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The cover shows a cut through a neutron star about one second after its birth in a supernova explosion. The neutron star has a radius of 21 km at this time. The colors visualize the absolute values of the plasma velocity inside the star as obtained by the first two-dimensional, hydrodynamical simulation of neutron star formation. While green indicates "quiet" regions, blue, yellow, orange, and red mean higher and higher velocities, the maximum velocities being around 3000 kilometers per second. A significant fraction of the hot neutron star is stirred up by these violent convective currents which transport matter and energy from regions deep inside to layers close to the surface. An understanding of the physical processes in nascent neutron stars is essential to explain supernova explosions like the famous supernova SN 1987A in the Large Magellanic Cloud. (For more information, see Sect. 2.4 in this report.)

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1 General Information

1.1 A brief overview of the MPA

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

Research at MPA is devoted to a broad range of topics in theoretical astrophysics. Major concentrations of interest lie in the areas of stellar evolution, stellar atmospheres, supernova physics, astrophysical fluid dynamics, high energy astrophysics, galaxy structure and evolution, the large-scale structure of the Universe, and cosmology. The MPA has traditionally been strong in studies of General Relativity, but in mid-1995 most of our relativity group moved to the newly founded MPI für Gravitationsphysik in Potsdam near Berlin. Their departure has allowed a consolidation of MPA activities in extragalactic astrophysics, as well as an expansion in a new area, high energy astrophysics. While most MPA research addresses theoretical issues, the neighbouring institutes provide complementary expertise and there are many collaborative projects with them. Major research programmes at MPE are concerned with instrumental and observational aspects of infrared, X-ray and gamma-ray astronomy, together with supporting theoretical work, while ESO carries out a broad range of instrumental and observational projects in the optical and infrared.

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

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

1.2 Current MPA facilities

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

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

The MPA has always placed considerable emphasis on computational astrophysics and has therefore ensured access to forefront computing facilities. The current in-house system is based on a central cluster of about 10 IBM RS6000 workstations, with additional SGI graphics workstations for graphics applications. Users have free access to all workstations and are in general connected via large-screen X-window terminals or desk-top workstations. For larger computing tasks MPA scientists use the facilities of the central computing centre of the Max-Planck Society (known as the RZG). This is part of the MPI für Plasmaphysik and is located a few hundred metres from the MPA. Current facilities at the RZG include a 528-processor CRAY T3E, an 18-processor IBM SP2, a 16-processor Cray Jedi, a large cluster of high-end workstations and a Terabyte mass storage system. MPA scientists have free access to the RZG and are among the top users of the facilities there. An AFS file system ensures that the transfer of data among the MPA machines and from MPA to the RZG is now almost transparent to the user. Further computing power is available at a second Max-Planck Society computer centre which is operated jointly with the University of Göttingen, and provides additional access to large parallel machines.

1.3 1996 at the MPA

New management structure implemented — 1996 was a busy year at the MPA. In March the Max-Planck Society ratified a new set of statutes which replaced the old leadership structure, a single permanent director, by a board of directors. The job of managing the institute will in future rotate among the members of this board. However, because of the incremental and deliberate pace of change within the Society, this event went unnoticed by everyone, including the director himself. By early 1997, all the formalities will be finally complete and the MPA will have a board of three directors: Wolfgang Hillebrandt, Rashid Sunyaev and Simon White. Simon White will carry on as managing director for several more years.

Fachbeirat visits — The biennial visit of the institute's Fachbeirat came around again in 1996. The current members of this Visiting Committee are I. Appenzeller, R. Blandford (chair), C. Cesarsky, B. Paczynski, J. Truran and N. Weiss. As usual, the hardest part of the visit was finding a date when everyone could come. Finally an opening emerged at the beginning of September and the committee spent two days at MPA listening to scientific presentations, talking to the directors, the scientific staff and the students, and trying to evaluate the work of the institute. In addition, a variety of social events provided some lighter relief as well as giving Fachbeirat members the opportunity to chat to MPA members under less formal conditions. It seems that the committee was pleased with what it saw; their final report to the President of the Max-Planck Society praised the overall level of scientific achievement, the recent broadening of the institute's scientific interests, the change in the institute's leadership structure, and the use of appointments committees to fill all posts through openly advertised international competition. The main thing they complained about was the terrible Internet access, which made it hard for them to read e-mail on their home computers. Luckily the Max-Planck Society has already cured this problem which was affecting its whole research network.

MPA joins EARA — Earlier in the year another party accompanied a more novel event, the accession of MPA to EARA, a European Association for Research in Astronomy. This organisation was set up four years ago as part of a programme sponsored by the French CNRS. It originally linked l'Institut d'Astrophysique de Paris with Leiden Observatory and the Institute of Astronomy in Cambridge. Its goal is to foster joint research programmes based on the complementary strengths of the partners and on the differing opportunities and facilities available in each country. Funds came from internal resources, from the CNRS, and from the European Commission which supported coordinated proposals by the EARA members for networking funds, for postdocs at the three institutions, and for conference support. During this first phase EARA projects led to many postdoc exchanges and to several joint PhD projects. When the founding convention came up for renewal the three original members asked MPA to join as the fourth member.

One of MPA's first roles within EARA was to act as the coordinating partner for a network studying the Formation and Evolution of Galaxies. This was one of only four astronomy-related networks funded in the first phase of the European Commission's programme to promote Training and Mobility of Researchers. The network brings scientists from the EARA institutions together with colleagues from Padova and Durham in a concerted effort to understand the flood of new data on high redshift galaxies and the intergalactic medium. Over its four-year duration it will support both observational and theoretical work on these problems. An organisational meeting was held at MPA in February, and, in response to a joint advertisement, six postdocs were recruited and took up their posts at the various network sites in the last months of 1996. By the end of the year the first papers based on network collaborations had already appeared in print.

SFB in full swing — Another more local collaboration involving the MPA also made substantial progress in 1996. The Special Research Area (Sonderforschungsbereich or SFB) devoted to Astroparticle Physics has been funded by the German Research Foundation since the beginning of 1995. It links the MPA to the two Munich universities and to the MPI für Physik in a broad programme encompassing related aspects of experimental particle physics, theoretical particle physics, statistics, astrophysics and cosmology. Most of the programme's projects were operating at full steam in 1996, and a particular highlight of the year was a 5-day school held in Munich in October which attracted about 30 students from all over Germany. Lectures were given entirely by local scientists active within the SFB, and both students and lecturers appeared to find the whole experiment a great success. An earlier event also closely related to the SFB's scientific programme was a workshop in March on Nuclear Astrophysics. These meetings, organised by the MPA, are now almost an annual tradition. The 1996 workshop attracted an international group of about 40 scientists to Ringberg Castle.

Parties for old friends — An important event in 1996 was the retirement of Friedrich Meyer. This was marked by a three-day EARA-sponsored workshop on accretion disks, one of Herr Meyer's favorite topics and one to which he has made major contributions. After the conclusion of the "regular" programme, there was a special session attended by many of the Meyers' friends and colleagues. Rudolf Kippenhahn, the MPA's director until 1991, gave an entertaining personal appreciation of science with the Meyers, and Yoji Osaki from Tokyo gave a celebratory lecture. This was followed by a party. The whole proceedings were necessary not only because they gave the MPA a chance to express its appreciation for Herr Meyer's enormous contribution to scientific life at the institute, but also because, without it, his retirement might have gone unnoticed – since the party there has been no discernible change in his enthusiasm for and participation in astrophysics at MPA.

A further good excuse for inviting old friends to a party at MPA was provided by the 70th birthday of Prof. Kippenhahn himself. The institute's seminar room was filled for a special celebratory lecture by Norman Baker of Columbia University. Unfortunately, last minute illness prevented Professor Baker from attending, but part of his lecture was ably read by Hans-Christoph Thomas, Professor Kippenhahn's first student, who is still a scientist at MPA. In a reply to this lecture Professor Kippenhahn mixed reminiscences with humour in a way which showed again that retirement has only sharpened his public speaking abilities.

New observational collaborations? — Old friends met in a very different environment as part of the China Academy of Science/ Max-Planck Society joint workshop on "The Universe at High Redshift". This meeting grew out of long-standing contacts and exchanges between MPA scientists and Chinese astronomers. It was held in Hangzhou in September, and a group of 10 speakers, most of them from the MPA, lectured to an enthusiastic group of about 20 young Chinese graduate students and researchers. A particularly interesting project discussed at this workshop and at related meetings is a Chinese plan to build a large telescope designed specifically to carry out multi-object spectroscopy over a wide field. The surveys produced by such a telescope would be of great interest for the galaxy evolution and large-scale structure programmes at MPA.

An observational project of more immediate relevance is the ESO Imaging Survey. MPA scientists played a significant role in the planning of this ESO project which will be carried out in late 1997 and will provide survey imaging to allow the identification of targets for the Very Large Telescope, scheduled to begin operation the following year. The imaging survey should be particularly effective at identifying distant galaxy clusters which will be of particular interest for the MPA's gravitational lensing and large-scale structure groups. An MPA student is currently playing a major role in preparing the reduction software for the survey at ESO, an involvement which may well develop into a jointly supervised PhD.

A different project which also is of great interest is the Cobras/Samba microwave background mapping mission which ESA approved in the summer of 1996 and renamed Planck Surveyor in early 1997. The MPA has expressed interest in acting as a principal data centre for this mission which has the potential to make truly revolutionary contributions to cosmology. Discussions are underway with other potential participants, in particular with the consortia likely to build the instruments, in order to clarify how best to work together in planning and executing the mission. At the time of writing (April 1997) the design of the Planck Surveyor is being reassessed as part of ESA's effort to carry out its core programme without serious delay in spite of serious financial difficulties. Detailed planning of the mission and of MPA's possible role will have to wait for the outcome of this exercise.

Parallel (and other) problems — Throughout 1996 the RZG maintained and ran a 128-processor Cray T3D supercomputer. This was intended as an interim machine while awaiting the summer 1996 delivery of a much larger T3E. In fact, installation of the T3E was not complete before the end of the year, resulting in two major benefits for the MPA. First, the T3D remained until well into 1997, and a substantial body of calculations could be completed as part of the Virgo Consortium, a UK-German-Canadian grouping dedicated to carrying out very large cosmological simulations on parallel supercomputers. Second, the delay ensured not only that the T3E, when finally installed, was significantly bigger (528 processors) than originally planned, but also that there was more time to rewrite simulation codes so that they would run on the new machine. Murphy's Law had ensured that the programming model adopted by the Virgo Consortium for their T3D codes was not implemented by Cray on the Garching T3E.

In 1996 the MPA issued the 1000th preprint in its "Green Report" series. After considerable jockeying for the honour of this number, the place was claimed by Achim Weiss and his collaborators. Achim had to pay for his luck by sticking a special "celebration" label on each of the 300 copies of his preprint. He had plenty of time, however, since the preprint reduced the age of the Universe (or at least of the globular clusters) by a billion years or more. Another milestone was the replacement, after many years, of the tables and chairs in the MPA's central coffee area. The administration's previous attempts to do this had always failed as a result of the scientific staff's inability to agree on a design; this time, in desperation, they managed to convince S. White to decide unilaterally without consultation. Luckily, most people seem happy with the result. Less easy for the Managing Director to fulfil was a rash democratic promise to turn the director's parking space at the centre of the institute into a staff bicycle shed. It took two years and innumerable designs to get the promise carried out. Furthermore, the (very nice) new bicycle shed ended up costing more than many new cars. We look forward with interest to seeing how the MPE fares in constructing their recently approved (and long overdue) new building.

1.4 How to reach us

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

World Wide Web:
http://www.MPA-Garching.
MPG.DE

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

2 Scientific Highlights

2.1 The theory of Asymptotic Giant Branch stars

Although the death of a few unusually massive stars is associated with a spectacular event, a supernova explosion, the vast majority fade away much more gently. Nevertheless, for a short time they can evolve through bright but short-lived phases that can be observed even in distant galaxies: the "Asymptotic Giant Branch" or AGB phase and its successor, the "Planetary Nebula" or PN phase (the origin of both terms owes more to history than to physics). These can not only be used to deduce the history and distance of the host galaxies, but also play a significant role in the evolution of the latter. Indeed, a prerequisite for understanding the nature of galaxies is to understand the evolution of their stars.

For most of their life stars supply their energy needs by quietly burning hydrogen into helium. This lasts some 10 billion years for a star like the Sun, but only about 10 million years for an eight times heavier star. After the fuel runs out at a star's centre, the helium "ashes" form a compact core, and hydrogen continues to burn in a surrounding shell. Finally the helium itself becomes hot and dense enough to burn, leaving behind carbon and oxygen. Since helium burning produces less energy than hydrogen burning, this phase lasts for only a tenth of the total lifetime. During it the onion-like structure of AGB stars develops: A central carbon-oxygen region is surrounded by a very thin helium burning shell and, somewhat further out, an even thinner hydrogen burning shell. Although occupying only about the same volume as the Earth, these three components, referred to as the core, contain between 0.6 and 1.0 solar masses, depending on the initial total mass. The core produces the whole luminosity, which on the AGB can increase dramatically to tens of thousands times that of the Sun. The rest of the star, the "envelope", is so inflated that the Earth's orbit could fit within it. The surface temperatures drop to the lowest values a star can achieve, about 2000K.

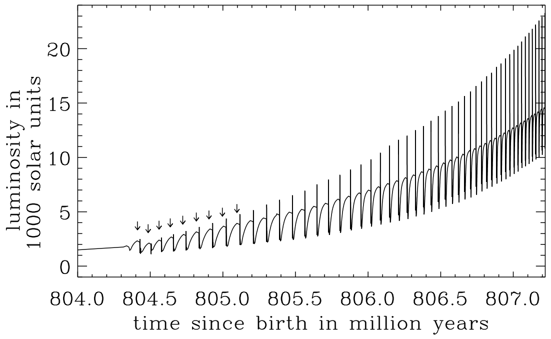

Figure 2.1: The luminosity during the AGB phase of a 2.5 solar mass star as a function of time. The rapid variations are due to thermal pulses (see text). Arrows indicate some initial quiescent phases between pulses.

In most cases the envelope pulsates with periods of about one year. Together with the low temperature, this produces conditions in which solid material ("dust") can condense and can be accelerated outwards by the star's radiation, carrying away as much as an earth mass per week! Expanding dusty envelopes around AGB stars are presently subject to intensive observational study (see the following article by Martin Groenewegen). Eventually the whole envelope can be lost. The hot former core can then be seen directly, surrounded by the still expanding former envelope, which for some 10 000 years appears as a gorgeous, extended PN; the rarefied material is ionized by the radiation of the central star and fluoresces in bright colours.

Understanding the evolution of AGB stars is difficult because helium shell burning occurs in short, violent outbursts, known as *thermal pulses*, separated by quiescent periods. This produces a very complex long-term behaviour of the luminosity (see Fig. 2.1). The enormous amount of energy deposited in the helium shell can be transported outwards only by convection, just as the heat of a fire beneath a pot of boiling water is carried upward by rising water currents. Hence combustion products, predominantly carbon, are mixed up into all layers which the convection reaches. As a result, events deep in the interior of AGB stars influence the chemical composition of their outer envelopes. As the envelopes are lost, the nuclear burning products are ejected and contribute significantly to the overall chemical enrichment of galaxies. Up to two thirds of the carbon we are made of may have been produced in this way.

The stars which now are AGB stars or PNe must have been born as far in the past as is necessary for their initial hydrogen burning phase (and subsequent more rapid phases) to have been completed. Counting the number of AGB stars of given luminosity in a galaxy can therefore reveal its star formation history, provided the relation between AGB luminosity and stellar age is known. It is easy to see that this depends on two factors: the fuel consumption by nuclear burning inside the star, and the mass loss from its envelope caused by dust. The less mass is shed, the higher the core mass reached, the more luminous the star becomes, the more thermal pulses take place, and the more nuclear burning products finally ejected into the interstellar environment.

Unfortunately, theory is not yet able to quantify the mass loss rate, which is an extremely sensitive function of stellar parameters like luminosity, temperature, mass and composition. The makeshift descriptions we have at hand contain a free “efficiency” parameter that may vary by three orders of magnitude. Furthermore, there is still considerable uncertainty concerning the description of convection itself, which involves yet another free parameter. Turning this screw also leads to changes of the theoretical surface temperatures. *One* stellar evolution calculation on the AGB with *one* fixed choice of these parameters, however, still takes some days even on a modern computer — an unsatisfying situation. In order to be able to perform statistical investigations of whole stellar populations, one therefore needs simplified relations that trace back all the complicated behaviour on the AGB to as few basic quantities as possible without oversimplifying the situation. In fact, it turns out that many quantities of interest do not depend strongly on uncertain physical or numerical approximations, or depend on them in a way that can be handled in a relatively simple fashion.

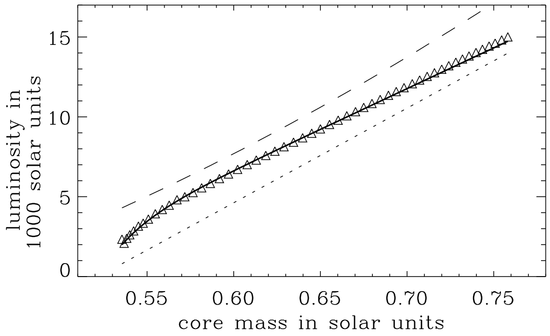

Figure 2.2: △: The luminosity at the quiescent maxima of Fig. 2.1 (the first ones are marked by arrows there) as a function of the core mass together with some approximations. Full line: this work, dotted and dashed: other authors.

For example, consider the luminosity maxima during the quiescent phases. Some of them are marked by arrows in Fig. 2.1. When considered as a function of the core mass, they obey a nice relation, shown in Fig. 2.2. The initial total mass determines the initial core mass on the AGB and the initial bending of the curve, which is crucial for low-mass stars that experience only few thermal pulse cycles. This result together with similar ones for other characteristics of AGB lightcurves allows us to arrive at a comprehensive description of the evolution of the luminosity, surface temperature, core mass and total mass on the AGB as a function of time. Such models let us calculate the time spent on the AGB, the mass of the stellar remnant at the end of the evolution and the nuclear yields for given initial conditions with a computational effort that is almost a million times smaller than would be required for full evolutionary calculations.

These results help provide the fundamental knowledge required for a statistical analysis of the flood of new data which observations are delivering. Yet, they are only part of a full description of a star's final fate. Another interesting question is how AGB stars finally evolve into PNe at all. If the evolution of the core from the AGB towards hotter surface temperatures were too slow, the ejected material would form a bubble of extremely dilute gas; if it were too fast, the envelope would not have enough time to expand and would stay very small and dense. In both cases no PN would be visible. So far there are only a few calculations of the transition from the AGB to PNe, and these in part contradict each other. The work carried out at the MPA significantly enlarges the theoretical data available on this topic, but both observations and theory remain scanty. There is ample room for further developments. (Josef Wagenhuber)

2.2 The mass loss phenomenon in late-type stars

What can become quite an obsession for some humans after a certain age, i.e. losing weight, comes naturally to some classes of stars when they are near the end of their lives.

In fact, the process of mass loss in so-called asymptotic giant branch (AGB) stars is arguably the most important characteristic of this evolutionary phase. The mass loss rates may become so large that they dictate the evolution, in contrast to almost all other phases in stellar evolution where the nuclear processes in the core of the star determine the evolutionary speed. The effects of mass loss on AGB evolution go beyond the AGB *per se*. The large amounts of matter ejected into the interstellar medium, often enriched by the products of nuclear burning (see below), influence the chemical composition of later generations of stars which are formed out of the interstellar matter. For these reasons, an understanding of the mass loss process, both from theory and observations, is of crucial importance for the understanding of stellar evolution in general.

As is well known, stars spend most of their lifetime on the main-sequence (MS). The stars that later will go through the AGB phase have masses on the MS between about 0.7 and 6 times the mass of the Sun. The lower limit is set by the age of our Galaxy; less massive stars simply did not have the time to evolve from the MS to the AGB. The upper limit is set by stars that are massive enough to end their lives in a supernova explosion. Stars between 0.7 and 6 $M_\odot$ will at some point evolve off the MS and climb up the Red Giant Branch (RGB). In a later phase they become horizontal branch stars, and finally they become AGB stars. Hence their name, because in a color-magnitude diagram (a way of looking at stars which observers love) the AGB initially asymptotically approaches the RGB and finally

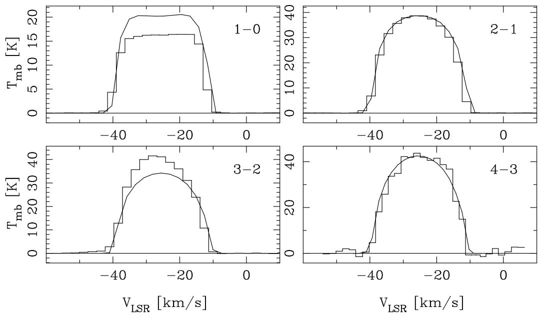

Figure 2.3: Observations of various CO transitions (the histograms) are compared to a model calculation (the solid line). The object is the carbon star IRC +10 216. The mass loss rate for this model is 2.1×10^{-5} $M_\odot\,yr^{-1}$.

extends to higher luminosities and lower effective temperatures.

The internal structure of AGB stars is characterised by what is called double-shell burning. The core of the star consists of carbon and oxygen and is inert. Surrounding the core are two shells. For most of the time the outer shell provides the energy; hydrogen (H) is transformed into helium (He) there. The He is dumped onto a second shell located closer to the core. At regular intervals there is so much He accumulated that part of it will burn explosively into carbon and oxygen. For a short amount of time this He-burning will provide the energy. Most, and sometimes all, of the carbon and oxygen is dumped onto the core, and after a while the H-burning will take over again and a new cycle starts. This phenomenon is called a thermal pulse (TP) or a helium shell flash.

A very important side effect is that, under some conditions, some of the carbon, oxygen and unburned helium is mixed into the envelope of the star (a phenomenon referred to as third dredge-up). This will influence the chemical composition of the star and may lead to the formation of so-called carbon stars. In carbon stars, so much carbon has been dredged-up after consecutive TPs that there are more carbon than oxygen atoms in the envelope of the star. This has important observational and physical consequences, in particular as molecules based on carbon chemistry are formed (e.g. C_2, HCN) in contrast to the oxygen-rich stars where oxides are important.

The modeling of the internal structure and evolution of AGB stars is done at the MPA (see the accompanying paper by Josef Wagenhuber). For those models the "things" that happen at the surface of the star are simply boundary conditions in a mathematical problem. As discussed earlier, however, what occurs in the very outer layers of the star (mass loss and the related phenomenon of stellar pulsation) is of great importance for stellar evolution itself.

The research described here focuses on observations of the mass loss phenomenon in AGB stars (mostly carbon stars) and the determination of mass loss rates through modelling.

The mass loss phenomenon manifests itself through the formation of circumstellar shells. The actual physical processes involved are extremely complicated and it is beyond the scope of this report to provide any details. In short, it is believed that stellar pulsation elevates material from the photosphere (where the effective temperature is typically between 2000 to 3000 K) to locations where the temperature of the gas is cool enough (1000-1500 K) to form dust particles. Stellar photons drive the dust particles outward. The gas is dragged along as it is coupled to the dust. In this way huge (up to 10^{18} cm; that is 1500 times the size of the solar system) expanding (with velocities between 5 to 40 km s^{-1}) circumstellar shells containing dust and gas are formed.

From this description it is clear that information about the mass loss process can be inferred by studying the gas and/or the dust. Both methods are described here.

Because of the low temperatures in the stellar photosphere and the circumstellar shell essentially all gas is in the form of molecules. The most abundant molecule is molecular hydrogen (H_2) but its transition lines are weak and difficult to observe. It turns out that carbon monoxide (CO) is the most suitable tracer of the molecular gas. It is the most abundant molecule after H_2 and is formed in both oxygen-rich and carbon stars. Several hundred AGB stars have been detected in CO.

With an appropriate model, CO line profiles can be calculated and by comparing those to observations one can then derive information about, amongst other things, the mass loss rate. This is illustrated in Fig. 2.3 where observations and model calculations are compared for a famous carbon star.

The other tracer of the mass loss is dust. The nature of the dust formed depends on the chemical composition in the stellar photosphere. In oxygen-rich stars silicates are formed. Silicates have characteristic features at 9.8 and 18 micro-meter (μm). In carbon stars the principal dust components are silicon carbide (SiC) and amorphous carbon, a less structured form of diamond. SiC has a characteristic feature near 11.3 μm. In addition, one can observe the dust continuum at other wavelengths, in the optical (0.4 – 1 μm), the near-infrared (1.25 – 4.8 μm), and the far-infrared (beyond 20 μm). To observe the latter wavelength region one must use space-based telescopes (like IRAS, which flew in the early eighties, and ISO which was launched in November 1995 and is expected to be operational to the end of 1997). For the optical and near-infrared work mostly ground-based telescopes are used.

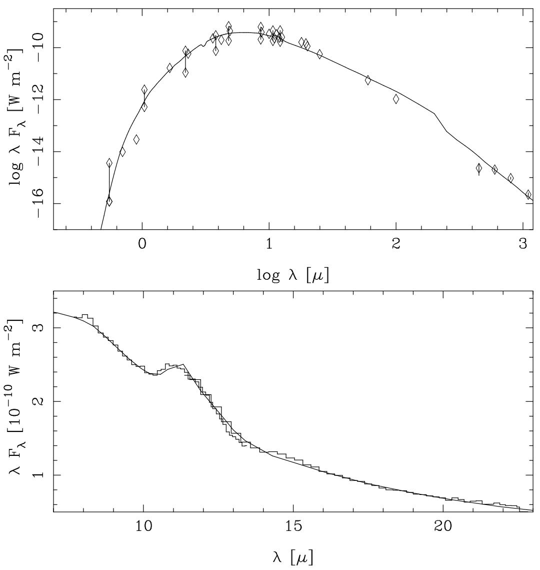

Figure 2.4: Broad band observations and a mid-infrared spectrum of the carbon star AFGL 3116. The solid line is a model fit. The mass loss rate is 1.6×10^{-5} $M_\odot\,yr^{-1}$.

By observing the dust emission at various wavelengths one can construct the spectral energy distribution. Using a model for the dust emission one can then derive the mass loss rate. An example of such a model fit to observations is shown in Fig. 2.4.

Summarising, one can say that the observational study of the mass loss phenomenon has gained enormous momentum in the last ten years. It is now universally accepted that all AGB stars lose mass, with mass loss rates which vary between 10^{-8} and 10^{-4} $M_\odot\,yr^{-1}$. That is quite an effective diet indeed, since a mass loss rate of 10^{-6} $M_\odot\,yr^{-1}$ corresponds to shedding one earth mass *every three years*. (Martin Groenewegen)

2.3 The interplay between theory and observations for the case of Polars

AM Herculis systems or Polars belong to the class of cataclysmic variables, i.e. to binary systems with mass transfer from one star to the other one. They consist of a white dwarf with a strong magnetic field, called the primary, and a low mass main sequence star, the secondary, which loses mass to its companion.

The prototype of the class was already detected as a variable star in 1923 by M. Wolf, but the unusual properties of this binary system were only revealed after its discovery as an X–ray emitter by the UHURU satellite in 1970. Since then most Polars have been detected by X–ray satellites and before the launch of the ROSAT satellite 17 such systems where known. The current census exceeds 55, mostly found through the identification of soft, highly variable X–ray sources in the ROSAT All Sky Survey. Thus our knowledge about these systems is rapidly growing. This will allow us to study their distribution in the Galaxy, the detailed structure of the magnetic field on the white dwarf, the characteristics of the stream of matter from the secondary to the primary. The increase in information will also lead to a better understanding of the evolutionary history of Polars.

The defining characteristic of this class is a magnetic white dwarf in or close to synchronous rotation with its orbiting companion. Most of the radiation is emitted in the vicinity of the accretion region, a small area on the white dwarf near one of the magnetic poles, onto which the stream of matter is channeled by the field. There are different components in the emission which are produced by different radiation processes. The main energy losses occur by hard X–ray bremsstrahlung, soft X–ray blackbody emission, and a polarized cyclotron quasi–continuum in the UV to infrared bands of the electromagnetic spectrum (Fig. 2.5). The optical spectrum is characterized by strong line emission (Balmer lines, lines from neutral and singly ionized Helium) originating in the accretion stream and on the illuminated part of the surface of the companion. Field strengths range from 7 to 70 MG, periods from 80 min to 8 h, white dwarf masses from 0.4 $M_\odot$ to $\approx$1.3 $M_\odot$, and masses of the companions from 0.1 $M_\odot$ to $\approx$0.5 $M_\odot$. Depending on the orientation of the system with respect to the observer the accretion region due to the rotation of the white dwarf may vanish behind the horizon for part of the orbital period or even never come into view.

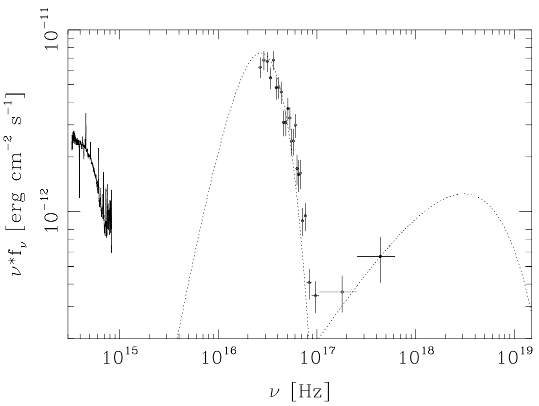

Figure 2.5: Radiation as a function of frequency for RX J1957.1–5738. Dotted lines show the model fits for an absorbed blackbody and a bremsstrahlung spectrum.

The fundamental parameter of a binary system is its orbital period. Through Kepler's third law it relates the distance between the two stars to the total mass of the system. There are two ways to determine it, either by observing periodic light variations or by measuring the frequency shift of the emission lines due to the orbital motion in a series of spectra. Since the velocity of the accretion stream increases with decreasing distance from the white dwarf, the lines emitted from the stream are usually very broad. However, one often can identify a narrow component in the lines, emitted from that side of the secondary illuminated by radiation from the accretion region, which in its periodic shift reflects the velocity of the orbital motion. This not only leads to a determination of the period but also provides another clue to the parameters of the system. The amplitude of the velocity variation for a given period relates the mass ratio to the orientation of the binary orbit relative to the observer, with the following caveat.

Since the emission line is generated on the illuminated side of the secondary, its frequency shift reflects only the motion of this part of the secondary's surface. Because the center of the emission is closer to the mass center of the system than the secondary itself, one has to correct the observed shifts for that. This can be done by computing the variation of the illumination on the secondary's surface from the geometry of the system.

From the period one can also estimate the mass of the secondary star under the assumption that it is an unevolved star, which for such low masses is generally justified. For that one needs to know how the radius of an unevolved star depends on its mass. Such a relation can be calibrated through observations of low mass stars in eclipsing binaries. A second relation between radius and mass of the secondary is obtained from the condition that mass overflow must occur from its surface towards the other star. That relation depends mainly on the period of the system and only weakly on the mass ratio and thus we can combine these two relations to obtain the mass of the secondary.

How can we learn something about the mass of the primary star? The velocity with which the accreting matter reaches the surface of the white dwarf depends only on the white dwarf mass, since the other parameter determining the velocity, namely the radius, is already fixed by Chandrasekhar's mass–radius relation for white dwarfs. This velocity determines the temperature of the plasma in the accretion region which can be measured by observing the hard X–ray bremsstrahlung radiation. However, because of the presence of a strong magnetic field, the accretion flow is also cooling via the emission of cyclotron radiation. Therefore, in order to deduce the velocity of the infalling matter from the observed temperature, one has to solve the hydrodynamic equations for the flow together with the radiative transfer equation. This requires a determination of the magnetic field strength.

In the presence of a magnetic field the infalling electrons are forced to gyrate around the field lines. Due to this nearly circular motion they emit radiation predominantly at the gyration frequency and multiples of it. Since the gyration frequency is determined solely by the magnetic field strength, spectral analysis of this radiation in the optical wavelength range often allows one to identify several of the higher harmonics. From their spacing one can obtain the gyration frequency and thus the magnetic field strength.

Finally we want to show two quite different examples for the lightcurves of Polars (Fig. 2.6). The upper curve is on a low level between phase 0.2 and 0.7 and its maximum occurs near phase 0.9. This is typical for an accretion area which for part of the orbit vanishes behind the horizon of the white dwarf (phases 0.2 to 0.7). From that one can deduce the approximate position of the accretion area on the white dwarf. It is located between 15° and 25° south of the equator (if we use the convention that the observer is looking at the northern hemispere of the star) and 30° ahead of the direction to the companion star (i.e. the observer faces the accretion area at phase 0.92). The lower one cannot be caused by such an effect because the maximum is found near phase 0.4. The variation here reflects the angular dependence of optically thin cyclotron radiation which emits most of its energy in the direction vertical to the magnetic field. So at phase 0.4 the observer looks almost vertical to the field direction and half an orbit later nearly along the field lines. From model fits to the data (dotted line) one obtains an accretion area located about 60° north of the equator and again 30° ahead of the direction to the companion star. A schematic drawing of this system is shown in Fig. 2.7.

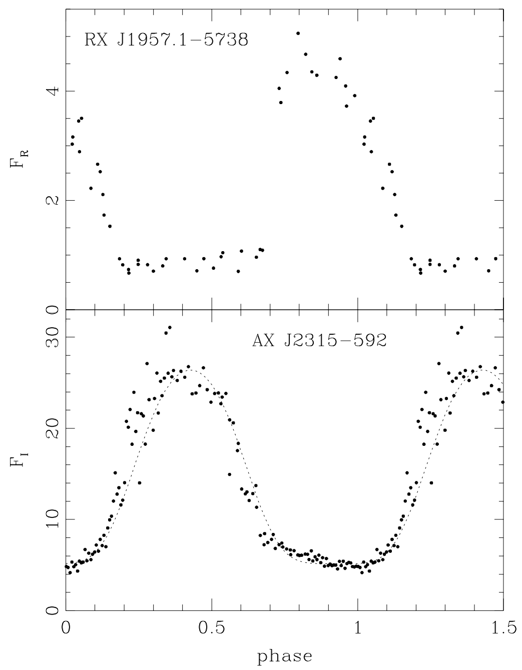

Figure 2.6: Lightcurves for two Polars. Phase zero corresponds to that moment of the orbit when the secondary star is closest to the observer.

These were just a few glimpses on the wealth

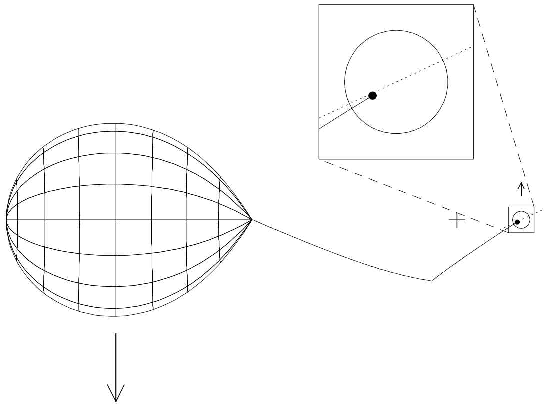

Figure 2.7: Schematic drawing on scale of a Polar projected into the orbital plane. (The inset panel shows an enlargement of the white dwarf.) The arrows indicate the velocities and directions of motion around the center of mass (cross) for the two components. The stream leaves the orbital plane when it is caught by the magnetic field of the white dwarf and therefore changes its direction. The dotted line shows the projection of the polar axis, the accretion spot is marked by a dot.

of data obtained in recent investigations of these fascinating binary systems and on the physics involved in the interpretation. The study of new Polars, done in close collaboration with the Göttinger Sternwarte, the ROSAT team of the MPE, and the AIP in Potsdam, will be continued. (H.-C. Thomas)

2.4 Simmering supernovae

On Feb. 23, 1987, a bright flash of ultraviolet light hit the earth and brought the first evidence that the blue supergiant star Sanduleak $-69°202$ in the Large Magellanic Cloud had been destroyed in a catastrophic disruption some 150000 years ago. The star, about 20 times more massive than our Sun, had ended its life in a supernova explosion which was given the name SN 1987A. Although it did not blow up in the Milky Way but in the largest of its irregular companion galaxies, SN 1987A was the closest visible supernova since Kepler's in 1604. Its light carried a wealth of information, and astronomers, equipped with modern instruments, eagerly made use of this historic chance to gain new insights into the final moments of a star's life.

Stars with more than about 8 solar masses continue to burn nuclear fuel in their central regions until iron has been formed. Since iron is the most strongly bound atomic nucleus, the star cannot gain any more energy by nuclear fusion and starts to contract in response to the inward pull of gravity. This contraction accelerates into a dynamical collapse when the increasing density leads to faster and faster conversion of electrons and protons into neutrons and escaping neutrinos. The implosion of the stellar core is not stopped until the moment when the centre reaches the density of nuclear matter and the stellar material can resist further compression. The infalling matter then bounces back and a shock wave forms and starts to propagate outward. This shock travels into the stellar mantle and envelope and disrupts almost the whole star in the supernova explosion. A neutron star with a mass between one and two solar masses remains behind as a compact remnant of the cataclysm.

Despite 30 years of computer simulations, the mechanism that leads to such an explosion of a star is still not satisfactorily understood. Computations have revealed that the shock which forms at core bounce is not energetic enough to reach the stellar surface layers directly. Energy losses by neutrino emission and disintegration of iron nuclei into free nucleons are so harmful that the shock stagnates before it gets out of the iron core of the star. The physical processes that "revive" the stalled shock and finally cause the explosion of the star are a matter of lively debate and exploration. The idea most widely favored is the so-called "delayed explosion" scenario. According to it, high-energy neutrinos, abundantly emitted from the nascent neutron star at the center of the collapsed stellar core, deposit energy in the medium behind the stalled shock and thus drive the reexpansion of the shock and the explosion of the star.

Neutrinos carry away 99% of the gravitational binding energy set free during the stellar collapse. Since this energy is more than 100 times larger than the kinetic and photon energy responsible for the spectacular optical display of the explosion, one would expect that neutrinos should be easily able to power the explosion. However, their interaction probability with the particles of the medium behind the supernova shock is quite low because this medium is much less dense than the neutron star. The crucial question is thus whether the energy transfer from neutrinos to the gas is sufficient or not.

Certainly one of the most remarkable and important achievements in connection with SN 1987A was that neutrinos from a supernova were detected on earth for the first time. Despite their extremely weak interaction with matter – roughly one out of a billion supernova neutrinos crossing the earth collides with an atom – a pulse of 24 neutrinos from SN 1987A was captured within an interval of 10 seconds in three experiments in the United States, in Japan, and in Russia. This fact was interpreted as a direct confirmation of our current picture of core collapse supernovae as described above. Unfortunately, a signal of only two dozen neutrinos could not provide enough information to unravel the processes in the deep interior of the star which led to the explosion.

However, other observations of SN 1987A were able to shed new light on this question: Gamma-rays from the decay of radioactive nuclides and X-rays were observed from the supernova much earlier than predicted by theoretical models. Infrared emission lines of metals, in particular of iron group elements, showed these products of explosive nucleosynthesis to be moving at very high velocities, much faster than expected according to the models. Both of these observations suggested that elements which can only be formed during the very early moments of the explosion in the stellar layers adjacent to the nascent neutron star, must have been mixed outward into the stellar mantle and envelope. Further support for this interpretation came from the observations of clumpiness and inhomogeneities in the expanding supernova debris, as well as indirectly from the smoothness of the lightcurve. The latter could again only be reproduced by theoretical models, if hydrogen from the envelope of the exploding star was mixed inward and metals were mixed outward on large scales.

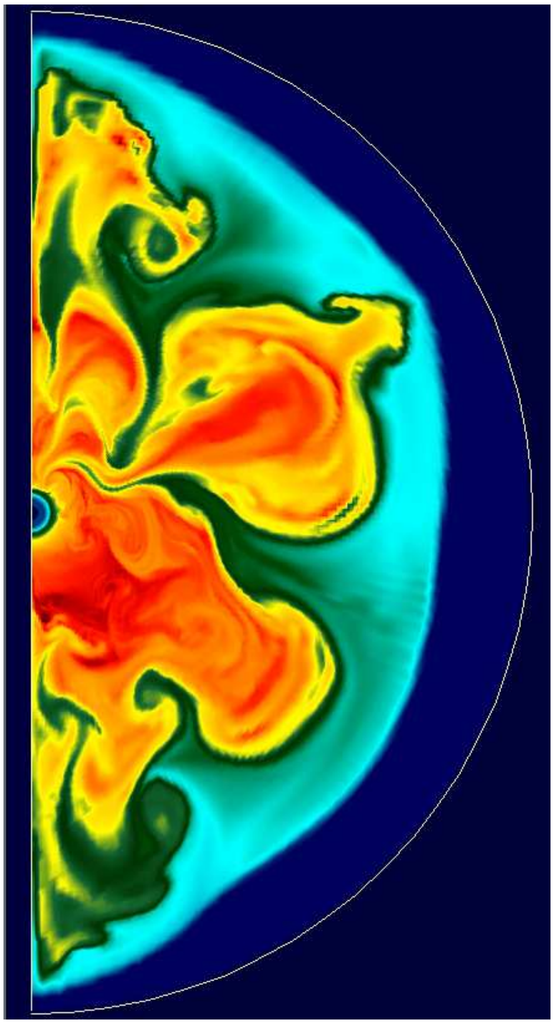

Figure 2.8: Inhomogeneous distribution of cool and hot gas between the nascent neutron star (left side, middle) and the supernova shock front (bumpy, hemispheric discontinuity) during the first second of the explosion. Neutrino-heated matter rises and expands in mushroom-like bubbles, while cool gas flows down toward the neutron star in narrow streams. The radius of the semicircle is 1600 kilometers.

SN 1987A has revealed supernovae as a highly turbulent and anisotropic phenomenon and has destroyed the simple theoretical picture that orderedly stratified onion-shell like layers are ejected during the explosion. These observational findings therefore provided a challenge to supernova modelers. Only very recently two- and three-dimensional computer simulations of the explosion have become feasible due to the enormous increase of computer power. The result of such a simulation is displayed in Fig. 2.8. The figure shows a cut through a two-dimensional, hydrodynamical model where rotational symmetry around the vertical axis was assumed. A snapshot about 0.2 seconds after the formation of the supernova shock is given. The latter is visible as bumpy, deformed discontinuity. Already at this time the layers behind the expanding supernova shock develop large-scale anisotropies and inhomogeneities. Neutrino-heated, hot and light material expands and rises in mushroom-shaped bubbles, whereas cool, heavy matter sinks in long, narrow tubes toward the newly born neutron star at the center.

This overturn instability between the neutron star and the supernova shock increases the efficiency of energy transfer from neutrinos to the stellar gas and thus aids the explosion. The

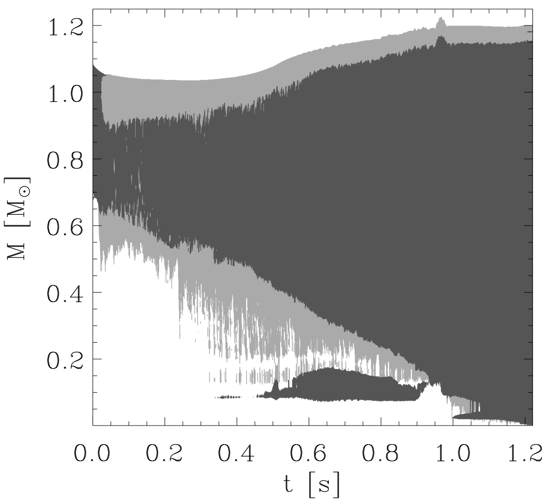

Figure 2.9: The vertical axis represents a cross section through the newly formed neutron star where the enclosed mass is given in solar masses. The dark grey areas mark convectively unstable regions as a function of time (horizontal axis, measured in seconds), the light grey regions indicate those parts of the star which are affected by penetrating rising or sinking convective mass elements.

main effect is that cool matter which is accreted through the shock is channeled into the region of strongest neutrino heating very close to the neutron star where it replaces the hotter gas which has already absorbed energy from the intense neutrino fluxes from below. Thus the total amount of gas that is exposed to high neutrino fluxes is increased and the explosion gains power.

While Fig. 2.8 displays the surroundings of the nascent neutron star out to a radius of 1600 kilometers, the cover of this report shows a zoom into the innermost 20 kilometers of Fig. 2.8, i.e., into the neutron star itself. A few tenths of a second after the supernova shock has been launched, the neutron star is stirred up by violent convective currents which transport hot matter from the central regions to layers close to the surface. The color coded quantity in the figure is the absolute value of the velocity of these mass motions. Green indicates very small velocities, blue, yellow, orange, and red mean higher and higher values, and the maximum velocities being around 3000 kilometers per second. Almost the whole neutron star is involved. In Fig. 2.9 one can see that the region of convective activity (dark area) encompasses an increasingly larger fraction of the neutron star and within only one second it has advanced to the center of the star.

Convective currents inside the neutron star contribute strongly to the transport of energy which would otherwise occur through neutrino diffusion. They thus accelerate the cooling of the hot, young neutron star. The corresponding increase of neutrino emission from the surface layers also helps the supernova explosion because the energy deposition by neutrinos in the vicinity of the neutron star increases sensitively with the neutrino luminosity.

The turbulent phenomena both inside and around the nascent neutron star therefore favor neutrino-driven explosions. Both can be important constituents of a theoretical model capable of explaining the complexity of supernova explosions which became even more evident in SN 1987A. The clumpiness and anisotropy of the supernova seem to have their origin in inhomogeneities imparted on the ejecta already during the very early phases of the explosion. The distribution and composition of the products of explosive nucleosynthesis depend on the interactions of neutrinos with the stellar material and thus on the properties of the neutrino emission from the newly formed neutron star. Moreover, the large number of young pulsars observed to be moving through interstellar space with large velocities suggests that they might have been given a kick at the moment of their birth in the supernova explosion. Recoil acceleration by aspherical mass ejection and anisotropic neutrino emission offers an interesting possibility to explain these speeding pulsars. Multi-dimensional and turbulent phenomena in supernovae will undoubtedly remain an exciting field of research in the coming years! (H.-Thomas Janka, Wolfgang Keil, Ewald Müller)

2.5 The rings around Supernova 1987A

When Supernova 1987A exploded in the Large Magellanic Cloud it provided astronomers with a dazzling display of phenomena, some of them so new and unexpected that they seemed to challenge the fundaments of our understanding.

After some weeks and months the rapid pace slowed down and now, in the nebulosity around the exploded star, another mysterious structure took shape. A sequence of pictures taken from the ground and from space, of increasing clarity and culminating in the beautiful Hubble Space

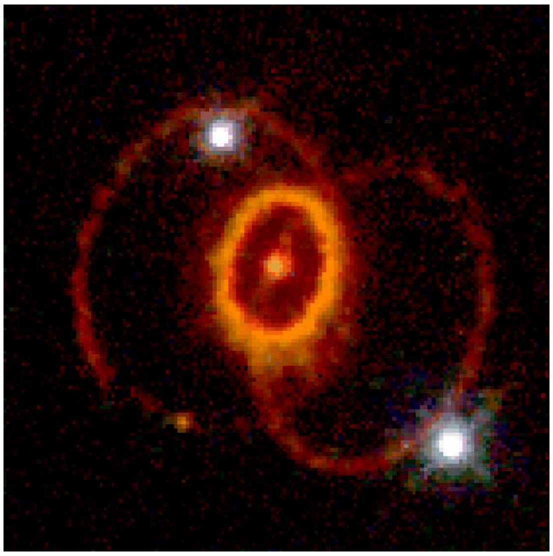

Figure 2.10: Hubble Space Telescope picture of Supernova 1987A taken in visible light (hydrogen-alpha emission) in February 1994, seven years after the explosion. The supernova is seen as a spot in the center, the two bright spots to the upper left and lower right are nearby stars. The ring system encircling the site of SN 1987A consists of three rings of glowing gas that was ionized by the energetic radiation from the early phase of the supernova explosion. A pronounced but smaller inner ring lies in the plane containing the supernova, the two fainter and larger rings lie in front and behind it. (courtesy of Christopher Burrows, ESA/STScI and NASA)

Telescope picture shown in Fig. 2.10 revealed a strange and delicate three-ring system.

An inner ring around the exploded star seems to define an equatorial plane from which the two outer rings, farther away and larger, are symmetrically displaced as if to float above and below the plane of the inner ring. The whole system appears to be seen by us under an inclination of about 45°.

Spectroscopic observations indicate that the inner ring and the outer rings expand with speeds of roughly 10 and 25 km/sec, respectively. Had they come from the central star this would place their origin some 20000 years ago, long before the supernova exploded and into the era when the progenitor star went through its last great evolutionary change from an extended and cool red supergiant to the more compact and hot blue supergiant as which we saw it before the explosion.

Most amazing is the narrow width and the striking brightness contrast of the outer rings indicating a density up to a factor of 100 larger than elsewhere. What might have caused this unexpected and strange phenomenon? First ideas of a precessing jet emanating from the remnant of the exploded star and inscribing a circular shape of impact points in the interstellar gas quickly became difficult to reconcile with the observations.

Attention was therefore naturally drawn to the interaction of the fast moving wind of the later and final blue supergiant phase of the central star with the slow wind from the preceding red supergiant phase. This scenario has been considered by many investigators. According to it the dense red supergiant wind is pushed and compressed from behind by an expanding "bubble" of hot gas which was created and is fed by the fast but tenuous blue supergiant wind. To complete the picture, we add that the hot bubble of blue supergiant wind gas contains inside a small volume in which the blue supergiant wind freely streams until at its boundary it is abruptly slowed down by a ("reverse") shock and joins the hot bubble gas.

This scenario needs amendment. A simple spherically symmetric expansion is at odds with the observed inner equatorial ring and the clearly defined outer ring structure. This has suggested that the inner ring is the result of some high concentration of mass in the equator before the blue supergiant wind started to blow and now acts as a collar on the wind gas confining it at the equator while it expands in the other directions giving it the shape of an "hourglass" with a narrow waist. But more difficult is the explanation of the outer rings with their narrow width and their clearly defined opening angle with respect to the central star.

Their present distance requires a strong blue supergiant wind if they are to define the interaction front between the two winds. The compressed shell of red supergiant wind around this interface may project as arcs of brighter light at its edges but quantitatively fails by orders of magnitude to give as strong a contrast as observed and can never yield the narrow widths of the mysterious rings. This led observers to call for "new physics".

The solution of this dilemma has now turned out to be surprising and of classical simplicity. It lies in the charming way in which non-linear hydrodynamics can create structure. We only have to dismiss the whole interaction scenario and consider what drastic change occurred when the cold flowing red supergiant wind was suddenly irradiated by the ionizing flux of ultraviolet photons that was switched on when the central star contracted to the hot blue supergiant stage at which it finally exploded. An ionization front was started that quickly ionized the red supergiant wind and raised its temperature to about 10000 K. This had a slow but profound effect: The gas suddenly feels pressure where before there was only density. Density falling radially off like the inverse square of the radius, there are now corresponding pressure gradients that accelerate the gas outward. Under these forces the more interior gas is accelerated faster, the gas farther out needs more time to reach similar speed because of its larger inertia. Then the inner parts "bump" into the still slower outer parts and a characteristic shock pattern forms within the red supergiant wind that travels outward in time. The shock separates the asymptotically still unaffected outside region from the inner region of shocked gas that reexpands from the high density to which the gas had piled up at the shock.

Thus internal motion triggered by ionization creates a high density spherical shell in the red supergiant wind that moves out with constant speed. With standard values of $10^{-5} M_{\odot}/\mathrm{yr}$ mass loss rate and 10 km/s speed in the wind, this structure would have reached the present distance of the outer rings 15000 years after ionization.

This structure would still not suffice to explain the strong density contrast and narrow width of the outer rings. But one can now exploit the same physical process again: If the original red supergiant wind had a higher density in the equatorial direction than in the polar direction, a lateral pressure gradient would appear on ionization, driving gas poleward. One must now note that the pressure gradients vanish on symmetry grounds both at the equator and at the pole and are largest at some intermediate declination. So it is material at intermediate polar angle that is set into motion. In due time this material will pile up against more poleward and less accelerated matter. As in the case of radial acceleration, here in the poleward direction the gas is compressed to a very high, sharp density peak by the cooperation of radial and lateral flow. This whole complex pattern is triggered by only ionization heating within the original cool red supergiant wind. It can be mathematically analysed using a similarity solution which shows the development of this amazing structure in detail.

This pattern of compression to two slender and high-density rings (followed by reexpansion) moves outward with time always showing two rings, one in each hemisphere. Their location travels outwards along a conical surface. We cannot discuss here the detailed agreement of this solution with the observations. Let us mention only that one particular observed feature is fully explained by the solution: In the first few months after the supernova event, while the light wave from the explosion was still travelling outwards through the region of the inner and outer rings, the pictures seemed already to show the ring system but in an incomplete state. This led the observers to the interesting notion that the light path to the parts of the ring farthest from us was too long to show already the arrival of the illuminating light front. These parts of the ring system were still seen in darkness and thus must have been neutral before the light front arrived, in spite of the fact that their formation depended on ionization in the first place. Even that finds a natural explanation: The calculated density in the narrowing region is so high that recombination overcomes ionization from the blue supergiant star and this material becomes neutral. Later, on reexpansion, the density decreases enough to allow the ionizing radiation to win again.

What about the blue supergiant wind that had so unsuccessfully been evoked to explain the ring phenomenon? Its interaction region must now lie inside the outer ring structure, because the undisturbed red supergiant wind evolution was the decisive element for forming the outer ring structure. This puts stringent limits on the unknown strength of the blue supergiant wind. An estimate yields a mass loss rate less than about $10^{-7} M_{\odot}/\mathrm{yr}$, an order of magnitude less than assumed before. Further interesting questions concern the cause of a slight asymmetry between the rings in the two hemispheres, the relation of the inferred density variation in the wind to a possible rotation of the red supergiant, and the role of the inner ring. Thus Supernova 1987A may still shed light on many aspects of the stellar evolution that led to this extraordinary event. (Friedrich Meyer)

2.6 Gravitational microlensing, dark matter and Galactic structure

It appears that most mass in the Milky Way is dark. The strongest evidence comes from the fact that light of the Galaxy decreases much faster than mass if we move (radially) outward from the Galactic center. There is no lack of suggestions as to what the dark matter is, ranging from elementary particles to massive astrophysical objects such as planets and brown dwarfs. The latter class of objects emit very little light themselves, hence they are difficult to detect directly. Paczyński proposed in 1986 that gravitational microlensing might be used to indirectly detect these objects.

Gravitational microlensing refers to the fact that when an object (luminous or dark) is well aligned with a background source and an observer, it acts as a gravitational "lens" which makes the source appear brighter. Due to their relative motions the light intensity of the background source changes. This variation lasts for days to months with an amplitude larger than 30%.

The difficulty in observing this effect lies in the fact that the probability for a star in nearby galaxies to be microlensed is tiny, only one in a million. This means that millions of stars have to be monitored, a task inconceivable for human eyes. Fortunately, with the dawning of the computer age and new charge-coupled devices, this has become technologically feasible. It is still a challenge to sort out the microlensing variability from all kinds of intrinsic variation exhibited by stars. Fortunately (in most cases) a microlensing light curve has a simple symmetric shape that is the same in different wavelengths and has a vanishing probability of repetition.

Since 1991, a few groups have started to search for dark matter using microlensing toward the Large and Small Magellanic Clouds, the bulge at the center of the Milky Way, and the Andromeda galaxy. Millions of stars in these fields are monitored each night. Dedicated software is used to reduce the huge amount of data and single out the stars undergoing microlensing. So far about one hundred fifty microlensing events toward the Galactic bulge and about ten events toward the Large Magellanic Cloud have been discovered. Figure 2.11 shows two examples of these.

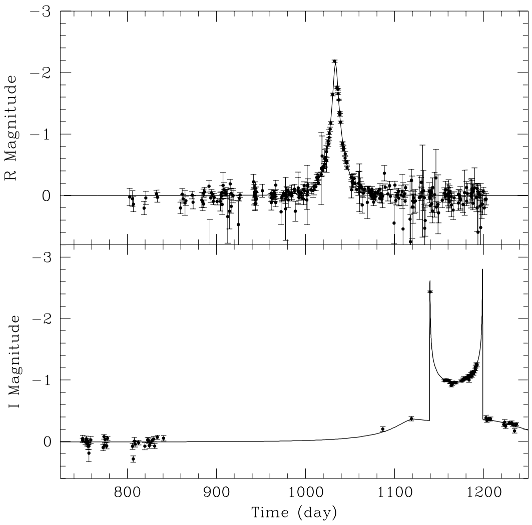

Figure 2.11: Two examples of microlensing light curves. For each light curve, the filled dots with error bars are observations, while the solid line shows a theoretical model. The top panel is the first microlensing candidate discovered toward the direction of the Large Magellanic Cloud by the MACHO collaboration. Most microlensing events have symmetric light curves like this. The source star becomes brighter when the lens moves closer to the line of sight, and then becomes fainter when the lens moves away. The bottom panel shows the first microlensing candidate produced by a binary system, discovered by the OGLE collaboration. The spikes are caused by a "resonance" induced collectively by the lenses. Even planets around stars can produce such peaks and this has been suggested as a way to detect them. About 5% of the microlensing candidates are due to binary systems.

The number of microlensing candidates toward the Large Magellanic Cloud, if interpreted in the simplest way, implies that about half of the dark matter in the outer parts in the Galaxy has been discovered with the lenses typically having a mass of about one half the solar mass. We can rejoice that perhaps one half of the dark matter has been found, but also wonder what the other half is. The lens masses are no less intriguing. Although several types of stars can have masses around half a solar mass, deep searches with the Hubble Space Telescope do not reveal as many such stars as implied by the microlensing experiments. In addition, the existence of these objects may be in conflict with the abundances of the chemical elements in our Galaxy. The escape may be that our model of the Galaxy and our understanding of how the lenses and the sources move around are too naive. For example, the mass distribution of the Galaxy may be flattened, whereas spherical geometry is adopted in the simplest model.

The results toward the Galactic center are equally interesting. The microlensing rate is a factor of two or three higher than expected. It has recently been realized that the Galactic bulge is not spherical, but instead is cigar-shaped with the long axis pointing to us. This geometry is favorable for lensing because there will be more objects in the light path to act as lenses and sources.

The experiments toward the Andromeda galaxy are more difficult to perform since the stellar fields are so crowded that no individual stars can be resolved. Direct frame to frame comparison has to be attempted. Due to variable observing conditions, this is usually quite difficult. So far, people have only found variable stars using this method. However, it is clear that the future of this method is very promising.

The group at MPA is involved in interpreting the observational results. A strong emphasis is on how these experiments can constrain Galactic structure, for example the Galactic bulge mass, orientation and axial ratios. Although microlensing candidates are routinely observed in a broad (energy) band, only few have been observed with high spectral resolution, allowing detailed study of the source star. The most detailed spectral analysis has been performed at MPA in collaboration with the Universitäts-Sternwarte in Munich. Observational time has been allocated to do further spectroscopic observations, in collaboration with scientists from Universitäts-Sternwarte and the European Southern Observatory. These future observations should yield valuable information about the spectral properties of the source stars and their motions in space.

The future of microlensing is bright. The increasing number of microlensing events should improve the statistics, and provide a more stringent limit on the amount of dark matter in the outer Galaxy and also constrain the Galactic structure. Furthermore, several groups can already detect microlensing events in real-time. Detailed photometric observations of ongoing events are being carried out by at least two groups. These real-time observations may offer a new way to detect (extrasolar) planets around other stars (cf. Fig. 2.11). A major frustration in microlensing is that we cannot infer the lens mass uniquely from the light curves, since the light curve depends not only on the lens mass, but also on the relative motions and the distances to the lens and to the source. A satellite separated by a few times the distance of the Earth from the Sun would help overcome this difficulty, since it would observe a different light curve from a different viewing angle and thus provide additional information. Even more far-reaching, perhaps, the microlensing surveys have proved that we can handle huge amounts of data to search for variability. This technique can be extended to search for many other kinds of rare and variable object all over the sky. Many surprises are surely in store for us from such future surveys. (Shude Mao)

2.7 Dark matter halos

One of the most striking properties of the Universe is the existence of 'missing mass,' or 'dark matter.' The existence of dark matter is inferred from observations of visible matter. In galaxies visible matter takes the form of stars, and the observation concerns their motions relative to each other. Most astronomers believe that the observable motions of stars around the Galaxy are too fast to be explained except by the presence of invisible mass—dark matter binds the stars to the Galaxy by its gravitational force. The visible content of the Galaxy has about ten billion times the mass of the Sun, but this accounts for only ten percent of the total mass. Similar arguments apply to galaxies other than our own, to groups and clusters of galaxies, and to still larger structures: they all contain dark matter. In fact the whole Universe is thought to contain much more dark matter than visible matter, which accounts for as little as a few percent of the total mass. The nature of the dark matter is somewhat mysterious, but it is often supposed to consist of elementary particles which interact with each other (and with the rest of the Universe) only through gravity.

Schematically, galaxy formation proceeds in two stages. The Universe was initially very smooth, as shown by observations of the microwave background, but contained tiny bumps and ripples. First gravity acted on the dark matter and amplified the initial bumps and ripples until they collapsed under their own weight and formed self-contained subunits. In this way they became much more dense than their surroundings. In the second stage the visible matter fell into the centres of these subunits and formed stars. The result is a visible galaxy surrounded by a 'halo' of dark matter. These halos are only observable indirectly through their effects on the motions of the visible matter.

The above picture of galaxy formation is highly simplified, most notably in the second stage where star formation occurs. Ideally one would like to be able to connect the observed properties of visible matter in galaxies with theoretical models of galaxy formation, using known physics. In fact, the processes involving visible matter are very difficult to model and to understand in detail. Much progress has been made in this direction by members of this institute and others (see the article by Guinevere Kauffmann in this report). However, it is also instructive to adopt a 'bottom up' approach and to look in more detail at the properties and structure of the dark matter halos themselves. This not least because the properties of the visible matter depend to a large extent on what is happening to the dark matter, since the latter provides nearly all the gravity.

We cannot directly study dark halos in Nature, since they are by definition invisible, but we can draw on the wealth of information provided by computer simulations of dark matter. Such simulations often represent dark matter as a large number (N) of point masses, and as such are known as 'N-body' simulations. The N bodies interact with each other only through Newton's law of gravity, which causes initial irregularities to be amplified in the same way as supposedly happens in galaxy formation. Dark matter in the real Universe is thought to consist of particles which are generally much, much smaller than those used in simulations, but the simulations are nevertheless thought to represent quite faithfully the structure and properties of halos. Generally, the larger the value of N, the more detailed the information which can be extracted from simulations. The largest value of N accessible with current, massively parallel computers is around 70 million. Simulations have been employed extensively by members of this institute to investigate the properties of dark matter halos. The largest of these are carried out as part of two international consortia named VIRGO, and GIF. The former is a large collaboration involving the MPA and scientists from the UK and Canada. It is mainly concerned with simulating very large patches of the Universe in order to determine accurately how halos cluster on large scales. The latter is a joint effort between the MPA and institutes in Potsdam and Jerusalem. It concerns smaller sections of the Universe, and hence enables one to focus in more detail on individual halos.

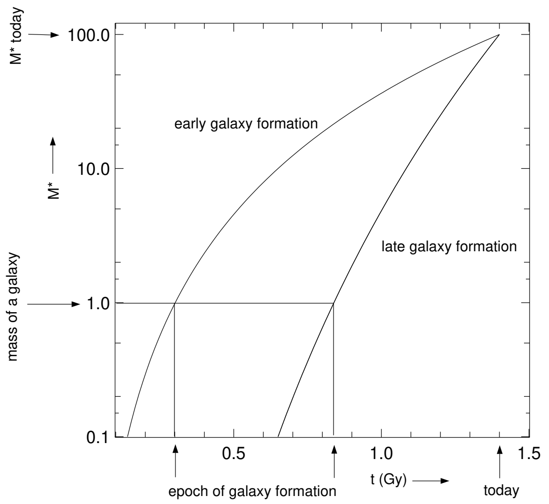

Figure 2.12: The curves showing M_* as a function of time in two hierarchical cosmologies: the halos which are just forming at any given time have a mass M_* which increases with time (the vertical axis is logarithmic). The curves intersect at the present value of M_*. The steeper one corresponds to late galaxy formation because it reaches the mass of a galaxy at a later time than the other.

The formation of halos can in principle occur in two distinct ways: either small halos form first, and then merge to form bigger halos; or large halos form first, and then fragment into smaller units. Most popular theories of structure formation are of the first type, and are referred to as 'hierarchical.' At any given time, there will be a particular set of halos which have the "typical" mass of the halos present at that time; these are referred to as 'M_* halos'. At present in the real Universe they are the halos containing small groups of galaxies. Each has a total mass roughly a hundred times that of the Galaxy. Other halos, such as that of the Galaxy or of a big galaxy cluster, will have masses M which are smaller or bigger than M_*. An important discriminant between cosmologies, both hierarchical and non-hierarchical, is the precise way in which M_* grows with time. This is encoded into the initial fluctuations in the otherwise smooth Universe, and hence appears in the initial conditions for an N-body simulation. When M_* increases rapidly with time, the halos of galaxies formed only shortly before the halos

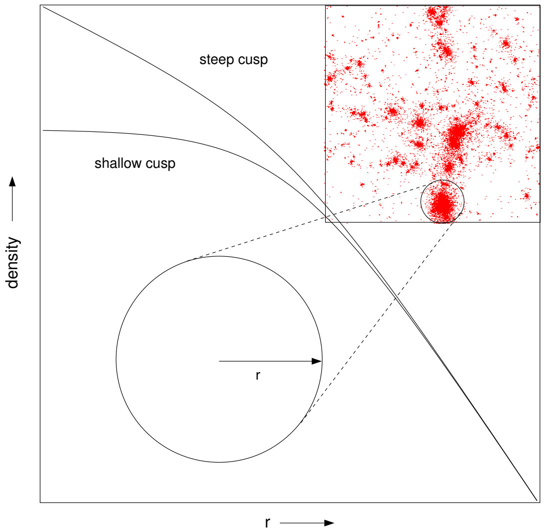

Figure 2.13: The inset panel shows a patch from a cosmological N-body simulation, in which each particle's position is marked with a dot. Halos of different sizes are evident; the small ones will eventually merge with each other and with the larger ones. Two examples of density profiles are shown in the main box. One has a steep cusp, and the other has a shallow (or absent) cusp. It was found not only that all halos have steep cusps, but that they are also all equally steep.

of clusters of galaxies, and we say galaxy formation is 'late.' On the other hand, when M_* increases slowly with time, galaxy halos formed a long time ago, and thus galaxy formation was 'early.' This is illustrated in Fig. 2.12.

A dark matter halo is more dense in its centre than at large radius. In the late 80s it was first noted that the density in large halos, which are the easiest to measure, continues to increase the closer to the centre one is able to look; for this reason we say that halos contain 'density cusps' at their centres, or that halos are 'cuspy' (see Fig. 2.13). More recently it was found that not only are all halos cuspy, but that they are also remarkably similar to each other; halos spanning a factor of over a thousand in mass were found to be all scaled copies of an M_* halo. A further surprise comes in the observation that the scale required to translate between different halos depends only on the ratio of their masses, for a given cosmological model. These two findings are surprising for halos of different mass at the same cosmological epoch, but the same relationships are in fact expected to hold between M_* halos at different epochs. Thus the favoured interpretation is that all halos of a given mass form roughly at the same time—the time at which their mass was the current M_*.

An important process in a hierarchical cosmology is the merging of small halos to form larger ones. Large halos grow by accreting their neighbours of all sizes. Most mergers can be characterised by the swallowing of a smaller halo by a larger one. Mergers between peers are also important, but happen less frequently. The distribution and frequency of mergers between halos of different sizes was studied at this institute in specially designed N-body experiments, and compared with theoretical predictions where possible. The formation time of halos was also studied, defining this for a given halo as the instant at which the largest progenitor had half the final mass. Such work gives empirical support for the above theoretical understanding of dark halo formation.

A particular aim at MPA has been to understand whether the formation of cuspy halos could be a natural consequence of hierarchical merging. Since small halos form early when the Universe is dense, they are themselves denser than large halos. The central cusps in large halos may then be built by mergers with dense and small companions. Since there is no limit to how dense the Universe was at earlier times, there is also no limit to how dense a small companion can be. Furthermore, small dense halos tend to sink and collect at the centre of a larger one with which they are merging. The centre of the final merged object thus reflects the density of its smallest progenitors. In this picture one predicts that a cosmology in which small halos form particularly early, and so are particularly dense, will produce final merged halos in which the central cusp is particularly strong. Unfortunately, it seems that this prediction is not borne out by simulations of halo formation in different cosmologies. Halos in all cosmologies appear to have similar cusps. It seems likely that the resolution of this conundrum will lead to interesting insights into the formation of dark halos. (David Syer)