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Cover figures: *Upper left:* Turbulent nuclear burning on the surface of a white dwarf during the nova outburst phase. The false color image shows the abundance of the radioactive ^{15}O isotope produced by the nuclear reactions (Kerzek, Hillebrandt).
Upper right: The 6.4 keV fluorescent line of neutral iron observed by ASCA from the giant molecular clouds in the Galactic Center region could be an echo of AGN-like activity around the supermassive black hole in Sgr A* a few hundred years ago (Churazov, Gilfanov, Sunyaev).
Lower left: The distribution of galaxies and dark matter in a region of size $21 \times 21 \times 8$ Mpc/h within a simulation where the dark matter distribution is followed on a supercomputer and galaxy formation is treated by semi-analytic methods. The galaxies are colour coded according to their star formation rate, with blue meaning high rates and red low rates (Kauffmann, Colberg, Diaferio, White).
Lower right: The intensity of the X-ray emission from Comet Hyakutake calculated from a model (colour) and measured by ROSAT (white contours). The Sun is to the right. The cross indicates the position of the cometary nucleus. The image extends 200.000 km to each side of the nucleus (Wegmann).
Back: Three-dimensional Newtonian hydrodynamic simulation of the mildly relativistic ($v = 0.26\,c$) precessing twin jets of the galactic binary star SS433. The figure shows the interface between one of the jets and the ambient gas (Müller).

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Editors: H.-Th. Janka and S.D.M. White.

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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"). In 1996 the institute's management structure was altered to replace the third director, Simon White, by a board of directors, currently Wolfgang Hillebrandt, Rashid Sunyaev and Simon White. Simon White is acting as Managing Director until the end of 1999.

Research at MPA is devoted to a broad range of topics in theoretical astrophysics. Major concentrations of interest lie in the areas of stellar evolution, stellar atmospheres, nuclear astrophysics, supernova physics, astrophysical fluid dynamics, high energy astrophysics, radiative processes, galaxy structure, formation and evolution, gravitational lensing, the large-scale structure of the Universe, particle astrophysics and cosmology. For many years the MPA had a strong group in General Relativity, but in mid-1995 most of this group moved to the newly founded MPI für Gravitationsphysik in Potsdam near Berlin. Their departure allowed a consolidation of MPA activities in extragalactic astrophysics, as well as an expansion in a new area, high energy astrophysics. 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 post-doctoral 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. Such collaborations are also supported by membership in a number of EC-funded networks, two of which are coordinated from the MPA. Interaction with local institutions is enhanced by a Special Research Area funded by the German Research Foundation in the field of astroparticle physics. Other participants in this programme include the physics departments of the two universities, the observatory of the LMU, and the MPI für Physik.

1.2 Current MPA facilities

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

The MPA and the MPE share a large and fully stocked astronomical library which is housed in the MPA building. 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 748-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 1997 at the MPA

A year of broadening collaborations – international... — As a result of its large and active visitor programme, the MPA has always been an outward-looking and international institute. During 1997, however, a number of new external collaborations were established or extended. Discussion of new initiatives such as joint student conferences and a joint "flagship" project got underway within the EARA grouping during their 1997 Board Meeting in Garching, but as always most scientific progress was made through smaller bilateral and trilateral collaborations supported by exchange programmes or by networking funds. Two new networks involving the MPA were funded in 1997 by the European Commission under its TMR programme, one coordinated from the MPA in the area of "Accretion into Black Holes, Compact Stars and Protostars", the other in the area of "Gravitational Lensing". These join the existing TMR network on "Galaxy Formation and Evolution" (also coordinated from MPA) as a primary stimulus to exchanges within the European Union.

An international initiative of a different sort, grouping scientists from the UK, the MPA, Canada and the US, the Virgo Consortium, uses the latest generation of parallel supercomputers to address problems related to the formation of galaxies and larger structures. In 1997 the T3E at the RZG was the largest machine available to the group (which also uses machines in

Edinburgh and Cambridge), and the RZG itself provided substantial support to adapt the Virgo simulation software to run efficiently on this machine. As the year came to an end, this effort was rewarded by the initiation of the largest cosmological simulation ever, the first integration of the gravitational N-body problem with N equal to one billion, making it possible to study the statistics of structure over a large fraction of the observable universe.

Another very fruitful set of international links have opened up at MPA as the high energy astrophysics group has become established. The close ties of this group to the Space Research Institute in Moscow have made it possible to bring a broad spectrum of excellent Russian astrophysicists to Garching. This has not only brought new expertise to the MPA in many areas with close overlaps to existing programmes; it has also substantially enhanced joint activity between the MPA to the X-ray and γ-ray groups at the MPE.

...as well as local — The German Research Foundation funded Special Research Area in Astroparticle Physics (SFB 375) was very active in 1997 with most of its research programmes in full swing. Particularly successful collaborations involving the MPA address neutrino astrophysics (with the MPP), nuclear chronometers (with the physics department of the TUM), large-scale structure (with the physics department at the LMU) and gravitational lensing both by galaxy clusters and by Galactic stars (with the Observatory of the LMU). The last project uses microlensing to facilitate spectroscopy of faint bulge stars, and for a few hours in 1997 the Sternwarte/MPA collaboration found that the ESO NTT + gravitational lens was functioning as a telescope with an effective collecting aperture of almost 25 metres!

1997 also saw the end of the first three-year funding period of the Special Research Area, and so the visit of an evaluation committee set up by the German Research Foundation. The visit provided an enjoyable opportunity for everyone participating in the SFB to review progress in the many subprojects it supports. The committee also seemed to enjoy themselves and to be impressed by progress across a scientific spectrum ranging from early universe field theory and cryogenic dark matter detectors to the statistics of large-scale structure and observations of galaxy evolution. Their concluding report supported the SFB strongly and resulted in continued funding for three more years at close to the requested level.

MPA sponsored meetings — During 1997 the MPA continued to make good use of the Max-Planck Society's conference facilities at Schloss Ringberg, a neo-medieval castle in the Bavarian mountains. In January a group a gravitational lensing enthusiasts got together amid deep snow and laid the basis for their successful network proposal to the European Commission. By May the sun had come out and the castle was filled for a week by the annual meeting of the Galaxy Formation network which the EC had funded the previous year. In October the leaves were beginning to fall as the SFB on Particle Astrophysics got together for their annual workshop, this year on the topic of Neutrino Astrophysics and organised primarily by MPA scientists.

Opening the doors — Every two years the MPA and its neighboring institutes hold an Open Day for the public (Tag der Offenen Tür). This happened in October 1997 and was very ably organised by Hans-Christoph Thomas. Many of the MPA's old exhibits were updated for the occasion to reflect the institutes changing research interests and to place greater emphasis on modern technical developments and computing than in previous years. The event was well attended despite bad weather and seemed to be much appreciated by the visitors. As usual a surprising number of very well informed "amateurs" turned up to discuss astrophysics issues with the MPA scientists "on duty".

The Biermann Lectures — The summer of 1997 also saw the first series of Biermann Lectures. This new MPA-sponsored initiative is aimed at stimulating scientific activity across the Munich astronomical community. Each year it brings a world-ranked astrophysicist to Garching for a month with the task of giving a series of prize lectures and interacting broadly within the various local institutes. The 1997 Biermann Lecturer was Joe Silk, from Berkeley, and his series on "The Formation of Galaxies" set a high standard, consistently filling the MPA lecture theatre to overflowing and beyond. The 1998 Biermann Lecturer will be another Californian, Roger Blandford from Caltech, the chairman of the MPA's Visiting Committee. We eagerly await his lectures.

The fellowship programme of the Alexander von Humboldt Foundation provides another way to bring distinguished foreign astrophysicists to the MPA for extended periods. In 1997 a third Californian, Stan Woosley of UC Santa Cruz completed the last of a series of highly successful AvH-sponsored visits to the MPA. He (and his guitar playing) will be missed, but since his collaborations with the MPA supernova group continue to be very fruitful, it seems certain he will be back for a shorter visit soon. As Stan was preparing to leave, another Humboldt fellow arrived for a year. Mike Norman is Director of the Laboratory for Computational Astrophysics at the National Center for Supercomputing Applications. We hope he will enjoy interacting with the supercomputing groups at MPA.

From stars to cars — Although the cosmology group's "Hubble Volume" simulation filled the Cray T3E and produced so much output that the archive system spent days in a jam reminiscent of summer on the Munich-Salzburg autobahn, by far the most demanding use of the T3E came from the MPA's nuclear astrophysics/supernova group. In an effort to understand the explosion of classical novae they carried out the first ever fully three-dimensional simulation of turbulent burning front propagation in an astrophysical context. Simulation of the complete combustion of the surface layers of the star required about a quarter of a million processor-hours of computation, and although it did not produce a fully satisfactory nova, it demonstrated the ability to carry out realistic modelling of a process which is of considerable interest in areas well removed from astrophysics – for example, in the design of car engines. In late 1997 this led to plans of the MPA's first substantial joint venture with industry – a project with the research division of BMW (the local car company) to simulate the propagation of burning fronts in turbulent fuel-air mixtures.

Max-Planck and the Planck Surveyor — 1997 was an important and difficult year for Planck Surveyor, ESA's planned mission to map the cosmic microwave background with high resolution and sensitivity over a wavelength range of one and a half decades. As a result of severe budget pressure ESA proposed combining Planck with FIRST, its far-infrared observatory. By year's end apparently insurmountable technical problems with the original plan had emerged and other options, for example, separate satellites on a common launcher, or separate "cheap" launches, were being studied. The final decision is not expected until summer 1998, and the related uncertainty has greatly complicated planning of the mission. Despite this, MPA's proposal to act as one of the principal data centres has made substantial progress, and a suitable role has been worked out with the instrument teams, each of which will now include MPA co-investigators. MPA will support the two instruments equally and will take major responsibilities for setting up an integrated data, software and documentation environment, as well as for preparing the final public release versions of the mission's primary data products, maps of the sky at each of the Planck frequencies and in each of the primary emission components (intrinsic microwave background, Galactic dust, Galactic synchrotron and free-free, point sources,...). The Max-Planck Society has endorsed this proposal by providing seed money for the initial phases of the activity; details of the longer term financing will be worked out with the relevant government agencies during 1998 and 1999.

Space for space (and other things too) — Substantial new activities like the Planck Surveyor data centre or the MPA exchange programme with the Space Research Institute and related Russian astrophysics centres cannot be implemented without providing suitable working areas. In addition the MPA/MPE library is running out of shelf space, and the part of its collection housed in a temporary "container" is suffering seriously from the unsuitable conditions. For years, space in the MPA building has been (more than) fully allocated, largely as a result of the decision to help our MPE neighbours by providing them with temporary space to relieve their own, much more critical accommodation difficulties. Both institutes thus greeted the decision to build a major new wing for the MPE with considerable relief. Ground will be broken in 1998 and building should be complete in 2000. The planned extension should allow all the "temporary" buildings to be dismantled, the X-ray and infrared groups to be properly housed in permanent MPE accommodation, and the construction of a modern 200-seat lecture theatre to serve both institutes. The space freed in the MPA building will be sufficient for the library's needs for at least 20 years, will house the Planck Surveyor data centre, will provide adequate seminar rooms for small meetings, will allow the joint MPA/MPE administration to be brought together in a single place, and will relieve the severe office overcrowding at MPA during popular visitor periods. Thus although no one is looking forward to 18 months of building work on our doorstep, everyone is looking forward to the result.

1.4 How to reach us

- Postal address:

  MPI für Astrophysik
  Postfach 1523
  D-85740 Garching
  Germany

- Telephone (country code 49):

  89-3299-00 (switchboard)
  89-3299-3214 (secretary)
  89-3299-3235 (FAX)

- Electronic address:

  e-mail:
  user-id@mpa-garching.mpg.de
  (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 Why do white dwarfs and pulsars rotate?

White dwarfs and neutron stars (radio pulsars) are observed to rotate with typical periods of a day and a second, respectively. These stars are the end products of stellar evolution. Starting their life as main sequence stars like the Sun, they lose a large fraction of their mass before ending as neutron stars or white dwarfs. They also lose almost all of their rotation: the angular momentum of a white dwarf, for example, is less than a per cent of what its main sequence progenitor had, and for pulsars the ratio is even smaller. The customary explanation for this is that the mass lost from the star has somehow taken with it just the right amount of angular momentum. MPA work described below suggests that this is probably not correct. It proposes, instead, that the rotation of single white dwarfs and neutron stars is a product of processes in the final stages of stellar evolution, and has nothing to do with the rotation of the main sequence progenitors.

The argument centers on the state of rotation in the interiors of red giant stars. As a star evolves away from the main sequence, its core contracts while its envelope expands, eventually reaching sizes of a few astronomical units. An envelope of this size rotates very slowly, with periods of tens of years or more. In the absence of mechanisms transporting angular momentum between core and envelope, the core would rotate with periods of minutes or less, some 10^6 times faster than the envelope. Only a small amount of coupling between core and envelope can be tolerated if this differential rotation is to survive the star's life-time as a giant (10^5–10^7yr). On the other hand if angular momentum transport were efficient, the giant would rotate approximately uniformly and the rotation period of the core would be tens of years or more. A white dwarf emerging from such a giant might then be expected to rotate with a similar period. Which of these extremes, approximately uniform rotation or a core spinning 10^6 times faster, is closer to the truth?

An observational indication is given by the Sun. Helioseismological observations show that the core of the Sun rotates essentially uniformly, with deviations in rotation rate substantially smaller than the 30% seen at the surface. Such a low degree of differential rotation is hard to explain with the known hydrodynamic mechanisms for angular momentum transport. Stellar evolution calculations which include these mechanisms, as well as the spin-down torque of the solar wind, leave the core of the Sun rotating 2–3 times faster than the surface. A very efficient mechanism is apparently at work that is not accounted for by present stellar evolution calculations. If such a mechanism is present in the Sun, why couldn't it work in giants as well? A second argument is theoretical. There is, in fact, a very plausible candidate for this mystery mechanism, namely a weak magnetic field. Since the first developments of astrophysical magnetohydrodynamics in the early 50's it has been known that a field of less than 1 Gauss should be sufficient to keep the Sun in approximately uniform rotation. Differential rotation winds up fields and increases their strength; a detailed analysis shows that an initial field of 0.1 G should be sufficient to keep the Sun in approximately uniform rotation from its birth. Unless stars typically have field strengths smaller than this, uniform rotation would appear to be a safer bet than rapidly rotating cores.

If these arguments are accepted, white dwarfs would be expected to have periods of decades, while neutron stars formed by the collapse of corotating cores would have periods of 100–1000 seconds, much longer than observed. In both cases, however, there are additional processes that can add back the missing angular momentum. Starting with neutron stars, it is known that most pulsars are born with a 'kick' that gives them a space velocity of 100–500 km/s. These kicks are probably caused by asymmetries in the emission of neutrinos during the collapse of the core. The nature of these asymmetries is not entirely clear at present, but because of the huge amount of energy emitted in neutrinos, a small asymmetry ($\sim$ 1%) would be enough. If one now supposes that the kick process is such that its net thrust vector does not pass exactly through the center of mass, it will also induce rotation, just as a billiard ball spins if it is hit slightly off-center. An elementary analysis of billiard balls the size (10 km) and mass (1.4 solar masses) of neutron stars shows that the spin periods expected for kicks of 100–500 km/s are in the range 0.01–10 sec, depending how far off-center the balls are hit. This covers the range of inferred initial periods of pulsars.

The observed rotation of pulsars can therefore be explained as a natural by-product of the kicks they receive at birth. This explanation can be tested in principle, since it predicts correlations between spin and space velocity, both in magnitude and direction. Though the predicted correlations may turn out to be rather small (depending on presently unknown details of the kick process), they could conceivably be detected in pulsar observations. Another prediction is that a certain population of neutron stars may be born with periods longer than two seconds, and never show up as radio pulsars (a minimum rotation frequency of 0.5 Hz is needed before pulsar emission is generated at radio frequencies). Some recently detected anomalous X-ray pulsars with periods of 5–11 sec may be such cases.

Present single white dwarfs must have formed from stars with initial masses of at least 2 $M_\odot$, hence must have lost at least a solar mass. This mass loss is observed as a 'superwind' lasting about 10^4 years. In this stage, the star is about 10^4 times as large as the white dwarf that will emerge when the envelope is gone. With such a large 'lever arm', the mass loss process must be extremely accurately axisymmetric to avoid introducing some angular momentum in the remaining envelope. The situation is somewhat analogous to the neutron star case, with mass loss replacing neutrino emission. The superwind mass loss is believed to be driven by radiation pressure on dust shells ejected at intervals of a few years. The kicks due to this ejection, if slightly nonaxisymmetric, add small amounts of angular momentum in random directions to the envelope, causing a random walk of the angular momentum vector of the envelope in angular momentum-space. Most of the angular momentum acquired by past kicks is lost again, however, with the continuing mass loss. The final angular momentum is set by the amount of envelope mass, δM, that settles back onto the white dwarf at the end of the mass loss process. This is deduced, from theoretical models for well-observed white dwarfs, to be in the range 10^{-5}–10^{-3} $M_\odot$. The observed distribution of white dwarf rotation rates can then be reproduced by assuming an asymmetry of the order 10^{-2}, and a range of final envelope masses $\delta M = 2 \times 10^{-5}$ – $5 \times 10^{-4} M_\odot$. A larger (smaller) asymmetry combined with lower (higher) δM is also possible. An example is shown in Fig. 2.1.

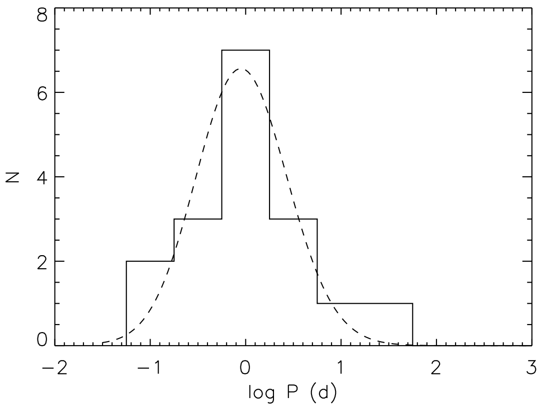

Figure 2.1: Predicted distribution of rotation periods of single white dwarfs (broken line) for asymmetry parameter $\epsilon = 10^{-2}$, and a log-normal spread in final envelope mass from 2×10^{-5} to $5 \times 10^{-4} M_\odot$. Histogram: observed distribution.

Whether this degree of asymmetry is quantitatively realistic is hard to tell from current observations. It is known, however, that the surfaces of red supergiants are quite inhomogeneous. Hot spots, with the sizes and temperatures expected from convection in the envelope, have been observed in nearby supergiants such as Betelgeuze and Mira. Also, asymmetries in the mass loss process have been observed directly through interferometric measurements of SiO masers in the atmospheres of red supergiants.

In our explanation, the rotation of white dwarfs and neutron stars is more interesting than before, since it gives new clues on the latest stages of stellar evolution: the mass loss process that transforms a supergiant into a white dwarf[1], and the core collapse process in supernovae.

The processes described are relevant mainly for single white dwarfs and pulsars. The rotation of millisecond pulsars and of white dwarfs and pulsars in binaries is markedly different, and is closely related to mass exchange (previous or ongoing) between the components of these binaries. (Henk Spruit)

2.2 Nova outbursts

The term "stella nova" means "new star" and historically refers to stars which suddenly appeared on the sky and then disappeared after weeks or months. Systematic observations of such novae were made by Chinese astronomers already about 2000 years ago, mainly in order to predict political changes. The first novae observed and registered in Europe were novae CK Vul (1670), WY Sge (1783) and V841 (1848), and extensive observations began only in the 19th century.

Today we denote celestial objects as (classical) "novae" if they change their optical brightness by up to 15 magnitudes within a few days. There are typically about 35 novae per year in our own Galaxy and about 26 per year in M31. In our Galaxy novae are concentrated towards the disk plane and towards the center. They are classified according to the rate at which they decline from maximum brightness into fast, medium and slow novae. Because of their high luminosity they can be observed even in rather distant galaxies, and a well defined relation between maximum light and the rate of decline makes them good candidates for calibrating the cosmic distance scale. They also contribute significantly to the production of certain heavy elements, for example ^{26}Al and ^{7}Li.

Recent supercomputer work at MPA sheds light on the mechanism which produces these enormous explosions. We know that novae occur on white dwarfs in close binary systems with a main sequence star. They are a sub-class of the so-called cataclysmic variables. Hydrogen-rich material from the companion first flows onto a disk surrounding the white dwarf and is then accreted onto its surface. Compression of this envelope can heat it enough for hydrogen to start burning into helium, first by the proton-proton chain and later by CNO-cycles in which C, N and O nuclei act as catalysts. Previous numerical work has suggested that these reactions can release energy fast enough to eject the envelope, provided the matter is electron degenerate and the CNO-abundances are sufficiently high, several times the solar values. If these conditions are met, the outburst can resemble observed classical novae.

In fact, however, there are problems. Nova ejecta show He, C, N and O abundances up to 100 times solar, the peak temperatures obtained in the models, usually below 4×10^8 K, although sufficient to burn hydrogen into helium, cannot produce elements like C, N or O. The companion star is observed to be a low-mass main sequence star, so the accreted gas should have roughly solar composition. The only possible origin for the heavier elements is then the white dwarf itself. This is quite plausible since we know that most white dwarfs consist of C and O, and a few of the more massive ones of O, Ne, and Mg, but current explosion models do not explain how this material gets into the ejecta. There is clear evidence that the majority of novae originate from C+O white dwarfs. In the following we shall therefore concentrate on such objects

The presence of C, N, and O can dramatically enhance the energy production during the violent stages of the nova outburst. Spherically symmetric hydro-dynamical simulations of the accretion process and the following outburst suggest that a large overabundance of CNO nuclei in the H-rich envelope is needed at the onset of the violent phase in order to get an explosive thermonuclear runaway (TNR) at all. According to these calculations almost half the envelope mass must be CNO nuclei for a strong outburst and a fast nova. The crucial question is then: Why should there be huge CNO abundances in the accreted envelope of the white dwarf? Here N is not a problem since it is produced from C and O during H-burning. The problem elements are C and O.

Several ideas have been put forward for mixing C and O from the white dwarf into the envelope during the accretion phase. One is simply diffusion of hydrogen into the white dwarf accompanied by diffusion of C and O into the enve-

[1] This process produces a *planetary nebula*. Many spectacular images of such nebulae have been obtained with the Hubble Space Telescope. See them at `http://oposite.stsci.edu/pubinfo/PR/97/pn`.

lope. However, diffusion is slow and this process can work only in exceptional cases with very low accretion rates. Another idea is mixing due to shear instabilities since material is accreted from a disk with high orbital angular momentum. Finally, because the envelope becomes convectively unstable during the accretion stage, convective motions may penetrate the surface of the white dwarf, leading to dredge-up of C and O. However, in spherically symmetric models this effect appears much too weak to be relevant.

On the other hand, one might suspect that violent motions driven by nuclear reactions *during* the TNR may lead to rapid and efficient mixing. To be more precise, one may hope that convective motions can dig into the white dwarf and mix some C and O into the envelope. The enhancement of C and O could then increase the burning rate, generating more violent motions and even more dredge-up and mixing. It is obvious that modeling this effect requires multidimensional simulations of a reacting fluid under extreme conditions. The published results of some recent two-dimensional simulations suggest considerable self-enrichment and a fast nova outburst may be possible.

Here we present the results of simulations we have carried out for a white dwarf of one solar mass (1 $M_\odot$) accreting hydrogen-rich gas at a rate of $5\times10^{-9}\,M_\odot$ per year. The calculations were carried out in a cartesian coordinate system. Only a fraction of the white dwarf's surface was covered by the computational grid, and periodic boundary conditions were applied horizontally.

Our first simulations were done in two spatial dimensions, assuming that all physical quantities are independent of the third dimension. In this symmetry convective eddies will be represented by infinitely long rolls. Some of our results are displayed in Figs. 2.2 and 2.3. Figure 2.2 shows snapshots of the absolute value of the velocities obtained in this 2D simulation. A small temperature increase was imposed on one zone as an initial perturbation. Already 14 seconds later sound waves emerging from the ignition region ignited the whole bottom layer of the envelope (Fig. 2.2a). As time progresses quasi-stationary axially symmetric flow fields appear (Fig. 2.2b) which dominate the flow patterns after about 100s (Fig. 2.2c). These vortices are very stable and carry a considerable amount of the turbulent kinetic energy. They disappear only when nuclear energy generation reaches its maximum after several hundred seconds.

The appearance of axisymmetric quasi-stable structures in 2D flows is not new. It was found in earlier 2D simulations of convection in plane-parallel geometry, and has also been observed in the Earth's atmosphere. Our simulation is the first, however, where such deviations from standard inertially driven turbulence (in which energy is fed into the turbulent eddies on the largest scales and cascades down to small scales where it is dissipated by viscosity) have been found in an astrophysical application where they could have important implications.

One consequence is that we do not confirm the results of earlier simulations. We find considerably less dredge-up of C and O, mainly because on average less turbulent kinetic energy is available for the largest (and fastest) convective eddies. This effect can clearly be seen in Fig. 2.3, which shows the ^{12}C mass fraction shortly after ignition (Fig. 2.3a) and at maximum energy generation rate (Fig. 2.3b) for this sequence. Although 500 seconds after ignition a considerable amount of ^{12}C can be seen in the envelope (40%) the mixing process has been too slow to yield a strong nova outburst. This contrasts strongly with earlier calculations.

In order to make sure that all relevant scales have been resolved in our simulations we performed one additional run with five times higher spatial resolution. There were no major differences in the global properties, although mixing was slightly less efficient. Thus we conclude that, at least in 2D, self-enrichment of a nova envelope by violent convective motions is a rather unlikely process. As a final more stringent check, we carried out the first ever 3D simulations of a nova explosion, using the same input physics and similar resolution. This produced even less mixing and substantially smaller eddies than in 2D (as might have been suspected). It is clear that 3D simulations are needed to capture the physics correctly, and that models are still missing some critical element of physics.

Our conclusion is, therefore, that nova outbursts require severe enrichment of the H-rich envelope *prior* to the TNR. If this does not happen, the white dwarf will enter a phase of quiet hydrostatic burning and will, if the envelope fulfills certain requirements, resemble a super-soft X-ray source more than a nova. Our results also show that direct simulations of reaction hydrodynamics are now feasible, even in 3D, and are required whenever fuel and ashes are well mixed

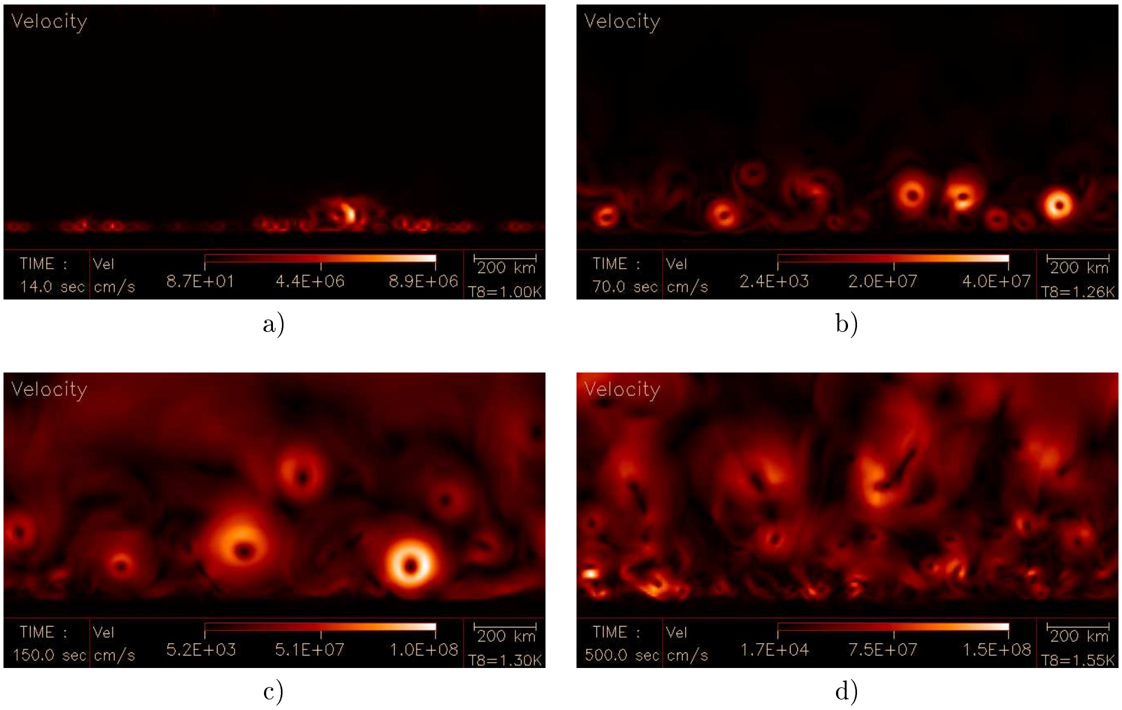

Figure 2.2: Velocity field at different stages of the evolution for the 2D model discussed in the text. Color indicates the absolute value of the velocity at each point. T8 denotes the temperature of the hottest individual zone in units of 10^8K.

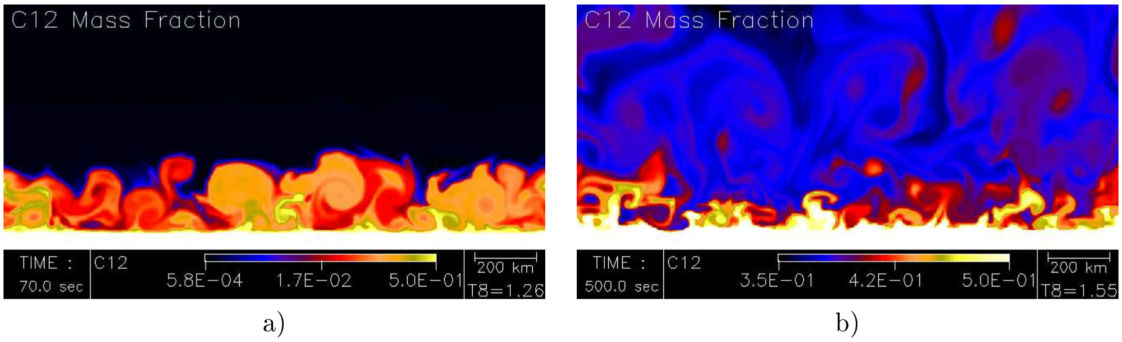

Figure 2.3: ^{12}C mass fraction for the same run shortly after ignition (a) and at peak energy generation rate (b).

and burning times are much longer than those of turbulent mixing.

All our simulations were performed with PROMETHEUS, a Eulerian PPM code with a nuclear reaction network and a realistic equation of state. This version of PROMETHEUS was modified to run very efficiently on massively parallel computers such as the CRAY T3E of Rechenzentrum Garching. (A. Kercek, W. Hillebrandt)

2.3 Ages of globular clusters and the age of the Universe

The most widely accepted cosmological model is the 'Big Bang' theory, which accounts in a simple way for the cosmic abundances of the light elements, the cosmic background radiation and the expansion of the universe. According to this theory, the Universe began a finite time ago with the Big Bang; determining the age of the Universe (usually denoted t_0) is one of the fundamental problems of astrophysics.

At least two routes have been proposed to answer this question. The first makes use of theoretical stellar models to determine the age of the oldest known stars, those belonging to globular star clusters (GC). The underlying idea is trivial: since the Universe cannot be younger than its stars, the age of GC provides a lower limit on t_0.

The second route requires a determination of the Hubble constant (H_0), that is the ratio of the recession speed of distant galaxies to their distance. This expansion rate changes with time because of the mutual gravitational attraction of all the matter in the Universe. Given the cosmic density of matter relative to that needed to eventually halt the expansion (this ratio is denoted Ω – current observational estimates span the range $0.3 \leq \Omega \leq 1.0$, with some preference for the lower value) t_0 is simply proportional to the inverse of H_0. For example, assuming Ω=1, a value H_0=70 kms^{-1}Mpc^{-1} implies t_0=9 Gyr (1 Gyr=1 billion years), while H_0=60 kms^{-1}Mpc^{-1} implies t_0=11 Gyr.

Until a couple of years ago these two independent routes came to contradictory answers. Age measurements for the oldest GC gave $t_0 \geq 16$ Gyr, while studies of H_0 gave values in the range 55–75 kms^{-1}Mpc^{-1}, implying $t_0 \leq 14$ Gyr (for $0.3 \leq \Omega \leq 1.0$). The only way to resolve this "age conflict" appeared to be the ad hoc introduction of a non-vanishing energy density for the physical vacuum, the so-called cosmological constant (Λ). The effect of a non-zero Λ is to change the expansion rate of the Universe in such a way that for fixed H_0 and Ω the Universe is older than when Λ=0. This unsatisfactory situation motivated a group of MPA scientists to start a project aimed at computing new stellar models with the most up-to-date input physics, and to use them to estimate accurate GC ages.

How is it possible to determine the age of GC? Let us briefly review the basic properties of cluster stars. GC are gravitationally bound systems populating the halo of our Galaxy (and of the other galaxies) and made up of $10^5 - 10^6$ stars all with mass less than that of the Sun. All the stars in a GC are to a very good approximation at the same distance from us, and they have the same age and initial chemical composition, an almost primordial helium abundance and a low metallicity.

One of the main tools for studying stellar populations is the so-called colour-magnitude diagram. The y-axis of this plot usually displays V magnitude, a measure of the brightness of each individual star in the visible part of the spectrum; higher values of V correspond to lower luminosities. The x-axis shows a measure of the colour of the star, for example (B-V), that is related to its surface temperature. Higher values of (B-V) correspond to lower temperatures. Figure 2.4 shows the colour-magnitude diagram of Messier 15, one of the oldest GC. It displays a very clearly defined Main Sequence (MS), made up of stars experiencing hydrogen burning in their cores. This terminates at the Turn Off (TO - the bluest point on the MS) hydrogen is exhausted at the centre of the star. On the Subgiant and Red Giant Branches (SGB and RGB), stars have an electron-degenerate helium core surrounded by a hydrogen burning shell. Finally the Horizontal Branch (HB) is populated by stars experiencing central helium burning and hydrogen shell burning.

Deriving the age of a GC from its colour-magnitude diagram has been one of the main goals of stellar evolution theory for the last 40-45 years, starting with efforts by Schwarzschild, Hoyle, Sandage and Arp. A fundamental requirement is the computation of evolutionary models for stars. This means that one has to integrate the equations of the stellar structure

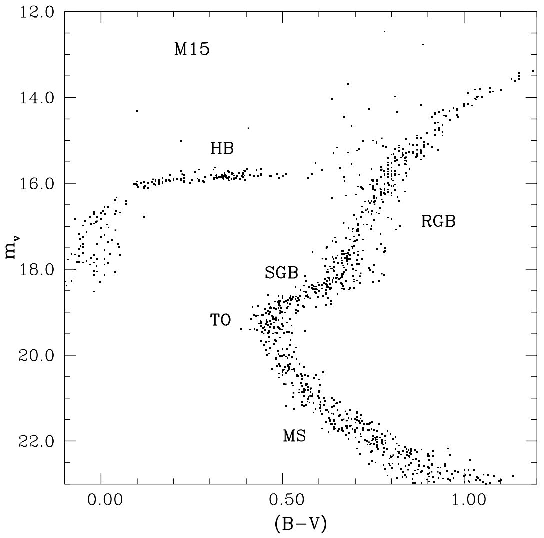

Figure 2.4: Colour-magnitude diagram of the globular cluster M15.

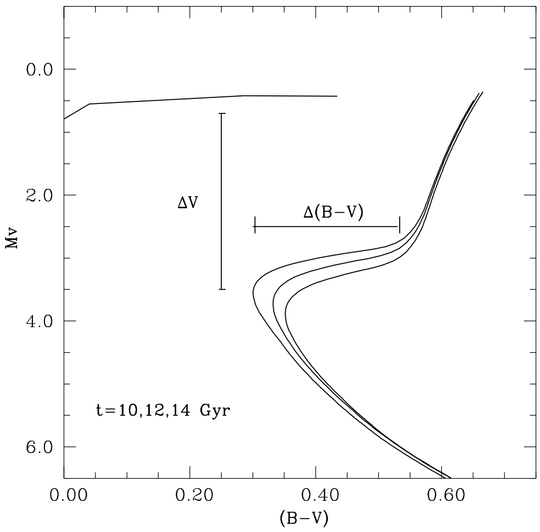

Figure 2.5: Globular cluster isochrones with fixed initial chemical composition and ages between 10 and 14 Gyr. For increasing ages the TO is dimmer and redder. The horizontal and vertical age parameters described in the text are also displayed.

for a star with a fixed value of the mass and a certain initial chemical composition. In this way it is possible to derive the evolution with time of the V magnitude and (B-V) colour of the star, and also the values at each radius within the star of many other physical and chemical variables, for example pressure, density, H and He abundances. By computing the evolution of stars of different mass but the same initial chemical composition (which is the case for the stars in a GC) one can determine the locations in the colour-magnitude diagram occupied by stars with a fixed age, the so-called "isochrone".

In Fig. 2.5 isochrones for different ages and fixed initial chemical composition are displayed. Apart from the reassuringly close correspondence between theoretical isochrones and observed colour-magnitude diagrams, one can notice that the position of the TO changes with changing age; higher ages correspond to less luminous and redder TO's, while the lower MS, the RGB and the HB are basically unaffected. It seems obvious, therefore, to compare theoretical isochrones with the position of the observed TO in a cluster in order to derive its age. The main problem in practice is that one must determine an accurate distance and reddening (a change in apparent colour caused by intervening material along the line of sight) in order to measure the absolute position of a cluster's TO and so estimate its age.

Figure 2.5 shows, however, that the vertical brightness difference between TO and HB (ΔV) and the horizontal colour difference between TO and RGB base ($\Delta(B-V)$) are both strongly dependent on the age. These differential quantities are obviously independent of the distance and reddening of the cluster. Moreover, when comparing these quantities for isochrones with different chemical composition, one finds that, at fixed age, the vertical and horizontal parameters are only weakly affected. It is therefore natural to try to use one or both of these parameters for estimating GC ages. Each of them has both advantages and shortcomings, and a combination appears to be the best choice for deriving accurate ages for a large sample of GC.

MPA work has applied a sophisticated procedure designed to minimise residual uncertainties to derive ages for a sample of 28 GC. This measurement uses a set of newly computed theoretical isochrones which include the most recent updates of the input physics in the stellar evolutionary models, for example updated values for radiative opacities and for the equation of state.

The results are displayed in Fig. 2.6 (the 1σ errors for each cluster are about ± 1 Gyr.). The age of the oldest GC lies between 11 and 12 Gyr, suggesting $t_0 \leq 13$ Gyr if one assumes an upper limit of 1 Gyr between the Big Bang and the formation of the first stars. Another important conclusion from Fig. 2.6 is that the most metal-poor GC (the points to the left of the figure) ap-

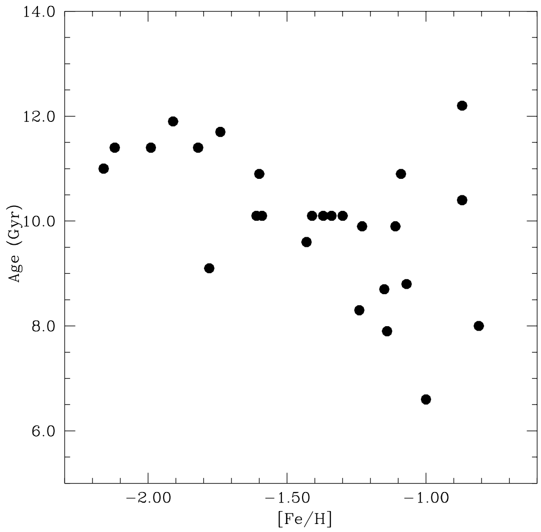

Figure 2.6: Age distribution of Galactic GC as a function of their metal content (expressed in terms of the ratio between iron and hydrogen abundance).

parently formed in a very short time span, while the metal-rich ones show a larger age spread. This provides an important constraint on models of galaxy formation. An extension of this analysis to GC belonging to the disk and the bulge of our Galaxy should give further information about the sequence of formation of the Milky Way.

In conclusion, up-to-date theoretical stellar models now predict GC ages suggesting t_0=12–13 Gyr, in good agreement with $t_0 \leq 14$ Gyr as deduced from current determinations of Ω and H_0. For the first time the age of the Universe as determined from the age of its oldest stars agrees with the age determined from the Hubble constant. (Maurizio Salaris)

2.4 X-rays from comets

Comets have always been among the most spectacular objects in the sky at visible wavelengths, but it came as a big surprise when the ROSAT satellite detected X-ray emission from comet Hyakutake in 1996. Recent MPA work shows how this emission is produced by the comet's interaction with the plasma wind blowing off the Sun.

The nucleus of a comet is a huge dirty snowball, about 10 km in size, built of ice (mainly water ice) and dust. As the comet approaches the Sun, the ice sublimates to form a cloud of neutral gas surrounding the nucleus. This releases dust which moves under the combined influence of solar gravity and the repulsive force of solar radiation. Each particle finds its own way. The resulting swarm of dust particles forms a broad and slightly curved dust tail. The dust scatters sunlight and so is visible with a yellow-red colour. With the naked eye one can in general see only the comet's dust tail.

The gas has a different fate. The gas molecules become ionized, i.e., they lose an electron, by various processes, for example interaction with solar ultraviolet radiation. They then interact with the solar wind, a continuous flow of particles, mainly protons and electrons, emanating from the Sun and carrying a magnetic field. The magnetic field acts like a net that fishes newly created ions from the gas cloud and forces them to move with the solar wind. These ions form the plasma tail. Since the solar wind moves much faster than the comet, the plasma tail indicates, like a windsock, where the wind comes from – it points almost directly away from the Sun.

Molecules and ions are too small to scatter visible light, but they can absorb light, thereby attaining an excited state, and then almost immediately reradiate it again. This 'resonant fluorescence' is effective only at certain wavelengths, depending on the molecule and the state of excitation. As a result, fluorescent material shines only in certain colours. The neutral gas cloud around a comet appears green and the plasma tail appears blue.

Atomic hydrogen is most abundant as a dissociation product of water. The single electron can switch between the two lowest levels, producing fluorescent radiation at a wavelength of 1216 Ångstrom in the ultraviolet part of the spectrum. This is about four times shorter than visible light, and is about the shortest wavelength where one might expect significant fluorescent emission from comets stimulated by solar radiation.

The unexpected X-ray emission seen by ROSAT is, however, at much shorter wavelengths. It came from a crescent-shaped region in front of the nucleus, extending out about a million kilometers. The shape of the emitting region shown in Fig. 2.7 already gives important constraints on the emission mechanism. The radiation must be generated by the interaction of something which comes from the Sun with something which comes from the comet. The solar agent must be consumed by the in-

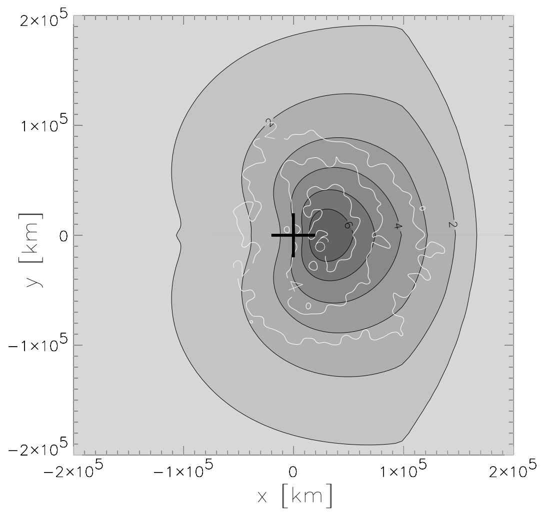

Figure 2.7: The black smooth contour lines denote the radiation emitted by charge exchange as obtained from model calculations. The rugged white contour lines represent the X-ray intensities measured by ROSAT on 27.57 March 1996 at comet Hyakutake. The nucleus is indicated by a cross. The Sun is to the right. (See the cover for a colour image.)

teraction, since otherwise radiation would also be seen from the tail. This rules out solar X-rays which pass through the comet almost undiminished. On the other hand, cometary dust reaches only about 25.000 km on the sunward side before it is forced to turn around by solar radiation pressure. It thus cannot provide a big enough target.

It follows that the observed X-rays must have been generated by the interaction of the solar wind with the cometary gas cloud. There are two possibilities:

An electron which collides with a molecule is deflected and decelerated. According to the laws of electrodynamics it must radiate. This 'bremsstrahlung' is basically the same process Wilhelm Roentgen used to generate X-rays 100 years ago and is still used in X-ray tubes today. Electrons are shot onto a solid wall and emit X-rays while stopping. Such bremsstrahlung is not very effective. If an X-ray tube were operated at a voltage of 220 V from the socket and with water as target, only about one millionth of the electron energy would be transformed into X-rays. The spectrum, however, would resemble that seen by ROSAT.

The comet acts like an X-ray tube in the following way. The solar wind is decelerated and heated by the addition of cometary ions. It can, however, digest only a small amount of such material before a shock occurs which transforms a large fraction of its kinetic energy into thermal energy. Its velocity decreases by a factor of three and its density increases by the same factor. The electrons are compressed and heated. Their thermal velocity increases. Hot electrons are then shot along magnetic fieldlines onto the cometary gas cloud, where they generate X-rays by bremsstrahlung.

On their way through the comet, the electrons lose their energy by collisions. By the time they reach the nucleus and the tail their energy is too low to make X-rays. The predicted morphology of X-ray emission by this mechanism closely resembles the observed emission but its predicted intensity is more than 1000 times too low. The cometary X-ray tube is similar to the 220 Volt X-ray tube described above. It has the same low efficiency.

Thus although the solar wind electrons do generate X-rays, the main contribution must come from another process. About 0.1% of the solar wind is made up of heavy particles such as oxygen, nitrogen, carbon, silicon and iron. The solar wind originates in the solar corona which has a temperature of more than a million degrees. This is much hotter than the visible surface of the Sun, where most of the radiation - the sunshine - comes from, and where the temperature is "only" about 6000 degrees. The high coronal temperature causes atoms to lose most of their electrons and become highly ionized. An oxygen atom, which normally has eight electrons, loses six or seven at these temperatures. In the very tenuous solar wind these heavy ions do not find sufficiently many electrons to recover. Even after a four day trip the heavy elements are still highly ionized when they are measured by earth-orbiting satellites.

When the solar wind hits a comet, however, electrons are available in large numbers, mostly bound in neutral water molecules or oxygen atoms. When a solar wind ion collides with a neutral molecule it can happen that an electron jumps from the molecule to the ion. This electron does not then, in general, occupy the lowest possible energy level, corresponding to the orbit closest to the atomic nucleus. Instead it first occupies a more distant orbit and after some very short time jumps to the lowest orbit. It is this second process which generates radiation. The energy produced is proportional to the square of the charge of the nucleus. A bare nucleus of

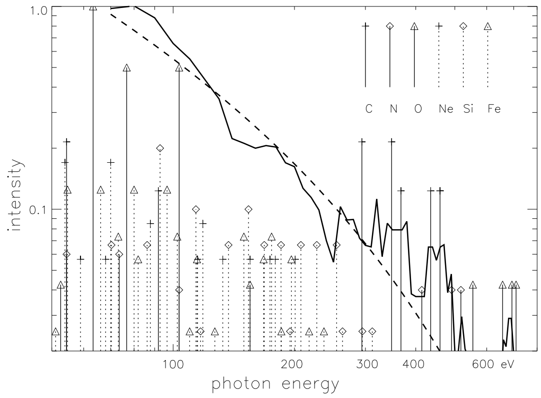

Figure 2.8: Line spectrum calculated for charge exchange of solar wind heavy ions with water molecules. The lines from different elements are distinguished by different symbols. The thick line is the smoothed spectrum and the dashed line is a bremsstrahlung spectrum from 200 eV electrons.

oxygen has eight times more charge than a proton. If an electron jumps to the lowest orbit, the energy emitted is 64 times that emitted by the excited hydrogen atom discussed above, and the wavelength is smaller by the same factor. This puts it in the soft X-ray band.

Figure 2.8 shows the spectrum of the radiation calculated using measured values of the concentration of heavy ions in the solar wind. The radiation consists of more than 100 different discrete lines characteristic of the various ions. The left end of this spectrum, corresponding to a wavelength of 240 Ångstrom, is in the transition region between ultraviolet and X-ray. There are no lines with a wavelength shorter than 15 Ångstrom, corresponding to a photon energy of about 650 eV.

The ROSAT satellite has rather poor energy resolution. Instead of individual lines it sees a blurred version of the spectrum which can be simulated by averaging the theoretical prediction over a certain energy interval. The result looks very like the spectrum of bremsstrahlung from electrons with 200 eV energy (Fig. 2.8). It turns out that the charge exchange process explains the observed spectrum very well.

Even more, one can calculate the flow of the solar wind through the comet. The heavy ions are successively neutralized by the charge exchange process. They reach neither the cometary nucleus nor the tail. The emission comes from a region on the subsolar side of the comet. Figure 2.7 shows that the calculated emission reproduces the ROSAT data very well, not only in shape but also in absolute intensity. (Rudolf Wegmann)

2.5 Neutral iron K_α diagnostics — X-ray archaeology of the Galactic Center

While the majority of objects of interest for High Energy Astrophysics consist of completely ionized plasma at extremely high temperatures and emit X–Ray or Gamma–Ray photons, matter in many others remains entirely neutral at temperatures just tens of degrees above absolute zero. Recent MPA work focusses on how emission of neutral iron K_α photons can be used to explore physical conditions when these two kinds of objects share neighboring regions of space. Fluorescent K_α 6.4 keV photons appear whenever neutral matter is illuminated by hard X-ray radiation. Photoionization creates a hole in the inner shell of the iron atom which (with a probability of $\sim 30\%$) is filled by radiative transition of electrons from higher shells. Among the objects known to be bright in the iron K_α line are accreting sources in X–ray binary systems, Active Galactic Nuclei (AGN), Quasi Stellar Objects (QSO), flaring stars etc. The Japanese satellite ASCA recently found that the central region of our Galaxy is very bright in the iron K_α line. The presence of the line was in fact predicted earlier, since this region is known to host a huge mass of molecular gas along with many X–ray sources.

The next decade could mark a "golden age for X-ray astronomy" since a number of powerful new X–ray observatories (AXAF, XMM, ASTRO–E, ABRIXAS, SPECTRUM–X) will be launched in the next few years. These observatories will provide an order of magnitude better sensitivity, angular and spectral resolution than existing X–ray telescopes. Their spectral resolution will range from the "standard" X–ray CCD's value of 150 eV up to 5–10 eV (calorimeters on ASTRO–E and Bragg spectrometer on SPECTRUM–X). Even more ambitious X–ray projects, CONSTELLATION and XEUS, with energy resolution of $\sim$2 eV (and much more sensitive) are under discussion for launch in the second half of the next decade. It is therefore time to investigate how to use the K_α line as a diagnostic tool in high-resolution

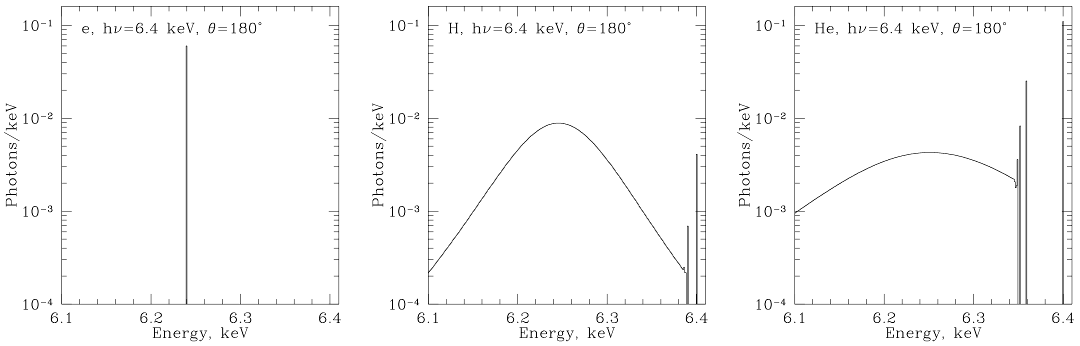

Figure 2.9: Spectra of the 6.4 keV photons scattered by 180 degrees by free electrons at rest (left), hydrogen atoms (middle) and helium atoms (right).

spectroscopy. Physics previously beyond the reach of astronomers might become important and bring the most interesting new information. Progress in the energy resolution and sensitivity of X–ray telescopes is significantly widening the class of potential applications.

One can, for example, consider how scattering of the K_α photons in the molecular clouds changes the profile of the line. Shown in Fig. 2.9 are the spectra of the 6.4 keV line scattered by 180 degrees by free electrons at rest, by hydrogen, and by helium atoms. For free electrons at rest the energy of the photon after scattering is unambiguously related to the scattering angle (Fig. 2.9 left). The motions of electrons in atoms cause broadening of the energy distribution due to the Doppler effect (Fig. 2.9 middle and right). Features close to the initial line energy are related to the excitation of discrete levels of an atom. Comparing helium to hydrogen, one sees that a different structure of the energy levels and a larger binding energy of the electrons cause differences in the scattered spectra. In particular, the energy "gap" between the unshifted line and scattered features at lower energies is twice as big for helium as for hydrogen. In addition, in the helium atom (and in the hydrogen molecule) coherent scattering by two electrons will enhance elastic scattering. In principle these effects provide an opportunity to measure the abundance of helium in the molecular gas. Of course, high sensitivity and energy resolution are required to detect such subtle features, but with the next generation of X–ray observatories this might start to be accessible.

Another fascinating possibility is "**X–ray archaeology**" based on observations of K_α photons generated by a flaring compact X–ray source surrounded by neutral matter. If the light crossing time of the region occupied by neutral matter is long enough, K_α photons generated by primary X–ray radiation may be observable long after the fading of the compact source. This is very similar to the usual echo, but in the X–ray band. A characteristic feature of the spectrum which occurs in such a situation is a large equivalent width, $EW \sim 1$ keV, for the K_α line. (Equivalent width is the ratio of the line flux to the intensity of the continuum emission.) Thus the presence of a strong K_α line might hint at a violent outburst of X–ray emission in the past of an object which appears relatively quiet today. Promising applications of such "X–ray archaeology" are, for instance, compact X–ray sources embedded in molecular clouds or AGNs, and QSOs surrounded by molecular tori. The hard X–ray source known as the "Great Annihilator" 1E1740.7–2942, which is suspected to be located inside a dense molecular cloud, is an example of the first type. Time lags expected for this source are of the order of years – the characteristic size of the cloud is a few parsecs. For AGNs and QSOs the corresponding time lag may range from days up to hundreds and thousands of years, depending on the size of the region occupied by molecular gas. The prime example of this class of objects is the central region of our own Galaxy.

The map shown in Fig. 2.10 gives the distribution of the surface brightness of the neutral iron K_α line in the central $\sim 1°$ around our Galactic Center, based on the observations of the ASCA observatory. Most of the emission is elongated along the Galactic plane, resembling the distribution of the molecular clouds in the region. Especially bright in the K_α line is one of the largest molecular complexes in the Galaxy – Sgr B2. One can consider several alternative

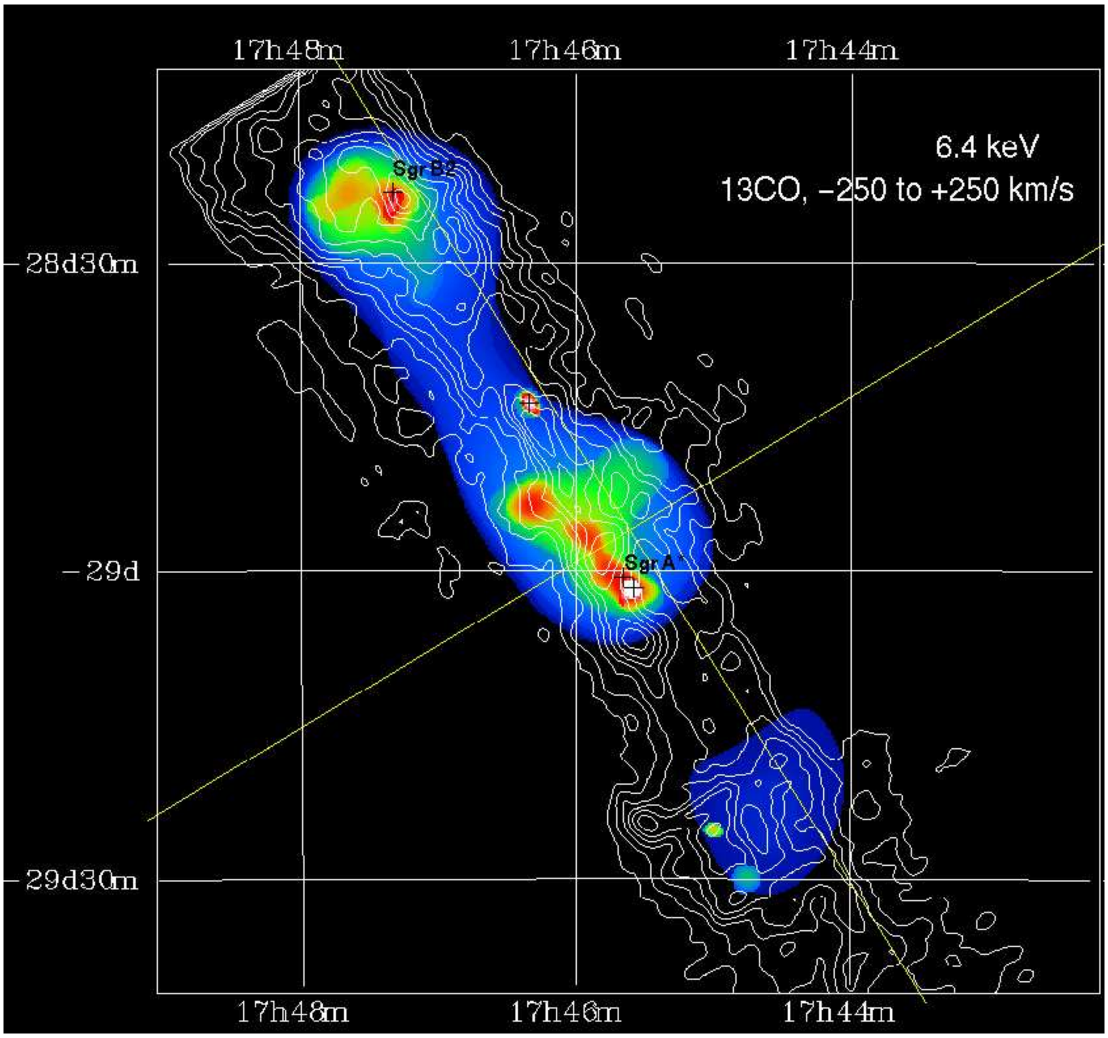

Figure 2.10: Map of the 6.4 keV line in the Galactic Center region according to ASCA public domain data. Contours show the brightness temperature of ^{13}CO integrated over a velocity range from -250 km/s to $+250$ km/s. The CO data were kindly provided by J.Bally.

explanations for the origin of this K_α emission. Since the production of K_α photons requires interaction of hard X–ray radiation with neutral matter, one can get the same flux in the line by varying the primary X–ray radiation intensity or the amount of neutral gas. In the optically thin case only the product of these two quantities is important. Since diffuse hard X–ray emission (which has a characteristic spectrum of thermal emission of optically thin plasma at a temperature of ~ 8 keV) is also observed from the same region, the most straightforward explanation would be to assume that this emission gives rise to the K_α line. However for the Sgr B2 cloud this diffuse emission is too weak to generate the observed flux in the line. One can somewhat reduce the discrepancy by assuming that there is an intrinsic correlation of the diffuse hard X–ray radiation and the distribution of the molecular gas (e.g. regions filled with hot plasma are associated with densest regions of the molecular clouds) or by assuming that the abundance of iron in the molecular clouds is substantially larger than the solar one. An alternative assumption is that a few compact sources of hard X–ray radiation are responsible for the observed K_α line emission. The most attractive hypothesis of this class, however, is the assumption that a supermassive black hole at the dynamic center of our Galaxy coinciding with Sgr A* is the responsible source. This source appears very quiet in X–rays now, but it might be that it was much brighter a few hundred years ago. For a mass of two million Solar masses, as

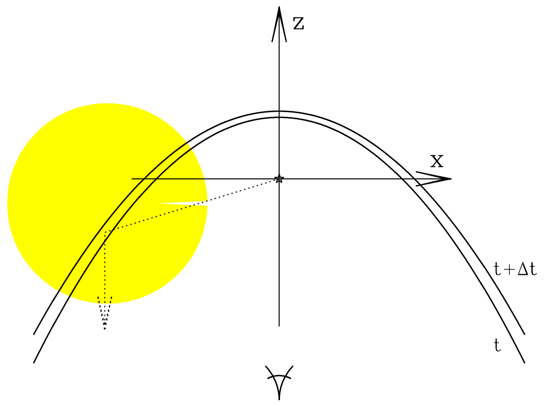

Figure 2.11: Each point on the surface of the parabola $z/c = (t^2 - (x/c)^2)/(2t)$ has similar delay t in propagation time from the source (marked with asterisk) to the scattering place and then to the observer. In the case of a short flare the fluorescent photons which are observed at a given moment of time are produced in the neutral matter located on the surface of the parabola. For a steady source which faded at a given moment of time the exterior of the parabola is filled with primary continuum photons.

typically assumed for Sgr A*, the Eddington luminosity is so high ($\sim 3 \times 10^{44}$ erg/s), that even a rather short flare (a few hours!) would be sufficient to power the K_α line flux observed today. In the case of a short flare one can expect that molecular clouds, which are exposed to the primary radiation at a given moment of time, are located along the surface of a parabola with the focus at Sgr A*. The geometry of the parabola (shown in Fig. 2.11) reflects the time delay associated with the propagation of primary hard X–ray photons from Sgr A* to the neutral matter and the further propagation of the K_α photon to the observer. Clouds not located on the surface of this parabola will not produce K_α emission visible at the considered instant of time. This would explain why some of the massive molecular complexes in the Galactic Center region are bright in the K_α line, while others (containing a similar amount of neutral gas) are weak. Note that in this case the whole picture will not be static: the illuminating front is moving and some molecular clouds may fade, while others will become brighter in the K_α line. Depending on the location of the cloud, the propagation of the illuminated surface may have apparent velocity higher than the speed of light. An exciting application for an imaging X–ray telescope would thus be to detect changes of the K_α morphology in this region on time scales of years or tens of years. (E.Churazov, M.Gilfanov, R.Sunyaev)

2.6 Formation of disk galaxies

The successful mission to repair the optics of the Hubble Space Telescope and the opening of the 10 metre Keck telescopes on Hawaii have had a dramatic effect on studies of galaxy evolution. It is now possible to study the structure of objects so distant that the observed light has taken most of the age of the Universe to reach us. As a result, these galaxies are seen when much younger than our own and other nearby galaxies, and the evolution, perhaps even the formation, of the galaxy population can be observed directly. A group of scientists at the MPA is developing theoretical models for these processes in order to interpret the flood of new data and to understand their implications for our overall picture of the growth of structure in the Universe. The last year has seen some particularly interesting theoretical and observational results for disk galaxies.

In a disk galaxy a substantial fraction of the stars are concentrated in a thin disk where they all move on nearly circular orbits around the galaxy centre. Such galaxies are very common. Roughly two thirds of all catalogued galaxies belong to this class, most of the rest being elliptical galaxies or irregulars. Our own Galaxy, the Milky Way, is a typical example. Like the Milky Way, most disk galaxies show spiral arms which are particularly striking if the disk is seen face-on. Figure 2.12 shows an example of such a spiral galaxy. Such galaxies are among the most beautiful of all astronomical objects. The abundance of stars in most galaxy disks falls roughly exponentially with increasing distance from the galaxy centre. The characteristic scale of this fall-off is a useful measure of the size of the disk and is about 10,000 light-years in the Milky Way.

Most galaxy disks contain both stars and gas. The gas also moves on near-circular orbits, and its motion can often be measured to radii several times larger than the visible stellar disk. The run of disk rotation speed with radius is referred to as the rotation curve of a galaxy; an example is shown in the right panel of Fig. 2.12. In many galaxies such rotation curves are flat at large radii, whereas Newton's law of gravity would