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Supernova Remnants, Pulsars and the Interstellar Medium

Summary of a Workshop held at the University of Sydney in March 1999

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Abstract: We summarise the proceedings of a workshop on ‘Supernova Remnants, Pulsars and the Interstellar Medium’ which was held at the Special Research Centre for Theoretical Astrophysics at the University of Sydney on 18 and 19 March 1999.

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1 Introduction

The study of Supernova Remnants (SNRs) and their interaction with the surrounding medium has made significant advances in the last decade or so, thanks in large part to detailed observations of SN 1987A and SN 1993J. The vast amounts of data obtained over several years of study have considerably improved our understanding of the evolution of young supernova remnants in general. The coincidence of occurrence of SN 1998bw within the error circle of the gamma-ray burst GRB 980425, suggesting a relationship between the two objects and new avenues to advance our understanding of them, has added an exciting new dimension to our investigation of supernovae (SNe).

With a view to discuss the latest results on these and similar topics, the Special Research Centre for Theoretical Astrophysics at the University of Sydney organised a workshop on Supernova Remnants, Pulsars and the Interstellar Medium. The two day workshop on 18 and 19 March 1999 brought together more than 65 observers and theorists from all over Australia (and even a few from overseas), providing a forum for frank discussion and vigorous interaction. The topic was broadly interpreted, and the agenda for the meeting was kept open to accommodate talks that would be interesting to the audience, even if they did not easily fall into one of the categories. Graduate students were especially encouraged to attend and present their work.

A discussion of supernovae naturally leads one to think of the stellar remnants that remain after the explosion. In recent years large-scale surveys have led to a large increase in the number of known pulsars. Thus pulsars and the nebulae around them formed an important part of the workshop, with two sessions being devoted to the study of pulsars and their properties, especially radio pulsars. There were also interesting reviews presented on contemporary topics such as Magnetars and Anomalous X-ray Pulsars.

Finally, the last session was devoted to the study of masers in SNRs, a field that, after a period of dormancy, is enjoying a great resurgence nowadays. Intriguing new observations were revealed, with the promise of more to come.

The following summary captures the essence of the science that was discussed at the workshop. The various sections correspond to the sessions at the meeting. Further details, and abstracts of talks, are available at the meeting home page:

www.physics.usyd.edu.au/∼vikram/snrwkshop/snmain.html

2 Supernova Remnants and Surrounding Medium I

The first session in this workshop dealt with supernovae (SNe) and their interaction with surrounding

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circumstellar material (CSM). In particular, papers were presented on the diversity of SNe in general, and on some detailed observations of two very young objects (SN 1987A and SN 1993J) which now show evidence for interaction between the expanding ejecta and the surrounding material.

It is clear that the evolutionary stage of the progenitor star determines the kind of SN that occurs. However, it is only rarely that we have comprehensive data on the progenitor. Typically, classification is made from the observation of the supernova event and its aftermath, and a great diversity is seen in these catastrophic explosions. **Brian Schmidt** (ANU) gave a comprehensive review of SN classification emphasising this diversity and the fact that many events do not fit the existing subtype classifications, based on studies of light curves and optical spectra (Filippenko 1997). Because there are so many SNe which are atypical, it may be that the broader groupings of 'thermonuclear explosions' (involving predominantly white dwarfs) and 'core collapse of massive stars' might lead to better predictions of the progenitor star type. It is clear that variations in age, mass and metallicity can all affect the SN light curve and spectrum. In the core collapse scenario, there are five phases which produce different spectral characteristics. These phases relate to shock break-out, adiabatic cooling, transfer of energy and subsequent radioactive heating in the core, and the eventual transition to the nebula phase. However, it is unclear what are the primary causes of differences in observed events. Present models involving variation in the energy of the initial explosion, mass loss rates and the condition of the CSM do not seem to explain the observed diversity. In a further twist, it may be that some types of SNe (for example Type Ib/c) may be linked to the phenomenon of Gamma-ray Bursters (GRBs).

The first specific example selected to demonstrate CSM interaction was SN 1987A, in the Large Magellanic Cloud. **Ray Stathakis** (AAO) presented results from optical and infrared monitoring with several instruments mounted on the Anglo Australian Telescope (AAT). Hubble Space Telescope (HST) images show evidence for the SN ejecta interacting with the edge of the CSM, from Hα and Ly-α observations. At the AAT the source is not well resolved. However, monitoring of optical CSM lines establishes valuable baseline levels against which future changes due to increasing interaction may be measured. Several spectral lines, both in the optical (e.g. Hα, OI) and infrared (e.g. FeII, Brγ) regimes are becoming strong enough to image. It is anticipated this program will continue.

Radio observations of SN 1987A, made with the Australia Telescope Compact Array (ATCA), were presented by **Lister Staveley-Smith** (ATNF). Evolution of both angular size and flux density is seen. Radio frequency observations have been an effective way of monitoring the expanding shock front (Gaensler et al. 1997). Finding a consistent model to explain the results is more problematic. The data show that the overall radio luminosity is increasing linearly and that the EW asymmetry in the brightness of the observed circular ring is also becoming more pronounced. From the change in image size over several years, it appears that the expansion velocity has slowed significantly. The morphology of the images suggests a thin spherical shell with an EW asymmetry, expanding and now very close to the ring of CSM. Evidence for the onset of interaction is seen in the HST Hα and Ly-α observations. It is speculated that the emission is coming from the reverse shock, consistent with the low value for the expansion velocity. Two possible models which might explain the observed results both have some unsatisfactory features. The minimum energy solution is inconsistent with a low shock velocity and the model invoking a dense HII torus to account for the slow shock velocity would not predict the symmetric ring observed, nor the inferred spherical shock. Overall, it seems that SN 1987A was an atypical Type II SN. It is expected that the shock will heavily impact the CSM ring in about 2004. High resolution observations at 20 GHz are planned with the ATCA for the anticipated impressive display.

The second object selected to illustrate early interaction with the CSM is SN 1993J. **Michael Rupen** (NRAO) showed results from VLBI observations of this young SNR (Bartel et al. 1994; Rupen et al. 1998), which was the brightest optical SN seen in the northern hemisphere since 1937. Early observations classified this event as a core collapse SN (Type IIb) of a massive progenitor star, probably about 15 $M_{\odot}$. This object has been closely monitored since 30 days after the explosion over several wavelengths in the range 1–20 cm. The SN occurred in M81, a galaxy $3 \cdot 63$ Mpc away. Distance estimates from the SN observations agree well with the independent estimate from Cepheid measurements. The object is now seen as a nearly-circular expanding shell with an asymmetric brightness distribution. There is some indication that the core may be located off-centre. However, there is clear evidence of source evolution and the shell is noticeably decelerating, even if the most extreme opacity effects are included.

From the review by Schmidt and the specific data on SN 1987A and SN 1993J, it is clear that even for very young remnants, the peculiarities of the individual SN explosion and the pre-existing CSM are far stronger influences than any underlying generic characteristics. This makes it hard to develop global theories and emphasises the need for continuing searches and subsequent long-term monitoring of SNe.

3 Supernova Remnants and the Surrounding Medium II

Miroslav Filipovic (U Western Sydney) presented evidence for a young, nearby SN remnant, RX J0852·0–4622, initially identified by its X-ray and γ-ray emission. He showed that the X-ray image obtained in the ROSAT all-sky survey shows a disk-like, partially limb-brightened emission region, which is the typical appearance of a shell-like SNR. The object's high temperature of $> 3 \times 10^7$ K indicates that RXJ0852·0–4622 is a young object which must also be relatively nearby (because of its large angular diameter of 2°). Comparison with historical SNRs limits the age to about $\sim$1500 years and the distance to < 1 kpc. Miroslav showed that any doubt on the identification of RX J0852·0–4622 as a SNR should be erased by the detection of γ-ray line emission from ^{44}Ti, which is produced almost exclusively in supernovae. Using the mean lifetime of ^{44}Ti (90·4 yr), the angular diameter, adopting a mean expansion velocity of 5000 km/s, and a ^{44}Ti yield of 5×10^{-5} $M_\odot$, Iyudin et al. (1998) derived an age of $\sim$ 680 yr and a distance of $\sim$200 pc, which argues that RX J0852·0–4622 (GRO J0852–4642) is the closest supernova to Earth to have occurred during recent human history. However, these observations are in apparent conflict with historical records. Miroslav also reported a positive radio-continuum detection at 4·75 GHz (PMN) which shows similarities to the X-ray emission. Further studies of this SNR will compare a mosaic radio-continuum survey to observations at other wavelengths such as the ROSAT and ASCA X-ray images and spectra (already observed) and UKST Hα, [SII] and [OIII] plates.

Vikram Dwarkadas (SRCfTA) presented work he, along with Roger Chevalier (UVa), is carrying out on SN-circumstellar interaction, motivated by the presence of a circumstellar bubble surrounding SN 1987A. The evolution of supernova remnants in circumstellar bubbles depends mainly on a single parameter—the ratio of the mass of the circumstellar shell to the mass of the ejecta (Franco et al. 1991). For low values, the supernova remnant, over many doubling times, eventually 'forgets' about the existence of this shell, and the resulting density profile looks as it would have in the absence of the shell. Vikram showed that analytical approximations and numerical models indicate that the evolution becomes more rapid as this ratio increases, and that the amount of energy transmitted from the shock to the shell also increases. Unless the shell mass substantially exceeds the ejecta mass, reflected and transmitted shocks are formed when the SN shock hits the circumstellar shell. Vikram demonstrated that the shock–shell interface is hydrodynamically unstable. The reflected shock moves towards the centre, and may rebound off the centre. Eventually several shocks may be found criss-crossing the remnant, leading to a highly complicated interior structure, with more than one hydrodynamically unstable region possible (Dwarkadas 2000). A rise in X-ray emission accompanies each shock-shell collision. When applied to the observations of SN 1987A, the SN-circumstellar shell model, with appropriate modifications, confirms the prediction of the outgoing shock colliding with the circumstellar ring in about 2005 (Chevalier & Dwarkadas 1995).

Chris Wright (ADFA) presented work on ISO observations of the SN remnant RCW 103. This supernova remnant has been studied extensively in the past in the near-infrared (NIR) by Oliva et al. (1989, 1990, 1999) who showed that the remnant blast wave is interacting with the interstellar medium and producing very bright emission in lines of [FeII] and H_2. The [FeII] emission coincides with the optical, radio and X-ray emission, but the H_2 emission occurs 20–30 arcseconds outside (i.e. in front) of it. This poses a problem in that standard shock excitation of H_2 predicts that the H_2 would reside either behind or coincident with the optical emission. Extinction arguments cannot be applied since the extinction to all of the optical, [FeII] and H_2 emission is independently observed to be the same. Further, the H_2 spectrum 'looks' thermal. Therefore, X-rays have been proposed as a possible excitation mechanism. Chris presented ISO observations which covered a large suite of pure rotational and ro-vibrational H_2 lines, out to 28 microns, as well as lines of H, [NeII], [OIV] and [FeII] and the X-ray sensitive molecules H_3+ and HeH+. The latter two were not detected, and their upper limits may imply interesting constraints on the amount of X-ray heating. Many H_2 lines were detected, and the spectrum still appears to be shock (i.e. thermally) excited, although more modelling is required to determine the type of shock. However, there are several cases where the line appears to have a non-thermal component to it.

Amy Mioduszewski (SRCfTA) discussed simulating Radio Images from Numerical Hydrodynamic Models (Mioduszewski, Hughes & Duncan 1997). She motivated her discussion by emphasising that while hydrodynamic simulations are widely used to understand objects such as supernovae or jets, the calculated pressure, density, and velocity must be linked to what is observed, the synchrotron radiation from the material. Assuming minimum energy, Amy demonstrated that the synchrotron emissivity and opacity can be related to the hydrodynamical pressure and the number density of the particles. Using these, she calculated the total synchrotron flux and created an 'image' of the source. Amy also pointed out that in case of relativistic jets it is important to consider light travel time effects, because they significantly influence the appearance of the jets. In addition she showed that the simulated total intensity light curves, even of non-evolving jets, are not easily related to the relatively simple and regular shock structure in the underlying flow.

John Patterson (U Adelaide) discussed the potential for using very high energy gamma rays to understand the high energy astrophysical processes which occur in objects such as supernova remnants, gamma-ray pulsars and AGN (BL Lacs), as well as the many unidentified EGRET (~1 GeV) sources. See Ong (1998) for a review of the field. As a leading member of the joint Australian–Japanese CANGAROO Project at Woomera, John is pushing the frontier of this ground-based observational area of photons with energies around 100 GeV. These high energy photons are produced in a variety of places by relativistic processes such as inverse Compton effect and shock acceleration. A new 10 m Cangaroo II telescope has been commissioned, and John warmly welcomes cooperation with other Australian facilities and universities.

4 Pulsars and the Interstellar Medium I

The first session on Thursday afternoon opened with **Simon Johnston** (SRCfTA) reviewing pulsar wind nebulae (PWN). Typically 1% of the spin-down luminosity of pulsars appears as pulsed emission, the remaining energy presumably coming off in the form of a relativistic particle wind, which is eventually stopped and shocked by the pressure of the surrounding interstellar medium (ISM), producing nonthermal radio emission. If the space velocity of the pulsar is low, the wind produces a bubble, or plerion, which can be imaged in radio/optical or X rays. On the other hand, if the pulsar has a high space velocity (and many do—see the next paragraph), the rapid motion through the ISM produces a bow shock, which can be seen in Hα or the radio continuum. Clearly what will be seen in individual cases will vary depending on the properties of the pulsar, its space motion, and the nature of the surrounding ISM. A search for PWN associated with 35 pulsars at 8·4 GHz with the VLA turned up 14 examples. There appear to be two classes of pulsars—young systems with $L_{\rm radio}/\dot{E} \sim 10^{-4}$ and middle-aged pulsars where this ratio is below 10^{-6}. Several hypotheses could account for this difference—perhaps the ratio of Poynting flux to particle flux decreases, or the energy spectrum steepens, or more pulse energy appears as gamma rays. Of course, more observations are needed: a survey of 50 pulsars with the ATCA is underway at 1·4 GHz using pulsar gating to increase the sensitivity 200-fold. The survey to date has turned up one bow shock in five pulsars examined—the Speedboat Nebula associated with PSR 0906–49.

Matthew Bailes (Swinburne) gave a talk on the distribution of pulsar velocities. The first part promoted the new supercomputer centre at Swinburne, extolling the processing power of the planned network of 64 linked workstations. This is impressive, but will be limited to problems that can be broken into many fairly-independent parallel modules. The second part discussed pulsar velocities, a topic that is important in understanding the Galaxy's pulsar population as a whole. He briefly reviewed the methods for measuring them. Generally the old millisecond pulsars have $v \leq 300$ km/s—they are likely bound to the Galaxy as one would expect. However, younger pulsars overall have higher velocities, which indicates that their progenitor supernova explosions had a substantial asymmetry.

Lewis Ball (SRCfTA) spoke about inverse Compton scattering by relativistic pulsar winds. Electrons in the wind can upscatter ambient photons—starlight or the cosmic microwave background—to TeV energies for the expected Lorentz factors $\sim 10^6$. Generally this effect is small except for pulsars embedded in strong radiation fields, such as those in close binary systems. The pulsar B1259–63, which is in an eccentric orbit about a Be star, is of particular interest: conversion of 0·1% of the pulsar's spin-down luminosity into 100 GeV photons would give a flux detectable by the CANGAROO II Cerenkov telescope. The scattering is a strong function of geometry and distance from the star—the pulsar must be rather close to the star for the effect to be significant. The distance of B1259–63 to the Be star ranges from 20 to 300 R_*, so the gamma-ray luminosity at periastron is large, with predictable variations around the well-determined orbit (Kirk, Ball & Skjæraasen 1999; Ball & Kirk 2000). Thus CANGAROO II observations will potentially be able to probe the properties of the pulsar wind, which is otherwise difficult to detect.

Kinwah Wu (SRCfTA) presented observations of optical and infrared lines in the spectrum of the X-ray binary Cir X-1. The emission lines are asymmetric, with a narrow component at +350 km/s and a broader blue-shifted component. Previously it had been suggested that the narrow component arises from rotation of an accretion disc, the corresponding blue-shifted component being absent because of a shadowing effect at that particular orbital phase. However, the new observations and archival data show that the profiles have varied systematically over the last 20 years: the narrow component always lies in the range 200–400 km/s, while the blue component varies somewhat both in shape and redshift (Johnston, Fender & Wu 1999). Kinwah offered a new model in which the narrow component is interpreted as arising from the heated surface of the 3–5 $M_\odot$

companion star, and the broad component arises in an optically thick outflow driven by super-Eddington accretion from the neutron star. The variability in the blue component reflects the eccentricity of the orbit: at periastron, the companion overfills its Roche lobe and dumps matter onto the star, producing the outflow. The overflow shuts off after periastron; near apastron the remaining overflow material settles into a quasi-steady accretion disc. This model explains the variability of the blueshifted component of the spectrum and the X-ray behaviour. One implication of this picture is that the system has a radial velocity of +430 km/s, which makes Cir X-1 one of the fastest binaries known. Even so, a sufficiently asymmetric supernova explosion can impart the required kick without unbinding the system (Tauris et al. 1999).

5 Pulsars and the ISM II

Extreme Scattering Events (ESEs) from pulsars were the topic of **Mark Walker's** (SRCfTA) presentation. ESEs were first discovered in extragalactic sources, the symptoms being a rapid change in flux density of the observed source. These flux density changes are attributed to ionised gas clouds in our own Galaxy. From the observational data, Mark Walker and Mark Wardle have determined the parameters of these clouds: they have a size of roughly 2 AU, an electron density of $\sim 10^3$ cm^{-3} and a filling factor of about 5×10^{-3}. They postulate that these clouds may solve the 'missing mass' problem, at least in our Galaxy (Walker & Wardle 1998, 1999).

If a pulsar undergoes an ESE, one can in principle measure three different quantities. These are the deflection of the image (which can be measured by VLBI techniques), the delay of the signal (which can be obtained from pulsar timing) and the magnification of the image. Pulsars are exceedingly small, and this implies both a large peak magnification and a large coherent path length. Pulsars are also bright at low frequencies where the effects should be strongest. Previous work on ESEs on pulsars include the time delay and flux changes in the millisecond pulsar PSR B1937+21 and the fringe patterns in the dynamic spectrum of PSR B1237+25. However, there has been no systematic observational program carried out and this is needed as a matter of some urgency.

The nature of pulsars means that more information can be gleaned from ESEs than from say quasars. This in turn will lead to a better understanding of the structures in the interstellar medium which cause ESEs.

Jean-Pierre Macquart (U Sydney) continued the theme of scintillations with his presentation on scintillation and density fluctuations in the ISM. In scintillation theory it is thought that energy is deposited at very large scales (kpc or more), that it then 'cascades' down to lower scales before finally dissipating at some small scale. However, although this sounds good, the questions of what provides the energy, how exactly it cascades down and what the dissipation mechanism is are all unanswered! (see, for example, Cordes, Weisberg & Boriakoff 1985)

If supernovae are providing the energy at the large scales then perhaps one might expect to see more turbulence in the vicinity of supernova remnants. Also, one might expect the power-law index of the turbulence, β, to be ~4 rather than the canonical (Kolmogorov) value of 11/3. Is there any observational evidence for this? In or near the Vela supernova remnant there is some evidence for $\beta = 4$. Two surveys of extragalactic point sources located behind supernova remnants have been ambiguous with no clear evidence for a higher power law index, although one group do claim an enhancement behind the Cygnus Loop (Dennison et al. 1984). In summary, although supernova explosions are the popular choice for the energy input there is no unambiguous evidence for this (Spangler et al. 1986).

Jianke Li (ANU) gave his talk on the topic of the spin-up mechanism for millisecond pulsars (MSPs). It is widely believed that MSPs are formed from low-mass X-ray binaries in which a neutron star accretes matter from its low mass companion. Along with the mass transfer, the neutron star 'accretes' angular momentum causing it to spin up. Typically, to end up with a 1 millisecond rotation rate requires the accretion of 10^{-10}M$_\odot$/yr over 10^7 yr.

Li argued that even a low magnetic field (say 10^4 T) is enough to truncate the inner edge of the accretion disk and thus one has to have a magnetic boundary layer. This magnetic boundary may impede angular momentum accretion on to the star, so that the angular momentum accretion could be far less efficient as compared to the standard model. This casts doubt on whether a low-mass X-ray binary system such as J1808–369, with a binary period of only two hours, is indeed spun up by accretion.

6 Exotics I

Much of this session was devoted to a discussion of Gamma-ray Bursts (GRBs) and their relationship to supernovae. **Ron Ekers** (ATNF) set the pace with an overview of GRB 980425 and its relationship to SN 1998bw. The 20 s outburst was detected by BATSE and localised using Beppo Sax. Information was quickly distributed on the GRB Coordinates Network (GCN). Like most well-localised bursts, follow-up radio observations were carried out using the VLA/ATCA telescopes. About 30% of GRBs have been detected in the radio, and about 50% in the optical. It is interesting that detection in the radio is always accompanied by the detection of the optical transient. The detection of a SN within the BeppoSax error box, which has a chance probability of one in 10^4, led to the suspicion that the GRB and SN were related. If so, the SN is the most luminous radio SN known, and the light curve is quite peculiar. The γ-ray luminosity was about 10^{41} J. Ron remarked that there had been a suggestion by Paczynski a few years ago postulating that GRBs could be the result of hypernovae, so this was one case where theory might have predicted the observation.

Ray Stathakis (AAO) presented the results of a cooperative spectral monitoring campaign of SN 1998bw, carried out on the AAT, UKST and MSSSO 2·3 m, between 11 and 106 days after the GRB (Stathakis et al. 1999). The spectra showed no H, He or Si lines, thus making it a Type Ic SN. They consisted of broad emission and absorption features which slowly evolved over the period. SN 1998bw had entered the supernebular phase by day 106 with the appearance of nebular emission lines. In comparison to a typical Ic supernova, SN 1994ai, SN 1998bw was much bluer, and the features were broader and more distinct at early times. However, observed transitions and spectral evolution appeared similar, confirming SN 1998bw as a peculiar type Ic supernova. While the broader lines (approximately 45% broader than classical supernovae at similar epochs) explain much of the peculiarities of the spectra of SN 1998bw, there is some indication that additional contribution from line species such as nitrogen, carbon or titanium may be needed to reproduce the observations.

Following this, the GRB 990123 was reviewed by **Brian Boyle** (AAO). This GRB was first detected by BATSE, and the burst was of 90 s duration. Its brightness was in the top 0·3% of all BATSE sources. Optical observations were carried out within 22 s of the burst by the ROTSE telescope. Follow-up Keck spectra were featureless, apart from some absorption lines, arising perhaps from a foreground galaxy at $z = 1{\cdot}6$. The peak V Mag was 8·6, and the total estimated energy in γ rays was about $3{\cdot}4 \times 10^{47}$ J. The luminosity of the optical transient was about $3{\cdot}3 \times 10^{16}$ $L_\odot$. The host galaxy appears to be a blue star-forming galaxy, in common with many any other GRB hosts. Brian also summarised briefly some of the theory of GRBs and the afterglows. The optical decay can be approximated by three different power laws, due perhaps to the reverse shock and the forward shocks. The second break may be a signature of beaming effects.

GX 1+4, a low-mass X-ray pulsar toward the galactic centre, was observed by **Duncan Galloway** (U Tasmania/SRCfTA) with the Rossi X-ray Timing Explorer (RXTE) satellite during July 1996, ≈10 days before a short-lived 'torque reversal' event. Persistent pulsars such as GX 1+4 typically exhibit no correlation between luminosity (and hence mass accretion) and spin-up or spin-down rates, contrary to predictions of existing models. These sources are often found in 'torque states', where the spin-up or spin-down rate is almost constant over time-scales of up to 10 yr, with torque reversals occurring irregularly between states. Often the spin-up and spin-down torques are similar in magnitude. During the RXTE observation significant variations in the mean spectrum and the pulse profile were observed over time-scales of a few hours. Variations of this type have not previously been observed on such short time-scales, and it is suggested that these phenomena may be related to the (as yet unknown) mechanism causing the torque reversals (Galloway et al. 2000; Giles et al. 2000).

7 Exotics II

Both **Dick Manchester** (ATNF) and **Don Melrose** (SRCfTA) talked on the observations and theory of Anomalous X-ray Pulsars (AXPs). AXPs have periods of 6–12 s (cf. 'normal' pulsar periods range from 0·025 s to several seconds), soft X-ray spectra, and relatively low X-ray luminosities of $10^{28} - 10^{29}$ W, significantly below the Eddington limit 10^{31} W. Their X-ray emission is relatively steady on time scales longer than the pulse period—much more so than for accretion-powered binary sources—and they exhibit no evidence that they are binary star systems.

The pulse periods of AXPs increase with time (Mereghetti, Israel & Stella 1998). If the associated loss of rotational energy is attributed solely to magnetic dipole radiation, the inferred surface field is $B \sim 3{\cdot}2\times10^{15}(P\dot{P})^{\frac{1}{2}}$ T, whence $B \sim 3\times10^{10}$ T for typical AXP parameters: $P \sim 10$ s and $\dot{P} \sim 10^{-11}$ (corresponding to 3 ms/yr). This is much stronger than the inferred fields for 'normal' ($B \sim 10^8$ T) and millisecond pulsars ($B \sim 10^5$ T). The idea that their strong magnetic field may be the defining characteristic of AXPs has led to them being referred to as 'magnetars' (Thompson & Duncan 1993).

More specifically, a magnetar is a neutron star whose surface field exceeds the critical field strength $B_{\rm c} = 4{\cdot}4\times10^9$ T at which the energy corresponding to the cyclotron frequency $\Omega_{\rm e}$ equals the electron rest energy $\hbar\Omega_{\rm e} = m_{\rm e}c^2$. Electric fields of energy densities exceeding that of the critical field decay spontaneously via electron–positron pair creation. Magnetic fields which exceed $B_{\rm c}$ cannot decay in this way because of kinematic restrictions—the process of pair creation would violate momentum conservation.

The strong inferred fields of magnetars may arise in one of two ways. Usov (1992) has shown that the if the strong magnetic fields associated with some white dwarf stars are frozen in when they collapse as Type 1a supernovae, then neutron star fields of 10^7 T may result. Duncan & Thompson (1992) have shown that dynamo action could generate the inferred fields.

The energy loss rates, $4\pi^2 I/P\dot{P}$, where I is the moment of inertia, for normal and millisecond pulsars are much higher than the observed radiation luminosities, and these objects are thought to be rotation powered. In contrast, the spin-down luminosity of a neutron star with $P \sim 10$ s and $\dot{P} \sim 10^{-11}$ is 4×10^{25} W, much less than the observed X-ray luminosities of AXPs. It is therefore thought that AXP emission is not powered by rotation, but rather by the decay of their strong magnetic fields.

Some of the eight known AXPs are associated with supernova remnants and some with Soft Gamma-ray Repeaters (SGRs). There is some evidence that the AXPs associated with SGRs have the strongest inferred magnetic fields. The idea that a strong neutron star magnetic field suppresses radio emission has recently been placed on a firmer theoretical foundation by Baring and Harding (1998), invoking suppression of electron–positron pair formation due to increased photon splitting.

The best known SGR was the source of the 5 March 1979 event which attained a luminosity of 10^{37} J and had a clear $8 \cdot 1$ s periodicity. It is believed to be associated with a supernova remnant, N49, in the Large Magellanic Cloud. A specific model for this object involves the release of magnetic energy through fractures of the neutron star crust (Thompson & Duncan 1995).

In a supercritical magnetic field the cross section for the scattering of radiation with frequencies well below the gyrofrequency is highly anisotropic. In particular, scattering of the extraordinary mode is strongly suppressed with respect to that of radiation in the ordinary mode. The consequences of this effect are subtle: it allows extraordinary mode emission to escape even from close to the neutron star, and it clearly affects the interpretation of the Eddington 'limit' for accretion powered sources.

The Parkes Multibeam Pulsar Survey (Lyne et al. 2000), which has a flux sensitivity of 150 μJy and is seven times more sensitive than any previous survey, may double the number of radio pulsars from the 750 known before it began. It has already discovered 362 new pulsars, including PSR J1814–17 which has a period of around 4 s and a high $\dot{P}$ which places it in the part of $P - \dot{P}$ space occupied by AXPs. The AXP 1904+09, which has $P = 5 \cdot 16$ s, $\dot{P} = 1 \cdot 23 \times 10^{-10}$, and which is associated with SGR1900+14, has recently been claimed as a radio pulsar (Shitov 1999).

AXP/SGR/SNR associations, and the relationship between magnetic field strength and radio emission, may ultimately shed light on the apparent deficiency of radio pulsars that are associated with supernova remnants.

The collapse of a star and the resulting supernova explosion that produces a neutron star depends on neutrinos to revive the shock and eject the outer layers of the star (Bethe & Wilson 1985). Four neutrino flavours are necessary to explain all known neutrino anomalies, but only three ordinary neutrinos are allowed. **Yvonne Wong** (University of Melbourne) is investigating the possibility that the fourth flavour may arise through oscillations into 'sterile' neutrinos—those that do not participate in weak interactions as ordinary neutrinos do. The physics of such oscillations, in matter rather than in vacuo, has important implications for the understanding of supernova shocks (Nunokawa et al. 1997).

Roberto Soria (ANU/SRCfTA) and **Amy Mioduszewski** (SRCfTA) discussed observations of the sources GRS J1655–40 and CI Cam which have answered some questions and raised others. Optical spectra of GRS J1655–40 display both broad lines in absorption and emission ($> 1000\,\mathrm{km\,s^{-1}}$), and emission lines which are narrower than the minimum allowed if they originate in an accretion disk. This can be explained if the system is a black hole binary, and the narrow lines originate in an extended envelope surrounding the disk. The nature of the source CI Cam remains a mystery. It has been classified as a symbiotic star and as a Herbig B object. It is a bright emission-line star which exhibited a single uncomplicated X-ray brightening on 1 April 1998, detected by RXTE and CGRO/BATSE, brightening from ~ 0 to ~ 2 Crabs in less than 1 day and then slowly decaying. An associated optical brightening by 2 magnitudes was recorded (Fontera et al. 1998). A radio flare was detected with the VLBA on day 1 and then at intervals of a few days. The images, with a resolution of just a few AU, show a slowly-expanding synchrotron shell, with a speed of just $200\,\mathrm{km\,s^{-1}}$, and no evidence of the jet-like collimated outflows seen in all other soft X-ray transient-related radio transients observed with sufficient resolution.

8 Masers associated with SNRs

An overview of the field was presented by **Anne Green** (U Sydney). The first observations revealing the likely association of 1720 MHz OH masers with SNRs were made 30 years ago, but the field then lay dormant for many years, since the detailed follow up observations of high spatial resolution and high sensitivity were beyond the reach of the available instruments. Interest in the field was revived 5 years ago (Frail, Goss & Slysh 1994), with a three pronged attack: first, high resolution observations of the stronger masers known from the pioneering work; second, a general single dish survey to see how widespread the phenomenon was in the light of the better catalogues of SNRs now available; and third, a review of the theoretical explanation and implications. To date, about 75% of the known SNRs have been searched (Frail et al. 1996; Green et al. 1997). Overall, a 10% detection rate has been found, although the remnants containing masers are not uniformly distributed throughout the Galaxy; the detection rate is higher for SNRs located closer to the Galactic Centre, where there is a greatly increased density of molecular gas. Where high resolution observations have been made (with the VLA or with the ATCA), they reveal clusters of small diameter maser spots located predominantly at the periphery of the associated SNR. Zeeman splitting is often detectable, implying magnetic fields of typically 10^{-7} T or less. The masers tend to have only a small spread in radial velocity, irrespective of their location relative to the SNR boundary, and the inference has been drawn that they occur at points tangential to the shock front, and thus their velocity represents the systemic velocity of the remnant itself (but see later). If so, this provides a valuable distance indicator, and prompts the theoretical question of assessing the physical and chemical conditions needed, and whether the postulated shock provides them. These theoretical aspects were expanded on by **Mark Wardle** (SRCfTA). The basic pumping scheme was suggested 20 years ago and has required only minor refinements. It satisfactorily accounts for the fact that the 1720 MHz transition is seen without any accompanying masers at other OH transitions, occurring at a density too low for their excitation. More puzzling is how the required OH abundance, densities and temperatures arise. Remarkably good progress has been achieved with a strong consensus that non-dissociative (C-type) shock waves are a key factor. More contentious is the question of whether the soft X-ray emission from the SNR is also vital to the process.

Although the framework of understanding is in place, it is largely based on the very small number of objects studied in detail. This is slowly being remedied with follow up observations of more remnants, and new results were presented by **David Moffett** (U Tasmania). He found it difficult in several cases to confirm at high resolution the preliminary detections made with single dishes. This may be because in these cases the emission is of a commonly found diffuse variety of very low gain maser, which lies in the direction of the SNR purely by chance. And even where the maser emission was confirmed, further puzzles arose. In the case of SNR $332\cdot0+0\cdot2$, the velocity is large and if it represents the systemic velocity, then the implied distance is unexpectedly large. So perhaps the velocities can be significantly offset from the systemic velocity, a possibility that would reduce their value as distance indicators. Furthermore, the location of the maser spots is slightly outside the shell as defined by the radio non-thermal emission; so how well does the radio shell delineate the outer shock front? These puzzles highlight the need to enlarge our sample of well studied objects, since generalisations drawn from only a few may be quite misleading.

Because the collisional excitation is believed to occur as a result of the SNR shock impinging on an adjacent or surrounding molecular cloud (Frail et al. 1996; Lockett et al. 1999), one expects to be able to explore this putative cloud by other means. For a few objects, this investigation has begun, and **Jasmina Lazendic** (SRCfTA) described her work to extend these investigations to more molecular species in a larger number of remnants, using mm radio observations. Studies of molecular hydrogen using IR observations can also be used in such studies, and work by **Michael Burton** (UNSW) with Jasmina and others has revealed further unexpected phenomena. The Galactic object commonly known as the 'snake' intersects a likely SNR shell almost at 90 degrees; at the point of intersection is a 1720 MHz maser, not in itself unexpected since the required shock conditions could well be fulfilled here. More surprising is the discovery of a molecular hydrogen outflow jet, apparently emanating from the intersection point. The difficulty of accounting for this perhaps indicates that this is a chance alignment without significance, and more study is clearly required.

Overall, the session was a lively reminder that this field is now making rapid and exciting progress after a 20 year dormant period while we waited for the appropriate investigative tools to be developed.

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