hydrodynamics with a relativistic neutrino transport scheme based on the transport solver of the VERTEX code.

Within his PhD project supervised by E. Müller and in collaboration with N. Stergioulas (Univ. of Thessaloniki), Reiner Birkl has begun to extend the RNS code of N. Stergioulas, a numerical tool to compute stationary axisymmetric equilibria of general relativistic stars with purely circular flow, i.e. with rotation only. The newly developed GRNS code will allow for meridional flow, too.

Pablo Cerdá-Durán and his collaborators I. Cordero-Carrión, J.M. Ibañez (both Univ. of Valencia), H. Dimmelmeier (AREMA), J.L. Jaramillo (IAA, Spain), J. Novak and E. Gourgoulhon (both Obs. de Paris) have developed a new formalism within the CFC approximation to general relativity that allows one to solve the uniqueness problem of this approximation. The new formalism is used to perform simulations of the collapse of neutron stars to black holes. He together with I. Cordero-Carrión and J.M. Ibañez, has also applied the Meudon formalism of the Einstein equations (FCF) to extract gravitational waveforms from hydrodynamic simulations.

T. Mädler, 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. He is developing a numerical code which computes the coupled evolution of the geometric field equations and the relativistic hydrodynamic equations in twisting axisymmetry by using the Bondi-Sachs type coordinate system. This code has been successfully tested using the axisymmetric vacuum solution SIMPLE, and it reproduces the quasi-normal oscillations of a spherical symmetric Tolman Oppenheimer Volkoff star in Cowling approximation in two dimensions. The hydrodynamic part of the code has successfully passed several standard tests. In collaboration with B. Schmidt (AEI, Golm) the regularization of the vertex of the Bondi Sachs coordinate chart has been performed.

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 dimension 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 is done by A. Maselli and B. Ciardi to develop the radiative transfer code CRASH. The implementation of scattering of Ly-alpha photons (M. Pierleoni, A. Maselli, B. Ciardi) and x-ray physics (D. Schleicher [Heidelberg], A. Maselli, B. Ciardi, A. Kanekar, India) has been added, while a parallel version of the code is on its way (A. Partl [Potsdam], A. Maselli, B. Ciardi).

4 Publications and Invited Talks

4.1 Publications in Journals

4.1.1 Publications that appeared in 2008 (212)

Adelman-McCarthy, K. Jennifer, et al. (incl. S. White): The sixth data release of the sloan digital sky survey. Astrophys. J. Suppl. **175**, 297–313 (2008).

Amendola, L., M. Baldi and C. Wetterich: Quintessence cosmologies with a growing matter component. Phys. Review D **78**, No. 023015 (2008).

Anzer, U., and P. Heinzel: Prominence modelling: from observed emission measures to temperature profiles. Astron. and Astrophys. **480**, 537–542 (2008).

Appourchaux, T., E. Michel et al. (incl. J. Ballot): CoRoT sounds the stars: p-mode parameters of Sun-like oscillations on HD 49933. Astron. and Astrophys. **488**, 705–714 (2008).

Arcones, A., G. Martinez-Pinedo et al. (incl. H.-Th. Janka): Influence of light nuclei on neutrino-driven supernova outflows. Phys. Review C **78**, No. 015806 (2008).

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Ballot, J., T. Appourchaux, T. Toutain and M. Guittet: On deriving p-mode parameters for inclined solar-like stars. Astron. Astrophys. **486**, 867–875 (2008).

Ballot, J., T. Appourchaux, and T. Toutain: Effect of the stellar inclination angle upon theoretical errors of l = 1 p-mode parameters. In: European-Helio-and-Asteroseismology-Network Workshop on Low Degree and Low Frequency Modes. Astronomische Nachrichten **329**, 2008, 558–561.

Barreiro, R.B., P. Vielva, C. Hernandez-Monteagudo and E. Martinez-Gonzalez: A Linear Filter to Reconstruct the ISW Effect From CMB and LSS Observations. IEEE J. of Selected Topics in Signal Processing, **2**, 747–754 (2008).

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Borgani, S., A. Diaferio, K. Dolag and S. Schindler: Thermodynamical properties of the ICM from hydrodynamical simulations. Space Science Review **134**, 269–293 (2008).

Botticella, M., M. Riello et al. (incl. S. Taubenberger): Supernova rates from the Southern in Termediate Redshift ESO Supernova Search (STRESS). Astron. and Astrophys. **479**, 49–66 (2008).

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Boylan-Kolchin, M., C.-P. Ma and E. Quataert: Dynamical Friction and Galaxy Merging Timescales. Mon. Not. Roy. Astron. Soc. **383** 93–101 (2008).

Brüggen, M. and G. De Lucia: Ram-pressure histories of cluster galaxies. Mon. Not. R. Astron. Soc. **383**, 1336–1342 (2008).

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4.2.2 Publications available as electronic file only

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Asplund, M.: A stellar journey. Symposium in celebration of Bengt Gustafsson's 65th birthday. Uppsala, Sweden. Conference Proc. Physica Scripta, **133**, 011002-011003 (2008 - online)

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4.3 Books and popular articles

Börner, G.: Die Dunkle Energie und Ihre Feinde. Spektrum der Wissenschaft, Heft 11, 2008, 38–46.

Docenko, D.: Radioastronomijas dižie plāni. Terra, **53**, Mācību grāmata, Rīga, 2008, pp. 46–47.

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Jones, C., W. Forman et al (incl. E. Churazov: Dynamics of the hot intracluster medium. In Book: A Pan-Chromatic View of Clusters of Galaxies and the Large-Scale Structure. Springer Verlag, Dordrecht, The Netherlands, pp. 31–69.

Weiss, A.: "Sterne: Was ihr Licht über die Materie im Kosmos verrät". Spektrum Akademischer Verlag, Heidelberg. 123p.

4.4 Invited review talks at international meetings

M. Asplund:
Invited talk, "Nuclear astrophysics" (Ringberg, March 10-14)
– Invited review, "IAU Symposium 252: The art of modelling stars in the 21st century" (Sanya, China, April 7-11)
– Opening talk, "A stellar journey" (Uppsala, Sweden, June 23-27)
– Invited review, "Origin of the elements heavier than Fe" (Torino, Italy, Sept. 25-27)
– Invited review, "Isotopic anomalies" (Paris, France, Oct. 16-17)

M. Boylan-Kolchin:
– "The Future of Supercomputing: A German View" (München, 8.9-13.9)

P. Cerdá-Durán:
– "CoCoNuT school" workshop, MPA, Garching, Germany, (04.11-06.11)
– "Whisky Retreat 2008" workshop, Parma, Italy, (07.04-08.04)
– "Numerical modelling of astrophysical sources of gravitational radiation" workshop, Valencia, Spain, (8.09-12.09)

B. Catinella:
– "Pushing Arecibo to the limit: detection of HI emission from galaxies at redshift $z \sim 0.2$" (Arecibo, PR, USA, 01.02.–03.02.)
– "HI observations of gas-rich galaxies at redshift $z \sim 0.2$" (Socorro, NM, USA, 16.12.–18.12.)

E. Churazov:
– AAS/HEAD meeting, (Austin, USA, 07.01-11.01)
– "Putting Gravity to Work" conference, (Cambridge, UK, 21.07-25.07)

B. Ciardi:
– "XXIVth IAP Colloquium. Far Away: Light in the young universe at redshift beyond 3" (Paris, France, 7.7–11.7)
– "The Impact of Simulations in Cosmology and Galaxy Formation" (Trieste, Italy, 20.10–22.10)
–v"Astrophysics with E-LOFAR" (Hamburg, Germany, 16.9–19.9)
– "XXIVth IAP Colloquium. Far Away: Light in the young universe at redshift beyond 3" (Paris, France, 7.7–11.7)
– "VLBI and high resolution astronomy in the next decade" (Garching, Germany, 26.6)
– "21cm Cosmology" (Cambridge, USA, 12.5–15.)

G. De Lucia:
– "Probing Stellar Populations out to the Distant Universe", invited review (Cefalu', Italy, 7.09-19.09)

– Invited Colloquium, Osservatorio Astronomico di Brera (Milano, Italy, 26.05)
– Invited Seminar, National Radio Astronomy Observatory (Socorro, USA, 12.11)

K. Dolag:
– Invited Review at "Magnetic fields in the Universe II", Cozumel, Mexico
– Invited Review at COSPAR(E13), "Astrophysical Shocks: Space Observ. vs. Modelling", Montreal, Canada

T. Enßlin:
– "Magnetic fields in the Universe II: From Laboratory and Stars to the Primordial Universe" Conference, (Cozumel, Mexico, 28.01.-01.02)

M.Gilfanov:
– "Cool disks, hot flows" (Fuenasdalen, Sweden, 25.03.–30.03)
– Astronomy Symposium, Crafoord days 2008 (Stockholm, Sweden, 22.04.–23.04.)
– "Ultraviolet Universe" (Moscow, Russia, 19.05.–20.05.)
– "Astrophysics of Neutron Stars" (Istanbul, Turkey, 30.06.-4.07)
– "HEA-2007" (Moscow, Russia, 24.12.-26.12.)

S. Hachinger:
SNe Ia: Links between spectral signatures, physics and abundances", 14th Workshop on "Nuclear Astrophysics", (Ringberg, 14.3.)
– "Spectroscopic Luminosity Indicators in SNe Ia", International Astronomy Meeting, (Cefalù, 19.9.)

W. Hillebrandt:
– "Turbulent Flames in Type Ia Supernovae", SIAM International Conference on Numerical Combustion (Monterey, USA, 30.3.-2.4.)
– " Multidimensional Simulations of Type Ia Supernova Explosions", 3rd Biennial Leopoldins Conference on "Dark Energy" (Munich, 17.10.-11.10.)
– "Recent Progress in Type Ia Supernova Modeling and its Implication for Cosmology", RESCEU Symposium on "Astroparticle Physics and Cosmology" (Tokyo, Japan, 11.11.-14.11.)
– "Viel Lärm um das Nichts - Neues von der dunklen Seite des Universums", Colloquium, Research Center Jülich (Juelich, 19.9.)

H.-Th. Janka:
– "Supernovae, neutrinos and gravitational waves" Workshop, (Cascina, Italy, 26.11.)
– "Fireworks 2008" Workshop, (Tel Aviv, Israel, 14.12.–21.12.)
– "Next Generation Nucleon Decay and Neutrino Detectors (NNN08)" Workshop, (Paris, France, 11.9.–13.9.)
– "2008 APS April Meeting and HEDP/HEDLA Meeting", (St. Louis, Missouri, 11.4.–15.4.)

G. Kauffmann:
– "The Evolution of Galaxies through the Neutral Hydrogen Window" (Arecibo Observatory, Puerto Rico , 1.2.-3.2.)
– "Galactic Structure and the Structure of Galaxies " (Ensenada, Baja California, Mexico, 17.3.-21.3.)
– "AAS High Energy Astrophysics Division Meeting - HEAD2008" (Los Angeles, California, 31.3.-3.4.)
– "The Sloan Digital Sky Survey: Asteroids to Cosmology" (Chicago, Illinois, 15.8.-18.8.)
– "Galaxies in Real Life and Simulations", (Lorentz Center, Leiden, 15.9.-19.9.)
– "The Starburst-AGN Connection Conference", (Shanhai, China, 27.10.-31.10.).

P. Mazzali:
– Properties of SNe Ia" at the meeting "SN Rates" (Florence, Italy, 19.5.–23.5.).
– "Type Ia SNe and their progenitors" at the meeting "AM CVn Stars" (Cape Town, So. Africa, 1.9.–5.9.).

– "SNe and Gamma-Ray Bursts" at the meeting "High Energy Astrophysics" (Kathmandu, Nepal, 29.9.–3.10).
– "Properties of SNe Ia from the observations" at the meeting "Fireworks" Weizmann Inst. of Science, (Israel 14.12.–19.12.)

R. Moll:
– "The high-energy astrophysics of outflows from compact objects" Workshop, (Ringberg Castle, 7.12.–13.12.)

M. Obergaulinger:
– Numerical modelling of astrophysical sources of gravitational radiation, (Valencia, 8.9.–12.9.)
– Workshop on Turbulence and Hydrodynamical Instabilities, Excellence Cluster Universe, (Munich 17.11.–19.11.)

H. Ritter:
– Invited review talk at the School of Astrophysics "F. Lucchin", Advanced Stellar Evolutionary Phases (Tarquinia, Italy, 08.06-14.06)

J. Schaefer:
– "Zero-phonon emission bands of solid hydrogen at 6 - 12 um wavelength: An astrophysical phenomenon" Conference on Cryocrystals and Quantum Crystals 2008 (Wroclaw 31.7.–5.8.)

A. Serenelli:
–The Standard Solar Model. The Physics of the Sun and the Solar Neutrinos: an update, (L'Aquila, Italy, 16.10–17.10.)

V. Springel:
– JENAM 2008, "New challenges to European Astronomy" (Vienna, Austria, 7.-12.9.)
– "Galactic structure and the structure of galaxies" (Ensenada, Mexico, 17.-21.3.)

H. Spruit:
– Invited review, IAU Symposium 259 "Cosmic magnetic fields", (Tenerife, 3.11.-7.11.)

A. Waelkens:
– "CMB Polarization workshop: theory and foregrounds" Workshop, (Fermilab, Chicago, US, 23.06.-26.06)

A. Weiss:
– "A Stellar Journey" symposium, (Uppsala, Sweden, 23.06.–27.06.)

S. White:
– Invited Discourse, American Astronomical Society, (Austin, Texas, 8.1.-10.1.)
– Surveys & Simulations, (Berkeley, USA, 12.1.-18.1.)
– IPMU Opening Symposium, (Tokyo, Japan, 9.3.-13.3.)
Galactic Structure and the Structure of Galaxies, (Ensenada, Mexico, 15.3.-21.3.)
– SPIE Annual Conference, (Marseille, France, 24.6.-26.6.)
– KIAA Opening Symposium, (Beijing, China, 26.6.-29.6.)
– Putting Gravity to Work, (Cambridge, UK, 21.7.-25.7.)
– SDSS Symposium From Asteroids to Cosmology, (Chicago, 13.8.-20.8.
– Academia Europea Annual Meeting, (Liverpool, 18.9.-20.9.)
– New Vision 400, Beijing, (China, 11.10.-17.10.)

4.4.1 Public talks

M. Asplund: Grundschule am Kirchplatz, Ismaning (10.07.)

W. Hillebrandt: "Kosmische Sternexplosionen", Deutsches Museum München (10.12.)

H.-Th. Janka: Volkssternwarte Bonn (16.10.)

V. Springel: Philosophical Garden, ICI Berlin (14.10.)

M. Vogelsberger: Simulating the Universe on Supercomputers H.O.P.E. Conference, New York City (20.7.)

5 Personnel

5.1 Scientific staff members

Directors

M. Asplund, 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

R. Angulo (since 1.10.), A.J. Banday, J. Ballot (till 30.9.), J. Bolton, M. Boylan-Kolchin, L. Casagrande (since 15.9.), B. Catinella, P. Cerda-Duran, A. Chiavassa (since 1.10.), J. Chluba (till 31.10.), B. Ciardi, D. Christlein, E. Churazov, R. Collet, G. De Lucia, N. De la Rosa (till 31.5.), K. Dolag, T. Enßlin, A. Faltenbacher, D. Gadotti, D. Giannios (till 14.10.), M. Gilfanov, C. Hernandez-Monteagudo, J. Hu, H.–T. Janka, G. Kauffmann, K. Kifonidis (till 31.12.), F. Kupka, Ch. Li, L.-X. Li (till 31.12.), S. Lucatello (since 1.1.), A. Marek, A. Maselli, P. Mazzali, B. Metcalf, P. Montero (since 1.9.), E. Müller, M. Obergaulinger (since 1.2.), R. Overzier, E. Puchwein, I. Ramirez (since 15.9.), M. Reinecke, M. Revnivtsev (till 31.7.), H. Ritter, F. Röpke, D. Sauer (till 31.12.8), S. Sazonov, C. Scannapieco, I. Seitenzahl (since 1.9.), A. Serenelli (since 1.9.), F. Shankar (since 1.11.), S. Sim, V. Springel, H.C. Spruit, S. Taubenberger (since 1.2.), S. Weinmann, A. Weiss, V. Wild (till 16.10.), J. Zavala-Franco (since 1.9.), X.-G. Zhang (till 30.11.)

Associated Scientists:

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

Alexander von Humboldt Awardees

C. Hogan (till 30.3.), A. Szalay (20.7.-30.8.)

Minerva awardee

E. Neistein (since 1.10.)

Ph.D. Students

[1] M. Alves-Cruz*, M. Baldi*, A. Bauswein, R. Birkl, A. Bogdan*, S. Bonoli*, M.-P. Bottino*, M.A. Campisi*, M. Carrasco-Kind*, F. Ciaraldi-Schoolmann (since 1.12.), C. D'Angelo*, J. Donnert, E.

[1] *IMPRS Ph.D. Students

Donoso*, D. Docenko* (till 31.7.), F. Elsner, S. Fabello* (since 1.9.), X. Fei* (till 31.12.), M. Fink, M. Frommert, M. Gabler (since 1.10.), L. Graziani* (since 1.9.), M. Grossi*, Q. Guo*, S. Hachinger, N. Hammer, S. Hess, S. Hilbert (till 30.9.), F. Ianuzzi* (since 1.9.), J. Jasche, A. Jeeson-Daniel* (since 1.9.), P. Jofre-Pfeil*, M. Kitzbichler* (till 30.4.), M. Kromer, T. Mädler, U. Maio*, I. Maurer, F. Miczek (since 1.11.) S. Mineo*, M. Mocak*, R. Moll, B. Müller, M. Obergaulinger (till 31.1.), R. Pakmor (since 1.2.) M. Petkova* (since 1.3.), M. Pierleoni*, P. Piovezan* (since 1.9.), L. Porter* (since 1.9.), M. Righi (till 31.7.)*, T. Sawala*, V. Silva* (since 1.9.), F. Stasyszyn*, S. Taubenberger (till 30.1.), M. Ugliano* (since 15.10.), M. Vogelsberger, M. Wadepuhl (since 1.11.), A. Waelkens, L. Wang, J. Wang* (till 30.7.), A. Wongwathanarat*, F. Zaussinger, Z. Zhang* (since 1.2.), I. Zhuraleva* (since 1.9.), .

Diploma students

C. Auer (since 1.6.), S. Benitez (since 1.10.), X. Bian (since 1.4.), M. Häberlein (since 1.11.), L. Hüdepohl (since 14.11.), P. Kuchar (since 1.10.), M. Petkova (till 28.2.), M. Wadepuhl (1.1.-30.10.)

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 (till 31.8.), U. Dörl, W. Hovest, J. Knoche, J. Rachen, T. Riller.
Secretaries: M. Depner, S. Gründl (since 1.3.), G. Kratschmann, K. O'Shea, C. Rickl (secretary of the management).
Library: E. Blank, E. Chmielewski (head of the library), C. Hardt.

Staff news

Eugene Churazov: Member of Russian Academy of Sciences.

Gabriella De Lucia: European Research Council (ERC) Starting Independent Researcher Grant.

Cheng Li: Top 50 Excellent PhD Theses of Chinese Academy of Science, 2008.

Fritz Röpke: Emmy Noether Research Group *'Comprehensive Modeling of Type Ia Supernova Explosions'.*

Rashid Sunyaev: *'Crafoord Prize 2008'*, Royal Swedish Academy of Sciences.

Rashid Sunyaev: *'2008 Henry Norris Russell Prize* of the American Astronomical Society.

Simon White: *'Dirk Brouwer Award 2008* of the American Astronomical Society.

Simon White: Oort Professorship 2008, Leiden University.

Simon White: *'2008 Latsis Prize'* of the European Science Foundation.

Habilitation

Friedrich Kupka: Habilitation - Fakultät für Physik, Technische Universität München, (2.4.)

Fritz Röpke: Habilitation - "Thermonuclear Supernovae" Fakultät für Physik, Technische Universität München, (9.7.)

Ph.D. theses 2008

Dmitrijs Docenko: “High Z-Ions in the Hot Astrophysical Plasmas” Ludwig Maximilians Universität München.

Xiang Fei: “Impact of AGN on the gas in clusters of galaxies” Ludwig Maximilians Universität München.

Stephan Hilbert: “Gravitational Lensing with the Millennium Run” Ludwig Maximilians Universität München.

Agis Kitsikis: “Theoretical AGB and post-AGB Stellar Models for Synthetic Population Studies” Ludwig–Maximilians–Universität, München.

Manfred Kitzbichler: “Galaxy Formation Modelling in the Millennium Simulation” Ludwig–Maximilians–Universität, München.

Umberto Maio: “Switching on the first light in the Universe” Ludwig Maximilians Universität München.

Martin Obergaulinger: “Astrophysical magnetohydrodynamics and radiative transfer: numerical methods and applications” Technische Universität München.

Mattia Righi: “Observational consequences of the chemical elements production in the epoch of reionization of the universe” Ludwig–Maximilians–Universität, München.

Stefan Taubenberger: ”Interpretation of lightcurves and spectra of Type Ia supernovae.” Technische Universität München.

Jie Wang: “Simulating structure formation with N-body and semi-analytic models”. Ludwig Maximilians Universität München.

Lan Wang: “Building Halo Occupation Distribution Models for comparison with SDSS data” Peking University, China.

Diploma theses 2008

Benjamin Möbis: “Recollimation of the SS433 jets” Technischen Universität München.

Fabian Miczek: “Simulation of low Mach number flows” Technische Universität München.

Margarita Petkova: “An Implementation of Radiative Transfer in the cosmological simulation Code GADGET”. Ludwig Maximilians Universität München.

Markus Wadepuhl: “Simulations of the formation of a Milky Way like galaxy” Technische Universität München.

5.2 Visiting scientists

Name	home institution	Duration of stay at MPA
Tom Abel	Stanford Univ.	15.8.–8.9.
Evangelie Athanassoula	LAM/OAMP	15.05.-15-06.
Jerome Ballot	Toulouse, FR	30.11.–12.12.
Isabelle Baraffe	ENS, Lyon	17.11.–17.12.
Altan Baykal	ET Univ. Ankara	14.7.–29.8.
Sergey Blinnikov	ITEP, Moscow	1.8.–31.8.
Annalisa Bonafede	(Ira, Bologna)	15.9. - 16.12.
Albert Bosma	LAM/OAMP	15.05.-15-06.
Jonathan Braithwaite	CITA, Canada	14.7.–15.8.
Matthieu Brassart	IAP, France	till 30.9.
Alan Brito	Sao Paulo, Brazil	30.6.–26.7.
Brian Chaboyer	Dartmouth College, NH, USA	16.6.–27.8.
Gilles Chabrier	ENS, France	17.11.–17.12.
Yan-Mei Chen	IHEP, Beijing	until 31.10.
Candace Church	Ucolick, California	2.6.–28.6.
Paula Coelho	IAP, France	27.10.–9.11.
Stephane Colomobi	IAP, France	19.5.–6.6.
Jordan Del Nero	Belem, Brazil	16.11.–14.12.
Andrey Egorov	Sternberg Inst. Moscow	15.11.–15.12.
Celine Eminian	Brighton, U.K.	4.12.–21.12.
Chad Fendt	Univ. of Illinois	8.7.–24.7.
Ekaterina Filippova	IKI, Moscow	1.4.–31.5.
		1.10.–30.11.
Rohit Gart	IUCCA, Pune, India	11.5.–20.7.
Tuhin Gosh	IUCCA, Pune, India	1.4.–30.6.
Nicolas Grevesse	Univ. de Liege, Belgien	10.11.–19.12.
Timothy Heckman	JHU, Baltimore	18.4. –10.5.
Petr Heinzel	Astron. Inst. Ondřejov	21.4.-2.5.
Zhen Hou	Beijing, China	1.1.–31.12.
Nail Inogamov	Landau Inst. Moscow	20.11.–20.12.
Chunyan Jiang	Shanghai Obs.	till 31.9.
Patrik Jonsson	UC Santa Cruz	18.9.–17.10.
Anjor Kanekar	Pune, India	20.5.–25.6.
Dan Kasen	Univ. of California	22.6.–9.7.
Jasna Krivicic	Padova University, Italy	1.6.-19.12.
Jounghun Lee	Seoul Nat. Univ. Korea	27.1.–28.2.
Yang-Shyang Li	Kapteyn Astron. Inst., NL	
Shude Mao	Manchester, U.K.	1.7.–31.8.
Petar Mimica	Univ. Valencia, Spain	8.2.–22.2.
Sean Moran	Bloomberg Center, USA	23.4.–9.5.

Name	home institution	Duration of stay at MPA
Dmitrij Nadyozhin	ITEP, Moscow	30.7.–25.9.
Poul Erik Nissen	Aarhus, Denmark	8.9.–26.9.
Kai Noeske	CfA, Harvard	26.5.–19.6.
Ken'ichi Nomoto	Univ. of Tokyo	3.8.–22.8.
John Norris	Austr. Nat. Univ. Canberra	13.7.–27.7.
Sebastian Nuza	IAFE, Argentina	26.3.–26.9.
Feryal Ozel	Univ. of Arizona	15.6.–29.6.
Josef Paldus	Waterloo, Canada	01.09.–25.09.
Tiago Pereira	Austr. Nat. Univ. Canberra	1.11.–4.12.
Konstantin Postnov	Sternberg Inst. Moscow	15.11.–15.12.
Igor Prokopenko	Space Research Inst., Moscow	1.2.–31.8.
Dimitrios Psaltis	Univ. of Arizona	15.6.–29.6.
Alessandro Rettura	JHU Baltimore, USA	1.5..–31.5.
Kirsty Rhook	Univ. of Cambridge, U.K.	1.3.–31.8.
Luke Roberts	Santa Cruz	12.6.–10.7.
Tokuei Sako	Tokyo, Japan	06.09.–20.09.
Patrick Scott	Stockholm University	15.10.–15.11.
Nikolai Shakura	Sternberg Inst. Moscow	1.9.–30.9.
Shiyin Shen	SHAO, Shanghai	1.4.–30.6.
Pavel Shtykovskyi	Space Research Inst., Moscow	25.4.–24.5. and 21.10.–19.12.
Michael Specian	JHU, Baltimore	1.6.–31.8.
Nick Stergioulas	Univ. Thessaloniki, Greece	10.7.–23.7.
Tamas Szalay	Caltech, USA	21.7.–19.9.
Victor Utrobin	ITEP, Moscow	1.10.–30.11.
Jian-Min Wang	ITEP, Beijing	1.4–1.6 and 15.9.–15.10.
Jing Wang	USTC, Hefei	since 1.3.
Stan Woosley	Santa Cruz, USA	1.6.–9.7.
Shoichi Yamada	Waseda Univ., Japan	1.4.–30.9.
Tatsuya Yamasaki	CEA, France	since 2.11.
Sung-Chul Yoon	Ucolick Obs. Santa Cruz	1.6.–22.6.
Bin Yue	Bejing, China	18.1.–27.7.
Zhongli Zhang	Shanghai Obs. China	10.01.–10.05.