SUPERNOVAE THEIR PROGENITORS AND REMNANTS

EDITED BY

G. SRINIVASAN

V. RADHAKRISHNAN

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Edited by
G. Srinivasan & V. Radhakrishnan

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Preface

From ancient times astronomers have recorded the appearance of novae—or new stars—in the sky at positions where nothing was seen before. Fifty years ago Baade and Zwicky identified supernovae as rare events in the history of stars which are accompanied by a sudden increase in their luminosity by a factor of a hundred billion times or so and an ejection of matter at thousands of kilometres per second. They also made the suggestion that this spectacle represented the formation of a neutron star. To the Indian chronicler it is interesting that Raman tried to persuade Homi Bhaba when he came back to India in 1940 to take up the study of neutron stars.

The supernova phenomenon appears to be connected with every branch of astrophysics. While there is a broad consensus regarding its general characteristics, many aspects of it remain poorly understood, *e.g.*, the precise origin of the energetic particles, the magnetic field in the remnants, the connection with cosmic rays, the nucleosynthesis leading to the chemical abundances *etc., etc.* This and the fact that many Indian astronomers and astrophysicists are keenly interested in the field is the precise reason why this workshop on *Supernovae, their Progenitors and Remnants* was organized. It was one of several workshops, seminars and symposia held to mark the golden jubilee of the founding of The Indian Academy of Sciences in 1934 by Prof. C. V. Raman.

We are grateful to all participants from India and abroad for presenting so many interesting papers—and for submitting the written versions in time. A special word of thanks to Prof. L. Woltjer, a pioneer in this field, for giving such a perceptive overview and a final summary.

S. Ramaseshan

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L. Woltjer *European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-8046 Garching bei München, FRG*

1. Introduction

Supernovae (SN) and their remnants (SNR) have been extensively observed at radio, optical and X-ray wavelengths, but many aspects remain uncertain, ambiguous or controversial. The main motivation for being interested in the subject results from its connection to stellar evolution (progenitors of SN), to nucleogenesis (the contribution of SN to galactic abundances of the elements), to cosmic rays (acceleration of electrons and ions in or around SNR and their subsequent diffusion into the galaxy), to the energetics of the interstellar medium, to star formation and more speculatively to active galactic nuclei and galaxy formation.

Many catalogues of SNR and reviews of their properties and of related theoretical developments have been made (see for example IAU Symposium 101). Recent developments in the subject include X-ray observations of the structures and spectra of SNR, and studies of SNR in the galaxies of the Local Group, in particular in the Magellanic Clouds. While the spatial resolution in the extragalactic studies is of necessity more limited, the elimination of the uncertainty in the distances and the relative completeness of the samples are major advantages. Observations of extragalactic supernovae at radio and X-ray wavelengths also are leading to progress in the understanding of the very earliest evolution phases of the SNR. Finally, optical observations of SNR spectra have much improved in sensitivity and accuracy, and radio observations in spatial resolution.

The remnants of the historical supernovae are of particular interest because the ages are known, the distances can be at least crudely estimated and the relative youth of the remnants allows the preservation of features of the original outburst, which in older remnants are submerged in the large amount of interstellar gas that has been swept up.

In Table 1 some of the properties of these objects are presented. The historical data and in particular the V magnitudes at maximum are essentially taken from Clark & Stephenson (1977). Compact X-ray sources have been found only in two objects, even though all have been carefully searched (Helfand & Becker 1984). The distances of the Crab and Cas A have been obtained from their kinematics, that for 3C 58 depends on the interpretation of the controversial 21-cm absorption data (Green & Gull 1983), while for the others the estimates are based on a mixture of arguments including also the SN magnitude at maximum ($M_v = -19.6$ for SN I, Tammann 1982) for a Hubble constant of $50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. Errors of up to a factor of two cannot be excluded. The overabundances of particular elements have been derived from optical spectra (Crab, Kepler, Cas A) and from X-ray spectra (Tycho, Cas A), discussed in numerous articles in IAU Symposium 101.

Table 1. Remnants of historical supernovae.

Year	Type	V	Object	Point source X	D (kpc)	θ (min)	d (pc)	$\langle V_{exp} \rangle$ km s^{-1}	Overabundant elements
(185)		(−8)	RCW 86	...	(1)	50	16	4000	
1006		−9	P 1459-41	...	1	30	7	4000	
1054		(−5)	Crab	x	2	5	3	2000	He
(1181)		(0)	3C 58	x	2–8	7	4–16	3000–10000	
1572	I	−4	Tycho	...	3	7	6	8000	(Si, S, Ar, Ca)
1604	(I)	−3	Kepler	...	4	3	4	6000	N
(1650)			Cas A	...;	3	4	4	7000	N, O(S, Ar, Ca)

2. General Evolution of SNR

The basic scenario of a supernova explosion in a relatively uniform interstellar medium is simple enough and may be schematically divided into four phases (Woltjer 1972).

In phase I, the supernova ejecta have not yet had time to interact much with the interstellar gas; after the initial pressure in the supernova envelope has become negligible because of adiabatic expansion and radiative losses, they move at constant velocity, and the relation between radius and time is $r \propto t$.

In phase II, the ejecta have swept up an appreciable amount of interstellar gas and are thereby decelerated. A shock separates the SNR from the still undisturbed interstellar matter. With velocities above about 200 km s^{-1} the temperature behind the shock is so high that radiative losses are negligible. This is the adiabatic phase, and the global hydrodynamics is characterized by the Sedov similarity solution with $r \propto t^{2/5}$ or $V \propto t^{-3/5}$.

In phase III, radiative losses become dominant and the shock-heated gas cools rapidly. Pressure effects are small and the SNR expands now at constant momentum and $r \propto t^{1/4}$. This phase is sometimes referred to as the 'isothermal' phase.

Finally, in phase IV, the expansion velocity of the shell becomes comparable to that of the interstellar gas clouds, and the shell begins to lose its identity in the surrounding medium.

This simple scheme (summarized in Table 2) has only a limited relation to reality. Phases I and II may be significantly affected when much circumstellar matter is present which has been expelled before the SN outburst by the SN progenitor—as a stellar wind or in planetary-nebula-type ejections. The Sedov solution in phase II is an idealization, strictly applicable only to a zero mass point source explosion. Since in reality this phase begins only when the SNR has already a substantial radius, important differences occur. In particular, at the time that the interaction with the surrounding matter becomes important, a 'reverse shock' is formed which propagates back into the SNR, heating the original ejecta.

Of still larger importance is the fact that the interstellar medium is clumpy with cool, high density 'clouds' in rough pressure equilibrium with a warmer, more tenuous, intercloud medium which fills most of the volume. The high pressure behind the shock in the intercloud medium compresses the clouds and causes subsidiary shocks to propagate into them; because of the higher density, these shocks are slower. The net result may be to increase the radiative losses and/or to evaporate the clouds. The

Table 2. The global phases of the evolution of SNR, the corresponding integral numbers $N(<R)$ in a steady state and the ratio of the instantaneous velocity to the average velocity of expansion since the outburst. The formulae for phases II and III are only valid in an asymptotic sense for times long enough for the effects of the previous phases to have become negligible.

	Phase	R	$N(<R)$	$V/\langle V\rangle$
I	Free expansion	$\propto t$	$\propto R$	1
II	Adiabatic (Sedov)	$t^{2/5}$	$R^{5/2}$	2/5
III	Radiative	$t^{1/4}$	R^4	1/4
IV	Dissolution	$(V \simeq V_{\text{interstellar}})$		

resulting inhomogeneous distribution of density and temperature makes the interpretation of the emitted optical and X-ray spectra complicated.

Until now, we have tacitly assumed the validity of a hydrodynamical description of the interaction of the ejecta with the interstellar gas. A calculation of the mean free path of the electrons and ions, however, shows that the shock must be essentially collision-free. While plasma instabilities are likely to allow an effective interaction between the particles to occur and a Maxwellian distribution of the electrons to be set up, it is not at all clear that the electron and ion temperaturers should be the same. Furthermore, because of the suddenness of the electron heating and the long mean free path for collisional interactions the state of ionization need not at all correspond to that at equilibrium. This strongly affects the emitted spectra.

Itoh, Gronenschild and others have calculated the ionization and excitation conditions to be expected under these circumstances. In young remnants, the effects on the X-ray spectra are surprisingly large. For example, Gronenschild & Mewe (1982) find that with average parameters, a Sedov-type solution and an SNR age of 2000 years, the intensities of the Ly α like lines of ionized oxygen may be a factor of 10^2 larger and those of ionized nickel a factor of 10^5 smaller than at equilibrium. Even the total emission between 0.1 and 1 keV is more than a factor of ten larger than at equilibrium with the same T_e.

It is clear that these non-equilibrium effects are of major importance if abundances of elements in, or masses of, SNR are to be determined. In one example of a model for Tycho, it is found by Shull (1982) that the spectroscopically inferred abundance of Ca is reduced by a factor of 30 if the non-equilibrium calculations are used rather than the equilibrium ones. The combination of these effects and those due to inhomogeneities makes the analysis of the spectra of SNR a formidable task.

3. Comparison with observations

The relatively low expansion velocities observed in the optical filaments of objects like the Cygnus Loop ($= 100 \text{ km s}^{-1}$) initially led to the conclusion that typical remnants were in phase III. Subsequently, the X-ray data showed evidence for much gas at high temperatures corresponding to shock velocities several times larger. Since for typical interstellar conditions the transition between phases II and III occurs around 200 km s^{-1} (Woltjer 1972), this implies that most remnants are in phase II, and that the lower velocity optical filaments result from inhomogeneities.

Further information comes from the expansion velocities of the remnants of the historical supernovae (Table 3) and from the number-radius relation for SNR, by comparison with the expressions given in Table 2. The results in Table 3 show that the situation is quite complex. For SN 1006 and Tycho's remnant the available proper motions are compatible with phase II expansion. In the case of the Crab Nebula, the motion of the filaments is accelerated, presumably because of the pressure of the relativistic particles and magnetic fields. The large helium abundance in the filaments indicates that interaction with the interstellar medium is still limited. In the case of Kepler's remnant and of the low velocity filaments of Cas A (both nitrogen rich), there is no evidence of expansion. The fast filaments (oxygen rich) in Cas A show a relatively neatly expanding shell with a well-determined age of 326 years, but in the radio domain the expansion is non-existent or in any case much slower, depending upon which radio

Table 3. Expansion of SNR

SN 1006	1 filament	$V/\langle V\rangle = (0.47)$	Hesser & van den Bergh (1981)
Crab	filamentary shell	$V/\langle V\rangle = 1.10$	Trimble (1968)
Kepler	filamentary shell	no clear expansion	van den Bergh & Kamper (1977)
Tycho	radio remnant,	$V/\langle V\rangle = 0.47$	Strom, Goss & Shaver (1982)
	some filaments	$V/\langle V\rangle = 0.38$	Kamper & van den Bergh (1978)
Cas A	fast filaments	$T = 326$ yr (± 3)	
	'recent blue knots'	$T = 386$ yr (± 43)	Kamper (1983)
	'quasi stationary flocculi'	no clear expansion	
	radio structure	$T = 950$ yr	Tuffs (1983)
		no clear expansion	Dickel & Greisen (1979)
	Flamsteed's star	$T = 304$ yr	Ashworth (1980)

data one believes. While in each case one may provide some qualitative explanation, the picture emerging from Table 3 remains rather confused.

The situation is not much clarified by the $N(<R)$ relation. In our own galaxy, it is difficult to say much because of incompleteness and uncertain distances. In the Magellanic Clouds, the X-ray surveys have much improved the completeness, and, of course, the distance problem is eliminated. It was shown by Mills *et al.* (1984) that $N(<R) \propto R^{1.2}$, which would imply almost free expansion, low ages and a high supernova rate—one per century for the two Clouds together. The absence of historical SN then already may begin to be a bit surprising. With regard to the X-ray selected remnants (Mathewson *et al.* 1983), however, Fusco-Femiano & Preite-Martinez (1984) have pointed out that the observational selection of the remnants is very much dependent on the local interstellar density. If this is high, the remnant is rapidly slowed down, and the temperature becomes too low for inclusion in the X-ray sample. As a consequence, in the adiabatic phase the $N(<R)$ curve would be a superposition of $R^{5/2}$ curves for different interstellar densities, each with a different cutoff. These authors show in a detailed model that a net linear relation may be easily reproduced. As a consequence, the inferred supernova rate for the Large Magellanic Cloud is reduced to one per 700 years.

The discussion shows that while probably most SNR are in phase II, as expected from the average interstellar densities in the Galaxy, there remains much uncertainty also in the ages and SNR formation rates. The estimates for the latter in our own Galaxy tend to be around one to a few per century, compatible with the historical data and the extragalactic supernova rates, and comparable with recent estimates of the pulsar formation rates. However, the uncertainties in all these numbers are so large that no valid conclusions can be drawn about questions like whether every supernova leaves a pulsar or whether every pulsar originates in a supernova event.

4. Magnetic fields and relativistic particles

Of course, the outstanding characteristic of supernova remnants is the emission of synchrotron radiation by relativistic electrons in a magnetic field. With regard to the origin of these two components, in the case of the Crab Nebula it is generally believed that the electromagnetic fields around the pulsar are responsible for both. Simple-minded theory would, however, predict too few electrons with too high an energy. Various schemes have been devised to improve the situation by dividing the energy over a shower of electrons and positrons, but no convincing calculation of the energy spectrum appears yet to have been made. In addition, if SNR and cosmic rays were connected, the positrons would create an embarrassement.

The alternative possibility is to amplify the magnetic fields and accelerate the relativistic particles by quasi-turbulent motions in the shell of the remnant. While this seems a not implausible mechanism, the available calculations are still rather qualitative. Currently, this appears to be the mechanism accepted by most investigators for objects like Cas A and for most of the older remnants.

A particularly interesting observation in this context is the detection of nonthermal radio emission from the remnant of nova GK Persei by Reynolds & Chevalier (1984). Since a nova event is typically a factor 10^6 less energetic than a supernova event, this shows that particle acceleration and magnetic field amplification may occur with an efficiency of the order of one per cent under a wide range of conditions. While this would seem to favour the quasi-turbulent mechanisms, some doubt may perhaps still be entertained whether the binary responsible for the nova outbursts could not also be an efficient accelerator of relativistic electrons.

5. Nucleogenesis in supernovae

In order to synthesize very heavy elements, intense fluxes of neutrons are needed. Some decades ago, this gave rise to the idea that supernovae may be important in this context. Various scenarios were developed with which to understand the exponential decline of the type I supernova light curves as a result of radioactive input of energy into the supernova envelope. Current models of this type start with the production of copious quantities of Ni^{56} which then decays into Fe^{56}. As a result, it could be expected that the remnants of type I supernovae would contain of the order of a solar mass of iron. Unfortunately, the elements observed in the optical and X-ray spectra of young supernova remnants indicate the overabundance of several elements, but not of iron.

In the case of the Crab Nebula, there is some controversy about the degree of under- or overabundance of elements like oxygen, but there certainly is not an important overabundance. However, hydrogen is underabundant with respect to helium by a factor of three or more. Nomoto (1983) has shown that this may be understood if its progenitor had been a star of about 9 $M_\odot$. It is not impossible to have such a star at 200 pc from the galactic plane, but the probability is certainly low. It is also to be noted that while it is true that the earlier statements, that the Crab Nebula supernova was of type I, appear to be unfounded, this does not in any way imply that it was of type II.

The overabundance of nitrogen in the slow-moving filaments of Kepler and Cas A is perhaps not too surprising if stellar massloss occurred from an envelope in which the CNO cycle had processed the material. The overabundances of Si *etc.* in faster filaments also could be produced in explosive burning of O-rich material.

While there is no evidence for large amounts of excess iron in the X-ray spectra of the young SNR, it has been argued that iron could be present, but at so low a temperature that no observable emission would occur. The most likely picture is then one in which expansion has cooled the shell, but the reverse shock has not yet arrived to heat it again and to fully initiate phase II. Some evidence in this direction has been presented by Wu *et al.* (1983) who claim to observe iron in absorption in the ultraviolet spectrum of a star behind the SN 1006 remnant. However, the quality of the spectrum of this faint star is so low that further confirmation appears to be essential.

Further confusion has arisen from the apparent overabundance of nickel in the Crab Nebula. Dennefeld & Péquignot (1983) found an overabundance of Ni with respect to Fe of about 60 in one filament, but questioned its reality in view of the fact that in older remnants also rather large overabundances were found. This point was further confirmed by Henry (1984) who noted an apparent overabundance of Ni also in the Orion Nebula. It therefore seems not unlikely that there is something wrong with the calculation of the excitation and ionization conditions for nickel.

In conclusion, there appears to be some evidence for nucleogenesis in the supernova event (also further supported by the observations of SNR in the Magellanic Clouds), but the detailed comparison between observation and predicted yields remains to be made.

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Supernova Progenitors

Virginia Trimble *Astronomy Program, University of Maryland, College Park MD 20742 USA & Department of Physics, University of California, Irvine CA 92717, USA*

Abstract. Supernovae can occur whenever stars release large quantities of nuclear or gravitational energy quickly. The current consensus is that type I (hydrogen-free) events result from detonation or deflagration of degenerate C–O fuels in relatively low mass stars, either single 4–8 $M_\odot$ ones, or, perhaps more likely, $\sim 1\ M_\odot$ accreting white dwarfs in close binary systems. Some of the difficulties in getting enough events in both old and young populations and in avoiding hydrogen contamination can probably be circumvented if the immediate progenitor is a pair of white dwarfs that spiral together. Type II (hydrogen-rich) events, on the other hand, are thought to be due to core collapse in highly evolved, more massive ($\gtrsim 9\ M_\odot$) stars. The chief theoretical difficulty is in transferring enough of the released gravitational potential energy to the outgoing envelope. Both nuclear burning in the outer layers and latetime neutrino heating may help. There remains, perhaps, a problem in reconciling the extended, hydrogen-rich envelopes needed to reproduce type II light curves with the extensive massloss that transforms many massive OB stars to Of and WR types. It is possible that there is not a sharp cut in mass between progenitors of SN I's and progenitors of SN II's, particularly when allowance is made for effects of mass transfer and loss in close binary systems.

Key words: Supernovae, progenitors—stars, evolution—stars, binary

1. Historical introduction

Baade & Zwicky (1934) created the concept of supernovae with a class of progenitors ('ordinary stars') and an energy-release mechanism ('collapse to a neutron star') already attached. Though they did not say so, it was already clear from the work of Chandrasekhar on electron-degenerate stars (*e.g.* Chandrasekhar 1933) that the ordinary stars must be relatively massive ones. Triggering of the collapse was alternatively attributed to neutrino production (Gamow & Schoenberg 1941) or photodisintegration of iron (Hoyle 1946).

Hoyle & Fowler (1960) recognized that the distinctions between type I and type II events in spectra and parent populations (SN I = no hydrogen, Population II; SN II = hydrogen, Population I) would require distinct progenitors and mechanisms. Their detailed calculations made a strong case for SN I's being produced among stars a bit above 1 $M_\odot$ by means of explosive burning of degenerate carbon and oxygen, which would disrupt the entire star. Their SN II's, on the other hand, came from $\sim 30\ M_\odot$ stars whose cores imploded violently, heating outer layers until explosive nuclear reactions and ejection again occurred.

Work since then has established that, on the one hand, it takes rather bigger stars (of 3–8 $M_\odot$) to evolve explosive, degenerate cores, even in the absence of massloss (Paczyński 1970), and, on the otherhand, that core collapse must occur down to 6–10 $M_\odot$ in order to get enough pulsars (Ostriker, Richstone & Thuan 1974).

The possibility of a third class of progenitors, close binary systems in which mass transfer onto a white dwarf eventually drives it to instability, occurred more or less simultaneously to a number of people (Wheeler & Hansen 1971; Truran & Cameron 1971; Hartwick 1972; Whelan & Iben 1973; Mazurek 1973). Calculation of models based on this hypothesis has developed into a major astronomical industry, despite the recognition that the transfer rate must be rather carefully chosen to prevent explosive, degenerate, shell hydrogen burning from blowing everything back off (Paczyński & Rudak 1979, and many others) and that there are problems in identifying the precise precursor systems and in getting enough of them (Greggio & Renzini 1983).

Further details of the historical development of our ideas on supernova progenitors and mechanisms, with more extensive references, are given in my earlier reviews of the subject (Trimble 1982, 1983). The following sections address current ideas on the progenitors of unusual events (Section 2), type I supernovae (Section 3), and type II supernovae (Section 4).

2. Unusual supernovae

2.1 *Types III, IV, and V*

Zwicky (1965) advocated three additional, rare, but physically distinct classes. Type III (prototype 1961i) had hydrogen in the spectrum, but an unusually broad maximum and slow decline in its light curve. Type IV (prototype 1961f) showed faint Hγ emission, but an otherwise I-like spectrum, and stepped decline in its light curve. Finally, the prototype V (1961v in NGC 1058) was recorded on sporadic, chance plates at about 18 mag for more than 20 years, before rising about6 mag to a double-peaked maximum luminosity well within the normal supernova range. It then declined some 10 mag over the next nine years, eventually looking nebulous. The spectrum was of type II, showing an ejection velocity near 2000 km s^{-1}, the presence of both hydrogen and helium, but with He/H about four times the solar value, and an ejected mass of about 0.3 $M_\odot$ plus whatever neutral gas was also present. This all sounds remarkably reminiscent of something that might evolve into a Crab Nebula, presumably accounting for Zwicky's occasional remark (which I have not located anywhere in print), that SN 1054 was a type V. He included also η Carinae, which is surely a very massive object and part of a recent star-formation region, in this class.

Types III and IV sound transitional between I and II and might plausibly be modelled with either gravitational or nuclear energy sources, surrounded by a moderate sized envelope with a moderate amount of hydrogen. Tammann (1977a, b) lists other apparently transitional examples. The type V is more distinct and has prompted suggestions of a distinct progenitor—stars well in excess of 100 $M_\odot$, perhaps as large as 2000 $M_\odot$ (Utrobin 1983). These collapse due to electron-positron pair production during core oxygen burning (Bond, Arnett & Carr 1984) and can either disrupt or leave black holes. η Carinae (Andriesse, Donn & Viotti 1978) and R 136

(Cassinelli, Mathis & Savage 1981) could be either progenitors of this scenario, or somewhere in the middle of it.

2.2 *Cas A*

The strong radio source Cas A has all the properties of a young supernova remnant, including optical filaments whose measured proper motion implies that the expansion began in 1658 ± 3 (Kamper & van den Bergh 1983). But the event was either not seen at all or was considerably fainter than typical (Ashworth 1979). Chevalier (1976) proposed that the progenitor star had been largely stripped of its supergiant hydrogen envelope before core collapse occurred, resulting in relatively little radiation of visible light from an expanding envelope. The presence of optical knots in the remnant with large excesses of oxygen and its burning products indicates that the progenitor had proceeded at least that far in its evolution. Such abundance anomalies have been seen in optical and X-ray data for other young Milky Way remnants as well as objects in the Magellanic Clouds, NGC 4449, *etc.* (see Danziger & Gorenstein 1983 for recent data and references).

Litvinova & Nadyozhin (1983) suggest that partially stripped massive stars may be the progenitors of a class of relatively faint type II events. A still more extreme case is the collapse of O–Ne–Mg white dwarfs (triggered by electron capture) to neutron star densities. There is neither an extended envelope nor extensive production of Ni^{56}. The collapse is thus nearly invisible, or 'silent' in the terminology of the modellers (Miyaji *et al.* 1980).

2.3 *The Crab Nebula*

This most-studied of all remnants is unusual in the absence of a rapidly-expanding shell of radio emission (Velusamy 1983; Matveenko 1984) and in the presence of a neutron star and pulsar. The presence of a pulsar-driven filled remnant is also rare (Helfand *et al.* 1984; Srinivasan, Bhattacharya & Dwarakanath 1984). The combination, as well as the helium-rich nebular mass of $\sim 2\ M_\odot$, can nevertheless be modelled by an electron capture supernova in a $9 \pm 1\ M_\odot$ star that had previously shed most of its hydrogen-rich envelope (Nomoto *et al.* 1982; Hillebrandt, Nomoto & Wolff 1984). Current models for the nebula cannot distinguish among possible surroundings for the observed remnant–normal interstellar medium, red giant wind, or normal SN ejecta (Chevalier 1984).

Though the Crab Nebula thus seems fairly comprehensible, the rarity of objects like it casts some doubt upon the equation, neutron star formation = filled centre remnant = type II event (Weiler & Panagia 1978). On the other hand, SNR's with both shell and core emission could be fairly common and missed in standard low-frequency surveys because of the flat spectrum of the core component (Becker & Helfand 1984). If so, then the only thing unusual about the Crab's progenitor would be the absence of a hydrogen-rich envelope to be expelled at high speed; and the lack of pulsars in other historical remnants in the Milky Way would mean that the events were all of type I (except, presumably, SN 1181 = 3C 58 and SN 1480 = CTB 80 which have compact X-ray cores, representing non-pulsar neutron stars).

Discussion is nevertheless divided between the final two sections on the assumptions that at least the equation, neutron star formation = SN II holds true.

3. Type I Supernova

There is a long-standing controversy concerning typical SN I progenitors. It is generally phrased as a dichotomy between intermediate mass (*e.g.* 3–8 $M_\odot$) progenitors and low mass (*e.g.* $\lesssim$ 1–3 $M_\odot$) progenitors. In the light of recent close binary models, however, it seems to me that the proper way of phrasing the dichotomy is as between intermediate mass stars that were formed recently and ones that were formed long ago than their main sequence lifetimes. The arguments for recent star formation include correlations of SN I rates with elliptical galaxy colour and evidence for nuclear activity and the scale heights above the galactic plane of those seen in spirals. Oemler & Tinsley (1979), Kochhar & Prabhu (1984) and Trimble (1982) present these data in further detail.

3.1 *Single Star Models*

Recent star formation in this context means that the stars have lived no longer than normal, single-star evolutionary times before exploding. Observational evidence against this view is presented by van den Bergh (1983) and Trimble (1982) and includes the distribution of SN I's in ellipticals (like the general light, not concentrated toward the centre like the uv excess). In addition, the single star scenario has gradually passed out of favour. Partly this has happened because studies of young open clusters suggest that stars up to at least $7 \pm 2\, M_\odot$ become white dwarfs (Anthony-Twarog 1984; Reimers & Koester 1982; Wood, Bessell & Fox 1983; Weidemann & Koester 1983), while the maximum mass likely to yield degenerate carbon ignition has crept down roughly to meet this limit (*cf.* Trimble 1982). The other factor has been the great successes scored by the binary models discussed below.

It is not implausible that a very few single, recently-formed intermediate mass stars with anomalously large mixed cores (due perhaps to rapid rotation) shed only their hydrogen envelopes and produce carbon-detonation SN I's among relatively young stellar populations in spiral and irregular galaxies (Saio & Wheeler 1980; Tinsley 1980). Attempts have also been made to ride both horses and attribute type I events to two classes of progenitors (Shklovskiĭ 1983). A collateral argument for this, the apparent existence of two classes of SN I light curves, seems recently to have disappeared (Barbon *et al.* 1984; Tammann & Cadonau 1984, personal communication).

3.2 *Close Binary Models*

The general picture is that a primary of any mass 1–7 or more $M_\odot$ produces a white dwarf, which then waits patiently for the secondary to evolve away from the main sequence and transfer mass back onto it. The white dwarf's mass grows until it (1) collapses by electron capture on O, Ne, and Mg to make a neutron star, (2) ignites helium off centre, detonating the helium layer and leaving a CO core behind still at white dwarf densities, (3) ignites carbon off centre, so that dual detonation waves propagate inward and outward, incinerating and disrupting the whole star, or (4) ignites carbon at the centre, so that a deflagration runaway burns only the central part of the star, but disrupts the whole thing (Woosley, Axelrod & Weaver 1984; Nomoto 1984a; and earlier references therein). Which of these happens depends on (1) the mass and composition of the primary white dwarf ($\leqslant 0.45\, M_\odot$ of He, 0.45–1.1 $M_\odot$ of C–O, or 1.1–1.4 $M_\odot$ of Ne–O–Mg), (2) how long WD cools before back transfer begins, and whether O separates out and crystallizes in the mean time (Isern, Labay & Canal 1984; Mochkovitch 1983), (3) the rate at which fresh material arrives, and (4) the composition of the accreted material and thus the amount of heating produced when it burns.

One charm of this scenario is that the supernova event follows star formation after a time set by the lifespan of the lower-mass secondary, which can be long, yet the system has the mass of the primary to draw on, greatly improving the chances of getting close enough to 1.4 $M_\odot$ for one of the instabilities mentioned above to set in. Additional advantages are: First, there exists a fairly numerous class of objects, the cataclysmic variables (CV's, including novae, dwarf novae, recurrent novae, nova-like variables, symbiotic stars, and polars), which can be claimed as *en route* to producing such SN I's. Second, models based on this scenario (summarized in Wheeler 1980; Trimble 1982; Rees & Stoneham 1982; Iben & Tutukov 1984) provide fairly good matches to the spectra and light curves observed for type I supernovae.

The spectra near maximum light consist of an underlying blackbody from a ~ 8000 K photosphere expanding at $\sim 10{,}000$ km s^{-1}, plus broad P Cygni lines of common elements in roughly solar proportions, apart from a complete absence of hydrogen (Branch 1982). For instance, the products of the deflagration studied by Nomoto, Thielemann & Wheeler (1984) provide the right line intensities for SN 1981b if layers of the star are well mixed (Branch 1984 and personal communication). Spectra well past maximum light are dominated by iron lines. There is not yet complete agreement upon their interpretation, but one possibility is a large excess of iron and cobalt (Axelrod 1980). This is important because the model light curves (Weaver, Axelrod & Woosley 1980; Woosley, Weaver & Taam 1980) have two main energy inputs, instantaneous release as carbon and oxygen burn to iron-peak elements, especially Ni^{56}, and gradual release as the Ni^{56} beta-decays *via* Co^{56} to Fe^{56} (half lives 6 and 77 days). Next, such events, when the white dwarf disrupts, contribute significant amounts of oxygen-burning products (both abundant and rare species) to the galactic supply (Nomoto, Thielemann & Wheeler 1984). This will be especially important if very massive stars typically trap their entire processed cores in black holes.

Finally, the case where the white dwarf collapses gently rather than exploding is (apart from assorted capture mechanisms) seemingly the only way to make the low mass X-ray binaries like Her X-1 (Webbink, Rappaport & Savonije 1983; de Loore & Suntantyo 1984; van den Heuvel 1981a, b). In fact, one must be a bit careful not to let this happen too often and overproduce such systems (Taam & Fryxell 1984; Iben & Tutukov 1984). The implication is that an accreting white dwarf deflagrates or detonates and disrupts (either itself or at least the system) in all but perhaps those very few cases where its initial mass was very close to the Chandrasekhar limit (as in the systems discussed by Law & Ritter 1983). Van den Heuvel & Taam (1984) use this process also to account for the two binary pulsars with low mass companions. Such triggered collapses occur much slower than the free-fall timescale, and so are unlikely to give shock wave ejection or to make SNR's (Lipunov 1983).

3.3 *Some Difficulties with the Binary Model and a Proposed Solution*

The objections initially voiced to all carbon detonation supernovae were (Ostriker, Richstone & Thuan 1974) that, if they were at all common, (1) the pulsar production rate would not be sufficient to keep up the observed supply, and (2) we would be drowning in iron. The first of these problems has somewhat changed its form in the intervening decade. Many supernova remnants, including those associated with the 1572 and 1604 (Tycho and Kepler) events, simply do not contain neutron stars of the same age as the remnants (Helfand & Becker 1984). Thus we cannot object, *a priori*, to a supernova mechanism that leaves no compact core! The lack of correlation between SNe, SNR's and NS's remains a puzzle (Srinivasan, Bhattacharya & Dwarakanath 1984), and we are not going to explain it here.

The iron problem is still with us. Sutherland & Wheeler (1984) note that the maximum amount of iron we can tolerate from type I supernovae occurring every 50–100 yr in our galaxy is about 0.7 $M_\odot$, and that this is just about the minimum needed to give the disrupted star the observed expansion velocity. This much burning makes the event intrinsically rather bright, corresponding to a large extragalactic distance scale. The authors go so far as to say that, if the scale should be established at $H_0 \geqslant 100$ km s^{-1} Mpc^{-1} by other means, then the carbon detonation/deflagration model of SN I's would have to be abandoned.

Woosley, Axelrod & Weaver (1984) conclude, somewhat more gently, that no single model simultaneously yields believable element and isotope ratios in its burning products while matching typical light curves and spectra. They, however, suggest possible ways out through variations from one event to another and/or departures from the bare, spherically symmetric white dwarfs of their models.

Another difficulty with the consensus scenario is a statistical one: are there enough progenitors? Recent discussions, both simple (Greggio & Renzini 1983; Trimble 1982b) and elaborate (Iben & Tutukov 1984; Patterson 1984) conclude that our own galaxy is rather close to the ragged edge. Making enough cataclysmic variables is easy—either a few per cent of the low-to-intermediate mass binaries might function that way for $\sim 10^9$ yr each, or they might all do it for a few per cent of their lifetimes. But the SN I's are more difficult—nearly all binaries capable of growing an explosive ($\sim$ Chandrasekhar mass) white dwarf must do so without more mass being lost from the system than would be shed by similar single stars. I find this somewhat unlikely-sounding, given that the process of bringing the stars close enough together to get a cataclysmic system requires considerable angular momentum (hence mass) to be lost in a common envelope phase (Paczyński 1976).

There are, however, a good many factors of two to play with. And, if we look at measured masses of CV's (24 systems tabulated by Patterson 1984, 39 tabulated by Ritter 1984, with considerable overlap), we see that about a quarter of them already have white dwarf masses $\gtrsim 1\ M_\odot$ and about 40 per cent have total masses in excess of 1.4 $M_\odot$. These could all become SN I's if no further mass were lost, and they may be just about enough (Patterson 1984, *etc.*), except that the novae, at least, expel material from the system at least as fast as the secondary tries to give it to the primary. Even symbiotic stars may present a problem. Stauffer (1984) suggests that HM Sge had a nuclear flash in 1975, and four years later, expelled the excess hydrogen *via* wind pressure.

Patterson (1984) also worries about the eventual fate of CV's that don't give rise to supernovae. It now seems likely (Nather 1985) that continued mass transfer and ejection erodes them down to very small, short period binary white dwarfs, of which we currently know three examples (AM CVn, GP Com, PG 1346 + 082).

The preceding three paragraphs apply to Population I stars in our own Galaxy. We do not directly know the formation rate of binaries as a function of stellar mass and separation for any other galaxy, except for the very brightest stars in Andromeda and the Magellanic Clouds, which eclipse about as often as similar Milky Way stars (Herczeg 1982). In particular, there is no information on the giant elliptical galaxies, for which these binary models seem most vital.

We might, therefore, be tempted to assume without further worry that the binary formation rate, like the initial mass function (Scalo 1985) varies rather little from place to place, were it not for an apparent severe deficit of binaries among galactic Population II stars, which are as old as giant elliptical populations, though much poorer in heavy elements.

The precise extent of the deficit is debated from time to time, but there are no confirmed eclipsing (main sequence or giant) binaries among the globular clusters (Hogg 1973; Webbink 1980) or in the dwarf spheroidal Draco (Herczeg 1982). In addition, several searches for radial velocity variability among globular cluster stars (Mayor *et al.* 1984 on 47 Tuc, with references to earlier work) have found only atmospheric effects and no spectroscopic binaries, though corresponding investigations of open clusters found many. The tightness of the main sequence in many globular cluster colour-magnitude diagrams (Richer & Fahlman 1984, on M4; Sandage & Katem 1983, on M92) says that at most a few per cent of the stars are binaries with mass ratios $\gtrsim 0.7$ (among the commonest sorts in the solar neighbourhood). Even among field subdwarfs, colours suggest a lower-than-average binary incidence (Eggen 1983; Carney 1983). Finally, although the globular clusters have their fair share and more of cataclysmic variables and low-mass X-ray binaries, these were probably formed by capture processes among previously single neutron stars, white dwarfs, and main-sequence stars (Hertz & Grindlay 1983; Hertz 1984). Thus, we really cannot guess, even to order of magnitude, how many binary progenitors are available to make type I supernovae in elliptical galaxies. Shklovskiĭ (1978) has associated the declining SN I rate along the galaxy type sequence Sc-Sb-Sa-S0-E with declining binary frequency.

The problems noted thus far—non-production of pulsars, over-production of iron, and possible shortage of progenitors—apply to essentially all versions of the consensus model. Still, none of them sounds absolutely fatal. There are, however, two additional problems, potentially more serious, which a recent modification of the standard model enables us to avoid. If cataclysmic variables are the immediate predecessors of type I supernovae, then (1) the material being transferred to the white dwarf is necessarily mostly hydrogen, and (2) the maximum available time from star formation to explosion is the nuclear-burning lifetime of the secondary.

Having hydrogen around is, on the whole, a bad thing (Sutherland & Wheeler 1984), since type I spectra do not show any, and, unless the hydrogen is accreted at a carefully selected rate (which the secondary may not know about), it burns in violent flashes every 10^{4-5} yr, making nova explosions (Sion, Acierno & Tomczyk 1979). These blow off everything that was accreted, and perhaps some material from the white dwarf as well, so the white dwarf mass does not increase with time. The timescale problem arises because the secondary must be massive enough to be a useful donor, but small enough to live $\sim 10^{10}$ yr. In this connection, it is of interest that the type I event 1983n, whose radio emission (because of the kind of circumstellar shell needed to make it) appears to imply initial masses near $8 + 6.5\ M_{\odot}$ (Sramek *et al.* 1984; Chevalier 1984b) occurred in a spiral galaxy with considerable current star formation (M83). On the other hand, some of the SN I's whose infrared emission seems to be a 'light echo' from dust in similar shells (Evans *et al.* 1983) were in ellipticals.

The hydrogen and timescale problems both go away if the progenitor's biography has a chapter in which the secondary completes its evolution, becoming a second white dwarf (with or without CV phase), and the two degenerate stars then spiral together as angular momentum is drained from the system by gravitational radiation (Dyson 1963; Kraft, Mathews & Greenstein 1962) or magnetic braking (Taam 1983; Patterson 1984).

The transferred material will be largely helium or carbon and oxygen, with a normal admixture of heavier elements. This will neither flash nor contaminate the eventual spectrum. And the time available is expanded by however long it takes the pair to spiral together—anything from 10^8 to $>10^{10}$ yr, for plausible initial separations, with the longer times perhaps more likely.

In addition, the merger process can provide a good deal of extra heating, so that considerably less than a Chandrasekhar mass may be able to detonate. The white-dwarf-red-giant death spiral scenario of Sparks & Stecher (1974) shares this last advantage. And models where the donor star has already been stripped to a helium star avoid the hydrogen shell flash problem (Fujimoto & Sugimoto 1982). But only the double degenerate dwarf version has all three virtues. Webbink (1979) mentioned the possibility in a single sentence, while Tutukov & Yungelson (1979) approached it peripherally. The first extensive discussion (Paczyński 1983) remains unpublished, and I first heard of it (B. Paczyński, personal communication 1982) in connection with the problem of identifying pre-explosion systems. Recent detailed scenarios have been published by Iben & Tutukov (1984) and Webbink (1984).

Among the unanswered questions are how can we identify the precursor pairs and how many of them exist. The current white dwarf formation rate in the galaxy is about 0.5–1.0 yr^{-1} (Guseinov, Novruzova & Rustamov 1983; Weidemann & Koester 1983), so we need 2–5 per cent of existing white dwarfs (in steady state) to be reasonably massive binaries with timescales for angular momentum loss $\lesssim 10^{10}$ yr to keep up the SN I rate. The number presently known is zero. The three very close double white dwarfs (prototype AM CVn) all have total masses $\lesssim 0.5\ M_\odot$, which will not do (Nather 1985). And known more massive systems (like the Sanduleak–Pesch object, Greenstein, Dokz & Vauclair 1983; and G107-70, Harrington, Christy & Strand 1981) are visual binaries, with spiraling-in timescales rather in excess of the lifetime of the proton. Double degenerate dwarfs, even with orbital periods $\lesssim 3$ hr, are exceedingly unlikely to eclipse. Thus the proper phenomena to look for are variable radial velocity or spectral peculiarities (Paczyński 1983). Eggen (1984) has reported one white dwarf (CoD $-48°3636$) with possibly double lines (though I suspect these could be single broad lines with emission cores). And Greenstein & Trimble (1967) tabulated a handful of white dwarfs whose velocities were discordant on two or more apparently good 200 inch prime-focus-spectrograph plates. Observers with access to suitable instruments are invited to look for radial velocity variations $\gtrsim 100\ \mathrm{km\,s^{-1}}$ on timescales $\lesssim 3$ h for these stars and any others that appeal to them.

4. Type II supernovae

Type II supernovae arise within Population I. This, at least, has not been disputed in recent years. The evidence is: (a) that they occur only in Hubble types with dominant young components, at a frequency that increases with blueness of the galaxy (Oemler &

Tinsley 1979), though their low rate in the latest types remains puzzling; (b) that, within these galaxies, they happen mostly in the spiral arms (Maza & van den Bergh 1976); and (c) that their distribution in galaxies is generally like that of the neutral hydrogen (Tammann 1977b).

The preference for spiral arms implies an association with the most massive, short-lived stars. The implied lower mass limit depends on details of gas speed and pattern speed that must vary considerably from one galaxy to another, but is surely $\gtrsim 4\ M_\odot$ (Moore 1973). Moore's suggestion that SN II's were further confined, to the leading edges of spiral arms, would have required progenitor masses $> 35\ M_\odot$ and has proven to be a false alarm (Maza & van den Bergh 1976), which is lucky, since such stars are very rare!

The scale height (z) distribution (distances away from the galactic plane) of SN II's and their remnants does not contradict the presumption of massive progenitors. Supernova remnants cannot be separated by type once they are old enough for their structure to be dominated by interactions with the interstellar medium; but the whole class has a scale height (~ 60 pc; Clark & Caswell 1976) comparable to that of the ISM and largely determined by it. Pulsar, on the other hand, have a scale height (300–400 pc) much larger than that of massive stars, but they are themselves high-velocity objects, and their distribution is consistent with birth in the galactic plane (Lyne 1982) where Population I is concentrated. Notice that 400 pc is still smaller than the widths of spiral arms, so that the relatively large pulsar scale height does not contradict their association with arms (Harding 1981).

For the SN II events themselves, information on scale heights is rather scanty. Four extragalactic events in edge-on galaxies yield $\langle z \rangle = 1000$ pc (Tammann 1977a, b). The two putative type II's in the Milky Way, SN 1054 and 1181 = 3C 58, have distances from the plane of about 200 and 400 pc. Tammann (in Rees & Stoneham 1982) attributes them to runaway OB progenitors, since they are too young to have moved so far from the plane since the supernova events! This does not apply to older pulsars, which could have acquired their high velocities either from asymmetric supernova explosions or from asymmetric radiation patterns over their $\sim 10^6$ yr lives.

4.1 *Some Interesting Limits*

An additional constraint on the masses of SN II parents comes from the observed rate—there have to be enough progenitors to make the events we see! The constraint is not a perfectly clean one, since the SN II rate comes from external galaxies, and the Initial Mass Function (number of stars born per unit time per unit mass interval) can be measured only in the solar neighbourhood. Luckily, calculations of galaxy evolution suggest that a 'universal' IMF is a good first approximation (Tinsley 1980a, b). Nevertheless, even local determinations of the IMF differ by a factor of about 3 at the upper end (Lequeux 1979; Miller & Scalo 1979; Scalo 1985). Thus, even if a star's fate is a unique function of its mass, Tammann's estimate of the local SN II rate tells us only that all stars more massive than 5.6 to 9.6 $M_\odot$ (or 3.7 to 13 $M_\odot$ if a factor of two uncertainty in the rate is admitted) must become supernovae. If rotation, duplicity, or other properties besides mass help determine a star's eventual fate, then the lower mass cut becomes even more uncertain. It is, anyhow, at least in the general ballpark of the number arrived at for the white dwarf—neutron star mass cut from consideration of open clusters and of the minimum mass that seems able to form a neutron star *via* core collapse.

Looking outside our own galaxy, Kennicutt (1984) finds that SN II's in Sc galaxies come from stars of greater than $8 \pm 1\ M_\odot$ on the basis of the correlation of rates of events with Hα luminosity of the galaxies harbouring them. Pennington, Talbot & Dufour (1982) have analyzed the regions of M 83 that produced 1923a and 1957d, interpreted as containing stars of a single age. They find progenitor masses (*i.e.* current main sequence turn off masses) of $18^{+22}_{-8}\ M_\odot$ and $11^{+5}_{-2}\ M_\odot$ for the two regions. The former event was a type II, the latter unknown. Finally, Thompson (1982) has examined a photograph serendipitously taken about six weeks before the 1980 supernova therein. The absence of a visible star at the SN position limits the progenitor mass to $\leqslant 18 M_\odot$.

4.2 *Supernova Remnants Containing Neutron Stars*

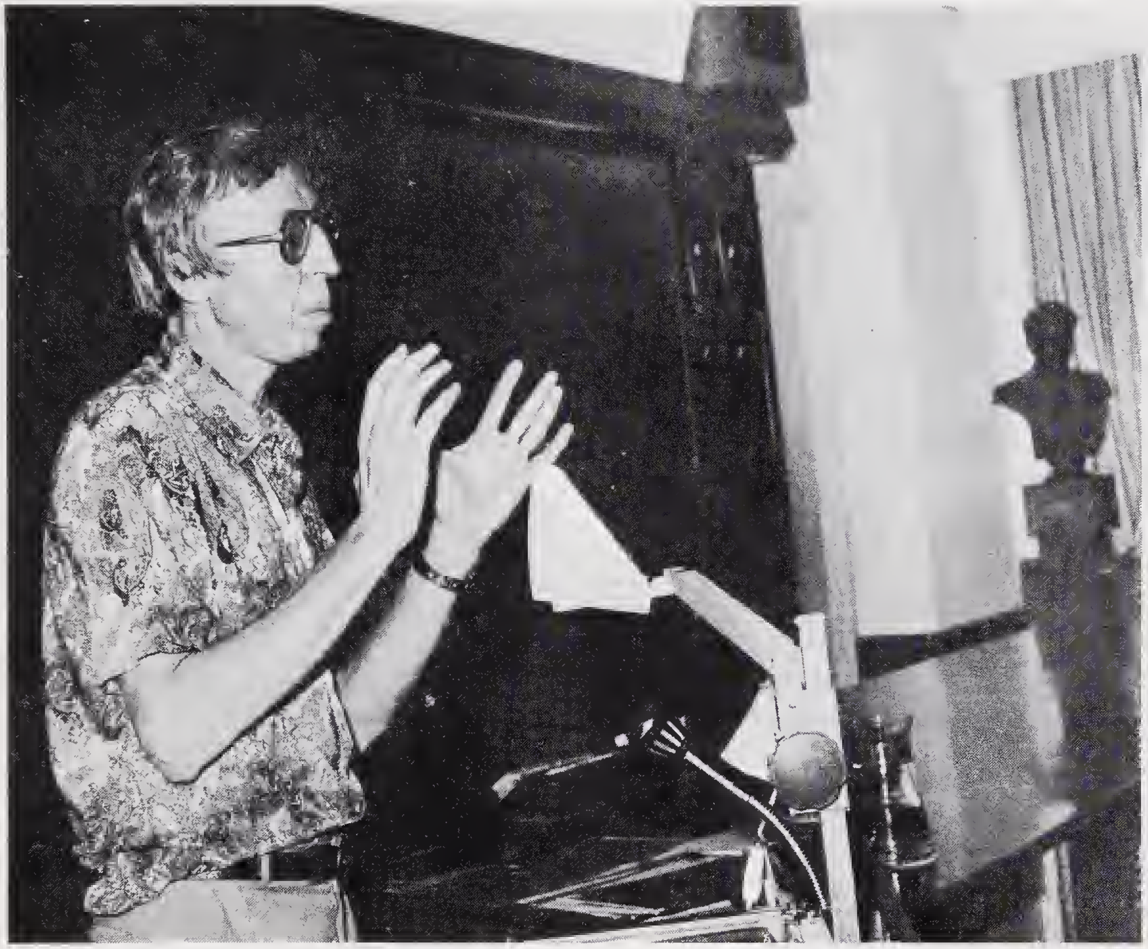
These are widely admitted to be rather rare, even when X-ray data for non-pulsing neutron stars is folded in. Possible explanations include black hole formation, a preponderance of type I's among, at least, the historical and other nearby remnants, and neutron stars that cool quickly and turn on magnetic fields slowly. A recent list of nine associations (Helfand & Becker 1984) can, at pleasure be reduced or augmented. Van den Bergh & Kamper (1984) suggest removing MSH 15–52 and its real (radio) but off-centre pulsar from the list as a chance superposition. Hughes *et al.* (1984) feel the same way about CTB 109 (the Fahlman–Gregory object) and its X-ray binary off-central object. In the other direction, 0540 – 693 in the LMC (Middleditch & Pennypacker 1984) looks increasingly like a real pulsar in a real SNR.

4.3 *Wolf-Rayets and the Hydrogen Envelope Problem*

The current majority viewpoint is that all or most single and wide binary OB stars shed their entire hydrogen-rich envelopes during post-main-sequence evolution, becoming first Of, then Wolf-Rayet stars (Conti *et al.* 1983; Falk & Mitalas 1983; Bertelli, Bressan & Chiosi 1984). This is very worrisome. Although 0.1–0.3 $M_\odot$ of H probably suffices to produce the spectral lines observed in SN II's (D. Branch 1984 personal communication), we need something like 3–5 $M_\odot$ of extended (*i.e.* $\sim 3 \times 10^{14}$ cm) hydrogen envelope to get the light curves right (Weaver 1984, personal communication; Woosley & Weaver 1984). If the pre-SN envelope is compact, most of the shock energy driving the event goes into expanding the envelope rather than into radiation, yielding a very dim SN. And if there is too little hydrogen in the envelope, its recombination cannot produce the prolonged plateau phase seen in most type II light curves.

Two recent studies may help reconcile progenitor behaviour with explosive behaviour. First, Schild & Maeder (1984) have looked again at numbers of OB stars *vs.* numbers of Wolf-Rayets and conclude that only stars in excess of 18 $M_\odot$ give rise to nitrogen-rich WR's (called type WN) and only those above 35 $M_\odot$ make the carbon-rich WC's. In addition, they find that most 18–40 $M_\odot$ stars need never go through a WR phase at all (*pace* Conti *et al. etc.*). This permits a reasonable range of intermediate mass stars to retain their extended, hydrogen-rich supergiant envelopes and make SN II light curves and spectra. The implication is that, if the progenitor of the Crab Nebula at


V L Trimble



$9 \pm 1\ M_\odot$ stripped most of its envelope before exploding, it was unusual in so doing (this is good; it helps explain the rarity of pure plerions).

In addition, Niemala, Ruiz & Phillips (1985) have been clever enough to catch the type II event 1983k in NGC 4699 nearly 10 days before maximum light. The pre-maximum spectrum showed NIII and HeII emission lines atop a strong blue continuum, suggesting a progenitor whose surface composition was that of a Wolf-Rayet. Near maximum light, the emission lines disappeared, leaving weak HI, HeI, and CaII absorption lines. A month after maximum, the spectra were dominated by P Cygni emission lines of HI. The implication is that we saw, first, emission from photospheric material as the shock wave emerged from the stellar core, then absorption in a normal-composition circumstellar envelope (shed by the star prior to core collapse), and, finally, emission lines from the hydrogen-rich zone when the shock reached and heated it. The light curve had a very broad peak, implying a very extended, pre-existing circumstellar shell. I am still not entirely happy about this, as in 30 days the photospheric radius (10,000 km s^{-1} × 86,400 s day^{-1} × 30 days) should only have swept up material shed in a 10 km s^{-1} wind over the past 90 years, surely less than 0.1 $M_\odot$, which suffices perhaps for the spectral lines but not the light curve in standard models. In addition, the event occurred 17 (75/H_0) kpc from the centre of its parent galaxy, in projection, and well away from any HII regions or spiral arms that could be seen in a deep CCD image, making a likely progenitor mass still harder to arrive at. The authors suggest something like the 7 $M_\odot$ red supergiant plus 1.7 $M_\odot$ circumstellar envelope studied by Falk & Arnett (1977).

4.4 *Models and the Envelope Ejection Problem*

A last constraint on type II progenitors comes from the necessity of transferring enough core-collapse energy to the envelope to eject it. A couple of years ago (Trimble 1983) things were looking pretty grim for all except possibly the smallest iron cores (belonging to the smallest stars capable of burning up to Fe). More recent work by K. Nomoto (1984, personal communication) and W. Hillebrandt (1984, personal communication) indicates that a shock wave set off by core bounce in 8–10 $M_\odot$ stars can be fed enough energy by oxygen burning in intermediate, infalling layers to keep going. And, in the 10–30 $M_\odot$ range, J. Wilson (1984, personal communication) finds that significant neutrino heating occurs at late times (after a second, rather than a millisecond) and so re-energizes stalled shocks, yielding the requisite ejection. Thus we seemingly have back again at our disposal the full range of progenitor masses needed to match observed SN II rates.

The effect of a close companion on a type II progenitor is, so far as I can tell (Trimble 1984) largely negative. That is, the enhanced massloss makes it much more difficult for a star to build up the 1.4 $M_\odot$ evolved core needed for collapse while retaining the extended, hydrogen-rich envelope required to produce a typical light curve. As a result, the most massive SN I progenitors (*e.g.* Chevalier 1984b) may well overlap the least massive SN II ones (Nomoto 1984b).

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Radio and X-ray Observations of Extragalactic Supernovae

K. W. Weiler *Division of Astronomical Sciences, National Science Foundation, 1800 G Street, N. W., Washington, D.C. 20550, USA*

Abstract. We present extensive new results on several radio supernovae (RSN) and discuss in det!il their analysis and modelling. Additionally, we collect the available results on other RSN for consideration. With this extensive and unique data set, we investigate the class properties of the RSN and derive descriptive parameters for the gross features of their 'light curves.' These are then applied to the several models available for the phenomenon to investigate their relative merits and their relations to the at least two distinct types of supernovae.

The results, based on an albeit very limited statistical sample, are that all RSN (3 examples) turn on very sharply in the radio with the turn-on occurring first at shorter wavelengths (higher frequencies) and progressing to longer wavelengths (lower frequencies) with time. This part of the phenomenon appears best explained, in all three cases, by a change of optical depth of thermal free-free absorption. This turn-on is obviously affected by the amount of thermal material in the vicinity of the supernova and the velocity of the supernova shock wave and has been observed to vary at 6 cm wavelength from 11 days before (SN 1983.51, type I supernova), to 1 month (SN 1980k, type II), to 1 year (SN 1979c, type II) after maximum optical light.

After this initially sharp turn-on, which has possibly the same physical origin for all RSN, a differentiation occurs. The type I supernova, SN 1983.51, shows a sharp decline of radio flux density ($t^{-1.6}$) at 6 cm with time after maximum and a relatively steep spectral index ($\alpha = -1.0$) while the two type II supernovae, SN 1979c and SN 1980k, show slower rates of decline ($t^{-(0.6-0.9)}$) and flatter ratio spectral indices ($\alpha = -0.6$). When available, models are applied to this optically thin part of the radio light curves, an excellent agreement between the light curve for the type I supernova, SN 1983.51, and the external shock-driven or 'mini-shell' model argues strongly for correctness. For the slower light curves of the type II supernovae SN 1979c and SN 1980k, none of the presently available models gives such an exact fit as that for SN 1983.51 and either external shock-driven 'mini-shell' or centrally-(pulsar-)driven 'mini-plerion' models provide reasonable fits to the gross properties.

As a supplement to this extensive radio information, the limited information available in the X-ray range, one definite detection of SN 1980k and several upper limits at different times for SN 1980k and SN 1979c, is presented and discussed. Finally, possible radio-supernova–supernova-remnant (RSN–SNR) relations are briefly discussed and new lines of study are suggested.

Key words: Supernovae, radio observations—supernovae, X-ray observations—supernovae, relationship with SNR

1. Introduction

Several hundred extragalactic supernovae have been identified by their optical light and catalogued since the first modern detection of a supernova (S Andromeda) in the nearby Andromeda Nebula (M 31) by Hartwig at the Tartfu Observatory in 1885. However, numerous searches at the positions of many tens of these objects for years revealed no detections to the limits of the largest and most sensitive radio telescopes available (see *e.g.*, de Bruyn 1973; Brown & Marscher 1978; Ulmer *et al.* 1980; Weiler *et al.* 1981; Cowan & Branch 1982) with the single exception of the supernova SN 1970g in M 101 (Gottesman *et al.* 1972). This last, showing itself as a weak increase in the integrated flux density from a region containing the position of the supernova and a nearby confusing HII region, nevertheless allowed the determination of a very rough radio 'light curve' (Allen *et al.* 1976). In the following decade, no more information on the radio emission from supernovae was obtained until SN 1979c in M 100 (NGC 4321) was found to be a powerful emitter of 6 cm radio emission in 1980 April (Sramek, van der Hulst & Weiler 1980; Weiler *et al.* 1981). Stimulated by this clear evidence that supernovae are significant sources of radio emission and that the study of these 'radio supernovae' (RSN) provides important information on the properties of the progenitor stellar systems and their immediate circumstellar environments, the detection and study of additional examples has progressed rapidly. Detailed radio light curves and spectral index properties have been determined for two type II supernovae (SN 1979c and SN 1980k), and for one type I supernova, SN 1983.51 (Sramek, Panagia & Weiler 1984), and very low upper limits or detections have been obtained for a number of other historical supernovae with ages ranging from < 1 to ~ 100 yr.

Here we attempt to summarize the knowledge presently available for RSN, essentially all of which has been obtained with the VLA*, with primary concentration on those from which the vast majority of detailed information about RSN has been obtained—the two type II supernovae, SN 1979c and SN 1980k, and the type I supernova SN 1983.51. Detailed model discussions are also presented.

2. Results

The general properties of all historical radio supernovae† known to the authors, along with those of their parent galaxies, are listed in Table 1. The supernova name in column 1 is given in the notation of year of optical discovery plus an alphabetical letter for sequence of discovery or in the notation of date of optical discovery expressed in decimal years. (*e.g.*, the supernova discovered optically on 1983 July 3 (Thompson 1983) has been designated SN 1983.51 from the discovery date and SN 1983n in the letter designation and the one radio-discovered supernova which was found first at radio

* The VLA (Very Large Array) is operated by the National Radio Astronomy Observatory through Associated Universities, Inc. under contract to the National Science Foundation.

† The category of historical radio supernovae is defined to include all radio sources with which a modern (*i.e.*, since 1885) historical optical supernova can be associated. The category includes such objects as SN 1981.58 where the radio source was identified first and then used to find an associated optical supernova but excludes such interesting and unusual, but optically unidentified, objects as the compact, variable radio sources in M 82 (see *e.g.*, Kronberg & Biermann 1983), the suspected young supernova remnant in NGC 4449 (see *e.g.*, Seaquist & Bignell 1978), and the centuries-old remnants of galactic supernovae (SN 1572-Tycho, SN 1604-Kepler, SN 1054-Crab Nebula, *etc.*).

Table 1. Radio supernovae.

	Position			SN optical maximum			Parent galaxy				
Name	RA (1950) h m s	Dec (1950) ° ′ ″	SN optical type	Date YY/MM/DD	Brightness m_v	Brightness M_B	Name	Class	Redshift[24] km s^{-1}	Dist[24] Mpc	References
SN1950b	13 34 03.8	−29 36 40.5	II?				NGC5236 (M83)	ScI-II	515	~7	29
SN1957d	13 34 14.3 ±0.1	−29 34 24 ±1.0	II?	57/12	≲17	< −12	NGC5236 (M83)	ScI-II	515	~7	1, 22, 23, 29
SN1970g	14 01 14.31±0.01	+54 28 56.2±0.2	II	70/08/01	11	−18.3	NGC5457 (M101)	Sc	402	7.2	8, 9, 10, 15
SN1979c	12 20 26.71±0.01	+16 04 29.5±0.2	II	79/04/19	12.2	−18.8	NGC4321 (M100)	ScI	1546	~16	2, 3, 4, 5, 6, 7, 11, 12, 15, 17
SN1980k	20 34 26.68±0.01	+59 55 56.5±0.2	II	80/11/05	11.2	−19.0	NGC6946	ScI	43	11	11, 12, 13, 14, 17
SN1981b*	12 31 56.3 ±0.03	+02 28 31.0±0.2	I	81/03/01	11.9	−19.6	NGC4536	Sc	(1800)	(20)	11, 12, 16
SN1981.58	12 16 31.23±0.15	+47 36 08.3±1.0	I?	~81/08/15	~13	~ −16	NGC4258	Sc	470	6.6[20]	18, 19, 20
SN1983.51 (SN1983n)	13 34 02.05±0.01	−29 38 46.1±0.1	I	83/07/17	~11.1	~ −18.2	NGC5236 (M83)	ScI-II	515	~7	21
SN1984.01*	12 24 24.01	+15 19 53.7	I	84/01/10	~12.8		NGC4419				25, 26, 27, 28

*Undetected at 6 cm, but new detection limits are reported here.

References:

1. Cowan & Branch (1982)
2. Weiler *et al.* (1981)
3. Johnson (1979)
4. Rosino *et al.* (1979)
5. de Vaucouleurs (1979)
6. Panagia *et al.* (1980)
7. Weiler & Sramek (1980)†
8. Gottesman *et al.* (1972)
9. Allen *et al.* (1976)
10. Deter (1970)
11. Weiler *et al.* (1983)
12. Weiler *et al.* (1982)
13. Wild (1980)
14. Sramek, van der Hulst & Weiler (1980)
15. Sandage (1961)
16. Wood (1981)
17. Sramek, Weiler & van der Hulst (1982)
18. Wild (1983)
19. Hummel *et al.* (1983)
20. van der Hulst *et al.* (1983)
21. Sramek, Panagia & Weiler (1984)
22. Pennington & Dufour (1983)
23. Pennington, Talbot & Dufour (1982)
24. Sandage & Tammann (1975)
25. Aksenov (1984)
26. Rosino (1984)
27. Rafanelli & Iijima (1984)
28. Argyle (1984)
29. Cowan & Branch (1984, 1985)

†(Circular confuses the position of the SN with that of a nearby radio source 1220+160)

wavelengths and later associated with an optical object photographed on 1981 August 1 (van der Hulst *et al.* 1983) has been designated SN 1981.58. The latter has no letter designation since it was not recognized as a supernova at the time of its optical visibility.) Of these known examples, there are only four supernovae which have detailed radio measurements: SN 1970g, SN 1979c, SN 1980k, and SN 1983.51 (SN 1983n). Of these 4 RSN, SN 1970g is relatively poorly observed and difficult to study in detail.

2.1 *SN1970g*

Because of generally large flux-density-measurement errors plus confusion from the nearby H II region NGC 5455, measurement of the radio light curve of SN 1970g is not straightforward. References for the available measurements are given in Table 2 and the results have been summarized earlier by Allen *et al.* (1976) and by Marscher & Brown (1978).

Most of the uncorrected measurement points, however, are only upper limits and all are contaminated by emission from NGC 5455. If we only consider those data for which:

(1) significant radio emission is detected from the region (*i.e.*, not upper limits),
(2) the detected emission is significantly greater than the measurement error (*i.e.*, $S > 2\sigma$), and
(3) the combined flux density detected is significantly greater than that expected for NGC 5455 alone (assuming NGC 5455 to be of constant flux density with time),

then only a few data points remain of which only four show reasonably clear detections of SN 1970g. These results are summarized, along with the most significant of the nondetections, in Table 2.

In order to remove the influence of NGC 5455, it is necessary to estimate its flux density and correct for it. Allen *et al.* (1976), from their pre- and post-outburst measurements at 6 cm when the supernova was undetectable, obtain estimates of 5.4

Table 2. Radio measurements of SN 1970g in NGC 5457 (M 101)*

Date YY/MM/DD	Time since optical maximum days	NGC5455 + SN 1970g mJy	Estimated flux density of NGC5455 mJy	SN flux density 49 cm mJy	SN flux density 20 cm mJy
70/08/01	0				
70/12	~ 140	6.6 ± 1.0	6.9 ± 1 (20 cm)		0 ± 1.4
71/12	~ 500	12.2 ± 0.9	6.9 ± 1 (20 cm)		5.3 ± 1.4
73/06	~1050	9.6 ± 2.7	6.9 ± 1 (20 cm)		2.7 ± 2.9
73/09	~1140	12 ± 2	7.6 ± 1 (49 cm)	4.4 ± 2.2	
73/12	~1230	12.8 ± 1.3	6.9 ± 1 (20 cm)		5.9 ± 1.6
74/03	~1320	13 ± 2	7.6 ± 1 (49 cm)	5.4 ± 2.2	
74/10	~1540	7.5 ± 0.8	6.9 ± 1 (20 cm)		0.6 ± 1.3
75/01	~1630	10 ± 2	7.6 ± 1 (49 cm)	2.4 ± 2.2	

*Data from Allen *et al.* (1976); (see also Marscher & Brown 1978)

± 0.7 mJy and 6.2 ± 0.9 mJy for NGC 5455 contained within a region < 4.5 arcsec $\times$ 13 arcsec in size. Thus, taking the approximate flux density value of 6 ± 1 mJy at 6 cm and using the expected spectral index of $\alpha = -0.11$ for an optically thin H II region, we obtain the flux density estimates of 6.9 ± 1 mJy and 7.6 ± 1 mJy for the H II region at 20 and 49 cm, respectively. These values have been subtracted from the measured total flux densities in Table 2 to yield the flux density estimates for SN 1970g.

The general conclusions which can be drawn for 1970g are that it showed a relatively late turn-on time t_1 in the radio at 20 cm (4 months $< t_1 <$ 16 months) and thereafter its flux density remained relatively constant for the considerable time interval t_2 of 16 months $< t_2 <$ 40 months. There is some evidence for a relatively sharp 20 cm turn-off at time t_3 in the interval (40 months $< t_3 <$ 50 months). At an age of $>$ 10 years it is undetectably weak in the radio range (R. A. Sramek 1983, personal communication).

2.2 *SN*1979*c*

SN 1979c was discovered near maximum light on 1979 April 19 (thus SN 1979.30) $\sim$ 100 arcsec SE of the nucleus of the galaxy M 100 (NGC 4321) by the amateur astronomer G. E. Johnson (1979) of Swanton, Maryland. It quickly became an object of intensive study in many wavelength ranges (Panagia *et al.* 1980) and has been firmly established as a peculiar type II supernova of the 'L' or 'linear' subclass. Its properties in many wavelength ranges have been summarized by Panagia *et al.* (1980) and in the radio range by Weiler *et al.* (1981, 1982, 1983). Additional references are given in Table 1.

The radio information available on SN 1979c is quite extensive. Since the initial detection of 6 cm radio emission on 1980 April 6 at an age for the supernova of approximately one year, monitoring has been carried out at both 6 and 20 cm at a rate of approximately once per month with the VLA. At much less frequent intervals, observations have also been done at 2 cm and very rough light curves obtained at that wavelength. The available data are plotted in Fig. 1. The change of the spectral index (α) between 6 and 20 cm with time is shown in Fig. 2, with the convention $S \propto \nu^{+\alpha}$.

2.3 *SN* 1980*k*

When the bright type II supernova 1980k exploded in NGC 6946 at the beginning of 1980 November (Wild 1980), an attempt was quickly made to detect it at 6 cm wavelength with the VLA. The initial attempt on 3 November was unsuccessful, but a month later, at an age after optical maximum of only 31 days, the supernova was detected and monitoring begun (Weiler *et al.* 1982; Sramek, Weiler & van der Hulst 1982). The supernova also turns out to have been of the 'L' or 'linear' subclass of type II supernovae as was SN 1979c (N. Panagia 1983, personal communication). Regular observations of 1980k were carried out in much the same way as those for SN 1979c.

Additional references for SN 1980k are given in Table 1. The radio light curves for SN 1980k are plotted in Fig. 3 and the change of spectral index (α) between 6 and 20 cm is shown in Fig. 4, both in a manner similar to that used for SN 1979c.

SN 1980k has the distinction of being the only supernova which has ever been detected in the X-ray range, that measurement giving but a single data point. At an age

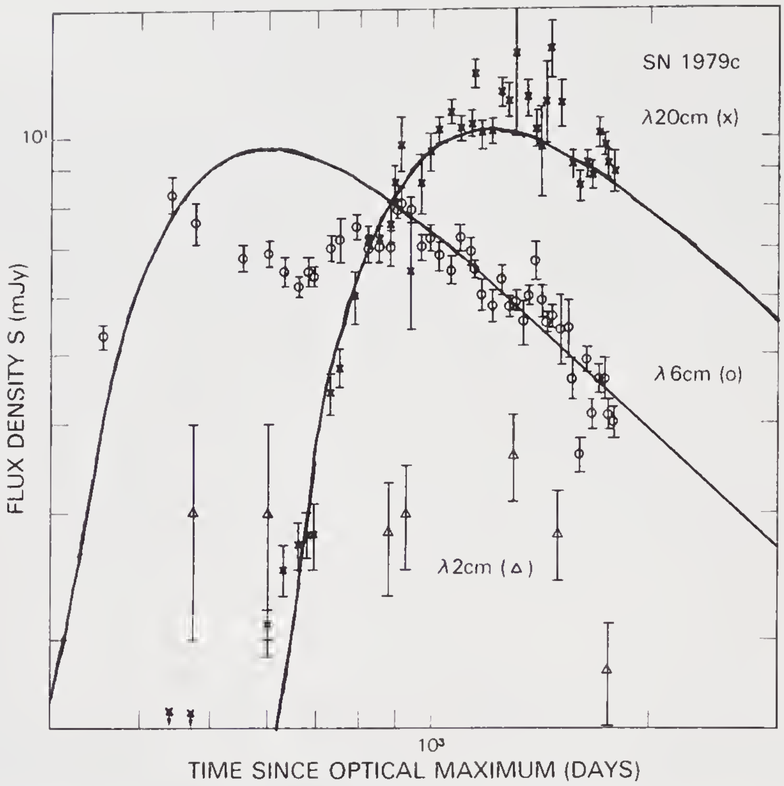

Figure 1. Radio 'light curves' for the type II supernova SN 1979c in NGC 4321 (M 100). All three wavelengths measured with the VLA are shown together; 20 cm (×), 6 cm (o), and 2 cm (Δ). The 'age' of the supernova is measured in days from the date of maximum optical light on 1979 April 19. The solid lines represent the 'best' fit of curves of the form $S = K_1 \nu^{\alpha} t^{\beta} e^{-\tau}$ where $\tau = K_2 \nu^{-2} t^{\delta}$ (see Section 3 and Table 3).

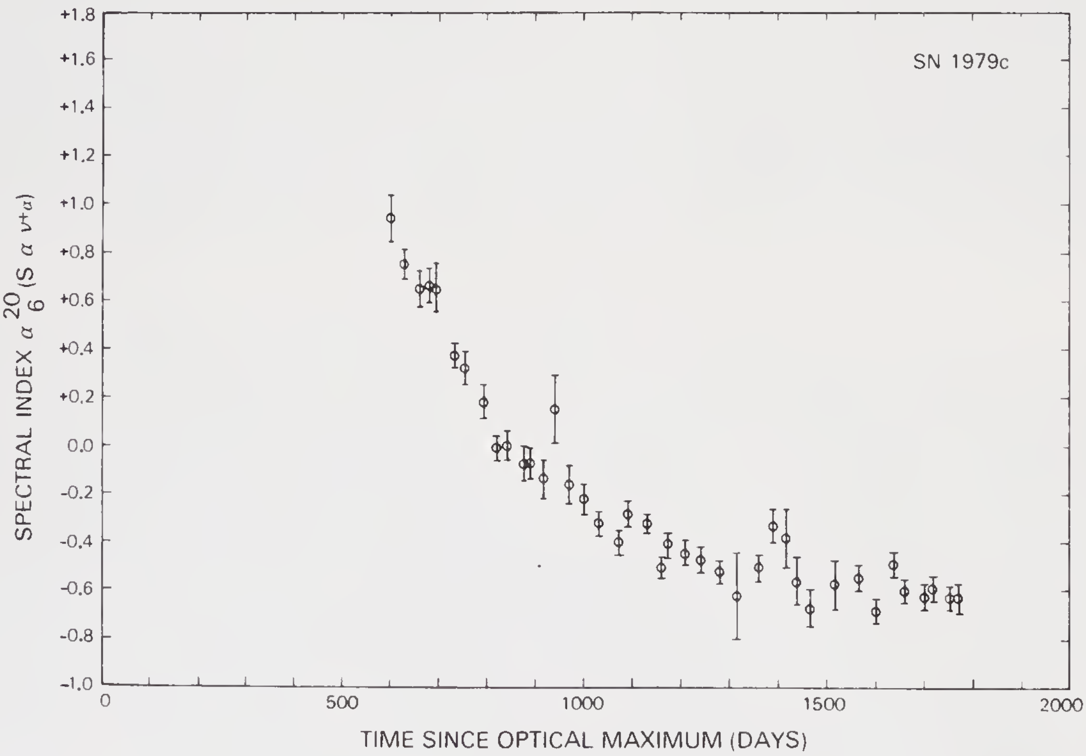

Figure 2. Spectral index (α) for SN 1979c between 20 cm and 6 cm ($S \propto \nu^{+\alpha}$) plotted as a function of time in days since maximum optical light on 1979 April 19.

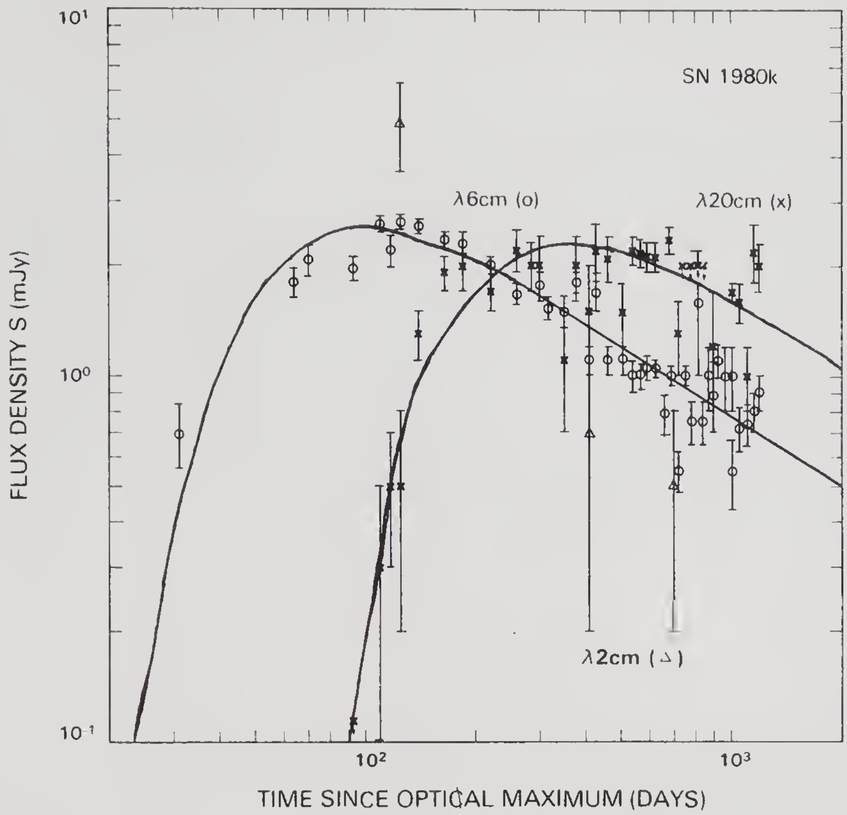

Figure 3. Radio light curves for the type II supernova SN 1980k in NGC 6946. All three wavelengths measured with the VLA are shown together as in Fig. 1. The age of the supernova is measured in days from the date of maximum optical light on 1980 November 5. The solid lines represent the 'best' fit of curves of the form $S = K_1 \nu^{\alpha} t^{\beta} e^{-\tau}$ where $\tau = K_2 \nu^{-2} t^{\delta}$ (see Section 3 and Table 3).

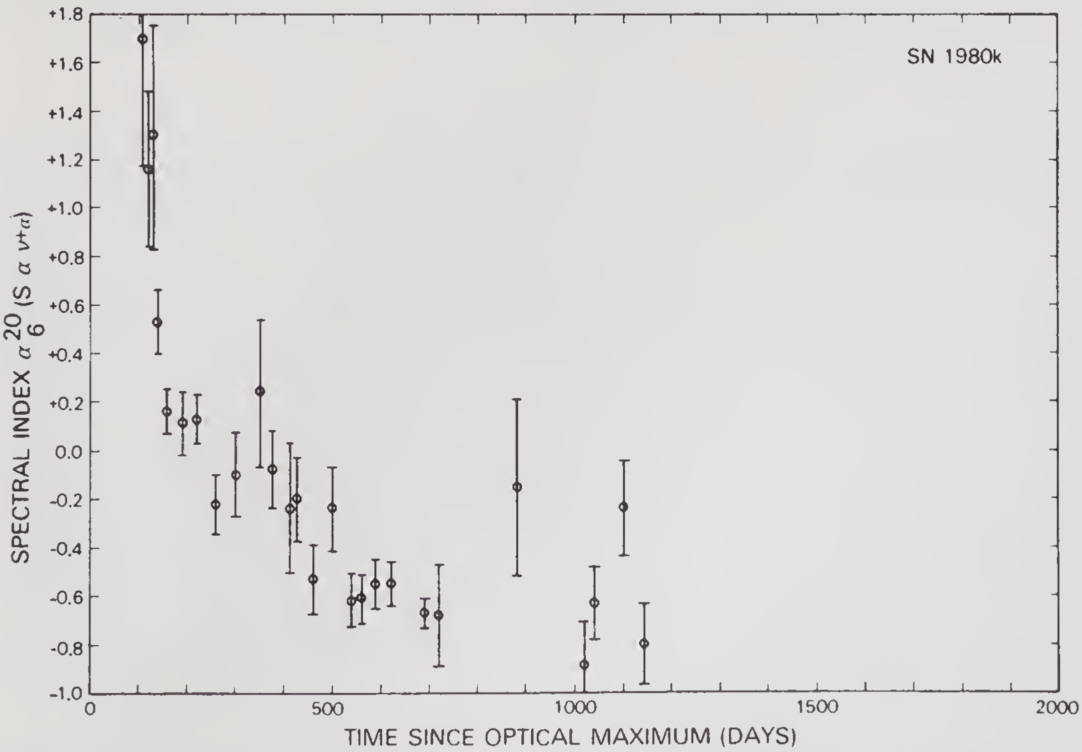

Figure 4. Spectral index (α) for SN 1980k between 20 cm and 6 cm plotted as a function of time in days since maximum optical light on 1980 November 5.

of 35 days after optical maximum, the Einstein satellite measured an X-ray luminosity of $\sim 2 \times 10^{39}$ erg s^{-1}. By an age of 85 days, X-ray radiation was no longer detectable with the Einstein satellite. All other attempts to detect type I or Type II supernovae in X-rays have been unsuccessful. Because there is only a single data point for the X-ray emission from supernovae, the discussion of mechanisms is very limited and few can be ruled out. At present, the two possible mechanisms to explain the observed X-rays are (1) inverse Compton scattering of relativistic electrons on optical photons or (2) a thermally hot plasma created by a shock propagating through a circumstellar shell left by the stellar wind of the massive supernova progenitor star in its last stages of evolution. Either mechanism can be made to work and give the observed value. Canizares, Kriss & Feigelson (1982) favour the inverse Compton mechanism, while Chevalier (1983) favours the thermal mechanism.

2.4 *SN* 1981*b*

SN 1981b was discovered optically by Wood (1981) in the Galaxy NGC 4536 and reached maximum optical light on approximately 1981 March 1. It was a type I supernova and although fairly distant, ~ 20 Mpc, monitoring at 6 cm with the VLA was started as soon as possible. The first radio observation was taken on 1981 March 11 and produced a rough upper limit of < 0.3 mJy (3σ) at 6 cm. Examination of the position of the supernova was continued approximately every quarter until 1983 February with upper limits as low as < 0.18 mJy (3σ), but no detections. At that point, the search for radio emission from SN1981b was suspended.

2.5 *SN* 1981.58

In 1982 January, van der Hulst *et al.* (1983) used the VLA to produce a 20 cm continuum map of NGC 4258. This showed an unresolved radio source of 5.5 mJy at position α (1950) $= 12^{h}16^{m}31^{s}.23$, δ (1950) $= +47^{\circ}\ 36'\ 08''.3$ which had not been present in previous continuum maps of the galaxy in 1974–1975 and 1979 to a limit of < 0.25 mJy at that wavelength (van der Hulst *et al.* 1983). Subsequent observations with both the Westerbork Synthesis Radio Telescope (WSRT) and the VLA confirmed the reality of the source and showed it to be decreasing in flux density with time. Its radio spectrum was determined to be nonthermal with an index of $\alpha \simeq -1.06 \pm 0.25$ ($S \propto \nu^{+\alpha}$). These results led the authors to conclude that the source could be the radio emission from an unidentified optical supernova which probably occurred between 1981 May, when a 6 cm WSRT map did not show a radio source at that position, and their discovery in 1982 January. Optical searches by Wild (1983) and Sargent & Kowal (van der Hulst *et al.* 1983) identified a transient optical object near the radio position with an earliest detection apparently on 1983 August 1 (hence the designation SN 1981.58) and an optical maximum near the middle of that month.

By agreement with the original discoverers, we have added this supernova to our monitoring programme and are continuing to obtain observations approximately quarterly at both 6 and 20 cm with the VLA. The most recent results are also shown in Fig. 5.

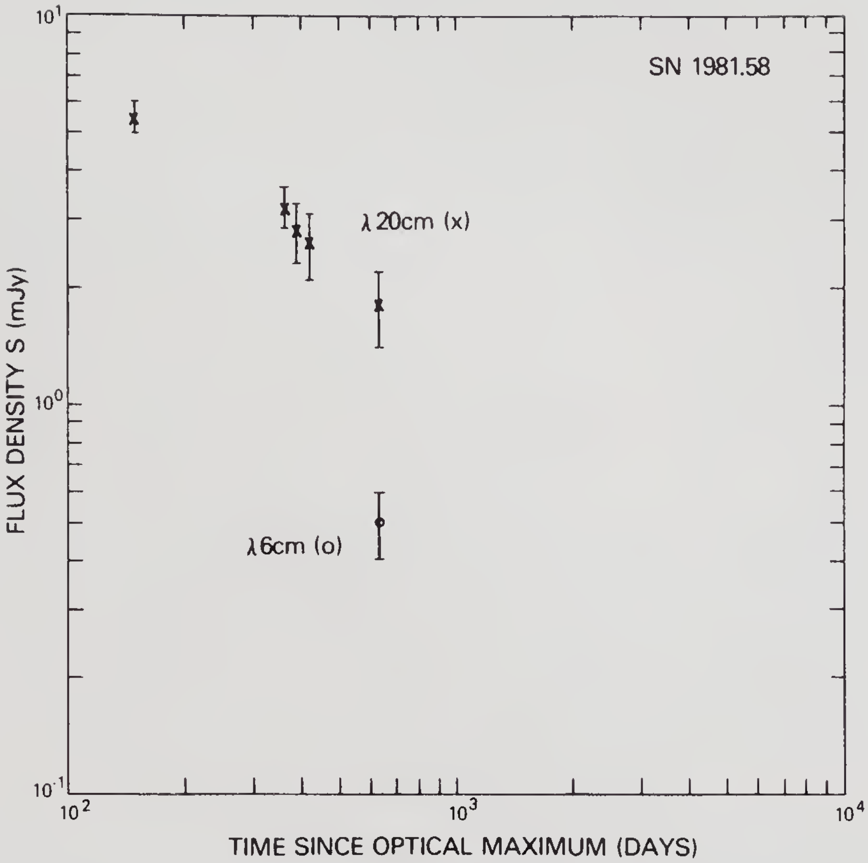

Figure 5. Radio light curves for the supernova SN 1981.58 in NGC 4258. Both wavelengths for which measurements are available are shown together as in Fig. 1. The age of the supernova is measured in days from the estimated data of maximum optical light on ~ 1981 August 15.

2.6 *SN* 1983.51 (*SN* 1983*n*)

SN 1983.51 was reported in the spiral galaxy NGC 5236 (M 83) by the Australian astronomer Robert Evans (Thompson 1983) and reached maximum optical light on 1983 July 17. Subsequent optical observations determined it to be a peculiar, apparently underluminous type I supernova (Panagia *et al.* 1985). Radio observations were started quickly and already on 1983 July 6, 11 days *before* maximum optical light, a detection at 6 cm with the VLA was obtained with a flux density of 2.0 ± 0.5 mJy. Subsequent monitoring at 6 cm, and after 1983 December at 20 cm, at a rate of approximately once per month established a rapidly declining radio light curve. The radio measurements, other observable properties of the radiation, a model for the progenitor stellar system, and a physical interpretation of the supernova mechanism have all been included in two recent papers by Sramek, Panagia & Weiler (1984) and Chevalier (1984). The results of the radio monitoring programme are shown in Fig. 6.

2.7 *Other RSN*

With the increasing sensitivity of observations with the VLA and with a number of radio detections of RSN demonstrating the viability of this new area of study, searches

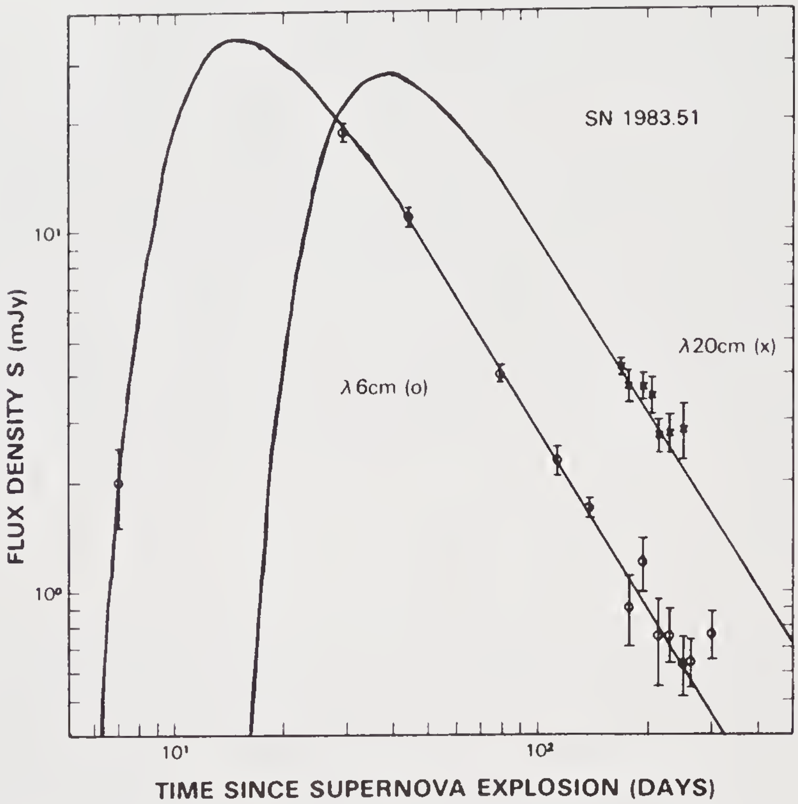

Figure 6. Radio light curves for the type I supernova SN 1983.51 (SN 1983n) in NGC 5236 (M 83). Both wavelengths measured with the VLA are shown together as in Fig. 1. The age of the supernova is measured in days from the estimated date of explosion on 1983 June 29. The solid lines represent the 'best' fit of curves of the form $S = K_1 \nu^{\alpha} t^{\beta} e^{-\tau}$ where $\tau = K_2 \nu^{-2} t^{\delta}$ (see Section 3 and Table 3).

for radio emission from known extragalactic supernovae and from newly discovered supernovae have led to a number of recent detections or very low upper limits. Since the number of candidates being examined and the rate of obtaining new detections or new limits is high, no absolutely complete list of known RSN can be given at any one time. However, beyond the examples discussed above, several other RSN have recently been discovered whose further study will certainly increase knowledge of the field.

SN 1957d was observed in 1957 December as a relatively faint optical supernova, possibly of type II in NGC 5236 (M 83). Cowan & Branch (1982, 1984) using the VLA have shown it to be a radio source of flux density 2.61 mJy at 20 cm and 1.9 mJy at 6 cm at an age of ~ 8500 days with a spectral index of $\alpha = -0.25$. More recent monitoring with the VLA reveals no significant change in the 6 cm flux density over a period of ~ 3 yr (Cowan & Branch 1984, 1985).

In their continuing studies of M 83, Cowan & Branch (1984, 1985) report the detection of 0.83 mJy flux density at 20 cm and 0.52 mJy flux density at 6 cm with spectral index $\alpha = -0.38$ probably associated with the optical supernova SN 1950b. Finally, of the results known to the authors, the type I supernova discovered in NGC 4419 by Aksenov (1984) has been studied with the VLA at 6 cm and an upper limit of 0.3 mJy (3σ) has been established for any radio emission on 1984 March 5.

3. Discussion

3.1 *Light curves*

In an attempt to impose some uniformity on the observations of RSN, the three supernovae where extensive data sets are available (SN 1979c, SN 1980k, and SN 1983.51—two type IIs and one type I, respectively), have each had their radio light curves fitted by the relation

$$S\,(\mathrm{mJy}) = K_1\, \nu^{\alpha}_{(\mathrm{GHz})}\, t^{\beta}_{(\mathrm{days})}\, e^{-\tau}$$

where

$$\tau = K_2\, \nu^{-2}_{(\mathrm{GHz})}\, t^{\delta}_{(\mathrm{days})}$$

and

$$\nu\,(\mathrm{GHz}) = 29.979/\lambda\ (\mathrm{cm}).$$

This formulation assumes that the change of flux density S and of optical depth τ with time since the optical maximum of the supernova (or since the supernova explosion, if known) are well described by power laws with powers β and δ as free parameters; the change of optical depth τ with frequency ν is assumed to be due to pure, external thermal absorption in an ionized hydrogen medium with frequency dependence ν^{-2}; and the change of flux density S with frequency ν is assumed to be due to nonthermal synchrotron emission with an optically thin spectral index α. K_1 and K_2 are two scaling parameters for the units of choice mJy, GHz, and days.

Because, especially for the two type II supernovae SN 1979c and SN 1980k, the above relation does not describe all of the details observable in the radio light curves very well, the 'best' values for the several free parameters must be viewed as reasonable but certainly not unique solutions. These values for the parameters are shown in Table 3 and the resulting curves are shown as the solid lines in Figs 1, 3, and 6.

3.2 *Properties*

Firm conclusions are impossible based on such a small sample of objects. This is even more hazardous since the general classes of optical supernovae, type I and type II, are gradually, on the basis of more modern and accurate observations, being broken into subclasses. Both SN 1979c and SN 1980k are members of the so-called linear or 'L' subclass of type II supernovae and SN 1983.51 was a peculiar, apparently underluminous type I supernova (Panagia *et al.* 1985). Finally, if models based on the radio

Table 3. Fitting parameters[a].

Name	SN Type	K_1	α	β	K_2	δ
SN 1979c	II	1.07×10^4	−0.56	−0.92	4.31×10^{10}	−3.54
SN 1980k	II	1.58×10^2	−0.59	−0.63	4.54×10^4	−1.89
SN 1983.51 (SN 1983n)	I	2.52×10^4	−1.04	−1.61	1.96×10^4	−2.64

[a]The radio 'light curves' are assumed to fit a curve of the form $S\,(\mathrm{mJy}) = K_1\, \nu^{\alpha}_{(\mathrm{GHz})}\, t^{\beta}_{(\mathrm{days})}\, e^{-\tau}$ where $\tau = K_2\, \nu^{-2}_{(\mathrm{GHz})}\, t^{\delta}_{(\mathrm{days})}$.

emission are correct, type I supernovae may be more dependent for their radio brightness on the properties of a companion star in a binary system than on the properties of the supernova itself and SN 1983.51 may have been uniquely bright in its radio emission (Sramek, Panagia & Weiler 1984).

However, with these limitations in mind, some preliminary conclusions may be drawn from inspection of the light curves and the values in Table 3:

(1) Type II supernovae (SN 1979c and SN 1980k) show a consistently flatter nonthermal spectral index ($\alpha \sim -0.6$, $S \propto \nu^{+\alpha}$) than type I supernovae (SN 1983.51) ($\alpha \sim -1.0$).
(2) Type II supernovae show a slower decline of flux density with time ($\beta \sim -0.6$ to -1.0; $S \propto t^{\beta}$) than type I supernovae ($\beta \sim -1.6$).
(3) If one assumes that free-free thermal absorption by surrounding matter (see below) is the principal cause of delay in the RSN 'turn-on,' there are apparently a wide range of environments surrounding the supernovae of both types. Generalizations at present are impossible because of this great variation, but there may be weak evidence for later appearance of type II supernovae ($\sim$ 1 *month* (1980*k*) *and* $\sim$ 1 year (1979c)) after maximum optical light than of type I supernovae ($\sim$ 11 days (SN 1983.51) *before* maximum optical light).

To consider point (3) further, this lack of strong distinction between the SN types in their optically *thick* radio properties implies a great variation in SN environments. However, the tendency for type II supernovae to 'turn on' later in the radio is generally consistent with a model where massive ($> 8\ M_{\odot}$) red-supergiant progenitors establish their own local environment through massloss in the last stages of stellar evolution. A range of masses gives a variation in massloss rates and a difference in free-free absorption effects, but all are relatively high. On the other hand, the progenitors for type I supernovae are considered under some models to be white dwarfs in interacting binary systems. The companion star is insufficiently massive ($2 < M_{\odot} < 8$; Arnett 1982) to become a type II supernova but is in its red-supergiant phase and losing mass rapidly. Through this massloss, it provides both the mass for accretion to its white dwarf companion which triggers the white dwarf as a type I supernova and for the stellar wind environment, similar to that for type II supernovae but less dense from this smaller mass star, where the radio absorption takes place (Sramek, Panagia & Weiler 1984).

3.3 *Models*

There are a number of models to describe the origin and development of the radio emission from supernovae. These vary greatly in their details and can involve at least three different absorption mechanisms to produce the optically thick part of the light curves, with two possible variations of one of these, and two intrinsically different nonthermal radiation mechanisms to produce the optically thin part of the light curves, with, again, two variations of one of these.

The optically thick part of the observations can conceivably have the three absorbing mechanisms: (1) the Razin–Tsytovich effect, (2) synchrotron self-absorption and (3) thermal free-free absorption, with this last separable into variations (a) internal or (b) external thermal gas absorption. For the optically thin part of the data, the two mechanisms suggested have been: (1) shock acceleration of relativistic electrons (and/or positrons) in a region external to the supernova photosphere and (2) 'pulsar' acceleration by the supernova stellar remnant with the two variations (a) observing at a frequency ν above a certain critical 'break' frequency ν_b ($\nu_{obs} > \nu_b$) and (b) its converse ($\nu_{obs} < \nu_b$). For simplicity, we have labelled these two main classes of relativistic particle acceleration mechanisms (1) 'mini-shell' from the resemblance of the shock model to shell-type supernova remnants like Cassiopeia A, the remnant of Tycho's supernova 3C 10 (SN 1572), *etc.* and (2) 'mini-plerion' from the resemblance of the 'pulsar' generation model to plerionic supernova remnants like the Crab Nebula (SN 1054), 3C 58 (SN 1181), *etc.*

In principle, this choice of four mechanisms (including variations) for absorption and three mechanisms (including variations) for emission requires us to consider 12 possible combinations to explain the observed radio light curves. Fortunately, however, most of these can be dismissed fairly readily. For example, Chevalier (1982) has discussed the four possibilities for the optically thick parts of the light curves and rejected the two cases (2: synchrotron-self absorption) and (3a: internal free-free absorption) as not important in the young RSN case. (It must be mentioned, however, that Bandiera, Pacini & Salvati (1984) prefer a synchrotron-self absorption mechanism.) Of the remaining two cases (1: Razin–Tsytovich effect) and (3b: external free-free absorption), the Razin–Tsytovich effect is not thought to be of importance under the local physical conditions by the time the supernova becomes observable in the radio (Marscher & Brown 1978). It will not be considered further here so that only external thermal free-free absorption appears important. According to Chevalier (1981a, b) it will have a form of

$$S \propto e^{-\tau}$$

with

$$\tau \propto \nu^{-2} t^{-3m}$$

where m is a model parameter ($0 < m < 1$) related to the time dependence of the radius of the supernova shock wave ($R \propto t^m$) and dependent on the amount of deceleration experienced by the supernova envelope. Values are expected to lie mainly in the range of $0.75 \lesssim m \lesssim 1.0$.

The three possibilities for the optically thin parts of the light curves, which, in principle, describe the evolution of the energy source, are less easily reduced, and require more discussion. The 'mini-shell' model involves the external generation of the relativistic electrons (and/or positrons) and the enhanced magnetic field necessary for synchrotron radio emission by a shock wave caused by the supernova explosion interacting with a high-density 'cocoon' surrounding the supernova system. This high-density volume is established by massloss in a stellar wind previous to the supernova explosion. Since such a shock interaction region is likely to be external to the supernova photosphere, there is little problem in allowing the radio radiation to escape after relatively little free-free absorption. This model has mainly been explored by Chevalier (1981a, b; 1983; 1984) with work also by Marscher & Brown (1978) and Fedorenko (1983). From the work of Chevalier (1984) its observable properties are given by

$$S \propto \nu^{(1-\gamma)/2} t^{-(\gamma+5-6m)/2} \qquad \text{(mini-shell)}$$

where γ is related to the optically thin radio spectral index α ($\gamma = 1 - 2\alpha$; $S \propto \nu^{+\alpha}$) and m is the same model parameter as is discussed above.

The 'mini-plerion' models involve a central source of generation of the relativistic electrons (and/or positrons) and the enhanced magnetic field necessary for synchrotron radio emission, presumably by the remnant of the supernova progenitor star which has become something like a pulsar, a rapidly rotating neutron star, or a black hole. This energy source builds up a volume of relativistic particles and magnetic fields, presumably resembling the very early Crab Nebula or other plerions. These models have been explored by several workers (Pacini & Salvati 1981; Shklovskiĭ 1981; Marscher & Brown 1978; Pacini & Salvati 1973; Bandiera, Pacini & Salvati 1983, 1984) and, for the two variations ($\nu > \nu_b$ and $\nu < \nu_b$) discussed above, predict (Pacini & Salvati 1973)

$$S \propto \nu^{-\gamma/2}\, t^{(1-\gamma/2)} \qquad \text{(mini-plerion, } \nu > \nu_b\text{)},$$

and

$$S \propto \nu^{(1-\gamma)/2}\, t^{(1-\gamma)/2} \propto \nu^{\alpha}\, t^{\alpha} \qquad \text{(mini-plerion, } \nu < \nu_b\text{)},$$

where $\gamma = 1 - 2\alpha$ and ν_b is a discontinuity or critical 'break' frequency in the electromagnetic spectrum related to the balance between continuing acceleration and decay of the relativistic electrons (see Pacini & Salvati 1973).

There is one obvious difficulty common to these centrally-driven 'mini-plerion' models and that is that on theoretical grounds one expects from one to several solar masses of material to be in the vicinity of the supernova explosion. Such a large amount of mass, even if only a small fraction of it were ionized, would totally preclude the observation of radio emission from a centrally-driven RSN for many decades. Two routes have been proposed to avoid this: (1) the matter in the supernova photosphere clumps very early into dense filaments which contain essentially all of the mass but block very little of the view into the centre of the supernova system *a la* Crab Nebula (Bandiera, Pacini & Salvati 1983); or (2) the magnetic field and relativistic particles generated by the central plerion 'leak' through the dense photosphere of the supernova, originating their radio radiation in an external region surrounded only by low-density matter (Shklovskiĭ 1981).

For the optically thin emission, the results for these three models are shown in Table 4. Comparison of the model predictions of this table and the results of fits to the optically thin data of a form $S \propto \nu^{\alpha}\, t^{\beta}$ given in Table 3 indicates that the mini-plerion case with $\nu > \nu_b$ is not a viable alternative. The two remaining models for the intrinsic synchrotron radiation both remain viable in principle. The undecelerated expansion of the supernova shell ($m = 1$, $R \propto t^{m}$) for the mini-shell model gives the same predictions as the mini-plerion ($\nu < \nu_b$) model and decelerated models provide, in some cases, even better fits.

Rather than explore these models in great detail at the present time, since that has already been capably done by their authors, we will concentrate on the larger question as to which models appear most likely to be able to describe the gross details of the observations. As will be seen below, both 'mini-shell' and 'mini-plerion' models can provide acceptable fits to some of the data.

3.4 *Comparisons*

Comparison of the available models with the observational data appears, at least in gross terms, to be relatively straightforward if one separates the RSN radio light curves into 2 regions: (1) an optically thick region at early times during the initial 'turn-on' phase giving us information on the predominant absorption mechanism and (2) an

Table 4. Synchrotron emission models, time and frequency dependence.

				Mini-shell[a] ($S \propto \nu^x t^y$)				Mini-Plerion[b] ($S \propto \nu^x t^y$)			
				$m = 1.0$		$m = 0.75$		$\nu < \nu_b$		$\nu > \nu_b$	
Name	SN Type	α ($S \propto \nu^{+\alpha}$)	γ ($\gamma = 1-2\alpha$)	x	y	x	y	x	y	x	y
1979c, 1980k	II	−0.6	2.2	−0.6	−0.6	−0.6	−1.4	−0.6	−0.6	−1.1	−0.1
SN 1983.51 (SN 1983n)	I	−1.0	3.0	−1.0	−1.0	−1.0	−1.8	−1.0	−1.0	−1.5	−0.5

[a] See Chevalier (1981, 1984). 'm' is a model parameter ($0 < m < 1$) related to the time dependence of the radius of the supernova shock wave ($R \propto t^m$) and dependent on the amount of decleration experienced by the supernova envelope. Values are expected to lie mainly in the range of $0.75 \lesssim m \lesssim 1.0$.

[b] See Pacini & Salvati (1973). 'ν_b' is a discontinuity or critical 'break' frequency in the electromagnetic spectrum related to the balance between continuing acceleration and decay of the relativistic electrons and/or positrons.

optically thin region at late times during the final 'decay' phase giving us information on the mechanism for producing the intrinsic, nonthermal synchrotron radiation observed.

Probably the greatest success for a model so far is the exceptionally accurate fit to the available data obtained for the type I supernova SN 1983.51 by the 'mini-shell' model (Sramek, Panagia & Weiler 1984; Chevalier 1984). For $\alpha = -1.0$ and $m = 0.8$ ($S \propto \nu^{-1.0}\, t^{-1.6}$), the radio observations are fit in essentially all particulars to such a degree as to virtually exclude consideration of alternative models (see Fig. 6). Such a correspondence between a type I supernova and a 'mini-shell' model is also very satisfying since it agrees, at least in principle, with the expectation that type I supernovae leave no stellar remnant (see *e.g.*, Weiler & Panagia 1980; Chevalier 1981a, b; Weiler 1983) to act as a central energy source for 'mini-plerion' models. These latter predict, in any case, a much shallower decline of flux density with time ($S \propto \nu^{-1.0}\, t^{-1.0}$), which is too shallow to fit the observations. The details of the stellar system can also be made to fit (Sramek, Panagia & Weiler 1984) the popular 'accreting white dwarf in a binary system' model for a type I supernova (see *e.g.*, Weaver, Axelrod & Woosley 1980).

The overwhelming success of the 'mini-shell' model for the type I supernova SN 1983.51 is not repeated for the type II supernovae SN 1979c and SN 1980k. They are both clearly different from SN 1983.51 having flatter radio spectra ($\alpha = -0.56$ (SN 1979c), $\alpha = -0.59$ (SN 1980k) *vs* $\alpha = -1.0$ (SN 1983.51)) and slower rates of decline after maximum ($\beta = -0.9$ (SN 1979c), $\beta = -0.6$ (SN 1980k) *vs* $\beta = -1.6$ (SN 1983.51)). Although both classes of models have been applied to the type II data ('mini-shell'—Chevalier (1981a, 1982); 'mini-plerion'—Pacini & Salvati (1981), Bandiera, Pacini & Salvati (1984)), neither fit the data precisely. A comparison of the measured parameters from the 'best' fit curves of the form $S \propto \nu^{\alpha}\, t^{\beta}\, e^{-\tau}$ for the optically thin phase ($\tau \sim 0$) given in Table 3 with the model predictions of the form $S \propto \nu^{x}\, t^{y}$ given in Table 4 shows that either of the two classes of models can be made to fit reasonably well.

However, examination of the actual form of the fitted curves shown in Figs 1 and 3 shows that the models do not describe the decline of the flux density very accurately. Also, on the optically thick, rising parts of the light curves, the available data points are not fit well and the time lag between the appearance of 6 cm emission and 20 cm emission, while approximately matched by the models, still shows some deviation.

Of the two examples, SN 1980k shows the closest fit between data and model and the results as shown by the solid curves in Fig. 3 are 'reasonable.' However, at 2 cm the first data point is far too high to be adequately described by the curve predicted from the 6 cm fit. At 6 cm a better fit for the rising part of the light curve would require a slower rise while at 20 cm the same portion of the curve appears to require a steeper rise. Additionally, the time lag predicted between 6 cm and 20 cm is not very close to the measured value. The initial decaying part of the light curves is not fit well at 6 cm, the curve being somewhat lower than the measured points, and the later part of the fitted curve, compared with the most recent measurements, may be dropping too rapidly at 20 cm.

SN 1979c shows even larger deviations between the data and the 'best' model curves. The 2 cm data, which has continually hovered at about 3 mJy, bears little resemblance to a model curve which requires much larger flux densities at early times followed by a rapid decay. At 6 cm, the time advance predicted over the 20 cm data does not appear to match, but has only one significant data point. More disturbing, after the initial peak in the data on day 437 the flux density declines until approximately day 700 when it again begins to rise (coinciding, perhaps accidentally, with a 'knee' in the rapidly rising 20 cm flux density at that time) which fits none of the simple models. After rising until approximately day 925, the 6 cm flux density again commences a decline which is reasonably well described by the form of the model prediction but with a suggestion, by the most recent data points, of an increasing, greater than power law rate of decline. At 20 cm, the initial rise is reasonably well described by the thermal free-free model but it appears to continue to a higher value of flux density and to decline less rapidly than the chosen model parameters would predict.

As discussed above, to the level of accuracy to which the data for these two type II supernovae are described by the model curves chosen, both the 'mini-shell' and 'mini-plerion' models remain viable. It must also be mentioned in passing that there is some theoretical support for the existence of something resembling a 'mini-plerion' in the centre of a type II supernova since this class of supernovae is expected to result in the formation of stellar remnants, such as pulsars or black holes, which could be energetic enough to drive the mechanism for the observed radio radiation. This assumes, of course, that some mechanism, such as those described in the preceding section, allows the radio radiation to escape.

3.5 *Old age*

The connection between these relatively young, well studied, but statistically few type II and type I RSN such as SN 1979c, SN 1980k, and SN 1983.51, and older, as yet relatively poorly studied and statistically few RSN such as SN 1957d and SN 1950b, to the well studied but statistically few very young, historical shell-type (Cassiopeia A, SN 1670; Kepler's supernova, SN 1604; Tycho's supernova, SN 1572; SN 1006) and plerionic (3C 58, SN 1181; Crab Nebula, SN 1054) supernova remnants (SNR), if there is any direct connection, is, as yet, relatively poorly explored and poorly understood (see also Cowan & Branch 1985). For a partial comparison, we have listed the intrinsic radio properties of the RSN in Table 5 and those of the youngest SNR in Table 6. Although a number of extragalactic variable radio sources in galaxies are thought, on relatively strong grounds, to be additional young SNR, applying the same criterion to the SNR (with the exception of the well-established case of Cas A) as we applied initially to the RSN, that of optical identification of the progenitor supernova, removes them from the present consideration. (For a more detailed discussion of these extragalactic SNR candidates, see *e.g.*, de Bruyn (1983), Seaquist & Bignell (1978), de Bruyn, Goss & van Woerden (1981), Kirshner & Blair (1980), Kronberg, Biermann & Schwab (1981), Kronberg & Bierman (1983).)

SN 1970g, SN 1979c, SN 1980k, and SN 1983.51 were all observed well enough in the optical at the time of their maxima that their optical types are well established, albeit with the subclass pecularities noted in earlier discussion. SN 1950b, SN 1957d, and SN 1981.58 were not well studied in the optical range, so that their types are not known *a priori* from older data. However, based on the radio information available for them and the assumption that the several RSN for which we have detailed radio information are typical of their classes, we can tentatively assign optical types to all three supernovae

Table 5. Intrinsic properties of radio supernovae (RSN).

Name	SN type	Dist. Mpc	Optical Max. m	Radio maximum: Observed peak 6cm mJy	Radio maximum: Spectral luminosity 6cm $\mathrm{erg\,s^{-1}\,Hz^{-1}}$	Radio maximum: Peak ratio to Cas A 6 cm	Optically thin radio spectral index α $(S \propto \nu^{+\alpha})$	Properties on 84/01/01: Age yr	Properties on 84/01/01: S_{6cm} mJy	Properties on 84/01/01: Angular[a] diameter mas[b]	Properties on 84/01/01: Physical[a] diameter pc
SN 1950b	II?	~7		0.5[6]	$\sim 3\times10^{25}$	~ 4	−0.4[6]	33.9	0.5[6]	10.5	3.6×10^{-1}
SN 1957d	II?	~7	≲17	1.9[6]	$\sim 1\times10^{26}$	~15	−0.25[6]	26.1	1.9[6]	8.1	2.7×10^{-1}
SN 1970g	II	7.2	11	~ 6	$\sim 3\times10^{26}$	~40	−0.7 ±0.1[2]	13.4	<0.1[4]	4.0	1.4×10^{-1}
SN 1979c	II	~16	12.2	8.3	$\sim 2\times10^{27}$	~250	−0.56±0.01	4.7	4.6±0.25	0.6	4.9×10^{-2}
SN1980k	II	11	11.2	2.6	3.5×10^{26}	~45	−0.59±0.18	3.2	0.9±0.1	0.6	3.4×10^{-2}
SN1981.58	I?	6.6	~13	~6[1]	$\sim 3\times10^{26}$	~40	−1.1 ±0.3[1]	2.4	≲0.5[3]	0.8	2.5×10^{-2}
SN1983.51 (SN1983n)	I	~7	~11.1	18.5	$\sim 1\times10^{27}$	~125	−1.0 ±0.2[5]	0.5	1.2±0.2[5]	0.2	5.3×10^{-3}

[a] Assumes an average radial expansion velocity of $5\times10^{3}\ \mathrm{km\,s^{-1}}$

[b] Milliarcsec (1 mas = 10^{-3} arcsec)

References:
1. van der Hulst *et al.* (1983)
2. Allen *et al.* (1976)
3. R. A. Sramek, K. W. Weiler & J. M. van der Hulst 1983, personal communication
4. Sramek (1983)
5. Sramek, Panagia & Weiler (1984)
6. Cowan & Branch (1984, 1985)

Table 6. Young galactic supernova remnants (SNR).

Supernova Name	SNR name	Optical SN type	Radio SNR type	Dist. kpc	Age (1984) yr	$S_{6cm}^{(1984)}$ Jy	Radio spectral index	Angular diameter arcsec	Physical diameter pc	Spectral luminosity 6 cm $erg\,s^{-1}\,Hz^{-1}$	Ratio to Cas A 6 cm	References
SN 1006		I	shell	1.3	978	8	−0.6	2000	13	2×10^{22}	0.002	3
SN 1054	Crab Nebula	II	plerion	2	930	660	−0.3	360	3.5	3×10^{24}	0.4	1, 2
SN 1181	3C58	II	plerion	8[a]	803	29	−0.1	480	18.5	2×10^{24}	0.25	1, 2
SN 1572	3C10, Tycho	I	shell	5	412	25	−0.6	500	12	7×10^{23}	0.1	3
SN 1604	Kepler	I	shell	10	380	7	−0.6	200	10	8×10^{23}	0.1	3
SN ~ 1670	Cas A	?	shell	2.8	314	900	−0.8	250	3.4	8×10^{24}	1.0	3

[a]Green & Gull (1982) prefer a distance of ~ 2.6 kpc

References:
1. Weiler (1983)
2. Weiler & Panagia (1980)
3. Clark & Caswell (1976)

based on two parameters, their optically thin spectral indices and the rates of decline of their radio flux densities. Both type II supernovae, SN 1979c and SN 1980k, have relatively flat spectral indices ($\alpha \sim -0.6$) and slow declines of their radio flux density ($S \propto t^{>-1}$) while the single type I supernova, SN 1983.51, has a steep spectral index ($\alpha = -1.0$) and a more rapid decline of its radio flux density ($S \propto t^{-1.6}$). Both SN 1950b and SN 1957d obviously decline slowly since they are still visible in the radio and both have flat radio spectral indices ($\alpha = -0.4$ and $\alpha = -0.25$, respectively) so that they were likely type II supernovae. On the other hand, SN 1981.58 exhibits a steep spectral index ($\alpha = -1.1$) and a rapid decline in flux density (see Fig. 5) so that it was possibly a type I supernova.

For comparison purposes, some of the properties of the galactic supernova remnants which have known ages due to optical observation of their outbursts (with the conspicuous exception of Cas A whose age is quite well established but whose optical supernova has not yet been clearly identified) are presented in a similar manner in Table 6. Measured rates of decline in flux density for the supernova remnants are all very small (< 1 per cent per year) and are poorly determined for all objects except for Cas A. Thus, this parameter, which appeared useful in the classification of RSN, is unavailable for SNR. The other useful classification parameter for RSN, the spectral index, has long been suggested (see *e.g.*, Weiler & Panagia 1980; Weiler 1983) as one characteristic separating SNR into plerions ($\alpha > -0.3$) and shells ($\alpha < -0.3$) (neglecting, for the moment, consideration of the more poorly understood combination (Class C) objects (see Weiler 1983)). That separation is, of course, apparent in Table 6. Comparison with Table 5 tempts one to suggest a relation between the flatter spectrum RSN from type II supernovae and the flat spectrum plerions, also thought to be generated by at least some type II supernovae. This leaves the steeper spectrum RSN of type I origin to relate with the steeper spectrum SNR shells, also of type I origin. Such a line of resoning is in agreement with the result that the single type I RSN, 1983.51, appears to fit a 'mini-shell' model extremely well while 'mini-plerion' models remain feasible for the two type II RSN, SN 1979c and SN 1980k. Because of the vast differences in age and the lack of direct observational or strong theoretical connection between RSN and SNR, however, such a connection remains quite speculative.

Although one expects SNR to be mainly determined by properties of the interstellar medium and RSN to be mainly determined by properties of the stellar remnant and the immediate stellar environment of the supernova, the possibility of direct development of these intrinsically bright RSN into older, fainter SNR must at least be considered. Any comparison must remain approximate, since Tables 5 and 6 show that the peak spectral luminosities of RSN (neglecting SN 1950b and SN 1957d which were first detected only long after their radio peaks) vary by a factor of ~ 10 and the spectral luminosities of SNR (neglecting SN 1006 which is the oldest of the group and appears to have been heavily affected by its local interstellar medium) also vary by a factor of ~ 10. However, assuming a simple power law decay from age ~ 0.5 yr and average spectral luminosity $F \sim 1.2 \times 10^{27}$ erg s^{-1} Hz^{-1} for the RSN to age ~ 500 yr and average spectral luminosity $F \sim 4.4 \times 10^{24}$ erg s^{-1} Hz^{-1} for the SNR with a form $F \propto t^{\beta}$, yields $\beta \sim -0.8$, a not unreasonable value compared to those found for the three well-studied RSN listed in Table 3. Such circumstantial evidence must still be strengthened with strong theoretical and/or observational evidence.

4. Conclusions

Although the radio supernova (RSN) phenomenon is very new, having been developed essentially in its entirety (except for one barely detected and poorly studied previous object) since the detection of SN 1979c in 1980 April (Weiler *et al.* 1981), its study has met with significant success during this relatively short interval. Multiwavelength radio light curves for two type II and one type I supernovae have been obtained; the number of high quality upper limits on other supernovae has been increased significantly; the number of definite detections of modern optical supernovae and the study of optically unidentified but possible 'older RSN' has increased dramatically; and a corresponding blooming of theoretical interpretation of the phenomenon has occurred. The gross structures of the radio light curves have been determined and can be related to the properties of the supernova's progenitor star, its immediate environment, and its likely state in the last stage of evolution before exploding.

The present work and the references given herein address all of these factors. Also, an attempt has been made to collect all presently available radio information on RSN in one place, analyze it in terms of available models, and, to a lesser extent, relate it to the star which preceeded it and the supernova remnant (SNR) which will follow it. Detailed model development is not within the scope of this paper but has been and will be treated separately elsewhere.

The study of the supernova phenomenon, as opposed to the study of supernova remnants, is a new one for radio astronomy, essentially opened up by the availability of the excellent resolution and sensitivity of the VLA. It has, so far, yielded detailed information on a very few objects (3) and sparse information on a very few more (~ 5). Its further development obviously must be directed to obtaining:

1. Detailed information on a few more cases, especially of type I supernovae, to confirm the suspected systematic differences between type I and type II and to check that the peculiarities of the presently available class representatives (SN 1979c and SN 1980k were both subclass 'L' type II supernovae and SN 1983.51 was a peculiar, subluminous type I) do not dominate the class characteristics.
2. Statistical information on what types of supernovae do indeed become RSN, both through observing a representative sample of supernovae of various ages at one given time and observing a representative sample of all new supernovae at an identical time series after optical maximum.
3. More data on 'old' supernovae in the gap from $30 < t < 300$ yr which exists in our presently available information and on the RSN–SNR connection, if there is one.
4. More morphological information, through the high resolution of VLBI, on the sizes, structures, and expansion rates for young RSN.

This last work, in particular, offers the fascinating possibility of studying changes of physically reasonably well understood phenomena on short time scales in external galaxies and may well be more revealing of insight into the conditions in extragalactic systems than the intractable 'superluminal motions' and complex structures in the cores of radio galaxies and quasars. It may also lead to an independent method of placing limits on the Hubble constant H_0 (Bartel *et al.* 1984).

In short, the study of radio supernovae is just in its initial stages of development and the expectation for continuing new and exciting results is high.

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Supernovae in Ellipticals

R. K. Kochhar *Indian Institute of Astrophysics, Bangalore 560034*

Abstract. We suggest that supernovae occur only in those elliptical galaxies which accrete gas and form stars. We show that there is a correlation between the occurrence of supernovae and nuclear activity in elliptical galaxies.

Key words: supernovae—elliptical galaxies, nuclear activity

1. Introduction

Whereas the late-type galaxies produce supernovae of both type I(SN I) and type II(SN II), elliptical (E) and lenticular (S0) galaxies have so far produced only SN I. E/S0 galaxies presumably consist of only old stars, and therefore one would expect SN I progenitors to be low mass stars. But, SN I rate per unit galaxy luminosity increases along the Hubble sequence along which the young stellar content increases. If SN I came from low-mass stars, the trend would have been just the opposite. The proportionality of SN I rates in spiral galaxies to their star formation rates demands that SN I progenitors have masses $\gtrsim 2\ M_{\odot}$. SN I's being not confined to the spiral arms means that the progenitor mass $< 7\ M_{\odot}$ (Oemler & Tinsley 1979).

From a consideration of SN I rates in I0 galaxies and other factors, Oemler & Tinsley (1979) have suggested that SN I came from short-lived stars (4–7 $M_{\odot}$).

Currently the most plausible models for SN I are those in which a C–O white dwarf formed from $\sim$ 1.5–2 $M_{\odot}$ helium stars explodes by carbon deflagration on undergoing fast accretion. Two C–O white dwarfs in a close binary could merge to give SN I (*e.g.* Nomoto, Thielemann & Yokoi 1984). The main sequence mass required to form a 1.5–2 $M_{\odot}$ helium star is $(6 \pm 2) < M/M_{\odot} < (8 \pm 2)$.

If one assumes that intermediate mass stars had formed in the E/S0 galaxies at earlier epochs and their end products, white dwarfs, are now exploding as SN I, one can explain the occurrence of SN I in E/S0 galaxies.

We would however like to argue in favour of SN I's resulting from ongoing star formation in E/S0 galaxies. We propose that a typical galaxy being gas-free does not form stars and will therefore not produce SN I. Only if an E/S0 is so placed as to accrete gas and form stars will it produce SN. (The absence of SN II in E/S0 galaxies implies that stars $> 7\ M_{\odot}$ do not form in them.) Indeed we introduce the concept of a supernovic E/S0 galaxy: a supernovic galaxy is one which produces SN. Of course some supernovic E/S0s will be more SN-prone than others.

A supernovic E may accrete gas from its own halo (*e.g.* N4406 = M86) or from the intragalactic or intracluster medium (N 1275 = Per A; N 4486 = M 87) or from a neighbouring galaxy (N 3226). Alternatively or simultaneously an E may swallow gas clouds or preferably gas-rich dwarf galaxies (N 1316 with two SN).

Other galaxies with two SN are N 5253 and A 1115 + 28. The small I0 galaxy N 5253 is a member of the Centaurus group, whose other members are the Sc galaxy N 5236 (with 4 SN), the radio galaxy N 5128 (Cen A) and the S0 galaxy N 5102. All these four galaxies appear to have accreted gas from a common envelope (Larson 1976). This gas has led to star formation in the ellipsoidal galaxy N 5253, enhanced the star formation in N 5236 and fuelled the radio source in N 5128. N 5102 in which a high HI content and young stellar population are superposed on a normal S0 appears to have undergone a burst of star formation a few times 10^8 yr ago (van den Bergh 1976).

Not much is known about A 1116 + 28 (MCG 5–27–53) which is in Zwicky cluster 156–14. It is an S0 galaxy (RC2) with a faint ring around it (Vorontsov-Velyaminov & Arhipova 1964; Zwicky 1967) on which both the SN lie. The galaxy forms a pair (Holmberg 244) with the barred spiral MCG 5–27–52 which is presumably the source of gas for A 1115 + 28.

2. Supernovae and radioactivity

Radio observations of E galaxies are interpreted in terms of a central engine (*e.g.* a black hole) which uses gas as a fuel. If an E galaxy accretes gas in course of time it would find its way to the nuclear region and give rise to nuclear activity. Thus star formation, occurrence of SN, and nuclear activity in elliptical galaxies are inter-related and a consequence of accretion of gas by the galaxy.

The connection between radio activity and accretion is well attested. Hummel (1980) has shown that elliptical galaxies with detected HI are much more likely to contain nuclear emission-line regions and nuclear continuum radio emission than radio ellipticals without detected HI, suggesting that the accreted gas fuels the source. Shostak *et al.* (1983) have shown that the HI detection rate in radio galaxies is consistent with the presence of thin HI discs of galactic dimensions in all radio galaxies. Sparks (1983) argues that the colours of radio ellipticals imply a dust extinction of ~ 0.18 mag in the V band. In the case of 8 radio ellipticals with dust lanes, radio axis is perpendicular to the dust lane (Kotanyi & Ekers 1979) again highlighting the connection between accretion and radio-activity.

The connection between radio-activity and SN occurrence is brought out by Table 1, where we see that the fraction of galaxies producing SN is significantly higher from among radio galaxies than among non-radio galaxies. A total of 59 per cent of the supernovic NGC ellipticals (10 out of 17; Table 1) have been detected in radio; from among the remaining, three have not been looked at in the radio. Furthermore, 33 per cent of the supernovic Es show [OII] λ 3727 emission, whereas only 15 per cent of all Es show this emission (Osterbrock 1960). Out of the 17 supernovic ellipticals, six have yet shown no evidence of gas, dust or radio emission. The correlation between SN occurrence and the other manifestations of the presence of gas is sufficiently strong to warrant a close look at these apparent exceptions.

The Virgo and the Coma clusters provide evidence in support of the accretion hypothesis. Most of the ellipticals in the region $12^h < \alpha < 13^h$, $0° < \delta < 20°$ are probably members of the Virgo cluster. Whereas this region contains only 11 per cent of the NGC E/S0s, it accounts for 30 per cent of the supernovic E/S0s. This shows that the Virgo E/S0s are nearly thrice as prolific SN-producers as the general sample of E/S0s. Although the Virgo cluster is a very well studied object, the SN yield does not seem to depend on the search intensity of fields in which they are located (Tammann 1974).

Table 1. Connection between radioactivity and SN occurrence.

Survey	Observed galaxies	Radio galaxies	Fraction per cent
(Dressel & Condon 1978) 2380 MHz Arecibo	204	52	25.4
	SNic		
	10	6	60
Hummel *et al.* (1983) 1400 MHz	123	24	19.5
	SNic		
	9	3	33
'Local sample' 1400 MHz	39	13	33
	SNic		
	4	3	75
	detected	nondetected	
Heckman (1983) Sample 2	44	60	
	SNic	SNic	
	6	3	
	(13.6 per cent)	(5 per cent)	

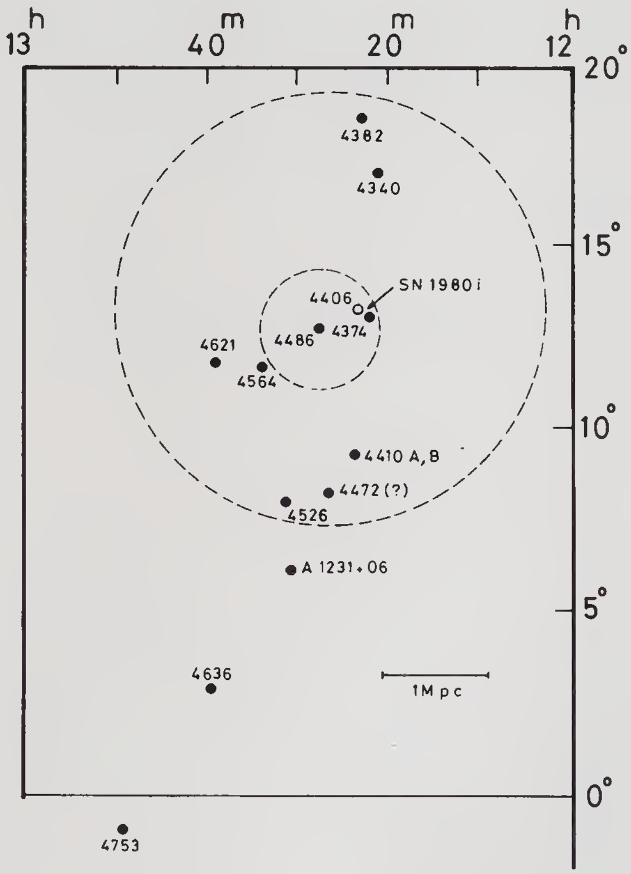

Figure 1. The supernovic ellipticals in the Virgo region covered by the Arecibo Survey. The numbers are the NGC designations. N 4753 lies just south of the boundary. The position of the intergalactic SN 1980i is marked. The outer circle is the boundary of Virgo I. The inner circle marks the boundary of the high density gas core of the cluster. The 3 arcmin x-ray emitting gaseous halo around N 4486 is not shown.

The Virgo cluster shows a two-component X-ray spectrum; the cluster is permeated by a hot ($\sim 10^8$ K) intracluster gas in which are embedded galaxies with individual cool ($\sim 10^7$ K) atmospheres (Forman *et al.* 1981). The non-thermal activity in the central regions of N 4486 (M87) is explained in terms of accretion from its massive halo (Mathews 1978). We hold this accretion responsible for the SN also. A similar case is that of the powerful X-ray and radio source N 1275 (Per A) (Fabian & Nulsen 1977), which has also produced a SN. X-ray haloes have been detected around M 84 and M 86 (Forman *et al.* 1981). It is reasonable to suppose that other ellipticals in the Virgo cluster too would have similar haloes, confined by the hot intracluster gas (Fabian *et al.* 1977). The presence of individual gas reservoirs around ellipticals from which they can accrete gas explains why Virgo ellipticals are predominantly supernovic and radio active (Fig. 1).

The hot gas (10^8 K) in the compact, dynamically evolved, spiral-poor Coma cluster is associated with the cluster as a whole and not with any individual galaxy. It approximates an isothermal gas sphere and shows no sign of radiatively regulated accretion (Forman *et al.*, 1981). There are indications that SN rate in Coma is about a factor of 3 lower than in Virgo (Barbon 1978). Coma cluster is fairly uniform in galaxy type and shows a central maximum density and a symmetrical decrease towards the boundaries. If all galaxies were equally likely to produce SN, we should expect the supernovic ellipticals to have the same distribution as the galaxies in general. This, however, is not the case. All supernovic E/S0s in Coma are confined to a plane (Fig. 2). Presumably, some gas in Coma has settled down in a disc and is accreted by the galaxies there, giving rise to supernovic activity. Of the 7 SN in the central regions of Coma, 2 have occurred in I0 galaxies, 4 in E/S0 galaxies and only 1 in a Sb galaxy (Thompson 1981). At the centre of the cluster and the disc lies the giant elliptical radio galaxy N 4874 which has produced 2 SN.

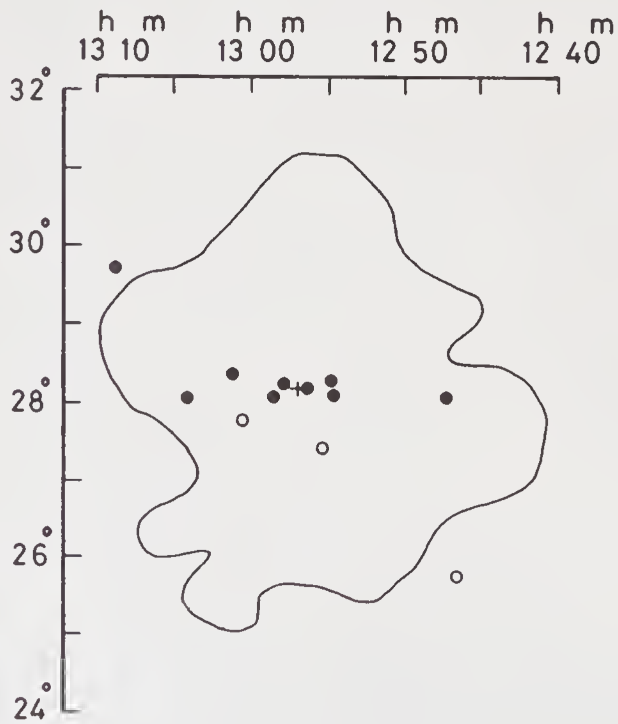

Figure 2. The supernovic galaxies in the Coma cluster (Barbon 1978).

Further support for the accretion hypothesis comes from Caldwell & Oemler (1981), who find that the spiral-rich outer regions of rich clusters of galaxies have higher SN rate in the E/S0 galaxies as compared to the spiral-poor and gas-poor central regions of such clusters. They also find that the E/S0 galaxies in the outer regions of rich clusters are bluer than the ones in the inner regions suggesting that recent star formation is more active in the E/S0 galaxies embedded in gas-rich outer regions of the rich clusters.

3. Colours of supernovic ellipticals

If SN I come from short-lived stars then the E galaxies that produces SN should be bluer than the ones which do not. This however is not the case. Sandage & Visvanathan (1978a, b) give corrected photoelectric colours for a sample of 354 unambiguous E/S0s out of which 12 Es and 8 S0s have produced SN. Excluding the very blue S0 galaxy N 4382 [$(U-V)_{0.5}^{\mathrm{KEM}} = 2.08$], one obtains a mean value of $\langle (U-V)_{0.5}^{\mathrm{KEM}} \rangle = 2.35 \pm 0.05$ for the supernovic E/S0s. This is not significantly different from the value $2.33 + 0.09$ for the whole sample.

The colour of a supernovic galaxy is contributed to by three factors: (i) the blueness due to star formation; (ii) the reddening due to dust (Sparks 1983); and (iii) the redness due to high metallicity (Kochhar & Prabhu 1984). It is conceivable that these three factors added up together will not let an elliptical be termed blue.

Star formation has been reported in some ellipticals (Sadler 1984) but this is in the nuclear regions. The star formation we are talking about occurs in the outer portions of

Table 2. Bright supernovic ellipticals.

NGC	UGC	Radio designation	RMT	S_{2380} mJy	R^*
1275	2669	3C 84	P	11700	18500
1316		PKS0320–37	PLXS0pec	89300	6600
2672	4619		E1 +	12	27
3226	5617		E2:pec	12	27
3834			E		
3904			E2+:		
4335			E2		
4374	7494	3C 272.1	E1	3635	759
4486	7654	3C 274	E+0+pec	134200	19398
4564	7773		E6	12	12
4621	7858		E5	12	3
4636	7878		E0+	64	34
4782		3C 278	E0pec	4500	5700
4874	8103	PKS1257+28	E+0	132	399
5090		PKS1318–434	E2	4900	4500
7619	12523		E2	22	26
7768	12806		E2	12	48

$R^* = S \ \mathrm{dex}\left(\frac{m-12.5}{2.5}\right)$ (Dressel 1981).

N 3834 is not classified in RC2. Other RC2 E galaxies with SN are 14051 (1950a), 15342 (1961n). A1248 + 28 (1961d) A1255 + 28 (1963 m), A2338 + 26 (UGC 12733; 1969 k) none of which are looked at in the radio region.

the galaxy. In this context it should be noted that the standard colours of galaxies are obtained by observing them at a given aperture. If the star forming regions lie outside the largest aperture employed, their contribution will not be taken into account.

The majority of SN in the Virgo ellipticals have indeed occurred outside the largest aperture used by Visvanathan & Sandage (1977). What is required is multicolour surface photometry of the regions around the recorded SN to see if these regions show signs of star formation.

4. Conclusions

We have argued that SN I result from short-lived stars and do not occur in an isolated typical E galaxy which is gas-free and does not form stars. Only those ellipticals which have access to gas can produce SN. This gas on falling onto the nuclear regions may fuel radioactivity if the central engine is present. Thus occurrence of SN and radio activity in elliptical galaxies are interrelated phenomena.

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Secondary Particle Production and γ-ray Emission from Supernova Exploding in Dense Clouds

S. A. Stephens *Tata Institute of Fundamental Research, Homi Bhabha Road, Bombay 400005*

Abstract. In order to understand the observed excess of antiprotons in cosmic radiation, we have examined the possibility of antiprotons being produced in supernova envelopes during the expansion phase and undergoing consequent adiabatic deceleration. For this purpose, we have considered in our investigation supernova explosions in dense clouds with $n_H = 10^4\ \mathrm{cm}^{-3}$ to $10^5\ \mathrm{cm}^{-3}$ and calculated the anti-proton spectrum by taking into account all energy loss processes. It is found that the observed antiprotons can be well explained if about 30 per cent of the cosmic ray nucleons originate from these sources. We have also investigated the spectral evolution of the γ-rays produced through π^0-decay and bremsstrahlung process. From these, the luminosity function of γ-ray sources in the Galaxy is derived for a set of simple assumptions and some of its implications are discussed.

Key words: cosmic radiation, antiprotons—supernovae, γ-ray production—Galaxy, γ-ray sources

1. Introduction

The observed flux of antiprotons ($\bar{p}$) in cosmic radiation (Golden *et al.* 1979; Bogomolov *et al.* 1981; Buffington, Schindler & Pennypacker 1981), in excess of the expected secondary particle production in interstellar space, has invoked many new ideas in recent years to explain three exciting observations. However, it has been pointed out that no satisfactory explanation has been put forward to understand these observations (Stephens 1981a; Ginzburg & Ptuskin 1984). The excess of $\bar{p}$ implies a large amount of matter to be traversed by cosmic rays, compared to that required to explain the light to heavy nuclei in cosmic radiation. If these $\bar{p}$ are to be created in different kind of sources in the Galaxy, the amount of matter traversed in these sources should be sufficiently large enough to destroy almost all the heavy nuclei accelerated in them. In this regard, Mauger & Stephens (1983) have suggested the possibility of producing $\bar{p}$ in the envelopes of supernovae exploding in dense clouds. The $\bar{p}$ thus produced are decelerated adiabatically during the expansion of the remnant and it is shown that the decelerated spectrum could fit the data satisfactorily (Stephens & Mauger 1985).

Cosmic rays, while traversing matter in such dense sources produce pions and kaons, in addition to $\bar{p}$. These unstable particles decay to γ-rays and electrons. γ-rays are also produced by the interaction of electrons with matter and radiation field through bremsstrahlung and inverse Compton processes respectively. Therefore, it is essential to examine the consequences of secondary particle production in the envelopes of supernovae exploding in dense clouds. In this paper, we consider dense clouds with hydrogen density in the range of 10^4 to 10^5 atom cm^{-3} (Linke & Goldsmith 1980). We derive the evolution of the energy spectrum of $\bar{p}$ and show how one could fit this evolved spectrum with the observed flux values. We also obtain the evolution of the γ-ray spectrum from these sources and calculate the luminosity function of the γ-ray sources in the Galaxy. We then compare this with the observed distribution of COS-B sources (Hermsen 1980) and discuss some of the implications.

2. Theoretical approach

The evolution of secondary particle production in supernova envelopes can be examined by solving a set of coupled differential equations given below.

$$\frac{\mathrm{d}J_p}{\mathrm{d}t} = \frac{\partial}{\partial E}\left(J_p \frac{\mathrm{d}E_p}{\mathrm{d}t}\right) + \int_{E'} \frac{\rho v}{\lambda} J_p \frac{\mathrm{d}E'}{E'} - \frac{\rho v}{\lambda} J_p, \tag{1}$$

$$\frac{\mathrm{d}J_{\bar{p}}}{\mathrm{d}t} = \frac{\partial}{\partial E}\left(J_{\bar{p}} \frac{\mathrm{d}E_{\bar{p}}}{\mathrm{d}t}\right) + \int_{E'} \frac{\rho v}{\lambda} J_{\bar{p}} \frac{\mathrm{d}E'}{E'} - \frac{\rho v}{\lambda} J_{\bar{p}} + Q_{\bar{p}}, \tag{2}$$

$$\frac{\mathrm{d}J_{e\pm}}{\mathrm{d}t} = \frac{\partial}{\partial E}\left(J_{e\pm} \frac{\mathrm{d}E_{e\pm}}{\mathrm{d}t}\right) Q_{e\pm}. \tag{3}$$

In the above equations, the first term on the right-hand side describes the continuous energy loss of particles. In the case of protons and antiprotons (Equations 1 and 2), this energy loss corresponds to ionization and adiabatic cooling, the latter being $(\mathrm{d}E/\mathrm{d}t)_{\mathrm{A}} = \{(E+2m)E/r(E+m)\}(\mathrm{d}r/\mathrm{d}t)$. The radius of the supernova remnant r and its derivative are obtained from the dynamics of supernova. The second term describes the energy shift due to the finite elasticity of the interacting particle and the third term corresponds to the loss of particles due to interaction. In these terms, the inelastic interaction mean-free path is given by λ and Λ includes annihilation also; v is the velocity of the particle and E is the kinetic energy. In the case of electrons (Equation 3), the continuous energy loss term contains loss due to ionization, bremsstrahlung, inverse Compton scattering and synchrotron radiation. For the inverse Compton process, we have used a radiation density corresponding to an optical outburst of 10^{43} erg s^{-1} soon after the supernova explosion, which then decay with an e-folding time of 0.2 yr. For the magnetic field inside the remnant, we have assumed the field strength to scale as $B^2 \propto n_{\mathrm{H}}$, with $B = 4\,\mu$G at $n_{\mathrm{H}} = 1$ atom cm^{-3}.

Equation (1), which describes the protons is the only independent equation in the above set, while Equations (2) and (3) are coupled to the Equation (1) through the production term Q. The production spectrum of secondary particle can be described by the following integrals

$$Q_{\bar{p}}(E,t) = \int_{E'} J_p(E',t)\rho v \,\mathrm{d}E' \int_{\theta} 2\pi \left(E \frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3}\right)_{\bar{p}} p_{\perp} \mathrm{d}\theta \tag{4}$$

$$Q_{e\pm}(E,t) = \int_{E_\mu} \frac{\mathrm{d}E_\mu}{\psi(e\pm)} \int_{E_\pi} \frac{\mathrm{d}E_\pi}{\psi(\mu)} \int_{E'} J_p(E',t)\rho v \mathrm{d}E' \int 2\pi \left(E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3}\right)_{\pi\pm} p_\perp \mathrm{d}\theta. \tag{5}$$

Here, the integral over θ describes the production of $\bar{p}$ and pions, where $p_\perp$ is the transverse momentum of the particle produced and θ is the angle of emission with respect to the interacting particle. $E(\mathrm{d}^3\sigma/\mathrm{d}p^3)$ is the invariant inclusive cross-section for the production of these particles and this depends upon the energy of the interacting particle. Therefore, the production cross-section is integrated over the energy spectrum of protons. For the production of electrons, the charged pions have to decay to muons, which in turn decay to electrons. The energy distribution of decay products is taken care of in the additional two integrals, one over the energy of pions and the other over E_μ; the energy distributions are characterized by the function ψ. All these parameters described above are taken from the work of Badhwar & Stephens (1977) and Stephens (1981b).

The set of coupled Equations (1) to (3) has been solved by stepwise integration method by setting the initial time at T_A, when the acceleration of the particles in the remnant is complete. At this time the initial energy spectrum of the accelerated particle is taken to be a power law in rigidity of the type $AR^{-2.75}$, where the constant A is similar to that in the interstellar space. For the nucleon spectrum $A = 2.5 \times 10^4$ nucleons/(m^2 sr s GV) and for electrons $A = 1.25 \times 10^2$ electrons/(m^2 sr s GV). These constants can be scaled on the basis of the required cosmic ray power output from a supernova to account for the interstellar energy density.

The parameters relating to the evolution of supernova in dense clouds have been obtained for our investigation by scaling those derived for ordinary interstellar medium. We do not consider the phase when the supernova expands ballistically. The adiabatic phase starts at time $t = T_E$ and the radius of the remnant expands as $r \propto t^{2/5}$. This phase ends at T_c when the radiative loss becomes important. During the radiative phase, the radius expands as $r \propto t^{1/4}$. The values of T_E and T_c are found to be 6.9 yr and 254 yr respectively for $n_H = 10^4\,\mathrm{cm}^{-3}$, and 3.2 yr and 68 yr respectively for $n_H = 10^5\,\mathrm{cm}^{-3}$ (Stephens & Mauger 1985). We have considered two cases for our study, the first one assumes that the acceleration is complete at $T_A = T_E$ and the other at T_c. We also assume for the sake of simplicity that the size of the cloudlets are such that the total amount of matter traversed by cosmic rays by the time the envelope leaves the cloudlet is about 50 g cm^{-2} at relativistic energies.

During the propagation of cosmic rays inside the remnant, they interact with matter to produce neutral pions which decay into two γ-rays; bremsstrahlung γ-rays are produced by the electrons. These are calculated as a function of time using the following relations.

$$P_\gamma(t)_{\pi^0} = 4\pi \int_{E_{\pi^0}} \frac{2\mathrm{d}E_{\pi^0}}{\psi_\gamma(\pi^0)} \int_{E'} J_p(E')\rho v \mathrm{d}E' \int_\theta 2\pi \left(E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3}\right) p_\perp \mathrm{d}\theta, \tag{6}$$

$$P_\gamma(t)_B = 4\pi \int_{E'} \phi(E',E)\rho v J_e(E')\mathrm{d}E'. \tag{7}$$

In equation (6), the production of π^0 is given by the integrals over θ and E'. The energy distribution of γ-rays during the decay of π^0 is taken care of in the integral over E_{π^0}, where ψ_γ is the normalized distribution function. In Equation (7), ϕ is the differential probability per g cm^{-2} of material traversed by an electron of energy E' to radiate a photon of energy E. The cross-sections for these processes are taken from the work of

Stephens & Badhwar (1981). We have found that the contribution from the inverse Compton scattering process is very small, as the radiation density decreases by a large value when the remnant reaches the adiabatic stage. Therefore, we have not considered this process in this investigation.

3. Antiproton spectrum

We have shown in Fig. 1, the spectra of $\bar{p}$ during the evolution of the supernova in a cloud with $n_H = 10^4\ \mathrm{cm}^{-3}$. Various curves in this figure correspond to different stages of the evolution as indicated by the time elapsed after the explosion. T_A is taken to be T_E in this figure. The flux of particle is normalized in such a way that it represents the flux $\bar{p}$ in interstellar space, if all the observed cosmic ray nucleons originate from such supernovae. Curve A, which represents the spectrum at about 10 yr since the occurrence of the outburst, is similar to the production spectrum (Stephens 1981b). As the time increases, the flux of $\bar{p}$ increases due to the increase in the amount of material traversed

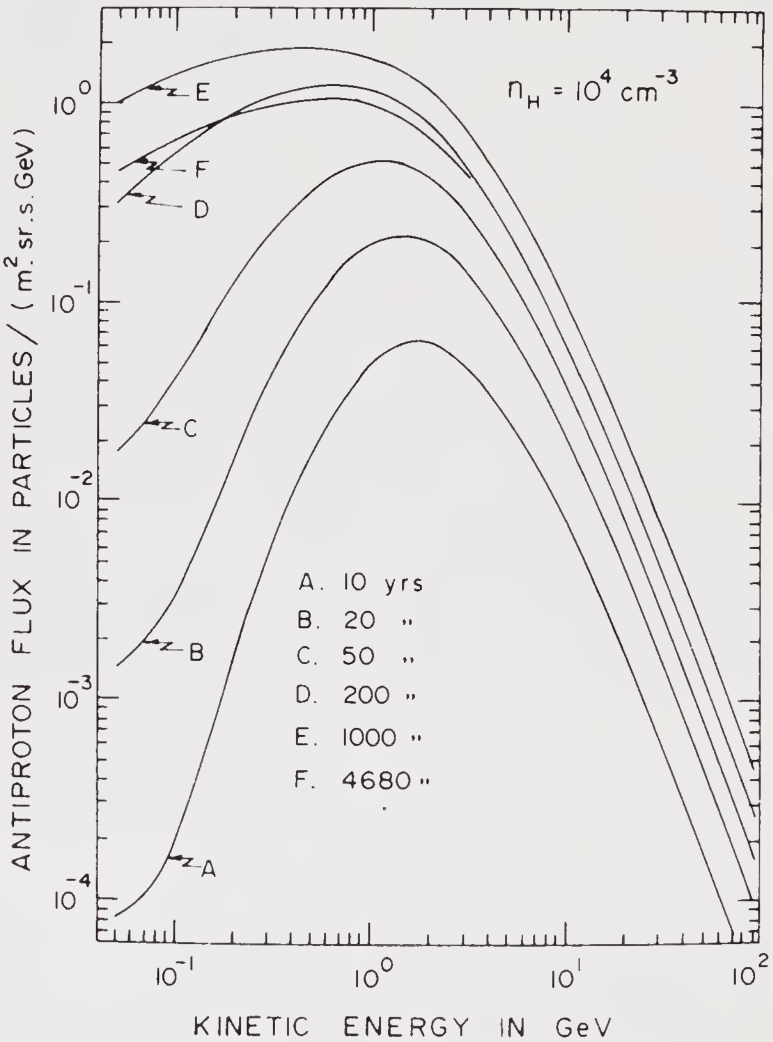

Figure 1. Energy spectra of $\bar{p}$ are shown at various stages of the evolution of supernova in a dense cloud with $n_H = 10^4\ \mathrm{cm}^{-3}$.

by cosmic rays, and the spectral peak shifts to lower energies due to adiabatic cooling. The spectral broadening results from the finite elasticity of the particle while interacting. It can also be noticed that after 30 $g\,cm^{-2}$ of matter traversal ($t > 1600$ yr), the absolute flux of $\bar{p}$ decreases. This behaviour results from the fact that the attenuation of $\bar{p}$ dominates over production. It may be noted that the spectral evolution of $\bar{p}$ for $n_H = 10^5\,cm^{-3}$ is similar to Fig. 1 during the later stages of the evolution due to the large amount of matter traversal, while during the early stages, the adiabatic cooling is slightly less than that for $n_H = 10^4\,cm^{-3}$.

We have shown in Fig. 2, the evolved spectrum of $\bar{p}$ along with the observed flux values. Curve A corresponds to a total matter traversal of 100 $g\,cm^{-2}$ and curve B for 50 $g\,cm^{-2}$. The solid curves are for $n_H = 10^5\,cm^{-3}$ and the dashed curves are for $n_H = 10^{-4}\,cm^{-3}$. Since the spectral shape of solid and dashed curves are identical, we have displaced them by a factor of 10 for the sake of clarity. All these spectra have been calculated with $T_A = T_E$. The spectral shape for $T_A = T_c$ does not differ much due to the dominance of spectral broadening effect, except for a small shift in the broad spectral peak towards higher energy. One notices from this figure that the calculated spectral shape is in good agreement with the observed flux values. If solar modulation plays an

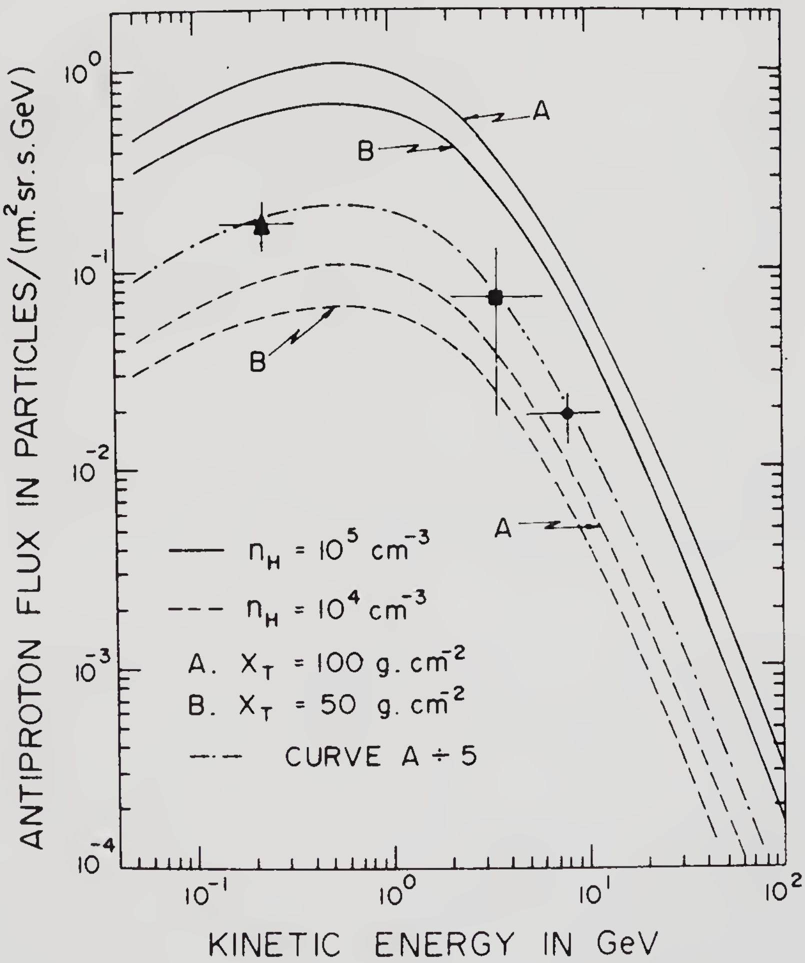

Figure 2. Differential energy spectra of $\bar{p}$ at the end of the supernova evolution are shown. Curves A and B are for a total matter traversal of 100 and 50 $g\,cm^{-2}$ respectively; the dashed curves are displaced by a factor 10 for clarity. The dash-dotted curve is one of the curves, normalized through the high energy data points.

important role, the low energy flux value would be affected and the low energy point will not be in good agreement with the calculated spectrum. However, it may be noted that the reliability of this observation has not been established (Stephens 1981a).

It is clear from Fig. 2 that, in order to explain the observations, one requires that about 30 per cent of the observed cosmic ray nucleons should come from supernovae occurring in dense clouds. In its face value the ratio of the number of supernovae in dense clouds to those in ordinary clouds would be 0.4:1.0. On the one hand, if cosmic rays are attenuated and decelerated during the expansion of supernovae in dense clouds only, the above ratio should correspondingly increase. For example, we find in the case of $T_A = T_E$, this ratio is 7.2:1.0 for $n_H = 10^5$ cm^{-3} and 16.4:1.0 for $n_H = 10^4$ cm^{-3}; the corresponding ratios for $T_A = T_c$ are 1.2:1.0 and 1.7:1.0 respectively. Though these values are rather large, we use these in the later analysis. On the other hand, if the rest of the cosmic rays also undergo adiabatic decleration, as they originate from supernova occurring in ordinary clouds, the adiabatic cooling effects would be of the same magnitude. Therefore, the main difference should come from the attenuation effect only and thus one obtains a ratio of 0.8:1.0. This ratio would further reduce if the adiabatic cooling is more in rarer medium.

4. Gamma ray spectrum

The differential energy spectra of γ-rays produced in the supernova envelopes are shown in Fig. 3 for $n_H = 10^4$ cm^{-3}. The solid curves in this figure are for γ-rays arising from the interaction of nucleons through π^0-decay (Equation 6) and the dashed curves are the bremsstrahlung radiation by the electrons (Equation 7). Curves denoted by A are the spectra at the time the supernova becomes active, which corresponds to either T_c or T_E, and the amount of matter traversed is considered to be 0 g cm^{-2}. The spectra at the end of 15 and 50 g cm^{-2} are shown by curves C and D respectively for $T_A = T_E$; Curve B is for $T_A = T_c$ at 50 g cm^{-2}. In order to fix the brightness scale, we consider a galactic space with radius 15 kpc and thickness 500 pc for the confinement of cosmic rays. This volume is filled by cosmic rays with an energy density of 1 eV cm^{-3} over a period of 3×10^7 yr. If 70 per cent of the observed cosmic rays are released by supernova, whose birthrate is about once in 50 yr, the mean energy release per supernova in cosmic rays is about 10^{61} eV. This value is assumed to be at T_A to derive the γ-ray brightness in Fig. 3.

Comparing the spectra of π^0-decay and bremsstrahlung γ-rays, one notices that the bremsstrahlung contribution decreases with time, due to the suppression of the electron spectrum at low energies by the ionization loss. This effect introduces a change in the spectral shape of γ-rays with time. The spectrum appears to be simple power law at the early stages, and it evolves to be π^0-decay dominated spectrum. In order to examine the variation of the total intensity with time, we have plotted in Fig. 4, the integral brightness above 100 MeV as a function of time. The solid curves in this figure are for $n_H = 10^5$ cm^{-3} and the dashed curves are for $n_H = 10^4$ cm^{-3}. The upper curves are for $T_A = T_c$ and the lower curves are for $T_A = T_E$. The brightness scale at left and the lower time scale are for $n_H = 10^5$ cm^{-3} and the others for $n_H = 10^4$ cm^{-3}. One notices that the time variation is rather marked for high density medium and is about 15 per cent at T_E reducing to 2 per cent at T_c for $n_H = 10^5$ cm^{-3}. It is also evident from this figure that the γ-ray sources are bright but are active only for a short period of time in the Galaxy. Higher the density, brighter are the sources and shorter are their life times.

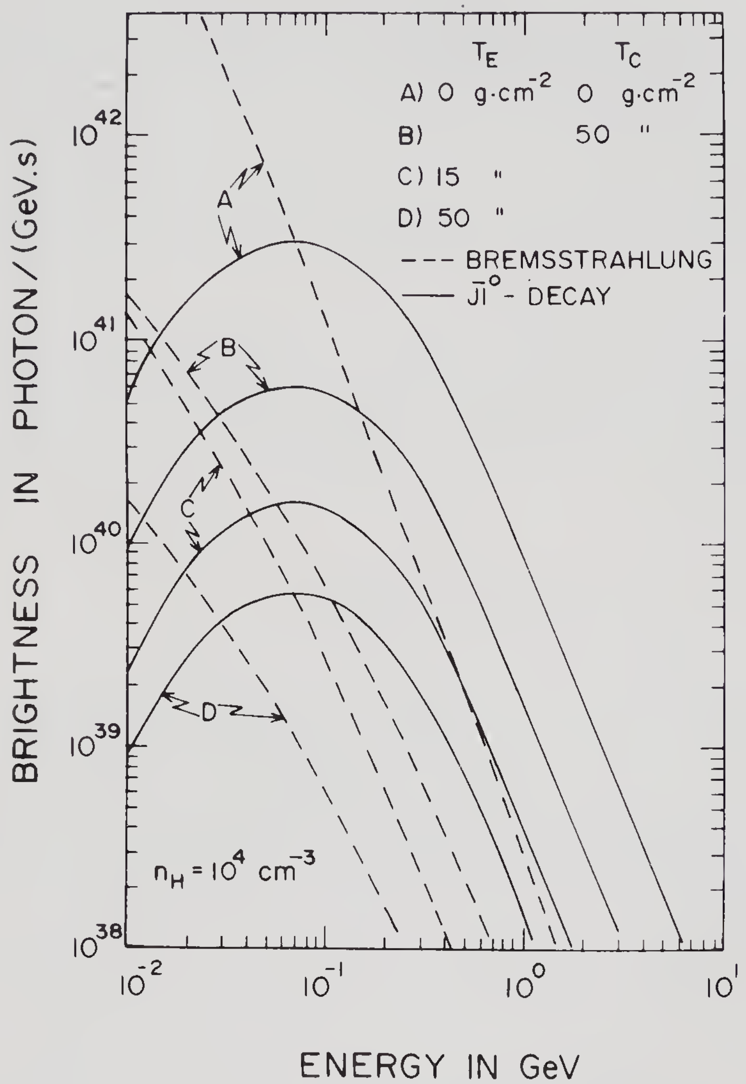

Figure 3. Differential energy spectra of γ-rays are shown at various stages of the evolution of supernova in dense clouds with $n_H = 10^4$ cm^{-3}. The solid curves are for γ-rays arising through π^0-decay and the dashed curves are for bremsstrahlung γ-rays. The curves correspond to different matter traversal in g cm^{-2}, are related to different stages in the evolution and for two different T_A values.

By making use of the curves in Fig. 4 and the supernova rates estimated in Section 3, one can derive the luminosity function of γ-ray sources in the Galaxy, by assuming an uniform distribution of sources. We have shown in Fig. 5, the luminosity distribution thus derived and compared with the observed distribution of γ-ray sources as seen by COS-B (Hermsen 1980). The solid curves are for $n_H = 10^5$ cm^{-3} and the dashed curves are for $n_H = 10^4$ cm^{-3}. The curves marked as A and B are for $T_A = T_E$ and T_c respectively, and the histogram marked as C is the observed distribution. One gets an impression from this figure that the estimated luminosity distribution is not in agreement with the observation. In reality, this is not the case because of the following reasons.

(a) We have assumed an uniform distribution of sources in the Galaxy. However, if one makes use of the observed distribution of molecular hydrogen for this purpose, all these curves in Fig. 5 would become steep at large flux values.

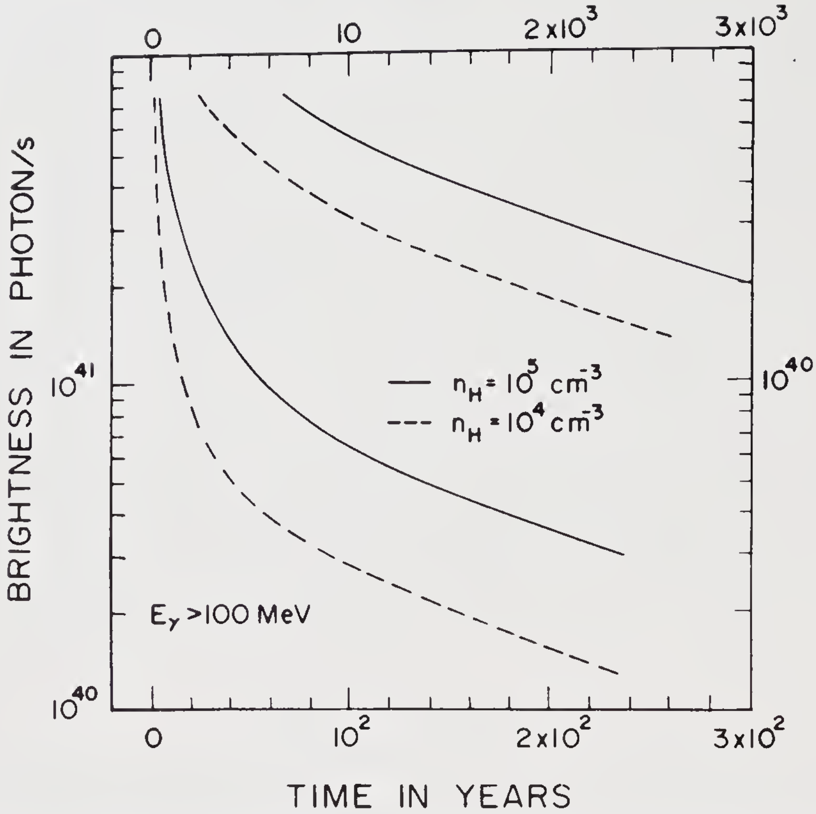

Figure 4. The time variation of the intensity of γ-rays > 100 MeV is shown; the brightness scale at right and the upper time scale are for $n_H = 10^4\ cm^{-3}$. The upper curves are for $T_A = T_c$ and the lower curves are for $T_A = T_E$.

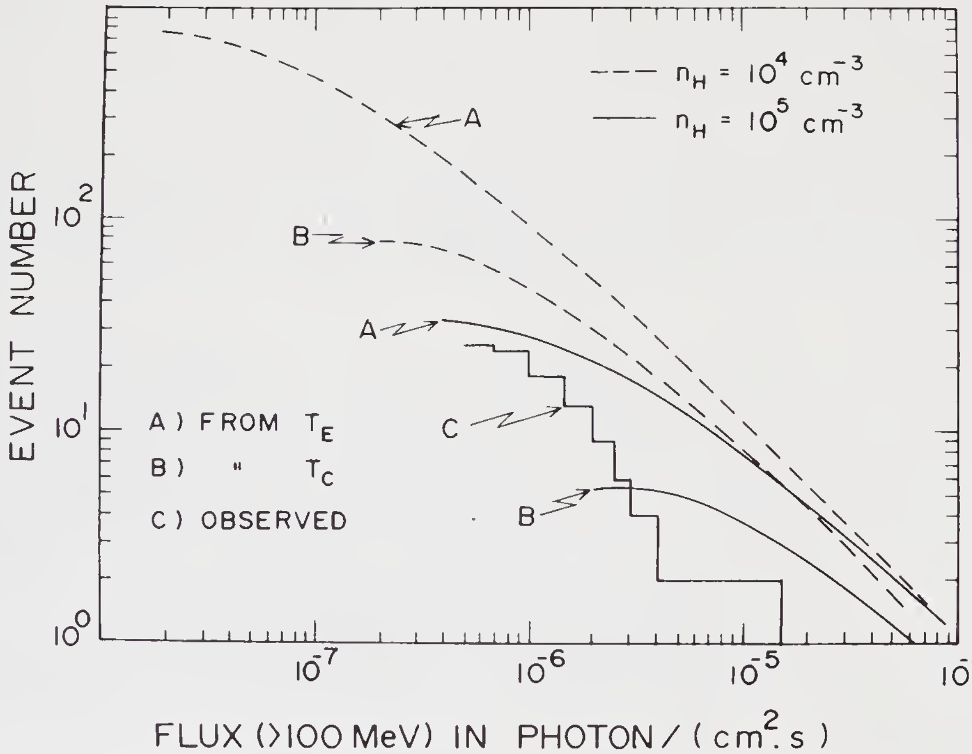

Figure 5. The luminosity function of γ-ray sources in the Galaxy is shown for different curves in Fig. 4. Curves A and B relate to $T_A = T_E$ and T_c respectively and the histogram represents the observed data.

(b) The number of supernovae estimated here is an upper limit and the supernova rate in dense clouds is small when adiabatic deceleration is included for cosmic rays of normal origin (Section 3); the supernova power would then increase by the same factor. As a result, all the calculated curves in Fig. 5 would shift to higher flux values at 45° towards the lower numbers.

(c) We have not considered here cloudlets with different n_H values. It is essential to fold in the distribution of clouds with different n_H values and calculate the luminosity curves.

If one takes all these into account, a better comparison can be made with the observation. Such an attempt is being made to examine the implication of the occurrence of supernovae in dense clouds. It will be also interesting to evaluate the radio spectrum emitted by the electrons and the consequences of e^+/e^- ratio in cosmic rays.

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The Radio and X-ray Emission from Supernovae

Roger A. Chevalier *Department of Astronomy, University of Virginia, P. O. Box 3818, Charlottesville, VA 22903, USA*

Abstract. The radio and X-ray observations of supernovae are interpreted in terms of the circumstellar interaction model for the emission. The early absorption of the radio emission is attributed to free-free absorption by the circumstellar wind outside of the interaction region. For type II supernovae, the wind is from the massive red supergiant progenitor star. For the one observed type I supernova, the wind is from a red giant companion star which is the source of mass accretion onto a white dwarf supernova progenitor. Wind parameters are determined. Type II supernovae are likely to contain central pulsars, but the pulsar nebulae become observable only tens of years after the explosion.

Key words: Supernovae, radio and X-ray emission—circumstellar wind

1. Introduction

SN 1970g was the first supernova to be detected as a radio source (Allen *et al.* 1976). Observations of this source were difficult because of its low flux and because of its proximity to an HII region. Discussions of these observations (Allen *et al.* 1976; Marscher & Brown 1978) made the points that the emission is likely to be nonthermal synchrotron radiation and that at early times the supernova envelope is expected to be optically thick at radio wavelengths. Marscher & Brown (1978) suggested a model for the radio emission in which the magnetic field is provided by the pulsar, but is outside the bulk of the supernova envelope. The energy for the relativistic electrons is derived from the kinetic energy of the freely expanding supernova gas. They did not discuss the details of how these circumstances come about.

Radio observations of the type II supernovae SN 1979c and SN 1980k (Weiler *et al.* 1982; 1983) have placed the subject on a firm observational basis. Radio light curves at $\geqslant 2$ frequencies are now available. These data created new theoretical interest in the radio emission. Shklovskiĭ (1981) suggested that the radio emission is from magnetic flux loops which emerge from outer regions of the supernova envelope. The energy source is a central pulsar. This model has not been developed in any quantitative detail, but its predictions of flat radio spectrum and significant polarization have not been confirmed. Pacini & Salvati (1981) suggested that the radio emission is directly from the magnetic fields and relativistic particles generated by a central pulsar. This requires that the effect of free-free absorption by the supernova envelope be avoided. Bandiera, Pacini & Salvati (1983) proposed that the envelope is broken into filaments by the Rayleigh-Taylor instability which results from the sweeping up of the envelope by the pulsar bubble. This process requires an energetic pulsar. If pulsars do have such a dramatic effect on supernova envelopes, the theories of supernova light curves and spectra need to be re-examined. However, the existing theories with smooth envelopes appear to be consistent with the observations (Chevalier 1981b; Branch *et al.* 1981). With pulsar energy input, the envelope tends to be swept into a thin shell, which is not consistent with observed velocity data (see review by Chevalier 1981b). Bandiera, Pacini & Salvati (1984) calculated radio luminosities for pulsar nebulae on the assumptions of fast or slow pulsar rotation and fast or slow envelope expansion. The models do give the right range of luminosities, but the authors do not attempt to fit the detailed radio light curves. In particular, they attribute the early radio absorption to synchrotron self-absorption and it does not seem that this process can reproduce the rapid turn-on of the observed radio emission (Chevalier 1982b).

In the model of Chevalier (1981c, 1982b), the radio emission is associated with the interaction between the rapidly moving supernova gas and slow moving gas from a dense wind from the presupernova star. Such a wind is expected from the red supergiant progenitors of type II supernovae (Chevalier 1981b). Relativistic particles are accelerated either by shock waves or turbulent processes in the interaction region. The early absorption of the radio waves is attributed to free-free absorption by the circumstellar medium. This model can fit the observed radio light curves in some detail (Chevalier 1984a). In addition the parameters required by the circumstellar interaction model are consistent with interpretations of observations at ultraviolet, X-ray, and infrared wavelengths (Chevalier 1984a).. This combined set of observational data provides strong evidence in favour of the circumstellar interaction model.

In view of this evidence, this review will concentrate on the circumstellar interaction model for the radio and X-ray emission from the supernovae. Section 2 summarizes the nature of the interaction. Section 3 applies the theory to type II supernovae, and Section 4 to type I supernovae. Type II supernovae are expected to contain central pulsars and Section 5 discusses when a pulsar nebula may become observable. Section 6 summarizes the current problems and future prospects for this field.

2. Circumstellar interaction

Red supergiant stars are expected to have massloss rates, $\dot{M}$, in the range 10^{-6} to $10^{-4}\ M_\odot\ \mathrm{yr}^{-1}$ (*e.g.* Zuckerman 1980) with a wind velocity $v_w \approx 10\ \mathrm{km\,s^{-1}}$. The age of the red supergiant phase varies from about 3×10^6 yr for a $9\ M_\odot$ star to 3×10^5 yr for stars with masses larger than about $20\ M_\odot$. If the wind properties remain constant, the density of the circumstellar wind is $\rho_{cs} = \dot{M}/(4\pi r^2 v_w) \equiv Br^{-2}$, where B is a constant. While there may be variations in the wind properties over the red supergiant age, the region of interest for the observed radio emission involves mass lost during only a fraction of that age. Thus the assumption of constant B should be adequate.

The supernova gas is expected to be in free expansion, *i.e.* $v = r/t$. The density distribution of the gas is uncertain, but a power law form for the distribution is plausible. Chevalier & Jones (1984) showed that power law profiles are the outcomes of the explosion of a variety of initial stellar configurations. They also carried out numerical calculations of the explosion of a massive star and found that the final profile could be approximated by a small number of power law sections. With the power law assumption, the density of the supernova gas can be expressed as $\rho_{sn} = At^{(n-3)}r^{-n}$,

Table 1. Properties of the interaction region.

n	R_1/R_2	b	ρ_2/ρ_1	M_2/M_1
7	1.299	0.25	6.8	0.77
12	1.226	0.036	41	2.5
20	1.207	0.0093	156	5.2

where A is a constant. The hydrodynamic models indicate than $n \geqslant 9$ (see also Jones, Smith & Straka 1981). The interaction between the supernova and the circumstellar gas leads to a shell of shocked supernova gas outside of which is shocked circumstellar gas. The advantage of the power law assumption for ρ_{sn} is that the radius of the contact discontinuity between the two shells of shocked gas can be expressed as

$$R_c = (bA/B)^{1/(n-2)}\, t^{n-3/n-2}$$

where b is a dimensionless constant. The value of b does depend on whether cooling is important for the shocked gas. Near maximum light, the radiation from a type II supernova may be sufficient to Compton cool the entire interaction region. At later times radiative cooling may be important for the inner denser shell and, later still, the flow may be energy-conserving. Chevalier (1982a) has solved for the structure of the interaction region if it is energy conserving, using self-similar methods. Chevalier (1982b) gave an analytic solution for the shell expansion if the entire shell cools. The case of an inner radiative shell is of particular interest for type II supernovae and some parameters for this case are given in Table 1 (see Chevalier & Fransson 1984). The table lists the ratio of outer shock radius to inner shock radius R_1/R_2, the ratio of densities at the shock waves ρ_2/ρ_1, and the ratios of masses in the shells M_2/M_1. The subscript 2 refers to shocked supernova gas and 1 to shocked circumstellar gas.

One property of the solutions is that the density of the inner shocked region is larger than that of the outer shocked region. For a decelerating shell, this situation is subject to the Rayleigh-Taylor instability. The instability is expected to grow into the nonlinear regime for length scales considerably less than the thickness of the interaction region. Some mixing of the two shocked regions is likely, but the detailed results of the instability are not known.

Large scale distortions of the shell due to asymmetric massloss are possible. While there is evidence for predominantly equatorial massloss from some late-type stars (*e.g.* Cohen & Schmidt 1982), this appears to be rare. In a study of the arcsec structure of OH maser clouds surrounding 20 Mira variables and late-type supergiants, Bowers, Johnston & Spencer (1983) found evidence for significant deviations from spherical envelopes in only one case.

3. Type II supernovae

As discussed below, the radio observations of type II supernovae lead to estimates of massloss rates from the progenitor stars. Once this is known, it is possible to estimate the thermal energy density, u_t, in the postshock region. This can be compared with the minimum energy density, u_m, of the relativistic electrons and magnetic field derived from the synchrotron luminosity. Chevalier (1982b) found that $u_m/u_t \lesssim 0.01$ which is comparable to the values found in young galactic supernova remnants. Thus, while the details of the particle acceleration and magnetic field generation are not understood, the analogy to supernova remnants shows that the circumstellar interaction is a plausible source of the supernova luminosity.

In order to model the radio light curves, an assumption about the evolution of the relativistic electron energy density, u_e, and the magnetic energy density, u_B, is necessary. Chevalier (1982b) made the assumption that u_e/u_t and u_B/u_t remain constant because it seemed most plausible. Reynolds & Chevalier (1981) discuss the basis for the assumption and use it for the evolution of shell-type supernova remnants. Tycho's remnant was subsequently found to have a rate of flux decline which is consistent with the prediction of Reynolds & Chevalier (Strom, Goss & Shaver 1982). For the supernova case, the implication is that the radio luminosity drops as $t^{-(\gamma+5-6m)/2}$, where γ is the power law index of the electron spectrum and $m=(n-3)/(n-2)$ describes the rate of increase of the outer shock radius ($R_1 \propto t^m$). At early times the flux increases approximately exponentially due to free-free absorption by the circumstellar envelope. Chevalier (1984a) took an exponential factor for the absorption but the decrease is more complicated because of the effect of limb darkening. This effect is fairly small.

Chevalier (1984a) fit the model to the available radio observations and found $m=1.0$, $\gamma=2.8$, and $t_{20}=950$ days for SN 1979c and $m=0.9$, $\gamma=2.0$, and $t_{20}=190$ days for SN 1980k, where t_{20} is the age at which there is optical depth unity to free-free absorption at a wavelength of 20 cm. The fits imply relatively steep density profiles ($n \geqslant 12$). There does appear to be variability in the observations which is not expected from the model. It may be due to density fluctuations in the stellar wind.

The time t_{20} leads to an estimate of $\dot{M}/v_w$ for the circumstellar wind if the radius of the outer shock is known. For $v_w=10$ km s^{-1}, Chevalier (1982b) deduced $\dot{M}=5\times 10^{-5}\ M_\odot$ yr^{-1} for SN 1979c and $\dot{M}=1\times 10^{-5}\ M_\odot$ yr^{-1} for SN 1980k. These estimates depended on an assumption about the rate of expansion of the interaction shell. Chevalier & Fransson (1984) argued that the late time Hα emission from SN 1979c is from a radiative shock wave at the inner shell. The cooling radiation is initially at X-ray wavelengths and is absorbed by a dense shell of gas, which emits the Hα line. The width of the Hα line then gives the shell velocity directly and $\dot{M}=6$–$7\times 10^{-5}\ M_\odot$ yr^{-1} for $v_w=10$ km s^{-1}. These massloss estimates assume that the temperature in the circumstellar wind is 10^4 K. Heating by ultraviolet and X-ray radiation may increase the temperature above this value (Fransson 1982). This decreases the radio absorption and requires a higher value of $\dot{M}$. On the other hand, clumping of the circumstellar gas decreases the value of $\dot{M}$. Thus the massloss rates are uncertain.

An exciting new development is the angular resolution of the radio emission from SN 1979c by VLBI (Very Long Baseline Interferometry) techniques (Bartel *et al.* 1983; Bartel 1984). The expansion of the radio emitting region has been detected, but it has not yet been possible to map the radio source. The circumstellar interaction model predicts that the emission should be from a shell. With a model for the radio emission, the distance to the supernova can be estimated (Bartel 1984; Marscher 1984; Chevalier & Fransson 1984). Chevalier & Fransson deduced a distance of about 18 Mpc, but the uncertainty may be as large as a factor of 2.

The deduced values of $\dot{M}$ for the winds are quite high and it is not clear that such high values would be maintained over the entire red supergiant lifetime t_{rs}. If a steady wind were maintained over t_{rs}, the final extent of the wind would be about 1 pc. For a low mass star ($M \simeq 9\ M_\odot$), the wind is limited by its interaction with the interstellar medium at about this radius. For a typical shell velocity of 10^4 km s^{-1}, the time of circumstellar interaction is expected to be $\lesssim 100$ yr. Radio supernovae several decades old have recently been detected—SN 1957d and SN 1950b in M 83 (Cowan & Branch 1984). However, these sources have relatively flat spectra and they may be associated with the activity of a central pulsar (see Section 5).

While searches for X-rays from supernovae had previously been carried out, the Einstein Observatory observations of SN 1980k provided the first X-ray detection of an extragalactic supernova (Canizares, Kriss & Feigelson 1982). At a distance of 10 Mpc, the X-ray luminosity about 40 days after discovery of the supernova was 2×10^{39} erg s^{-1}. This luminosity can be attributed to thermal emission from the shocked supernova gas in the interaction region. The value of $\dot{M}/v_{\mathrm{w}}$ derived from the radio observations predicts approximately the correct flux (Chevalier 1982b). The observed decline in the X-ray flux can be reproduced if the evolution of the interaction shell was adiabatic. During the early cooling phase, the X-ray flux is expected to be approximately constant (Fransson 1984). Another possible source of X-rays is the interaction of the radio-emitting relativistic electrons with photospheric photons (Canizares *et al.* 1982). In the circumstellar interaction model, the thermal flux is likely to dominate the inverse Compton flux. Spectral observations are required to distinguish between these mechanisms.

Attempts were made to detect X-rays from SN 1979c, but they were not detected (Palumbo *et al.* 1981). This can in part be attributed to absorption by a dense cool shell at the inner shock wave (Chevalier & Fransson 1984). The absorption decreases with time, so that SN 1979c may still be observable at X-ray wavelength with a telescope somewhat more sensitive than the Einstein Observatory.

4. Type I supernovae

The circumstellar interaction model for radio emission is plausible for type II supernovae because their progenitor stars are expected to have dense, slow winds. There is not a consensus on the progenitors of type I supernovae and radio emission from these events was not predicted. The detection of radio emission from SN 1983n in M 83 (Sramek, Panagia & Weiler 1984) came as a surprise. At first sight, the nature of the radio emission is quite different from that characteristic of type II supernovae. The emission was first observed considerably before maximum optical light and the flux was observed to drop by an order of magnitude in only tens of days. Chevalier (1984b) showed that these properties are compatible with a circumstellar interaction model if the supernova is taken to be an exploding white dwarf (Chevalier 1981a) and the circumstellar wind has a lower density than that deduced for type II supernovae. The early turn-on is attributed to more high velocity material in a type I supernova and a low value of $\dot{M}/v_{\mathrm{w}}$: for $v_{\mathrm{w}} = 10$ km s^{-1}, $\dot{M}$ is about $5 \times 10^{-6} M_{\odot}$yr^{-1}. In the optically thin regime, the observed flux declines as a power law t^{-s} with $s = 1.6$ (Sramek, Panagia & Weiler 1984). The model described for type II supernovae predicts a power law dependence with $s = (\gamma + 5 – 6m)/2$. The value of n for the outer parts of an exploding white dwarf is approximately 7 (Colgate & McKee 1969; Chevalier 1981a), so that $m = 0.8$. The observed radio spectrum (Sramek, Panagia & Weiler 1984) implies $\gamma = 3.0$. Thus the model value of s is 1.6, in good agreement with the observations. The radio luminosity is also consistent with synchrotron emission from a circumstellar interaction region.

While evidence for a circumstellar wind is strong, the supernova progenitor star is unlikely to be the source of the wind itself. Chevalier (1984b) argued for this on the basis of the required density distribution of the supernova gas. A stronger argument is that the earliest observations of the supernova indicate that the progenitor star was relatively compact and such a star is not expected to have a dense wind (Panagia 1984). Thus the source of the wind is likely to be a red giant binary companion star. This situation is expected in one possible evolutionary route to type I supernovae. Iben & Tutukov (1984) find that accretion onto a white dwarf from the wind of a red giant companion star can lead to explosions with a frequency which is not much less than the frequency of type I supernovae. The red giant lies within its Roche lobe. During the time of the radio observations, the radius of the interaction shell is much larger than the expected binary separation so that the wind is approximately spherically symmetric about the supernova.

The accretion onto the white dwarf in the progenitor system produces relatively hard radiation and the binary would appear as a symbiotic star. A recent radio study of symbiotics indicates that the red giant star has a massloss rate of 10^{-7} to 10^{-6} $M_{\odot}$ yr^{-1} (Seaquist, Taylor & Button 1984). For the system V 1016 Cygni, Kwok (1977) suggests a massloss rate of 10^{-5} $M_{\odot}$ yr^{-1}. The radio observations of the symbiotics indicate that the hot component can ionize a region of extent 10^{15} to 10^{17} cm, presumably in the red giant wind (Seaquist, Taylor & Button 1984). It is this gas which can give the early free-free absorption observed in the radio light curve of SN 1983n (Sramek, Panagia & Weiler 1984). Thus the model for the radio emission is consistent with a symbiotic star progenitor.

Optical, ultraviolet, and infrared observations of SN 1983n show that it was not a normal type I supernova (like SN 1972e), but it had peculiar properties (Panagia 1984). Of particular note is that its maximum absolute magnitude was about 2 magnitudes fainter than that of a normal type I supernova. This may indicate that the supernova was a relatively low energy event, which implies that the estimate of $\dot{M}$ should perhaps be reduced by a factor of 2 or 3. SN 1983n may belong to a class of peculiar type I supernovae which are primarily found in spiral galaxies (Panagia 1984). This suggests a relatively massive progenitor system. A moderately high mass is also indicated by the large value of $\dot{M}$ deduced for the red giant star (Sramek, Panagia & Weiler 1984). These considerations imply that there is likely to be considerable variability in the radio properties of type I supernovae.

There were attempts to detect X-ray emission from SN 1983n with the EXOSAT observatory, but it was not detected (Panagia *et al.* 1983). The upper limits on the X-ray luminosity are close to the luminosity expected in the circumstellar interaction model (Chevalier 1984b). The expected rapid decrease in X-ray flux shows the need for fast response time of X-ray observatories to the discovery of a type I supernova.

5. Pulsar emission

It is plausible that pulsars are born in type II supernovae so that pulsar nebulae should eventually be observable. At early times, the free-free absorption due to the supernova matter is very large, but the optical depth drops rapidly with expansion. Ionizing radiation from the pulsar nebula can presumably maintain the ionization of the supernova gas.

The absorption by the supernova gas depends on whether there is slow core material in addition to the fast envelope. Hydrodynamic models of supernova explosions show the presence of slow core matter if the envelope matter is initially greater than the core mass. This is expected from stellar evolution if there is not extensive massloss from the presupernova star. If core material of mass M is uniformly distributed in a sphere with outer velocity v_1, the time at which optical depth unity to free-free absorption is reached is (Reynolds & Chevalier 1984)

$$t_{ff} = 544\, T_4^{-3/10} \left(\frac{M}{2M_\odot}\right)^{2/5} \left(\frac{v_1}{300\ \mathrm{km\,s^{-1}}}\right)^{-1} \nu_9^{-2/5}\ \mathrm{yr},$$

where T_4 is the temperature of the gas in units of 10^4 K and ν_9 is the radio frequency in units of 10^9 Hz. If the undisturbed core material is present, it shields the inner radio emission for a long time. However, if there is considerable massloss from the presupernova star, the core material is not decelerated and v_1 is increased by a factor of 10 to 20. The pulsar nebula becomes visible after decades.

Even if a slow material is present, it may be driven into filaments by the Rayleigh-Taylor instability (Chevalier 1977; Bandiera, Pacini & Salvati 1983). The time for the pulsar nebula to sweep up the core material is

$$t_s = 9.3 \left(\frac{M}{2M_\odot}\right) \left(\frac{v_1}{300\ \mathrm{km\,s^{-1}}}\right)^{2} \left(\frac{L}{10^{40}\mathrm{erg\,s^{-1}}}\right)^{-1} \mathrm{yr},$$

where L is the initial rotational energy loss from the pulsar and 10^{40} erg s^{-1} is approximately the value of L for the Crab pulsar. After t_s, the pulsar nebula accelerates the core material and the Rayleigh-Taylor instability can occur. The pulsar nebula again becomes observable after decades.

If this is the typical timescale for the radio appearance of a pulsar nebula, this mechanism should be considered in interpreting the emission from intermediate age supernovae. The radio detection of SN 1957d is of particular interest in this regard because of its relatively flat spectrum, $F_\nu \propto \nu^{-0.25}$ (Cowan & Branch 1985). A flat spectrum is typical of radio nebulae which appear to be powered by central pulsars (*e.g.* Weiler 1983). The radio luminosity of SN 1957d is consistent with a pulsar nebula containing a pulsar similar to the Crab pulsar (Reynolds & Chevalier 1984; Bandiera, Pacini & Salvati 1984). It will be difficult to distinguish between the pulsar and circumstellar interaction models on the basis of time evolution because the evolution is so slow at this time. Polarization observations, if possible, will offer an important clue because significant polarization is expected in the pulsar model. Even stronger evidence would be VLBI observations which can distinguish a centrally concentrated source from a shell source.

X-rays from a pulsar nebula are affected by photoelectric absorption at early times. The supernova gas should become optically thin to X-rays somewhat before it is thin to radio emission (Reynolds & Chevalier 1984).

6. Future prospects

On the theoretical side, the main unsolved hydrodynamic problem is the effect of the Rayleigh-Taylor instability on the circumstellar interaction. The instability presumably grows into the nonlinear regime so numerical simulations will probably be needed to solve the problem. With the advent of increasingly powerful supercomputers, progress in this field should be possible.

Another major theoretical problem is the mechanisms responsible for the relativistic electron acceleration and the generation of the magnetic field. The observations show a range of spectral indices for the radio emission but it is not understood why any particular value occurs. With more observations of a number of radio supernovae, it may be possible to relate the nature of the circumstellar interaction to the properties of the radio emission. Radio supernovae provide a laboratory in which particle acceleration can be studied under relatively well understood conditions.

Future observations of radio supernovae by VLBI techniques are of particular interest. In addition to providing definitive evidence for the circumstellar interaction model, they should play an important role in determining the distances to supernovae. With the VLBA (Very Long Baseline Array), it should be possible to regularly map radio supernovae.

The subject of X-ray observations of supernovae is still in its infancy with only one supernova detected to date. X-ray light curves and spectra will provide a wealth of information on the circumstellar interaction. The X-ray flux should make distance estimates possible, when the supernova is observed at a range of wavelengths so that a model can be developed.

The study of radio and X-ray emission from supernovae is just beginning, but it has already led to interesting information on the surroundings of type II supernovae and to a particular evolutionary route to a type I supernova.

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Pulsars, Evolution of Plerions and Radiosupernovae

Franco Pacini *Osservatorio Astrofisico di Arcetri* and *Universita di Firenze, Largo E. Fermi 5, I-50125 Firenze, Italy*

1. Introduction

The interpretation of pulsars as rotating neutron stars has gained general acceptance since the discovery of PSR 0531 inside the Crab Nebula. Almost 400 pulsating sources are presently known and for a large fraction of them one has been able to measure the slowing-down rate. A great wealth of data on pulsar properties is now available. These have been reviewed in several articles and textbooks (see, *e.g.* Manchester & Taylor 1977; Sieber & Wielebinski 1981). In these lectures I will begin by recalling the basic concepts concerning the electrodynamics of pulsars and the radiation process. Then I will discuss the significance of recent discoveries which may cast new light on the origin of fast rotating neutron stars and on the evolution of pulsar powered supernova remnants ('plerions'). In the latter context I will deal with the question of whether the radio emission observed from the site of recent supernova outbursts ('radiosupernovae') can be interpreted as a manifestation of the birth of a new plerion.

2. Pulsar electrodynamics and radiation

It is well known that the slowing down of pulsars can be understood as loss of rotational energy from the underlying neutron star. In most cases the pulses of radiation are only a tiny fraction of the total energy loss measured from the increase of the period. It is generally agreed that the bulk of the energy lost by the star is converted into fast particles and large scale electromagnetic fields. Although a complete self-consistent theory of pulsar magnetospheres is not yet available, most proposed models involve a continuous outflow of electromagnetic energy across the so-called 'speed-of-light cylinder', at a distance $R_{cr} \sim c/\Omega$ from the star (Ω is the stellar rotation frequency). As an order of magnitude the energy lost $I\,\Omega\,\dot{\Omega}$ (I is the stellar moment of inertia) is given by

$$I\Omega\dot{\Omega} \sim \mathrm{B}_{cr}^2\, c(c/\Omega)^2, \qquad (1)$$

where B_{cr} is the magnetic field strength at $R = R_{cr}$. The rate of slowing down is therefore a measure of the magnetic strength at the speed of light distance. If one *assumes* that the field is dominated by a dipolar component $B \propto r^{-3}$, one can infer that it must be $\dot{\Omega} \propto \Omega^n$ with $n = 3$. Different field geometries would correspond to different values of n. In principle one can determine n by measuring the second time derivative of the pulsar period. Until now, meaningful values of n have been obtained only for two pulsars. In the case of PSR 0531 it has been found that $n \sim 2.5$, not too far from the value expected for a dipole geometry. Very recently, a similar value $n \sim 2.8$ has been reported for PSR 1509 (Manchester & Durdin 1984). The observed deviation from $n = 3$ can be understood qualitatively by noticing that in a radial field $n = 1$ and that the escaping plasma should push radially the field lines. Because of this reason one may expect that in general $n < 3$. Only in the case of very young and fast sources, where the speed of light cylinder is close to the stellar surface, multipolar components may become important and give $n > 3$ (gravitational radiation would also entail $n = 5$). In any case, if one assumes that the field internal to the light cylinder obeys a dipole law (at least as a first approximation), the typical surface strengths B_0 lie in the range 10^{11}–10^{13} g, with some notable exceptions which we consider later.

The general considerations presented above apply in particular to two specific models of neutron star electrodynamics which were proposed around the time of the discovery of pulsars and which have served as basis for later developments.

The first model is that of a neutron star with a magnetic axis inclined with respect to the rotation axis. In this case the star loses rotational energy *via* magnetic dipole radiation at the basic rotation frequency and can energize the surrounding space by accelerating particles in the resulting largescale electromagnetic wave fields (Pacini 1967, 1968; Ostriker & Gunn 1969). If the two axes are parallel, the star can still lose rotational energy through the effect known as 'unipolar inductor' (Goldreich & Julian 1969). The electric fields induced on the stellar surface can extract particles from the star and create in its surroundings a magnetosphere. Above the magnetic pole one expects a steady outflow of energetic particles which form a poloidal system of electric currents and therefore produce a largescale toroidal magnetic field.

Just as a summary of the basic concepts, Table 1 compares theory and real life for the two basic models (the observational evidence refers to the best studied pulsar PSR 0531 and the surrounding Crab Nebula).

As one can see from Table 1, the overall scenario may be regarded as satisfactory as far as the basic conversion of rotational energy into particles and fields is concerned. However it is clear that very little progress has been made in understanding why particles in the Crab Nebula are accelerated with a power law and why the number of accelerated particles exceeds by a large factor the magnetospheric charge density of the Goldreich-Julian model. Alternatively, the particles injected into the Crab Nebula are either a secondary process due to pair-creation in the magnetosphere or are accelerated well outside the pulsar (possibly in the Nebula itself) by largescale electromagnetic fields. A detailed description of recent developments in pulsar electrodynamics is beyond the scope of these lectures and can be found elsewhere (see *e.g.* Michel 1982).

We come next to the nature of the process by which a neutron star emits pulses of radiation in the radio band and, in some cases, also at higher frequencies. Concerning the radio emission, apart from the sharpness of the pulses, the most striking

Table 1. The Crab: model versus real life.

Theory	Observation
$\dot{\Omega} \propto \Omega^3$	$\dot{\Omega} \propto \Omega^{2.5}$
charge outflow $10^{33}\ \mathrm{s}^{-1}$	particle outflow $10^{40}\ \mathrm{s}^{-1}$
monocromatic energy distribution	power law energy distribution
$B \sim 10^{-4}$ G (in the nebula)	$B \sim 3 \times 10^{-4}$ G (in the nebula)

characteristic of the radiation is the very high observed brightness temperature, typically much above 10^{20} K up to, say 10^{33} K. The radio emission is therefore certainly coherent and it is often ascribed to the acceleration of bunches of particles sliding along curved field lines in the pulsar magnetosphere, possibly while these particles escape from above the magnetic poles (Radhakrishnan & Cooke 1969). If ρ is the radius of curvature of these lines and γ is the Lorentz factor of the moving particles, the characteristic emitted frequency ν_c

$$\nu_c \sim (c/\rho)\gamma^3. \tag{2}$$

Typically (since $R_{\rm star} < \rho < c/\Omega$) radiofrequencies would correspond to Lorentz factors of order 10^2. Also, because of the thermodynamic limitation on the brightness temperature $kT_b \lesssim mc^2\gamma F$, one can infer a lower limit to F, the number of particles radiating in phase. Just as an example, $T_b \sim 10^{26}$ K corresponds to a degree of coherence (number of particles per bunch radiating in phase) $F \sim 10^{14}$. The wealth of data available about spectral and polarization properties of pulsars also carries fundamental information on the radiation process and on the location of the emitting region, although without complete consensus among the researchers.

Concerning the optical emission, it must be stressed that this is a characteristic typical only of very fast pulsars. Indeed, optical pulses have been detected only in the case of PSR 0531 ($P = 33$ ms), PSR 0833 ($P = 89$ ms) and the pulsar recently discovered in the Large Magellanic Cloud PSR 0540 ($P = 50$ ms). This behaviour of the optical radiation from pulsars finds a natural interpretation if one assumes that (unlike the radio emission) it is incoherent synchrotron radiation emitted by the accelerated particles in the proximity of the speed of light distance. In this case it is easy to show that the bolometric synchrotron radiation should scale roughly as $B_0^4 P^{-10}$ (Pacini 1971).

This strong dependence on the period is largely due to the fact that, in a dipole field, slower pulsars have magnetic fields at $r \sim R_c$ much smaller than fast pulsars. More elaborate calculations (Pacini & Salvati 1983) have taken into account the possibility of synchrotron reabsorption and the shape of the energy spectrum for the particles accelerated. These calculations lead to the possibility of predicting the optical emission of various pulsars as a function of their period and period derivative (alternatively, period and magnetic field). The predictions for the optical luminosity of various pulsars are listed in Table 2.

(It is worthwhile to stress that these predictions only hold as far as the duty cycle of the various sources is comparable to that of the Crab pulsar PSR 0531). Fig. 1 shows the evolution of the optical luminosity for pulsar like PSR 0531 ($B_0 \sim 10^{12}$) which starts with an initial period P_0 in the millisecond range. The maximum optical luminosity is reached when $P \sim 16$ ms, and synchrotron reabsorption in the optical band becomes negligible. It may be interesting to notice that, at a distance of order 10 Mpc, such a

Table 2. Predicted optical luminosities of fast pulsars.

Pulsar	P(ms)	$P\dot{P}$	$L_{\rm pred}$ (erg s^{-1})	$L_{\rm obs}$ (erg s^{-1})
PSR 0833 − 45	89	1.25×10^{-13}	2.5×10^{29}	1.4×10^{29}
PSR 1509 − 58	150	1.49×10^{-12}	9.1×10^{29}	...
PSR 1913 + 16	59	8.6×10^{-19}	6.0×10^{21}	...
PSR 1937 + 21	1.56	1.0×10^{-19}	9.0×10^{29}	...

pulsar would have a peak apparent magnitude $m \sim 28$, barely within the limits of the forthcoming Space Telescope. The good agreement between theory and observations for PSR 0833 and for the secular decrease of the optical luminosity of PSR 0531 (J. Kristian, private communication) lends support to the idea that the optical pulses are indeed emitted close to the speed of light distance by the synchrotron process.

3. Millisecond pulsars

Although pulsars may in principle rotate as fast as thousand times per second, magnetic fields around 10^{12} G would slow them down in a very short time. Most pulsars should therefore be found with relatively long periods, in agreement with the observational evidence. Because of this reason (and also of the difficulties associated with the search of millisecond periodicities), for a long time one has not searched for very fast pulsars. This choice has clearly been connected with the theoretical bias of assuming that all pulsars should have very strong fields. Only in recent years one has been able to find the first two examples of a new class of pulsars rotating extremely fast and characterized by a very small period increase *i.e.* a relatively weak magnetic field $B \leqslant 10^8$–10^{10} G. Their discovery has not been the consequence of a systematic search but of a detailed study of peculiar objects. In the first case $P \sim 1.5$ ms, in the second $P \sim 6$ ms. Are these sources an exception or are they the tip of an iceberg not yet explored? We do not know but several groups are presently engaged in a systematic search for similar objects.

Speculations about the origin and evolution of very fast, weakly magnetized pulsars have been proposed by various authors. The most simple explanation is that they are not different from the other pulsars, except for the fact that they were born with weak fields and therefore can rotate for a long time with the initial period. This is not unreasonable: after all normal stars or white dwarfs also show considerable dispersion in the field strength. The problem is that the analysis of the data concerning the diagram P–P of the pulsars already discovered indicates a paucity of weakly magnetized neutron stars, say with $B < 10^{11}$ G. Not all fields seem to be equally probable. One may therefore be obliged to postulate a bimodal distribution of magnetic fields, possibly associated with different processes giving birth to neutron stars. An alternative possibility is that very fast pulsars are old objects which have already passed through the standard pulsar phase and have suffered a field decrease because of ohmic decay. If

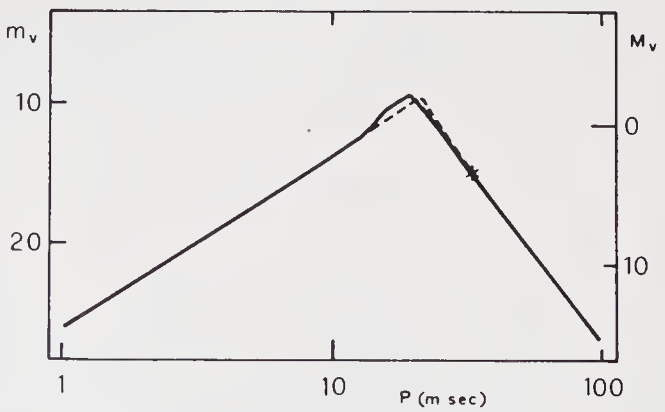

Figure 1. Optical luminosity of a pulsar like PSR 0531 as a function of period (solid line).

they have been associated with a binary system, they have undergone a phase of accretion with a consequent speeding-up. Various authors have suggested that millisecond pulsars are old neutron stars which have been rejuvenated by accreting matter and angular momentum from a companion and are now living a new phase of their life. The problem with this idea is that only the 6 ms pulsar is in a binary system. In the case of the 1.5 ms pulsar one must invoke the disappearance of the companion either in a second supernova explosion which has disrupted the system or through coalescence into the first neutron star. Personally, I am more keen to the first, more straightforward interpretation of very fast pulsars and I would like to add a more general remark concerning the formation of neutron stars. This remark also relates to the fact that all four binary pulsars discovered until now have relatively weak fields ($B < 10^{10}$–10^{11} G). It is well known that binary pulsars are rare in the sample of sources collected so far, roughly one binary every 100 sources. The accepted explanation invokes the run-away effect resulting from rapid massloss from the binary system, when one of the components becomes a supernova. If however the explosion occurs slowly with respect to the orbital period, the system is not disrupted. It then becomes tempting to speculate about the possibility of a relatively slow stellar collapse as the birthplace of binary pulsars and about a possible connection between the strength of the stellar magnetic field in the stellar core and the rapidity of the collapse itself. Indeed the stellar collapse is likely to be influenced by the rotation. If the magnetic field is strong, angular momentum will be removed fast and the collapse time will be of the order of the free-fall time. If however the field is weak, removal of the angular momentum will be slower ($\propto B^{-2}$) and the collapse time may be determined by the timescale of the removal. One can then expect that the ensuing massloss will not be sufficiently rapid to cause the disruption of the binary system. I have therefore suggested elsewhere (Pacini 1983) that the population of very fast, weakly magnetized pulsars to be discovered in the forthcoming surveys is likely to contain a large proportion of binary systems. Also, in this framework one may possibly understand the observational relation between magnetic fields and velocity of neutron stars discussed in this volume by V. Radhakrishnan.

4. The evolution of plerions and the nature of radiosupernovae

It is now recognized that several Galactic supernova remnants closely resemble the Crab Nebula and are probably driven by an undetected central pulsar. The properties of these remnants, the so-called 'plerions', are discussed in this same volume by G. Srinivasan and by K. Weiler. Their expected evolution can be studied assuming that the pulsar injects continuously into the surrounding space magnetic energy and relativistic electrons. One can then derive, as a function of time, the field strength in the remnant, the energy distribution of the particles and the resulting nebular synchrotron luminosity at various frequencies (Pacini & Salvati 1973; Bandiera, Pacini & Salvati 1984; Reynolds & Chevalier 1984).

Concerning the evolution of the nebular field B, its average value is determined by the following equation

$$\frac{\mathrm{d}U_{\mathrm{B}}}{\mathrm{d}t} = \frac{L_0}{(1+t/\tau)^2} - \frac{v}{R}U_{\mathrm{B}}, \tag{3}$$

where

$$U_{\mathrm{B}} = \tfrac{1}{6}B^2R^3.$$

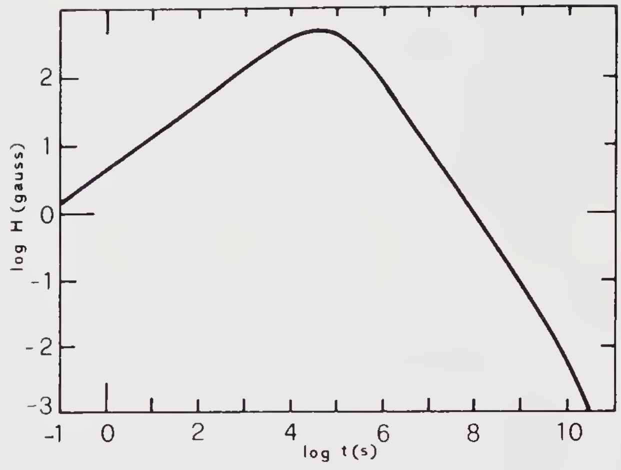

Figure 2. Evolution of the magnetic field inside the Crab Nebula.

This equation expresses the balance between the rate of change in the nebular magnetic energy and the input rate from the pulsar (initial energy loss L_0, decay time τ), minus the rate of adiabatic energy losses determined by the expansion velocity v. If one applies these considerations to the Crab Nebula ($L_0 \sim 10^{39}$ erg s^{-1}, $\tau \sim 300$ yr, $v \sim 10^8$ cm s^{-1}) one obtains the field evolution sketched in Fig. 2. Note that after the explosion, at $t \sim 1$ day, the average nebular field was of the order of 10^2 G and that one expects a present-day strength $\sim 3 \times 10^{-4}$ G, in agreement with the observational value. Once the time evolution of the field has been established, one can determine the history of the nonthermal nebular luminosity. One assumes that the pulsar injects continuously relativistic electrons with a power law energy distribution. These electrons evolve because of adiabatic and radiative losses. The reader interested in the details of these calculations is referred to the 'Kama-Sutra' on spectral evolution of plerions written with M. Salvati in 1973 (however he is also warned that this reading is not as stimulating as the original manual quoted above!). Fig. 3 shows the evolution of

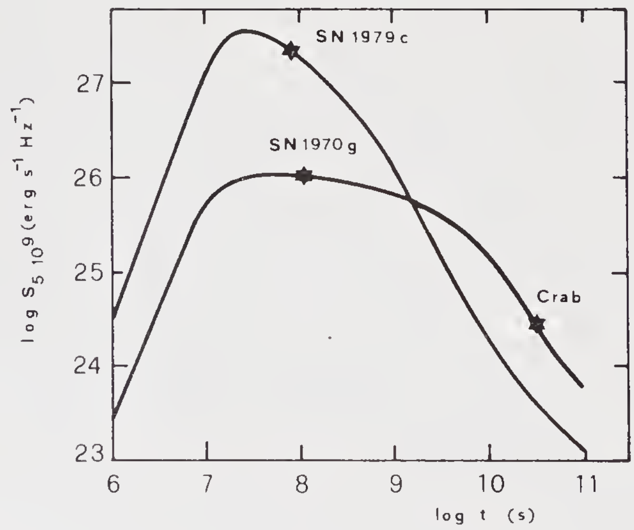

Figure 3. Evolution of the radio flux at 5×10^9 Hz from two plerions. The upper curve postulates a central pulsar with $P_0 \sim$ ms inside a remnant expanding with $v \sim 10^9$cms^{-1}. The lower curve postulates a central pulsar with $P_0 \sim 16$ ms inside a Crab-like remnant expanding with $v \sim 10^8$cms^{-1}.

the radio emission of plerions at $\nu = 5 \times 10^9$ Hz with two different assumptions concerning the properties of the central pulsar and the remnant's expansion velocity. The lower curve 'a' refers to a system where the central pulsar is similar to PSR 0531 and the nebula expands with $v \sim 10^8 \mathrm{cm\,s^{-1}}$; the upper curve 'b' refers instead to the case $P_0 \sim 1$ ms and $v_0 = 10^9 \mathrm{cm\,s^{-1}}$.

Quite generally, one can see that the early phases of the evolution are dominated by synchrotron reabsorption because of the very strong magnetic field. At later times, (say, some months after the explosion) the newly born plerion is expected to have a very strong radio luminosity. This remains constant for a time comparable with the pulsar slowing-down timescale. At later epochs there is a marked flux decrease due to the fact that the rate of injection has declined and the evolution of the source is dominated by adiabatic and radiation losses.

The expected very strong initial radio emission raises the question of a possible connection between the phenomenon of radiosupernovae and the early evolution of plerions. Radiosupernovae are described in this volume by K. Weiler. Because of this reason we recall only the main observational points:

1. the radio emission is generally observed in type 2 supernovae and it is usually delayed by several months with respect to the optical outburst (one notable exception is the type 1 supernova 1983n, see the article of K. Weiler in this volume).
2. the radio emission is nonthermal and it lasts at a level stronger than Cas A for several years, possibly > 10 yr. If this lifetime is common among radiosupernovae, a frequency of one type 2 event in each galaxy every 30 years entails that there should be at least one radiosupernova every 3 galaxies.

Table 3 lists the properties of several radiosupernovae detected in various galaxies: distance (in Mpc); absolute radio power; equipartition energy content; corresponding requirements for the minimum rate of energy input averaged over the lifetime of the source.

Two different models for the origin of the radio emission have been put forward. Chevalier (1982; see also his lecture in this volume) has proposed that the radio flux originates outside the expanding remnant and the particles are accelerated when the shell interacts with pre-ejected circumstellar matter. The alternative model (Pacini & Salvati 1981; Bandiera, Pacini & Salvati 1984) postulates the existence of a central pulsar which gives birth to a plerion. My preference for the latter model stems from the

Table 3. Radio supernovae.

SN	Galaxy	Reference time after maximum (days)	Distance (Mpc)	Absolute radio luminosity ($\mathrm{erg\,s^{-1}}$)	Equipartition energy (erg) [$\nu_{min} = 10^8$ Hz: $\nu_{max} = 10^{11}$ Hz]	Average input power ($\mathrm{erg\,s^{-1}}$)
1957d	NGC 5236	8553	4	7×10^{34}	5×10^{47}	6×10^{38}
1970g	NGC 5457	852	7	4×10^{35}	6×10^{46}	9×10^{38}
1979c	NGC 4321	1212	16	9×10^{36}	2×10^{48}	2×10^{40}
1980k	NGC 6946	463	5	2×10^{35}	2×10^{46}	6×10^{38}
1981	NGC 4258	609	6.6	1×10^{35}	2×10^{46}	4×10^{38}

fact that the radio fluxes expected from newly born plerions (say, at age $\sim$ months up to years) closely match the flux observed from radiosupernovae. In particular, Fig. 3 shows that a Crab-like object with age ~ 1 year would have a radio luminosity comparable to that of 1970 g. On the other hand, according to Fig. 3, a very fast pulsar inside a fast expanding remnant would produce a source very similar to 1979c. The main objection raised against this model is that a uniform distribution of ionized matter resulting from the explosion would prevent the escape of radio emission for at least 10^2 years. This objection becomes invalid if the supernova shell fragments very early into filaments because of Rayleigh–Taylor instabilities, a possibility suggested by Bandiera, Pacini & Salvati (1983).

In any case there is no way to discriminate at the present time between models of radiosupernovae on the basis of the short term light curve since both models appear to agree with the existing observational points (Weiler, this volume). Only in the case of the type 1 supernova SN 1983n, Chevalier's model seems to provide a better fit to the rapid decay. On the other hand the persistence of the radio emission from the sites associated with the relatively old supernovae 1950b and 1957d (Cowan & Branch, preprint 1984) may find a natural explanation in the framework of the evolving plerion model. Future radio observations of other supernovae which exploded during the last century will certainly be crucial in establishing whether there is a continuity between the radiosupernovae and the remnant phase. In any case, the observation of nonthermal phenomena from the site of stellar explosions provides a very important possibility of investigating the properties of supernovae in the post-outburst phase, a stage which was completely obscure up to recent years.

Acknowledgements

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Observational Aspects of Supernova Remnants

David Clark *Rutherford Appleton Laboratory, Chilton, Didcot, OXON OX11 0QX, UK*

1. Introduction

Of the $> 10^{51}$ ergs produced in a supernova explosion, less than 1 per cent is in optical and ionizing radiation. The bulk of the energy is contained initially in the expanding ejecta—much of this energy eventually being transformed to thermal energy of swept-up interstellar material. Thus on energetic grounds alone, supernovae are important as a source of energy input to the interstellar medium (the power input is comparable to that from early-type stars, although the rate of mass input is very much less than from stellar massloss: see Clark 1983).

As matter and energy are injected into the surrounding interstellar medium from a supernova explosion, a *supernova remnant* (SNR) is formed and may be observed most easily at radio, optical, and X-ray wavelengths. Emission from SNRs results from thermal bremsstrahlung and line emission which are important in the X-ray region, and synchrotron radiation which is dominant at radio frequencies, but is also recognized as the source of optical and X-ray emission in a few SNRs (*e.g.* the Crab).

2. Radio remnants

The radio remnants of supernova came under investigation in the very earliest days of radio astronomy. Shklovskiĭ was the first to propose that the radio emission was due to the synchrotron mechanism.

The criteria usually used to recognize supernova remnants in radio surveys (*e.g.* Clark & Caswell 1976) have been:

(i) Identification with an historically recorded supernova event, and/or identification with an optical filamentary structure characteristic of the optical remnants of supernovae (only observed for 'nearby' objects).
(ii) A non-thermal spectrum (*i.e.* radiated power decreasing with increasing frequency), and usually some linear polarization—both indicative of radiation by the synchrotron process. Hydrogen recombination lines, which characteristically accompany free-free continuum radio emission, is not expected to be present.
(iii) Where resolution permits, the recognition of a 'ring' or 'part-ring' structure characteristic of SNRs is indicative of an expanding shell.
(iv) Proximity to the Galactic plane.

On the basis of these selection criteria, catalogues containing > 130 Galactic SNRs have been prepared (*e.g.* Ilovaisky & Lequeux 1972; Clark & Caswell 1976; Caswell & Lerche 1979; Green 1984). It is now recognized that the above selection criteria excluded an important sub-class of 'filled-centre' or 'plerionic' SNR (Weiler 1979), the Crab Nebula being the classic example. These are characterized by central rather than peripheral brightening (thus not meeting criterion (iii)), and tend to have flat spectra (therefore not meeting part of criterion (ii)). The central brightening is thought to result from an active pulsar. Since plerionic remnants mimic HII regions in many of their properties, it is possible that a large number remain to be identified. Another likely cause of incompleteness is the 'poor' spatial resolution of the survey instruments used for SNR searches (typically ~ 3 arcmin). Thus small-diameter remnants ($D < 10$ pc) would not be resolved at distances $\gtrsim 15$ kpc, and would therefore be unlikely to be distinguished from background extragalactic sources. A recent survey of 32 small-diameter objects close to the Galactic plane using the VLA (Green & Gull 1984) have revealed 2 of them to be SNRs. There are, undoubtedly, other small-diameter Galactic remnants awaiting discovery. Other sources of incompleteness could include confusion of low-surface brightness SNRs with the non-thermal Galactic background, and the minimum detectable peak flux density of the survey instruments.

Despite these problems, existing catalogues of SNRs must be considered near-complete to some limiting surface brightness, except for an expected small number of young small-diameter SNRs plus distant plerions.

Although the spectrum and polarization of the radio emission from SNRs confirm that it is synchrotron radiation, there is no single completely satisfactory theory yet for the origin and evolution of the particles and fields. There is increasing evidence that these might be dominated by quite distinct physical processes at various stages of a remnant's evolution. In young remnants the stellar magnetic field is amplified by instabilities at the shock/ISM interface—the relativistic particles are accelerated ejecta (Gull 1973). In older remnants, the compressed interstellar field plus ambient cosmic rays are the likely source of radio emission (as first proposed by van der Laan 1962). Old supernova remnants certainly show a decreasing surface brightness with distance from the Galactic plane, commensurate with a decrease in interstellar magnetic field intensity. However, the presence of a tenuous hot component plus neutral cloudlets is well established, requiring a revision of the oft-used simplified evolutionary picture.

The simplified evolutionary picture for shell SNRs envisages four distinct phases (Woltjer 1972):

Free expansion phase

$D \propto t$ $\quad D =$ diameter, $t =$ time

(Assumption: mass of swept-up ISM is very much less than ejected mass, and is dynamically unimportant.)

Adiabatic (Sedov) phase

$D \propto (E_0/n)^{1/5}\, t^{2/5}$ $\quad E_0 =$ initial blast energy, $n =$ mean IS density

(Assumption: swept-up ISM dominates expansion—radiative effects ignored.)

Isothermal (momentum-conserving) phase

$D \propto t^{1/4}$

(Assumption: radiative cooling important.)

Extinction phase

The remnant merges with surrounding ISM.

Numerical computations of the full dynamical development of SNRs have been attempted—these have emphasized the uncertainties of assigning observed SNRs to one of the above phases, since the transitions between them are complex and with unknown timescales.

Whereas theoretical studies of the dynamical evolution of SNRs attempt to describe the variation of linear diameter D, with time t, elapsed since the supernova outburst, it is the surface brightness $\Sigma(=\text{flux density}/(\text{angular diameter})^2)$ which most easily lends itself to observational investigation.

Relationships of the following form are postulated:

$$\Sigma = AD^{\beta},$$

$$\Sigma = Bt^{\gamma}.$$

(These may be combined in form $D = Ct^{\delta}$, compatible with theoretical format.) Numerous attempts have been made to establish a 'Σ–D' relationship from observations of remnants with well-established distance estimates (*e.g.* kinematic distances, historical SN distances, *etc.*), and thus infer the distances to all SNRs with measured Σ. This technique remains controversial, since it is apparent that many SNRs show dramatic departure from 'normal' evolutionary behaviour. Caswell & Lerche (1979) have attempted to improve the 'Σ–D' fit by allowing for Σ variation with distance z from the Galactic plane. However there has been recent renewed criticism of the technique (Green 1984; Mills *et al.* 1984).

What one can calculate from the observational data is the cumulative distribution

$$N\ (\Sigma) = P\Sigma^{\varepsilon},$$

where N is the number of SNRs with surface brightness greater than Σ. Incompleteness of the catalogues can be allowed for

$$N(\Sigma) = P^1\ (1+f)\ \Sigma^{\varepsilon}.$$

Observationally $\Sigma = -0.86 \pm 0.16$ (Clark & Caswell 1976). Now, one can show simply that $\delta = 1/\varepsilon\beta$.

If the assumption of Sedov adiabatic expansion for middle-aged remnants is correct, $\delta = 2/5$. Since $\varepsilon = -5/6$ from observation, then $\beta = -3$. Thus, any departure from a $\Sigma = AD^{-3}$ relationship must call into question the adiabatic expansion assumption. (For free expansion, $\delta = 1$, so that there would be a $\Sigma = AD^{-1.2}$ relationship. Mills *et al.* 1984 claim such a relationship for LMC remnants).

The Σ–D technique may be unreliable in seeking distances to individual SNRs, and even its usefulness in statistical studies has been called into question (Green 1984). Nevertheless, the earlier observation of Clark & Caswell (1976) should still be heeded—'The Σ–D approach is at present an empirical one with little theoretical foundation, but the quality of the observational data and their statistical implications provide valuable restraints against which future theoretical models may be tested.'

Statistical studies of Galactic radio SNRs have shown that

(a) they are restricted to a little over the solar distance from the Galactic centre,
(b) they are restricted to ~ 100 pc of the Galactic plane
(c) $E_0/n \sim 5 \times 10^{51}$ ergs cm^3,
(d) the 'characteristic interval' between supernovae of the type producing long-lived remnants is ~ 80 years—more later.

Observations of SNRs at radio wavelengths remain important for the following reasons:

— best wavelength for surveys;
— Galactic distribution studies;
— investigations of evolutionary behaviour of remnants;
— monitoring interstellar magnetic fields;
— study of hydrodymanic and plasma processes.

3. Optical remnants

There are three distinct classes of optical supernova remnant.

Class 1: These are believed to have been produced from comparatively recent type I supernovae. They display only Balmer line emission, and are also characterized by low velocity dispersion. Examples are the remnants of SN 1006 and Tycho's SN. This characteristic spectrum has been explained in terms of a collisionless shock theory (Chevalier & Raymond 1978). A collisionless shock propagates into a neutral medium at high velocity. Initially hydrogen atoms are collisionally excited by a hot electron gas, giving rise to the Balmer spectrum; forbidden lines are not strong because collision strengths are small for post-shock electron temperatures. The Class 1 optical remnants reveal the important property of the ISM that, at least in the case of type I supernovae, it appears shocks are propagating into a neutral medium; (if a type I SN itself produced a pulse of UV photons sufficient to ionize the medium surrounding it, then recombination could not have taken place in the time since the outburst—this is direct evidence that type I supernovae produce negligible ionizing flux).

Class 2: Some remnants display spectra dominated by strong, high velocity lines of oxygen and other alpha-processed material. Examples are Cas A, and MSH 11–54. It is believed that here we are observing processed ejecta from the massive progenitors of type II supernovae, and possibly also circumstellar material from the progenitors. Some such objects suggest an equatorial asymmetry in the supernova explosion (presumably induced by the rotation of the progenitor star). The spectra of Class 2 optical SNRs provide important evidence on both the physics of type II SN explosions and the composition of their massive progenitors.

Class 3: In the later stages of evolution, the rich optical emission-line spectra of *many* SNRs display remarkable similarity—showing [S II], [O I], [O II], [O III], and [N II] lines are as strong as Hα. There is some confidence that the remnant is now dominated by swept-up ISM. Spectrophotometry of evolved remnants has given strong support to the hypothesis that a rediating shock wave is being observed. Characteristic line ratios can yield estimates of the shock velocity, temperature, density, and element abundances.

Optical remnants have been identified, traditionally, by the intensity ratio of the red [S II] doublet to Hα. The selection criteria used (*e.g.* Mathewson & Clarke 1973) is

$$\frac{\lambda\lambda 6717\text{-}31\ [\mathrm{S\,II}]}{\lambda 6563\ \mathrm{H}\alpha} > 0.7$$

—significantly higher than for H II regions. It is now realized that narrow-band [S II]/Hα surveys have revealed only optical remnants of Class 3. It seems that there has not been a systematic survey for optical remnants of Class 1 (these would be difficult to distinguish from H II regions on the basis of optical imagery alone) or Class 2 (perhaps using a narrow band [O III] filter); optical remnants of these classes would appear to have been discovered by accident or by directing spectroscopic observations at the sites of known radio and X-ray remnants.

Optical observations of supernova remnants tend to concentrate on the following aspects:

(a) Velocity mapping—using a long slit spectrograph, with slit stepped across the nebula, radial velocity estimates can be obtained over the face of the nebula. These can be used to investigate the dynamical evolution of an optical supernova remnant, and its three-dimensional structure (*e.g.* Clark *et al.* 1983).
(b) Relative emission-line intensities—these can be used to monitor the density, temperature, morphology, and composition of the optical nebula. A long-slit spectrograph can be used, with area coverage being achieved by stepping the slit (Clark *et al.* 1984)—alternatively, narrow-band emission-line filters have been used (although this technique is fraught with problems).
(c) Coronal-line mapping. Shklovskiĭ (1967) was the first to draw attention to the possibility that hot rarefied plasma ($T \sim 10^6$ K) in SNRs should be detected in optical coronal lines such as λ5303 [Fe XIV]. Woodgate *et al.* (1974) made a photometric detection of λ5303 in the Cygnus Loop—spectroscopic detections have been made in Puppis A, N49, and other objects. Detection of the coronal lines provides the capability to observe high-temperature regions in SNRs in other than X-rays—to estimate plasma temperature, and such derived parameters as shock velocity.

Observations of supernova remnants at optical wavelengths remain important for the following reasons:

Young remnants: —investigations of stellar nucleosynthesis products;
—nature of progenitors;
—study of circumstellar material.
Old remnants: —composition and morphology of ISM;
—investigation of evolutionary behaviour of remnants.

4. X-ray remnants

The EINSTEIN Observatory revolutionized our understanding of X-ray SNRs. For the first time, we have detailed pictures of their morphology; plus some spectral information. The X-ray emission for the vast majority of SNRs is believed to be thermal bremsstrahlung from hot gas (10^6–10^7 K). In a very few cases (*e.g.* the Crab Nebula) it is known to have a significant non-thermal component.

As in the case of young optical SNRs, emission from young X-ray SNRs is thought to come from ejecta or circumstellar material rather than the shock-heated ISM. Evaporation from fast moving knots of ejecta in the hot ISM has been invoked as the source of X-rays in such young objects as Cas A, Tycho's and Kepler's SNR, *etc.*

(Chevalier 1975). Only in comparatively old SNRs is one seeing shock-heated interstellar material, and it is here that X-ray spectral data are important. The EINSTEIN Solid State Spectrometer (SSS) produced spectra of several Galactic and LMC remnants, confirming a thermal origin for most of these. Spectra were fitted with the Raymond-Smith model for hot plasma in collisional ionization equilibrium. Despite some difficulties with the processing and interpretation of these data, it is accepted that relative abundances obtained from the X-ray spectra are probably meaningful.

Observations of supernova remnants at X-ray wavelengths remain important for the following reasons:

Young remnants: —investigation of stellar nucleosynthesis products;
—nature of progenitors.
Old remnants: —composition and morphology of ISM;
—energetics of supernovae.

5. Supernova remnants as probes of the interstellar medium

Although supernovae remnants are of enormous interest in their own right, both as the aftermath of the most energetic stellar phenomena known and as an important source of energy input to the interstellar medium, they are of strictly limited use as probes of the interstellar medium. Only 'old' optical and X-ray remnants, dominated by swept-up material, can be used to estimate the composition, temperature, density, and morphology of the interstellar medium. It would seem that the most effective probes of the properties of the ISM remain photoionized systems.

6. Supernova rates and formation of SNRs

There are three lines of investigation which lead to estimates of the birthrate of supernovae in the Galaxy. These are:

(1) Observations of supernovae in other galaxies which are considered similar to our own. This is the technique pioneered by Fritz Zwicky, and pursued more recently by Gustav Tammann.
(2) Arguments based on the few historical records of supernovae in the Galaxy.
(3) Arguments based on observations of Galactic supernova remnants (SNRs).

Methods (1) and (2) suffer from the problems of small number statistics and the comparatively short temporal coverage of observations. For method (3) observations to estimate the spatial distribution of remnants throughout the Galaxy need to be made at radio wavelengths since obscuration of shorter wavelengths limits the observed remnants to those comparatively nearby. The question then arises as to whether all supernovae leave long-lived radio remnants.

Method 1: Although almost 500 supernovae have been detected, only for about half of these is a definite Type known; further division for galaxy type leaves relatively few examples per classification and large uncertainties in estimates of rates. Tammann has used a distance-limited sample of Shapely-Ames galaxies ($r < 24$ Mpc, $H_0 = 50$) to give the following rates expressed in 'SNu'. (1 SNu = 1 supernova per $10^{10} L_{\odot}$ per century).

	E	S0	Sa	Sb	Sc	Im
Type I	0.16	0.15	1	0.2	0.6	0.4
Type II	—	—	—	0.2	0.6	—

There is some debate about compensation for spiral galaxy inclination effects; however Tammann suggests a characteristic interval between Galactic supernovae based on the extragalactic statistics of

$$\tau \sim 20 \pm 10 \text{ yr}.$$

with types I and II occurring in about equal numbers.

Method 2: There have been 7 or 8 Galactic supernovae recorded historically over the past two millenia (in AD 185, 386?, 393, 1006, 1054, 1181, 1572, and 1604), suggesting an average interval of 250 to 300 years between events recorded on Earth. For a supernova to have been recognized in the pre-telescopic era, it would have needed to have brightened to about apparent magnitude 3 at maximum, which allowing for a visual absorption of about 1 mag kpc^{-1} would require a supernova to lie within about 6 kpc of the solar system to be detected—that is, within an approximately one sixth portion of the Galaxy. This additional factor suggests a supernova rate of about once every forty years if all supernovae that could have been sighted were recorded. Allowing for some nearby supernovae being daytime events at maximum, others being too far south to be sighted by northern civilization with written histories, plus some written records being lost, introduces an additional incompleteness factor. This would be difficult to quantify; however assuming a factor 2 gives a characteristic interval between Galactic supernovae of order 20 years—with *large* uncertainty. A simple model allowing for light travel time produces 'bunching' of observed supernovae with intervals extending over many centuries between some observed outbursts (as actually occurred). Such simple modelling shows that the long time interval since the last observed Galactic supernova neither negates inferences from extragalactic and historical studies of an average interval between Galactic supernovae as low as 20 years, nor implies that we are seriously overdue for the next observable outburst.

Method 3: This technique has a number of advantages. Firstly radio remnants are identifiable for $\sim 10^5$ yr; since we wish to determine an 'average' supernova rate, long timescales are desirable. Additionally, since we can see to the extremities of the Galaxy at radio wavelengths, radio remnants provide an adequate volumetric statistical sample. However there are disadvantages. The technique depends on the thoeretical Sedov relationship between linear diameter D and age t ($D \propto t^{2/5}$), and can only give the rate for supernovae leaving long-lived remnants. A detailed analysis of Galactic radio SNRs using this technique implies a characteristic interval between Galactic supernovae *of the type that leave long-lived radio remnants* of 80 years.

Comparing the results of Methods 1 and 2 with Method 3 suggests that perhaps as few as 1 in 4 Galactic supernovae occur in the type of environment to leave a long-lived radio remnant. There is some support for the conclusion that only a subset of supernovae leave long-lived radio remnants from the EINSTEIN satellite survey of X-ray remnants in the Large Magellanic Cloud. Of the up to 50 objects in the EINSTEIN survey which on the basis of morphological and spectral properties might be X-ray SNRs, all but thirteen are radio sub-luminous.

In view of all the unknowns, we can probably do no better than to estimate a characteristic interval between Galactic supernovae of 30 years, with large uncertainty. We have not tried to distinguish between type I and type II events, but from extragalactic surveys they might be expected to occur in about equal numbers in the Galaxy (*e.g.* a characteristic interval between a supernova of either type $\sim$60 yr).

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A Search for Compact Sources in Supernova Remnants

J. H. van Gorkom *National Radio Astronomy Observatory, PO Box 0, Socorro, New Mexico 87801, USA*

R. D. Ekers *National Radio Astronomy Observatory, PO Box 0, Socorro, New Mexico 87801, USA*

K. Johnston *Code 7134, Naval Research Laboratory, Washington DC 20375, USA*

V. Radhakrishnan *Raman Research Institute, Bangalore 560080*

C. J. Salter *National Radio Astronomy Observatory, Tucson, Arizona 85721–0655, USA*

1. Introduction

Ryle *et al.* (1978) have suggested that there is a class of radio sources associated with supernova remnants, which are possibly the stellar remains of the outburst. Although many of the sources originally suggested by Ryle *et al.* are now known to be extragalactic, the class remains interesting since at least one of its members, SS 433, is definitely associated with the remnant W 50.

In addition, if an active pulsar within a shell type remnant is not detected because of statistical factors, one might still expect to see radio emission from a centrally condensed nebula produced by the pulsar, provided that the initial conditions of the pulsar are right (Srinivasan, Bhattacharya & Dwarakanath 1984). With the above considerations in mind we have performed a search for compact sources in supernova remnants. The search is biased toward the class of objects proposed by Ryle *et al.*: the observing wavelength was 6 cm, thus favouring flat spectrum objects, the search was insensitive to structures larger than 15 arcsec (Section 2)

In Section 2 we describe the sample, the observations and the data reduction. In Section 3 we discuss the results and give some comments on individual sources.

2. The sample, observations and data reduction

The sample consists of, 25 shell type remnants with diameter $<$ 10 arcmin, 3 shell type remnants with diameter $\geqslant$ 10 arcmin, and 11 filled remnants (all the known objects in class P and C).

The observations were made with the Very Large Array (Napier & Thompson 1983) in May 1981 during reconfiguration from the 30 km array to the 10 km array. The search was done at 6 cm to optimize sensitivity and minimize confusion problems. As flux calibrator, 3C 286 was used assuming a flux density of 7.4 Jy at 4863 MHz. The total bandwidth was 6.25 MHz making the effective field of view as large as possible. Each source was observed for 10 minutes.

Spacings less than 1 km were not included in the maps. The resulting synthesized HPBW is about 2 arcsec, structures larger than 15 arcsec remain invisible. Initially, maps were made of 6.4 arcmin in size. If there was an indication of the presence of a source outside this field a map was made of 13 arcmin. The FWHM of the primary beam at 6 cm is 10 arcmin. In Table 1 we list the observed remnants and the rms noise in the maps. The noise varies from map to map because of the effect of the flux from the supernova remnants themselves. In Table 2 we list the detected compact sources.

Table 1. List of observed SNR.

Source	Right Ascension			Declination			rms noise (mJy)
	h	m	s	°	′	″	
G 5.3 − 01	17	58	25.7	−24	49	20.0	0.8
G 5.3 X	17	58	03.9	−25	04	32.0	0.6
G 11.2 − 0.4	18	08	15.0	−19	22	00.0	2.3
G 11.4 − 0.1	18	07	54.0	−19	04	30.0	0.7
G 12.0 − 0.1	18	09	18.3	−18	38	25.0	1.5
G 15.9 + 0.2	18	15	50.0	−15	02	00.0	0.5
G 18.8 + 0.3	18	20	56.0	−12	25	00.0	0.6
G 21.5 − 0.9	18	30	47.0	−10	36	13.6	1.5
G 23.6 + 0.3	18	30	23.3	− 8	14	39.0	0.6
G 27.3 + 0.0	18	38	22.0	− 5	06	00.0	0.7
G 29.7 − 0.2	18	43	46.7	− 3	02	21.0	1.5
G 31.9 + 0.0	18	46	49.2	− 0	59	36.0	1.0
G 32.8 − 0.1	18	48	52.0	− 0	05	00.0	0.6
G 33.7 + 0.0	18	49	60.0	0	31	30.0	0.5
G 34.7 − 0.4	18	53	36.0	1	19	00.0	0.5
G 35.6 − 0.4	18	55	27.0	2	04	60.0	0.9
G 39.2 − 0.3	19	01	38.0	5	22	30.0	0.6
G 41.1 − 0.3	19	04	50.6	7	00	00.0	1.0
G 43.3 − 0.2	19	08	38.0	9	01	54.0	2.0
G 49.2 − 0.5	19	20	45.0	14	11	00.0	3.0
CL4	20	48	47.4	31	16	10.9	1.0
G 74.9 + 1.2	20	14	14.0	37	03	16.0	3.4
G 93.3 + 6.9	20	51	27.0	55	09	28.4	0.5
G 93.6 − 0.2	21	27	13.1	50	23	37.0	1.1
G 130.7 + 3.1	02	55	30.0	64	34	60.0	0.6
G 184.6 − 5.8	05	31	30.0	21	59	00.0	2.0
G 340.4 + 0.4	16	42	56.0	−44	34	20.0	2.0
G 340.6 + 0.3	16	44	03.0	−44	30	20.0	2.5
G 341.9 − 0.3	16	51	18.0	−43	54	20.0	0.6
G 342.1 + 0.0	16	15	11.0	−43	20	18.0	0.5
G 344.7 − 0.1	17	18	60.0	−41	37	18.0	0.5
G 346.6 − 0.2	17	06	42.0	−40	06	20.0	1.5
G 348.5 + 0.1	17	10	50.0	−38	07	30.0	1.1
G 348.5 W	17	10	24.0	−38	07	30.0	0.7
G 348.7 + 0.3	17	11	12.0	−38	30	00.0	0.7
G 349.7 + 0.2	17	14	36.8	−37	23	09.0	1.9
G 350.1 − 0.3	17	17	42.0	−37	23	00.0	0.8
G 351.2 + 0.1	17	19	06.0	−36	10	00.0	0.6
G 352.7 − 0.1	17	24	20.0	−35	04	15.0	0.8
G 357.7 − 0.1	17	37	04.0	−30	56	45.0	1.6

Table 2. List of detected compact sources.

Source	Right Ascension (1950) h	m	s	Declination °	′	″	Flux (mJy)*
G 11.4−0.1	18	07	47.5	−19	06	00.5	6.3 (1)
G 12.0−0.1	18	08	57	−18	37	06	157 (25)
CL4	20	48	47.4	31	16	11.2	628 (10)
G 74.9+1.2	20	13	37.0	37	01	44.5	1300 (100)
G 93.6−0.2 (CTB 104A)	21	27	13.7	50	24	04.1	33 (2)
G 349.6+0.2	17	14	47.0	−37	25	15.1	21 (3)

* The flux densities have been corrected for the effects of the primary beam; the number in brackets is the estimated error.

3. Discussion

3.1 *Significance of Detections*

In order to test the hypothesis that there is an excess number of point sources in these supernova fields we must first define a sample which is not biased with respect to finding these point sources. A suitable subsample includes the 25 known shell sources less than 10 arcmin in extent and the 11 filled remnants. Both these samples are complete and selected without bias with respect to any point sources in the field. For a comparison sample we have used a large survey of planetary nebula candidates (S. R. Pottasch & R. C. Bignell, private communication). Since this survey is also done with the VLA at the same frequency we can compare the detection rate as a function of peak flux without correction for the effect of the primary beam. In both surveys the effect of bandwidth smearing is small and will be ignored. The observations of Pottasch & Bignell cover 249 fields in the galactic plane and have higher sensitivity than our observations. The detected planetary nebulae have been removed in order to obtain counts for the background sources in the galactic plane. Table 3 is a cumulative distribution showing the comparison of the sources detected in this supernova search with that expected from the Pottasch & Bignell fields. It can be seen that there is a small excess of sources in the supernova fields in the highest flux densities and a deficiency at the lowest flux densities. The deficiency in the supernova fields at low flux densities is highly significant, but this is almost certainly caused by the differing resolution of the supernova search programme, and the Pottasch & Bignell survey which includes sources which are

Table 3. Distribution of detections.

S^* (mJy)	Total no. in 36 fields SNR	Expected	Excess
> 200	1	0	1
> 63	2	0.6	1.4
> 33	3	1.9	1.1
> 16	4	3.9	0.1
> 5.5	5	10	−5

* peak flux; no primary beam correction.

extended. More precise analysis of this point must await better statistics on the angular size distribution of background sources at this flux level. The small excess of sources in the higher flux density bins could correspond to a real detection of one or two objects associated with the remnants. However a Kolmogorov–Smirnov test gives a 30 per cent probability for having this difference occur by chance. Consequently we must conclude that we have no statistically convincing evidence for an association of point sources with either the small shell or the filled supernova remnants.

3.2 *Notes on Individual Sources*

Of the compact sources found in this search only the sources in G 11.4 − 0.1 and in CTB 104A have a position that falls within the supernova remnant. The distance toward both sources is unknown however and thus an association is uncertain.

CL4 is known to be extragalactic (Margon, Downes & Gunn 1981). The sources near G 12.0 − 0.1, G 74.9 + 1.2 and G 349.9 + 0.2 are all displaced from the supernova remnants by several arcmin and are therefore probably not associated with the remnants.

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How Often are Remnants like the Crab Nebula Born?

K. S. Dwarakanath & G. Srinivasan *Raman Research Institute, Bangalore 560080*

Most of the 140 or so supernova remnants (SNRs) found in our Galaxy have the morphology of an optically thin shell. The mean radio spectral index of such SNRs is −0.45. Tycho and Kepler are examples of this type. However, there is a small sample of remnants which are centrally condensed like the Crab nebula and which have a much flatter spectral index ranging from 0 to −0.3. They also show a fairly high degree of linear polarization. For a long time, of course, Crab nebula was unique in its class. It was Weiler (1969) who first drew attention to the fact that 3C 58, believed to be the remnant of the supernova explosion of 1181 A.D., shares all the properties of Crab mentioned above. Since then, the list of such objects which have come to be known as plerions, has grown to a modest 10 or so (Weiler 1983).

In addition, there is a small list of SNRs with hybrid morphology. These have the canonical shell structure but with a central plerion. MSH 15–52 and G326.3 − 1.8 are examples of this kind.

If the plerions are in fact supernova remnants like the Crab nebula, then, they too must be powered by a central pulsar, although one has detected a pulsar only in Vela X and MSH 15–52. This suggestion was made a few years ago by several people including Radhakrishnan & Srinivasan (1978, 1980a), Weiler & Shaver (1980), and later by Weiler & Panagia (1980). The failure to detect the central pulsar in the other plerions may be due to a variety of selection effects such as beaming factor, high dispersion measure, low flux, *etc*. The recent discovery of an X-ray pulsar in 0540 − 69.3 is an interesting case. The discovery of the X-ray and radio plerions preceded the discovery of the pulsar. Also, in some cases it appears that the discovery of the pulsar in X-rays is easier than in radio.

If, as suggested, plerions are indeed supernova remnants powered by active pulsars in them, then it becomes important to compare the birthrate of pulsars with the birthrate of plerions. The mean birthrate of plerions can be obtained, for example, by estimating the age of the oldest among them and dividing it by the known number of such objects. Since we know only the luminosities of these objects, to derive an age one must assume that they are all standard objects and have similar evolutionary scenario.

Pacini & Salvati (1973) in their paper entitled 'On the evolution of supernova remnants' discuss the evolution of the particle content, the magnetic field and the luminosity of a nebula produced and maintained by an active pulsar. The pulsar inflates the bubble with relativistic particles and magnetic field. After the initial phase which relates to the explosion itself there are two distinct phases of evolution: Phase II, when $t < \tau_0$, where $\tau_0 = P_0/2\dot{P}_0$ is the initial characteristic slow down time of the pulsar. During this phase the pulsar output is assumed to be constant. For the crab pulsar, $\tau_0 \sim 300$ years. Phase III, $t > \tau_0$: in this phase the pulsar output decreases significantly and consequently the nebular luminosity decreases. Strictly speaking, of course, one must take into account the acceleration of the nebular boundary in the early stages. This is expected to be over by $t \sim \tau_0$ since after this time the pulsar is not expected to have significant dynamical effect on the ejecta. After this the pulsar bubble will essentially expand freely for a while. For a given amount of mass ejected this velocity will clearly be determined by the initial stored rotational energy of the pulsar.

The above evolutionary scenario requires a slight modification for remnants much older than the Crab nebula. Sooner or later the freely expanding filaments of the Crab nebula will decelerate and consequently the nebular luminosity will decrease less rapidly. Weiler & Panagia (1980) were the first to incorporate this feature in the evolutionary scenario for plerions. More recently several others including Reynolds & Chevalier (1984), Bandiera, Pacini & Salvati (1984) and Srinivasan, Bhattacharya & Dwarakanath (1984) have also taken this into account. The time when deceleration will become important is different in our approach from that of Weiler & Panagia. According to them, the remnant will enter the adiabatic phase of expansion soon after the pulsar has expended half its rotational energy, *viz.*, at time $t \sim \tau_0$. We feel, however, that there is no immediate connection between the initial characteristic slow-down time of the pulsar and the time when the freely expanding bubble will be significantly decelerated. In our opinion significant deceleration will occur when the mass swept up becomes comparable to the mass ejected and the remnant will enter the adiabatic phase of expansion only when the mass swept up far exceeds the mass ejected. For a given amount of mass ejected and the initial velocity of expansion, the time to sweep up a comparable amount of mass clearly depends on the density of the interstellar medium.

In the standard model, the ISM consists of cold, dense clouds in pressure equilibrium with the warm intercloud medium with a density $\sim 0.3\ \mathrm{cm}^{-3}$ (Spitzer 1978). According to McKee & Ostriker (1977), however, the intercloud medium is hot, low-density gas with density $\sim 0.003\ \mathrm{cm}^{-3}$. Although there is ample evidence for the existence of such a low-density coronal gas, there are strong observational reasons to believe in the presence of a denser intercloud medium also. Radhakrishnan & Srinivasan (1980b) have argued that a substantial fraction of the volume of the intercloud medium must be occupied by the denser component and the remnants expanding in that medium must therefore suffer significant deceleration. Recent analysis of the evolution of shell-type SNRs by Higdon & Lingenfelter (1980), and Srinivasan & Dwarakanath (1982) also lend support to the above picture.

Let us now estimate the time t_0 at which an expanding remnant like the Crab nebula will experience deceleration. Various observations suggest that the mass in the filaments of Crab is $\sim 1\ M_\odot$ (Henry & McAlpine 1982). If the Crab nebula is expanding in the coronal gas, t_0 will be ~ 8000 yr. While it will be ~ 1700 yr if it is expanding in the denser component of the ISM. Remember, at $t = t_0$, the mass swept up becomes equal to the mass ejected. Only for $t \gg t_0$, the radius of the nebula will increase as t^η with $\eta = 0.4$.

With this slight modification one can now extrapolate the evolution of the luminosity to longer times. This is shown in Fig. 1. What is plotted here is the radio spectral luminosity against the age of the nebula. The curve is normalized to the value for the Crab nebula at 1 GHz. The curve corresponding to $t^{-2\gamma}$ indicates the evolution of the nebular luminosity during the free expansion phase. Those corresponding to $t^{-2\eta\gamma}$ indicate luminosity evolution with deceleration in the two media. γ is the exponent of the particle spectrum injected into the nebula by the pulsar. γ can be related to the radio

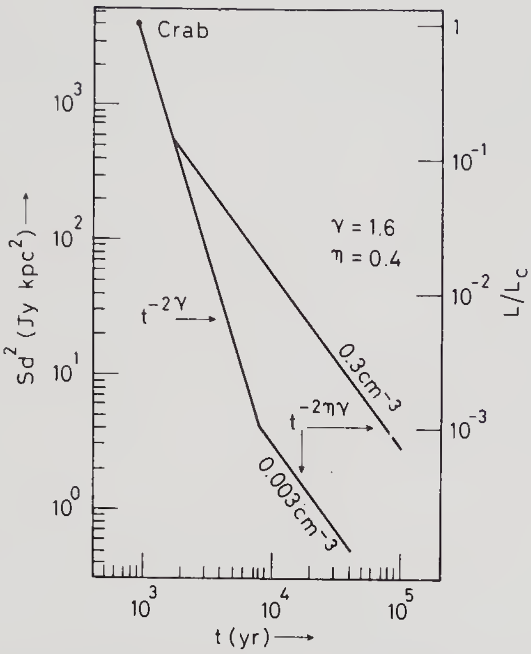

Figure 1. The secular decrease of the radio spectral luminosity of plerions ($L_\nu \propto Sd^2$). The evolutionary track has been normalized to the luminosity of Crab nebula at 1 GHz at an age of 1000 years. $\gamma = 1 + 2\alpha_R$, where α_R is the radio spectral index of the nebula. The nebulae have been assumed to expand into regions with two typical densities. The markings on the axis on the right side indicate luminosities in units of that of Crab.

spectral index α_R through the relation $\gamma = 1 + 2\alpha_R$. For the Crab nebula $\alpha_R = 0.26$ implying $\gamma = 1.52$. The sharp kink in the curve is, of course, an artefact of the approximation that the remnant expands freely upto $t = t_0$, and according to the Sedov solution beyond $t = t_0$. In reality the evolution of luminosity will be described by a smooth curve.

The above discussion of a smooth transition to the interstellar-medium-dominated phase ignores a subtle effect pointed out by Reynolds & Chevalier (1984). They have argued that during this transition a reverse shock is likely to compress the pulsar bubble resulting in a discontinuous increase in plerion luminosity. Also, in their model the plerion radius increases as $t^{0.3}$ rather than as $t^{0.4}$ and hence the luminosity will decrease more slowly than indicated in Fig. 1. As we will see this will go in the direction of decreasing the birthrate of plerions and in no way alter the conclusions that we will draw.

Another factor that determines the nebular luminosity is γ, the slope of the spectrum of particles injected into the nebula by the pulsar. For the Crab nebula $\gamma = 1.6$. On the other hand, for sources like G21.5 – 0.9 and Vela X, $\gamma = 1.0$. Allowing a range for γ between 1 and 1.6 has a significant effect on the lifetime of the nebula as can be seen in Fig. 2. Note that at an assumed distance of 0.5 kpc, Vela X is very close to the predicted curve corresponding to $\gamma = 1$ and expansion in the denser medium.

Given such an evolutionary scenario one can now estimate the ages of all the known plerions provided one assumes that the pulsars in all of them are identical to the Crab pulsar and that the velocity of expansion is the same in all cases. The latter is not really an independent assumption if the pulsar accelerated all of them and if the masses involved are comparable.

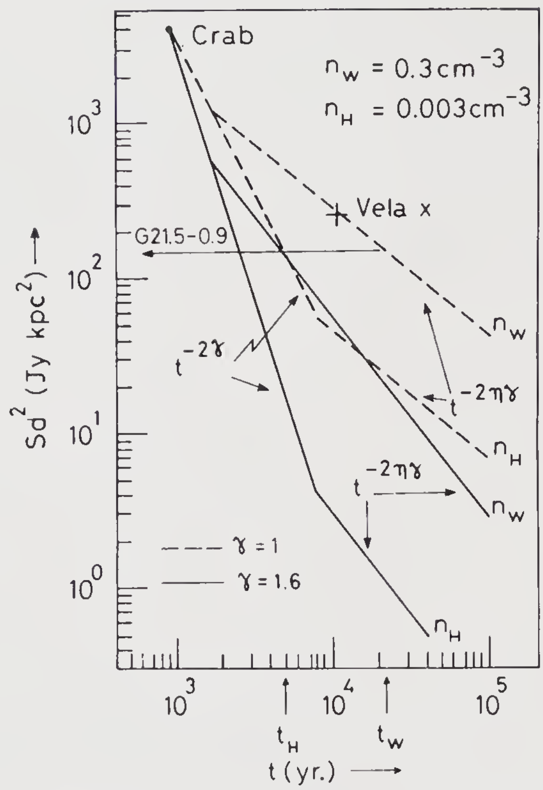

Figure 2. The secular decrease of the radio spectral luminosity of plerions at 1 GHz ($L_\nu \propto Sd^2$). The evolutionary tracks have been normalized to the luminosity of Crab nebula at an age of 1000 years. $\gamma = 1 + 2\alpha_R$, where α_R is the radio spectral index of the nebula; $\alpha_R = 0.26$ for the Crab and 0.0 for G 21.5 −0.9. The nebulae have been assumed to expand into regions with two typical densities, n_W and n_H; tracks corresponding to $\gamma = 1$ and $\gamma = 1.6$ are shown. The estimated age of G 21.5 −0.9 is ~4800 years and ~23000 years in the rarer and the denser media respectively.

Now, let us come to a brief discussion of the known sample of plerions. Weiler (1983), in his review on 'Supernova remnants resembling the Crab nebula' has compiled a list of plerions and plerion + shell sources. This list contains a total of 20 sources. Not all of them are well-established candidates as plerions to be used in the birthrate calculations. Out of this list we have chosen 8 sources shown in Table 1. We have left out those with doubtful morphology. (See, for example, Weiler (1984) for a discussion of the plerions and combination sources). We can now estimate the birthrate of plerions assuming that the pulsars in all of them are identical to the Crab pulsar.

Of the plerions listed in Table 1, the oldest one is presumably G 21.5 −0.9 since, except for MSH 15–52 it is the least luminous one. One knows that the plerionic component of MSH 15–52 cannot be older than 1600 years, the characteristic age of the pulsar. Its low surface brightness must be due to reasons other than old age and will be discussed by Srinivasan (1985, this volume). Of course, a remnant more luminous than a given one need not be younger because they could be expanding in different media. But we shall correct for that.

It now remains to estimate the age of the least luminous source in the sample, *viz.*, G 21.5 −0.9. Its age as estimated from the $\gamma = 1$ track, appropriate for its spectral index of $\alpha_R = 0$, is ~4800 years if expanding in the hot medium and ~23000 years if expanding in the denser warm medium. Since not all plerions have a spectral index of 0, we shall assume an 'average' value of $\alpha_R = 0.15$ implying $\gamma = 1.3$. If one uses the

Table 1. Sample of plerions.

Source	Flux (S) (at 1 GHz) Jy	Distance (d) kpc	Luminosity Jy kpc^2	References
G 21.5 − 0.9	6.4	4.8	147	1, 2
G 74.9 + 1.2	8.6	12	1238	1, 3
Crab	1000	2	4000	
Vela X	1100	0.5	275	
3C 58	33	8	2112	1
		2.6(a)	223	4
G 326.3 − 1.8	40	2(b)	160	1, 5
(centre)		4.6	846	
MSH 15–52	0.1	4.2	1.6	6, 7, 5
G 328.4 + 0.2	15	20	6000	1, 5

a) The distance to 3C 58 remains highly controversial, as does its association with SN 1181. Following Weiler (1984) we adopt a distance of 2.6 kpc.

b) Caswell *et al.* give a distance of 1.5 kpc, although they do not rule out a larger distance of 4.6 kpc. They regard the latter distance as unreliable without independent confirmation. The Σ-D relation for Galactic SNRs given by Mills (1983) yields a distance of 2.2 kpc. Hence we shall assume a distance of ~ 2 kpc.

References
1. Weiler (1983)
2. Becker & Szymkowiak (1981)
3. Kazes & Caswell (1977)
4. Green & Gull (1983)
5. Caswell *et al.* (1975)
6. Manchester and Durdin (1983)
7. Caswell, Milne & Wellington (1981)

evolutionary track corresponding to an 'average' $\gamma = 1.3$, the above estimates of the ages of G 21.5 − 0.9 get modified to 3600 years and 13000 years respectively. *These numbers represent the lifetimes above this luminosity in the two media.*

Now, to estimate the birthrate we can proceed as follows. If f_{H} and f_{W} are the filling factors of hot and warm media respectively, then,

$$N(L \gtrsim L_0) = \frac{1}{\tau}(t_{\mathrm{H}} f_{\mathrm{H}} + t_{\mathrm{W}} f_{\mathrm{W}}) \tag{1}$$

where N is the number of plerions with spectral luminosities greater than or equal to that of a given source. $t_{\mathrm{H}}, t_{\mathrm{W}}$ are the lifetimes in the hot and warm media respectively and τ is the mean interval between supernovae that produce plerions.

From the table of plerions shown before, we get 8 sources with spectral luminosities greater than or equal to that of G 21.5 − 0.9. Using the estimates of t_{H} and t_{W} for G 21.5 − 0.9, we get from Equation (1), that $\tau = 1625 - 1175 f_{\mathrm{H}}$ years.

This birthrate has to be corrected for a possible incompleteness factor of the sample. It is generally felt that not many sources above 1 Jy are likely to be missed in surveys around 1 GHz. The flux from the least luminous source in the sample will be 1 Jy if it happened to be at a distance of 12 kpc instead of its actual distance of 4.8 kpc. Therefore it is reasonable to assume that one has a complete sample of plerions within 12 kpc from the Sun and whose luminosities are greater than that of G 21.5 − 0.9. A simple scaling to the area of the Galaxy would suggest an incompleteness by a factor of 3 or so, above this luminosity. However, one knows that a source as luminous as the Crab nebula would not be missed even if it were placed at the farthest distance in the Galaxy. This would be true even for a source with, say, 1/5th the luminosity of Crab. So, what we actually need is a luminosity-dependent scaling factor. The crude scaling by areas is therefore likely to overestimate the incompleteness factor. However such an approach will give us a stringent upper limit on the birthrate. We find for the mean interval between the birth of plerions, $\tau \gtrsim 541 - 391 f_{\mathrm{H}}$ years. If 70 percent of the ISM is occupied by the coronal gas, one gets a birthrate of 1 in 270 years. Although the existence of the coronal gas component of the ISM has been established beyond doubt, its filling factor remains a controversial one. Several people including Chevalier (1978) have argued that its filling factor might be significantly less than that suggested by Mckee & Ostriker (1977). This would further reduce the birthrate. For $f_{\mathrm{H}} \sim 0.5$ one gets a birthrate of ~ 1 in 350 years.

There is an alternative way of estimating the birthrate of plerions using the same sample. One can ask for a luminosity limit such that one has a complete sample above this value. Helfand *et al.* (1984) have argued that the sample of plerions may be reasonably complete above $L = 0.1\ L_{\mathrm{crab}}$. They argue that the incompleteness factor may not be more than 2. One can estimate the age corresponding to the average track for $0.1\ L_{\mathrm{crab}}$ and this gives for the lifetime of a plerion above this luminosity limit approximately 2300 years and 4000 years in the hot and warm media respectively. *If* it is indeed true that the sample of plerions is complete above $0.1\ L_{\mathrm{crab}}$ to a factor of 2, then one gets a birthrate of ~ 1 in 530 years, using Equation (1) with $f_{\mathrm{H}} = 0.5$.

The plerion birthrate is ~ 1 in 450 years while the pulsar birthrates in the literature lie in the range of 1 in 10 years to 1 in 40 years as have been estimated by Phinney & Blandford (1981), Taylor & Manchester (1977) and Vivekanand & Narayan (1981). It has long been suggested that pulsar birthrates could be in error due to beaming factor, the interstellar electron density, selection effects in pulsar searches, *etc.* Recently, however, Vivekanand (1984) has made a systematic study of each one of these factors and has put strong limits on the pulsar birthrate around a mean of 1 in 40 years. The plerion birthrate estimated after allowing for a reasonable factor of incompleteness and the filling factor of coronal gas is very low compared to the pulsar birthrate.

Barring the possibility that the plerion sample is grossly incomplete, the first thing that this tells us is that pulsars like the one in the Crab nebula are extremely rare—meaning that the pulsars in the other plerions may have very different magnetic fields and initial periods compared to the Crab pulsar. Although the Crab pulsar and its nebula are always taken to be prototypes the above argument suggests that they are not. After all, there is a fairly wide spread in the distribution of the derived magnetic fields of pulsars. For all we know, there might be a big spread in the initial periods also. It must be remembered that only in the case of the Crab pulsar we have a reliable estimate of P_0. It turns out that the nebular luminosity and therefore the lifetime of the plerion depends quite sensitively on the initial period and magnetic field of the pulsar. This point will be discussed in great detail by Srinivasan (this volume).

As will be argued by Srinivasan, only if the central pulsar has the particular characteristics of the Crab pulsar, the plerion is expected to be long-lived. Vela X may be such an example.

An alternative conclusion one may draw is that pulsar driven SNRs are extremely rare.

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On Pulsar–SNR Associations

G. Srinivasan *Raman Research Institute, Bangalore 560080*

The true nature of the association between pulsars and SNRs has remained an intriguing and poorly understood problem even after all these years of research on them.

The idea that there should be an association at all owes its origin to Baade & Zwicky (1934) who advanced the view that supernovae represent the transition from ordinary stars into neutron stars. Following their suggestion all theories of supernovae for many years afterwards involved a neutron star as an essential member of the caste, and one capable in principle, of releasing upto 10^{53} erg of gravitational binding energy at the time of its formation. But the details of how a part of this energy could be coupled to the infalling envelope of the star to arrest its collapse, and to accelerate it outwards have remained a major problem. It is only in recent years that plausible scenarios are being advanced. It is now generally accepted that the formation of a neutron star is indeed the origin of type II supernovae. On the other hand, according to the current consensus, the mechanism of a type I supernova is very different; the star completely disrupts and no stellar remnant is left behind. It is also generally believed that in galaxies of morphology similar to ours, the frequency of type I and type II SN are roughly equal.

Though no supernova has been sighted in our Galaxy since the time of Kepler, the historical observations suggest that they occur once in about 30 years, as has been convincingly argued by Clark & Stephenson and others. At any rate, supernovae do leave behind relatively long-lived remnants (SNRs). As Clark & Stephenson have argued, there is SNR associated with almost every one of the historical supernovae. In all about 140 SNRs are known in our Galaxy. Soon after pulsars were discovered, and when it was suspected that they had to be spinning neutron stars, Woltjer (1968) predicted that they should be found in SNRs, and in particular that there should be one in the Crab nebula. It should be remembered, however, that in the case of the Crab nebula there was also the famous prediction by Pacini (1968) motivated at least as much by the need to have a central engine to explain its continuing activity, as to find a natural birthplace for neutron stars. The discovery of a pulsar in the Vela SNR within months (Large, Vaughan & Mills 1968) and one in the Crab soon after (Staelin & Reifenstein 1968) seemed at that time to have answered several questions all at once.

The extraordinary thing is that the total number of firm associations of pulsars with SNRs remained at these two for over a decade or so although the total number of pulsars and SNRs mounted up with time. Two years ago a third association was discovered, namely a pulsar in the SNR MSH 15–52 (Seward & Harnden 1982), and very recently one more in the Large Magellanic Cloud (Seward, Harnden & Helfand 1984). Even if neutron stars are associated only with type II supernova events, this poor association is very striking. This was reconciled by invoking selection effects like distance, dispersion, interstellar scattering, multipath propagation, small beaming angle *etc.* Such reasoning is implicit already in the famous paper by Woltjer (1968). Assuming that the number of these pulsars expected to be found is of the order of one or two, quite consistent with the observed number of associations.

If pulsars are associated with every supernova explosion, then the birthrate of pulsars must be consistent with the frequency of supernovae and the birthrate of SNRs. Current estimates of pulsar birthrate of one in 20 to 40 years (Taylor & Manchester 1977; Vivekanand & Narayan 1981) are indeed consistent with the previously mentioned supernova rate of 1 in ~ 30 years and the recent estimates of the birthrate of shell remnants of 1 in ~ 30 years (Srinivasan & Dwarakanath 1982; Mills 1983). Admittedly, there is a considerable uncertainty in all these birthrates; nevertheless the overlap of all these rates may be significant.

But not all was well with the seemingly 'satisfactory' explanation. It is remarkable that the first two SNRs to be associated with pulsars, namely the Crab and Vela X, are of filled-centre morphology unlike the majority of SNRs which have well-defined shells with hollow interiors. One, of course, expects to find such a synchrotron nebula surrounding a very active pulsar. If there are active pulsars inside shell remnants, they too will produce a centrally condensed nebula, which should be seen from any viewing geometry. Based on this, Radhakrishnan & Srinivasan (1980a) advanced the hypothesis that the hollowness of the interiors of young shell SNRs is consistent with the absence of a central *pulsar* in them. This did not, of course, rule out the possibility that there could be a central neutron star which for some reason was not functioning as a pulsar. It is interesting that the two recent pulsar–SNR associations I mentioned earlier, one in MSH 15–52, a shell remnant, and the other in $0540-69.3$ in LMC, have pronounced synchrotron nebulae surrounding the pulsar as envisaged by Radhakrishnan & Srinivasan (1980a).

If as Radhakrishnan and Srinivasan suggested, the neutron stars in the majority of shell SNRs do not function as pulsars then the 'agreement' between the pulsar birthrate and SNR birthrate is accidental and one will have to manufacture pulsars in supernova events which do not produce detectable SNRs. A possible way out is to say that long after the supernova remnants have faded away, the ageing neutron stars turn on as pulsars. We shall return to this possibility later.

A slightly different suggestion for explaining the absence of central emission inside shell SNRs, either in radio or in X-rays, was put forward by Radhakrishnan & Srinivasan (1983). They argued that the absence of central plerions in shells can *also* be reconciled if the majority of pulsars have rather long initial rotation periods. Such pulsars are expected to produce plerions of very low surface brightness which may be below the level of detectability at present. The possibility that shell-type remnants harbour slow pulsars had also been suggested by Weiler (1978) in a discussion which however involved the different types of supernovae. It is worth remarking that in every case a pulsar is associated with a plerion, whether inside a shell or not, it has a very high energy loss rate $I\Omega\dot{\Omega} \sim 10^{37}$ erg s^{-1}. Recently, Helfand and his collaborators have detected extended X-ray emission from 4 or 5 pulsars which are not associated with any SNR (see Helfand 1983). These nebulae are much more compact and very much less luminous than the standard X-ray plerions and imply $\dot{E} \geqslant 10^{34}$ erg s^{-1}. It appears that there should have been no difficulty in detecting X-ray emission at this level at the centres of any of the SNRs within 4–5 kpc but none was detected in any of the 36 closest remnants studied by the Einstein Observatory, implying rather small energy loss rate for the central pulsars (Helfand & Becker 1984).

The preceding discussion suggests that pulsars like the one in Crab or Vela X are not at all prototypes. In the remainder of this paper we wish to pursue a slightly different line of argument (Srinivasan, Bhattacharya & Dwarakanath 1984). According to the conventional wisdom, pulsars must be born spinning very rapidly. Since all fast pulsars endowed with strong magnetic fields are likely to produce bright synchrotron nebulae, one can ask the following question: Given a pulsar birthrate how many plerions do we expect to see in the Galaxy above a certain luminosity limit? In what follows we shall restrict our attention to radio plerions; the reasons for this we shall mention later. In order to estimate the number of expected plerions one must first have an evolutionary scenario for them.

In their pioneering paper Pacini & Salvati (1973) discussed the secular change in the luminosity of a synchrotron nebula produced and maintained by an active pulsar. For the sake of completeness, it is worth recalling the salient features of their approach.

The problem on hand is one of a freely expanding cavity into which a pulsar pumps relativistic particles with a frozen-in magnetic field. In the simplest approximation, it can be assumed that the energy lost by the pulsar is converted with equal efficiency into relativistic particles and magnetic fields. As the pulsar ages, its rotational energy loss rate, of course, decreases. In most pulsar models this takes a simple form

$$L(t) = L_0 \frac{1}{(1 + t/\tau_0)^2}.$$

Here $\tau_0 = P_0/2\dot{P}_0$ is the initial characteristic slowing-down timescale. One has now to calculate the magnetic field in the cavity and the energy spectrum of the particles. Care must be taken to allow for adiabatic losses in the nebular magnetic energy and the energy of relativistic particles. In addition, radiation losses are also important for particles, particularly in the high-energy end of the spectrum. The spectral luminosity of the nebula at a given time will depend on the expansion velocity and the initial luminosity of the pulsar, which in turn is determined by its initial period and the surface magnetic field. For $t > \tau_0$ the radio spectral luminosity is given by

$$L_\nu \propto B_*^{(3-5\gamma)/2}\ P_0^{2(\gamma-2)}\ V^{-3(1+\gamma)/4}\ t^{-2\gamma}\ \nu^{(1-\gamma)/2}$$

where B_* is the surface magnetic field of the pulsar, P_0 its initial period and V the expansion velocity. In the above expression, γ is the energy spectral index of the particles injected into the cavity by the pulsar. This is related to the radio spectral index α_R of the nebula by $\gamma = 1 + 2\alpha_R$. For most plerions α_R lies in the range 0–0.3 implying that γ is between 1 and 1.6. As can be seen from the above equation, the dependence of the luminosity on the pulsar field and the expansion velocity is quite strong. In view of this, in estimating the luminosity of a nebula for a given age, one should not assume that the Crab nebula or its pulsar is a prototype. Let us discuss each one of these characteristics separately.

Expansion velocity of plerions

One of the most remarkable aspects of the Crab nebula is its very low expansion velocity compared to expansion velocities of ejecta in typical supernovae. It has been well established that the kinetic energy of expansion of the filamentary shell as well as the acceleration experienced by it in the past can be understood in terms of the energy being derived from the stored rotational energy of the newly-born pulsar. The pressure of the relativistic wind from the pulsar pushed out the remaining mass and accelerated it to the present velocity. It was through such arguments that Trimble & Rees (1970) were able to estimate the initial period of the Crab pulsar. It is natural to assume, therefore, that the same is true of all the plerions, namely, that the boundary is expanding with a velocity which was given to it by the central pulsar within the initial characteristic slowdown time τ_0, while it still had a dynamical effect on it (we are grateful to Dr Woltjer for this suggestion). Since the pulsar dumps half its initial stored rotational energy at $t \approx \tau_0$, the velocity imparted to the ejecta by the pulsar can be estimated from the relation

$$\tfrac{1}{2}M_{\rm ej}V^2 \approx \tfrac{1}{2}E_{\rm R}^0, \qquad E_{\rm R}^0 = \tfrac{1}{2}I\Omega_0^2.$$

From this it follows that $V \propto 1/P_0$. In what follows, for simplicity, we shall assume that the mass accelerated by the pulsar is roughly the same as in the Crab nebula. In the calculations we have done, we have actually taken into account the acceleration of the nebular boundary during the initial phase.

The initial period and magnetic field of pulsars

According to the conventional wisdom, pulsars should be spinning with a period $\sim$a few milliseconds at birth. However, in the only case where we have a reliable estimate, namely for the pulsar in the Crab nebula, the initial period was 16 ms. We shall therefore allow the initial period of pulsars to lie anywhere between 1 to 20 ms with equal probability.

Although the distribution of the derived magnetic fields of pulsars extends from 10^{11}–$10^{13.5}$ G, there are strong reasons to believe that the distribution of fields at birth is much narrower (Radhakrishnan 1982). Pulsars with $B < 10^{12}$ G are presumably several millions of years old and consequently their fields would have decayed. If many pulsars are in fact born with fields less than 10^{12} G it is very hard to understand why no pulsar has been found with a field less than the Crab value and whose period is less than 150 ms since, with such low fields, it will take a long time before their periods lengthen to 150 ms and consequently the chance of detection is significant. We have therefore assumed the magnetic fields of pulsars at birth can lie anywhere in the range 10^{12}–$10^{13.5}$ G with equal probability in equal logarithmic intervals. Before we proceed with an estimate of the number of plerions one expects to see above a certain luminosity limit, it is worth looking at Fig. 1 which illustrates what an important role the pulsar field and its initial period play in determining the lifetime of a plerion. What is shown are contours of constant luminosities for a given age in the B_*–P_0 plane. All pulsars with initial characteristics which lie on a given contour will produce nebulae of the luminosity at a given age. In the figure on the left the different contours correspond to different luminosities but the same age whereas in the figure on the right different contours correspond to different ages for the same luminosity. It is clear that it is not meaningful to assert that nebulae with luminosities greater than that of a given one are necessarily younger. The case of MSH 15–52 is a very good illustration of this: even though the pulsar is roughly of the same age as the Crab pulsar, there is hardly any central radio emission surrounding it. If we are willing to allow a range of initial period

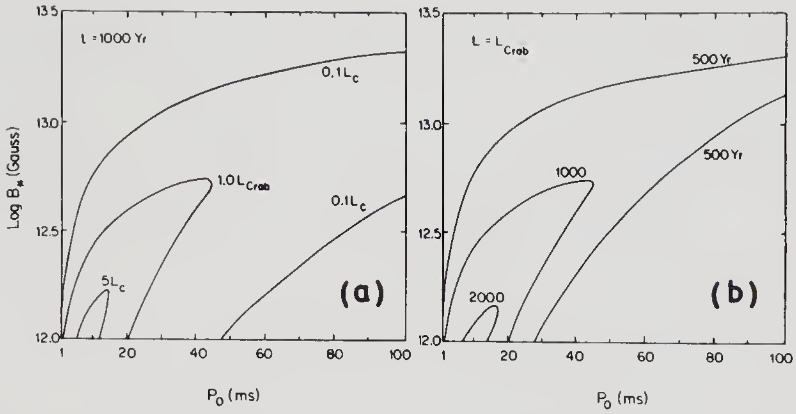

Figure 1. Contours of constant luminosity for pulsar-driven SNRs are shown in B_*–P_0 plane; here B_* is the surface magnetic field and P_0 the initial period of the pulsars. All pulsars born on a given contour will have the same luminosity at a specified age. (a) The three contours correspond to three different luminosities (measured in the units of the present luminosity of Crab) and an age of 1000 yr. (b) The contours correspond to different ages, but the same luminosity, *viz.*, the present luminosity of Crab.

and fields, it is not possible to estimate the ages of known plerions from their luminosities and therefore derive a birthrate.

We now return to the estimate of the expected number of plerions. First one has to decide on a luminosity limit such that if a nebula has a luminosity greater than that, one is unlikely to miss it anywhere in the Galaxy. The flux from the Crab nebula will be 10 Jy at 1 GHz if placed at a distance of 20 kpc. The flux from a source with 1/10th the luminosity of the Crab will be 1 Jy at the same distance. It is reasonable to suppose that many sources with flux greater than 1 Jy are unlikely to have been missed in surveys at frequencies around 1 GHz. Since plerions are likely to be more or less uniformly distributed in the inner Galaxy, we will take 0.1 L_{Crab} as the luminosity cutoff above which one should, in principle, be able to detect most of the radio plerions.

In Fig. 2, I have plotted several contours all corresponding to the above-mentioned luminosity. The labels on them represent the duration for which the nebulae will be more luminous than the specified value, or in other words, their lifetimes. The hatched area corresponds to the range of initial periods and fields in which we assume pulsars to be born uniformly once in 40 years. If τ is the mean interval between the birth of pulsars, then the number N of nebulae that one expects to see above the threshold luminosity is given by

$$N = \frac{1}{\tau} \int t f(t) \, \mathrm{d}t.$$

Here $f(t)\,\mathrm{d}t$ is the probability that the nebula will have a lifetime between t and $t + \mathrm{d}t$. Let $P(>t)$ be the probability that a nebula will have a lifetime greater than t. Clearly this is given by

$$P(>t) = \frac{a(t)}{A}$$

where $a(t)$ is the area enclosed by the contour corresponding to an age t and within the hatched area A specified above in the B_*–P_0 plane. This quantity is related to $f(t)$

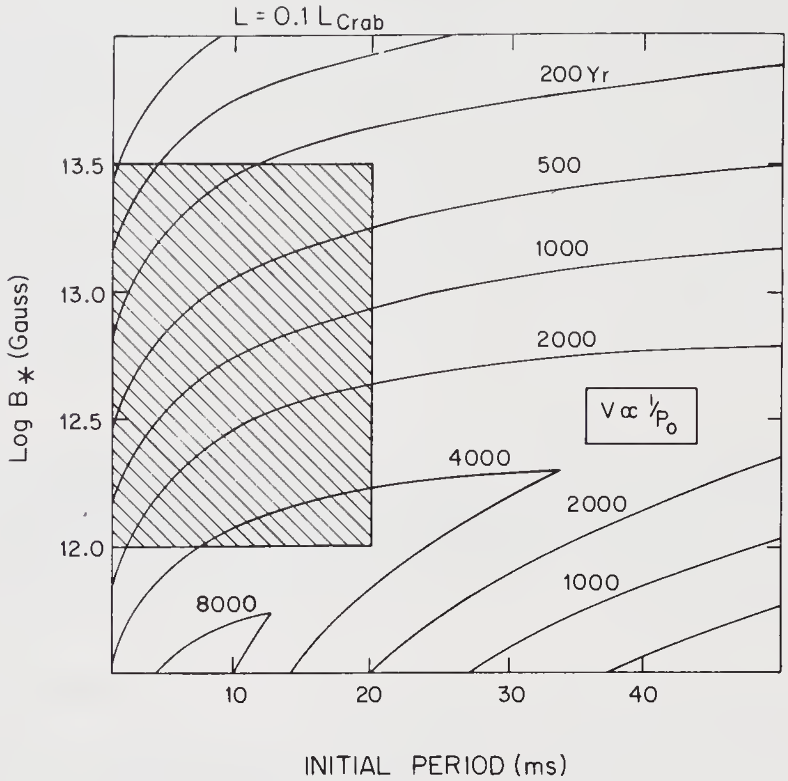

Figure 2. Pulsar-driven plerions. The contours of different ages for a luminosity of 0.1 L_{Crab}. In estimating the expected number of plerions with luminosities greater than the above-mentioned value we have assumed that pulsars are born anywhere inside the shaded regions.

through

$$P(>t) = \int_t^\infty f(t')\,\mathrm{d}t'$$

or

$$\frac{\mathrm{d}P}{\mathrm{d}t} = -f(t).$$

By following this procedure we find that given a pulsar birthrate of 1 in 40 years and the assumption that they are born in the hatched area, there should be 35 nebulae whose luminosities are *greater* than 1/10th that of the Crab nebula, or in other words, whose fluxes should be greater than 1 Jy *even if placed at* 20 *kpc*. However, only four of the known sample of 9 or 10 plerions have luminosities above this value. There is, of course, a remote possibility that the sample of plerions is grossly incomplete. But as Weiler (1983) has argued, it is extremely unlikely that they are incomplete by a factor as large as 10. The other possibility is that the pulsar birthrates available in the literature are seriously in error. But again it is very unlikely that this is so by a factor of 8 or 9. The most satisfactory resolution of this dilemma is to say that most of the pulsars are born outside this region considered in the B_*–P_0 plane, namely, with fields $< 10^{12}$ G or $> 10^{13.5}$ G or that their initial periods are much greater than 20 ms. Since the data on observed pulsars suggests that the majority of them have fields between 10^{12}–10^{13} G at birth, the only option left is to say that their initial periods must be rather long. The question is how long should the initial period be such that if plerions are pulsar-driven, the observed number is consistent with the pulsar birthrate? One can repeat the exercise one has just gone through but this time allowing the initial periods of pulsars to lie anywhere between 1 to 100 ms, say, and ask how many plerions we expect to see above our luminosity limit. Unfortunately this does not solve anything! The expected number of plerions is roughly the same as before; in fact a little more than when we had constrained the initial period to the range 1–20 ms. This, however, is not at all surprising. It is true that a pulsar with longer initial period has a much smaller stored rotational energy, but it has two things going for it.

(1) Since the energy loss rate is smaller, and therefore the initial characteristic slowdown time scale is longer, it will take much longer for the boundary of the pulsar bubble to reach its maximum velocity.
(2) The maximum velocity itself is inversely proportional to the initial period and therefore the pulsar bubble will be much smaller at any given age compared to that surrounding a fast pulsar. The smaller expansion velocity also means less adiabatic loss. This is not to say that a plerion produced by a slow pulsar will ever be as luminous as the Crab Nebula is today, but it could stay above a detectable limit for a long time.

It seems to us that one of the most natural conclusions one can draw from all this is that pulsar-driven supernova remnants in the sense we have discussed them must be very rare, meaning only very rarely the kinetic energy of expansion is derived from the stored rotational energy of the pulsar. The conclusion has also been arrived at independently by Bandiera, Pacini & Salvati (1984), Reynolds & Chevalier (1984) and Weiler (1983). The small number of plerions can also be reconciled if the initial period of pulsars is greater than 150 ms. Before leaving this scenario I would like to remark that if pulsar-driven supernova remnants are rare, those like the Crab nubula are even rarer. I shall return to this point later.

If the pulsar doesn't push the cavity into which it pumps relativistic particles and magnetic field, then one must go to an alternative scenario. In the standard model of a type II supernova, the ejecta are accelerated to a high velocity $\sim 10^4$ km s^{-1} by a shock wave driven by the core-bounce during the formation of the neutron star. In this picture unless the central neutron star is a millisecond pulsar and has a strong magnetic field, it will not have any dynamical effect on the expanding shell. Since the cavity is expanding much more rapidly than before, the adiabatic losses will be more severe. Also the energy density of the particles and the magnetic field will be smaller. Consequently one expects much weaker plerions around pulsars in the centres of rapidly expanding shells.

Once again, assuming that the initial periods and fields of pulsars are distributed as before, namely $1 \lesssim P_0 \lesssim 20$ ms, $10^{12} \lesssim B \lesssim 10^{13.5}$ G one can estimate the expected number of plerions with luminosities greater than 0.1 $L_{\rm Crab}$. Since one has now decoupled the velocity of expansion from the initial period of the pulsar, one is back to the scenario of Pacini & Salvati (1973). Fig. 3 shows contours corresponding to the chosen luminosity limit for different ages. By following the procedure described earlier, we arrive at the conclusion that there should be at least 16 plerions with luminosities greater than 0.1 $L_{\rm Crab}$ inside rapidly expanding shells. If one took into account the expected deceleration of the shell as it encounters the interstellar medium the expected number will be even larger. Although this number is less than the 35 predicted in the pulsar-driven scenario, the discrepancy with observations is even more glaring. There are only four plerions above our luminosity limit. Of these, the Crab clearly does not

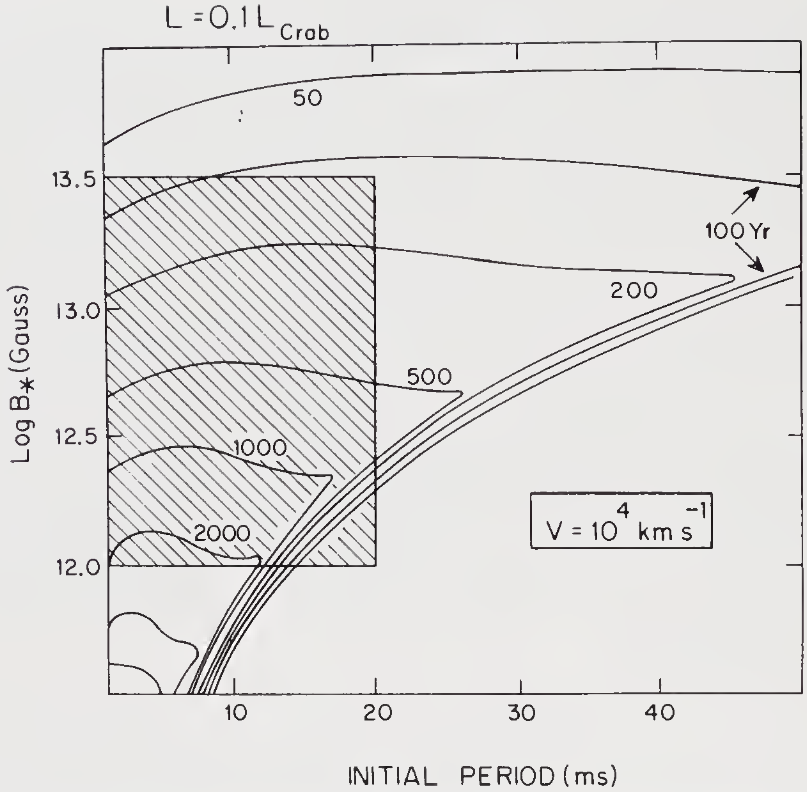

Figure 3. Plerions produced by pulsars inside standard shell SNRs expanding with a velocity 10^4 km s^{-1}. Once again the contours correspond to a luminosity of 0.1 L_{Crab}.

belong to the scenario in discussion. This leaves G 328.4 + 0.2, G 74.9 + 1.2 and 3C 58. We shall now argue that *even* these three do not correspond to the present scenario of a pulsar inside a fast-moving shock. When the shock sweeps up sufficient interstellar matter, one expects a pronounced radio and thermal X-ray shell. However, none of the three remnants mentioned above show any limb-brightening in the radio or an X-ray shell (Weiler 1983; Becker, Helfand & Szymkowiak 1982). One might argue that the radio shell is not pronounced because of very high central surface brightness due to the plerion. But one certainly expects to see an X-ray shell since the X-ray plerion will have a fairly small spatial extent compared to the diameter of the shell.

One is therefore once again faced with a dilemma! If there are pulsars in the shell remnants then their initial period must have been substantially greater than 20 ms. The absence of central emission in X-rays except in the case of MSH 15–52 places an even stronger constraint on the initial periods, but we shall come to this presently when we discuss X-ray from plerions.

We have so far discussed two mutually exclusive scenarios. One in which the pulsar decides the dynamics of the expanding shell and the other in which it is a passive observer. There have been some suggestions, notably by Chevalier (1976) and Weaver & Woosely (1980), that in some type II supernovae there is a shell of a few solar masses moving at speeds $\sim 10^4$ km s^{-1}, and core material moving much more slowly with velocities only ~ 300 km s^{-1}. The wind from the pulsar sweeps up the core material into a shell and inflates it with relativistic particles and magnetic field. Recently Reynolds & Chevalier (1984) have studied in detail the synchrotron radiation from such an expanding bubble. If this model applies to all type II supernovae, then the number of shell-plerion combinations one expects will be very large; in fact it will be the same number as we predicted in the pulsar-driven scenario. One of the questions discussed by Reynolds & Chevalier is the free-free absorption of the synchrotron radiation from the plerion by the surrounding ejecta. They conclude that the radio emission cannot be hidden for more than 200 years even in the case of very slowly expanding pulsar bubble. Thus, unfortunately, this mechanism cannot be entertained as a possible way to reconcile the small number of shell-plerion combinations.

What kind of pulsars may be present in historical shell SNRs?

According to the prevalent view historical shells such as Kepler, Tycho and SNR 1006 may be the remnants of type I supernovae which leave no compact remnant (Clark & Stephenson 1977; Trimble 1983). Indeed, the absence of point thermal X-ray sources in them may be consistent with the above picture. In what follows, however, we shall assume that there are pulsars present and ask what kind of initial periods and fields would they have had? In none of these shells is there significant emission from the centre. From limits on central surface brightness, knowing their ages and average expansion velocities, one can put bounds on the initial characteristics of the central pulsars. In Fig. 4 we have shown excluded regions for pulsars in the B_*–P_0 plane for each one of the remnants. The actual excluded region will in fact be much larger since

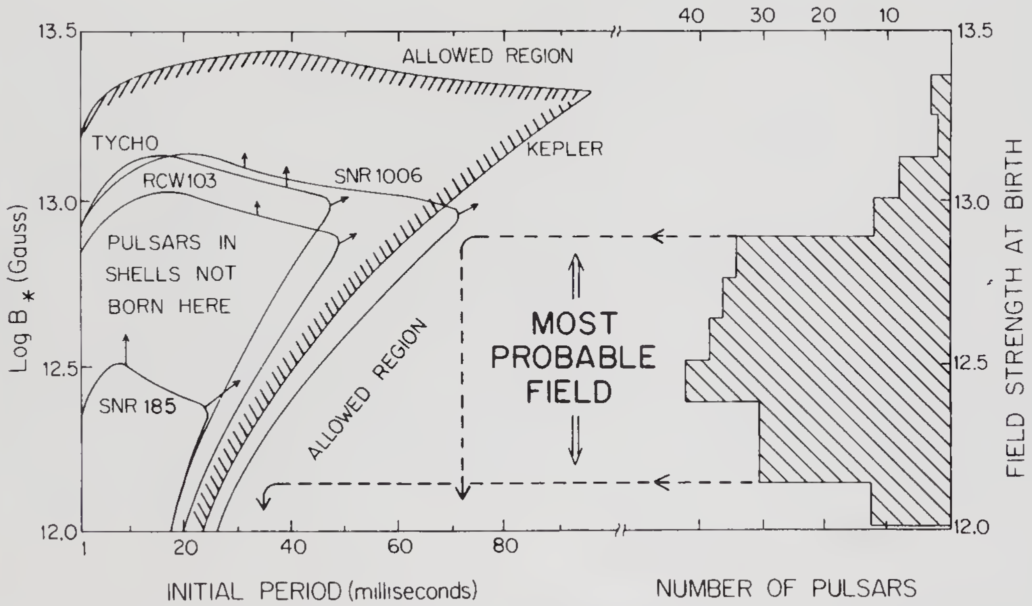

Figure 4. Pulsars inside the historical shells. The contours correspond to surface brightness of an assumed central plerion equal to 1/5th the average surface brightness of the SNR; the appropriate ages and expansion velocities inferred from their sizes were used. If pulsars in these shells were born inside the region enclosed by the contours, then the plerions produced by them should have been easily detected. The arrows on the contours indicate that the excluded region is likely to be much larger. Also shown is the histogram of pulsar fields at birth. Although pulsars in these remnants could have been born anywhere outside the region enclosed by the contours, the histogram suggests that for the majority of them the initial periods will be greater than 30 to 70 ms.

we have been very generous in estimating the limit on the central surface brightness. If these young remnants are typical, then the majority of pulsars must be born outside the shaded region. What is shown on the right is a constructed histogram of field strengths at birth derived from the observed properties of about 300 pulsars assuming a field decay time ~ 2 million years. Since the majority of pulsars have fields at birth between 10^{12}–10^{13} G, we conclude that their periods at birth must have been longer than 35–70 ms. We wish to regard this as a lower limit for the initial periods.

X-rays from plerions

So far, I have restricted the discussion to inferences one can draw from radio properties of plerions and avoided any discussion of X-ray emission. For various reasons the X-ray emission from a pulsar-produced nebula is a much better diagnostic tool to infer the characteristics of the central pulsar. The reason could be understood as follows. What determines the synchrotron luminosity in a spectral range is the nebular magnetic field and the number of particles at the right energy. Since the low-energy electrons which radiate in the radio region have a very long radiative lifetime, in calculating the radio luminosity one must take into account not only the particles freshly injected by the pulsar, but also the relic particles allowing for some adiabatic losses. This is one of the reasons why the initial luminosity of the pulsar matters. The X-ray emitting electrons, however, have a very short radiative lifetime. Consequently one needs to consider only the freshly injected particles. Thus the high-frequency luminosity of a plerion directly reflects the instantaneous energy loss rate of the pulsar. If one assumes a simple power law for the spectrum of injected particles it is straightforward to predict X-ray luminosities of plerions. Unfortunately there is a complication. The spectrum of injected particles is likely to have a break at high energies. Rees & Gunn (1974) have argued that there is strong evidence for such a break in the case of the Crab pulsar. In the first approximation one can ignore this break. This will lead to an overestimate for the X-ray luminosity; for the Crab nebula the ratio of the predicted to observed luminosity is ~ 3 or 4. But for none of the other observed plerions the ratio of L_X/L_R fits into any pattern. If the spectrum of injected particles is universal then one expects L_X/L_R to scale in a certain way with pulsar parameters, age *etc.* But it does not. This has also been noted by Reynolds & Chevalier (1984) and by Reynolds & Chanan (1984) in recent papers. It appears that whereas the spectral index of the particles at low energies may be 'universal', as suggested by the small spread in the radio spectral index of plerions the slope beyond the break might vary from pulsar to pulsar. The upshot of all this is that one has not been able to derive any reliable information on the characteristics of the unseen pulsars in the small sample of plerions which are X-ray emitters.

It was mentioned in the beginning that in every case where a pulsar has been seen in a plerion, it has a large energy-loss rate. One would, therefore, expect to see X-ray emission. One does! In fact in some cases like MSH 15–52 one sees only an X-ray plerion and there is no detectable radio emission. From the absence of X-ray emission from any of the 34 SNRs within 5 Kpc, one can put limits on the present energy loss rate of the central pulsar. From this, Helfand & Becker (1984) have recently concluded that if there are pulsars in these shells, they must have a very low magnetic field and long periods at birth.

An alternative approach

In addressing the question of the poor pulsar–SNR association we have adopted the point of view that there are functioning pulsars in all SNRs or at least in those produced by type II supernovae. We have then attempted to put constraints on the initial characteristics of pulsars, consistent with the absence of detectable plerions in the shells. Following the original suggestion by Woltjer in 1964, it has generally been accepted that neutron stars will be born with very strong magnetic fields, and hence will function as pulsars right from birth provided their periods are sufficiently short. If, however, the magnetic fields of neutron stars are built up after their birth, it can provide an alternative way out of dilemma. A variety of mechanisms have recently been suggested for thermally-driven magnetic-field generation in neutron stars after their birth (Woodward 1978, 1984; Blandford, Applegate & Hernquist 1983). According to Blandford *et al.* the timescale to build up the magnetic field to typical values observed in pulsars is $\sim 10^5$ yr. Long before this the SNRs would have faded away. It would appear that the scenario neatly explains the small number of plerions as well as SNRs of hybrid morphology.

Three pulsars, however, are an embarrassment to the above picture, namely, Crab pulsar, Vela pulsar and PSR 1509–58 in MSH 15–52. We know from various arguments that the neutron star in the Crab nebula must have been functioning as a pulsar practically from day one! The standard age of Vela SNR agrees very well with the characteristic age of the pulsar, implying once again that the neutron star must have been born with the present field. The pulsar in MSH 15–52 is a very interesting case. The characteristic age of the pulsar is only 1600 yr, but the standard age of the remant is $\sim 10^4$ yr. Blandford *et al.* have suggested that this discrepancy could be resolved if the neutron star turned on as a pulsar long after the supernova explosion. But 10000 years is an uncomfortably short time to build up field of 1.5×10^{13} G. Faced with this difficulty. Blandford *et al.* (1983) have suggested that the timescale for building up the field may be much shorter if the neutron star is a rapid rotator at birth. In most of the field build-up mechanisms, one relies on heat flux. The idea is that in a rapidly rotating neutron star one may be able to tap the rotational energy to generate additional heat flux, for example, by internal friction.

If the field builds up in a very short time in the case of rapidly rotating neutron stars, one can draw the following interesting conclusion, namely, that the neutron stars in the majority of shell remnants must have been born as slow rotators, for otherwise they might turn on as pulsars before the remnant disappears and one should see many more shell–plerion combinations.

Summary

It is time to take stock of where we stand regarding the question of Pulsar–SNR association. The considerations that we have put forward lead to the following conclusions.

1. If all plerions are pulsar-driven like the Crab nebula then given a pulsar birthrate of 1 in ~ 40 yr, one should see more than 35 radio plerions with luminosities greater than $\sim 0.1\ L_{\text{Crab}}$, unless their periods at birth are greater than ~ 150 ms.

There are only four plerions more luminous than this. This seems to suggest that either the majority of pulsars are born spinning slowly, or that pulsar-driven supernova remnants are extremely rare.

2. The Crab nebula must be a very rare object even among pulsar-driven plerions. Only in the rare case when the initial period of the pulsar is ~ 20 ms and its magnetic field $\sim 10^{12}$ G will the plerion be as 'bright' and as long-lived as the Crab nebula. The particular nature of the Crab must be understood in terms of the Crab pulsar having just these characteristics as surmised by Pacini a long time ago (Pacini 1972).
3. If the energy of expansion of the plerion is not derived from the stored rotational energy of the pulsar, then it must be derived from the energy released in the formation of the neutron star. In this case, one expects the nebular boundary to be expanding with velocities $\sim 10^4$ km s^{-1}. One expects to see more than 16 SNRs of hybrid morphology with the central radio plerion more luminous than 0.1 L_{Crab} if all pulsars are born spinning as rapidly as the Crab pulsar or faster. But none of the known shells has such a pronounced plerion. From this, we conclude that pulsars inside shell SNRs must have initial periods substantially longer than that of the Crab pulsar.
4. If there are pulsars in the historical shell SNRs then either they must have been born as slow rotators or, as envisaged by Pacini a long time ago, have very high magnetic fields.
5. An alternative possibility is that the magnetic fields of neutron stars get built up only after their birth and consequently they turn on as pulsars only much later.
6. The conclusion that most pulsars are born as slow rotators provides strong support for the conclusion arrived at by Vivekanand & Narayan (1981) from an analysis of periods and period derivatives of pulsars that the majority of them make their 'appearance' with periods $\gtrsim 100$ ms.

We conclude by listing some of the outstanding questions that deserve serious consideration.

1. What determines when pulsars play a dynamical role in the acceleration of the nebular boundary?
2. If only some pulsars are substantially endowed with fossil fields at birth, and not others, does it tell us something about their progenitors?
3. If the majority of pulsars are indeed born spinning relatively slowly, under what circumstances are the fast pulsars like the Crab born? Is the initial period related to the mass surrounding the core material or the magnetic field of the core, or perhaps both?

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On the Nature of the Supernova Remnant 0540–69.3 in the Large Magellanic Cloud

D. Bhattacharya & G. Srinivasan *Raman Research Institute, Bangalore 560080*

1. Introduction

In view of the poor association between pulsars and supernova remnants (Srinivasan, this volume), the recent discovery of an X-ray pulsar within the supernova remnant 0540 – 69.3 in the Large Magellanic Cloud (Seward, Harnden & Helfand 1984) is a very important one, being only the fourth known case of such an association. Very recently optical pulsations have also been detected from this pulsar (Middleditch & Pennypacker 1985), but no radio detection has yet been possible. The supernova remnant 0540 – 69.3 has been extensively studied in radio, optical and X-rays over the past few years and it appears to exhibit features very similar to the Crab nebula. In fact, Crablike character of this remnant appeared to be so convincing that the presence of a pulsar in this remnant was already conjectured (Clark *et al.* 1982) before this discovery. Some of the observed properties of this remnant are summarized below.

2. Observed properties of SNR 0540 – 69.3

Radio: The most recent radio map of this object obtained by Mills *et al.* (1984) is shown in Fig. 1. Observations were done at 843 MHz using Molonglo synthesis telescope. Though this is the highest resolution map available (half-power beam-width = 43 arcsec), it is still not adequate to resolve the structure within. Some general properties, however, can be derived as has been done by Mills *et al.* (1984). They suggest that the remnant is a centrally condensed one, and has a linear diameter of ~ 9 pc. The total flux is estimated to be ~ 1055 mJy. The spectral index $\alpha_R = -0.43$, however, is suggestive of a shell remnant rather than a plerion.

X-rays: Fig. 2 shows an X-ray map obtained using the HRI on board the Einstein Observatory (Mathewson *et al.* 1983). It clearly looks like a centre-brightened nebula. The angular extent of more than 12 arcsec suggests an X-ray diameter of more than ~ 3 pc. The X-ray luminosity in 0.15–4.5 KeV band is $\sim 1.2 \times 10^{37}$ erg s^{-1}. However, as we now know, roughly 25 per cent of this emission is due to the pulsar itself (Seward, Harnden & Helfand 1984b). Spectral observations of this remnant in X-rays have been carried out by Clark *et al.* (1982). They find a featureless spectrum which is best fit by a power law of index $\alpha_X = -0.8$. This strongly suggests that the X-rays are nonthermal. While pointing out that a featureless spectrum could in principle be produced by a hot plasma at 4×10^7 K, Clark *et al.*, however, favoured the synchrotron origin for the observed X-rays.

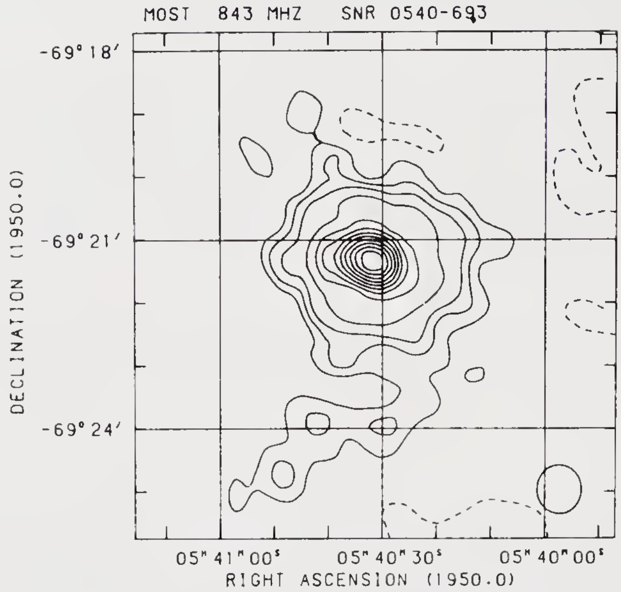

Figure 1. 843 MHz MOST map of SNR 0540 – 69.3 and its surroundings. While the central portion corresponds to the supernova remnant, the large extended emission around it may be related to the 30 Doradus region. (Taken from Mills *et al.* 1984.)

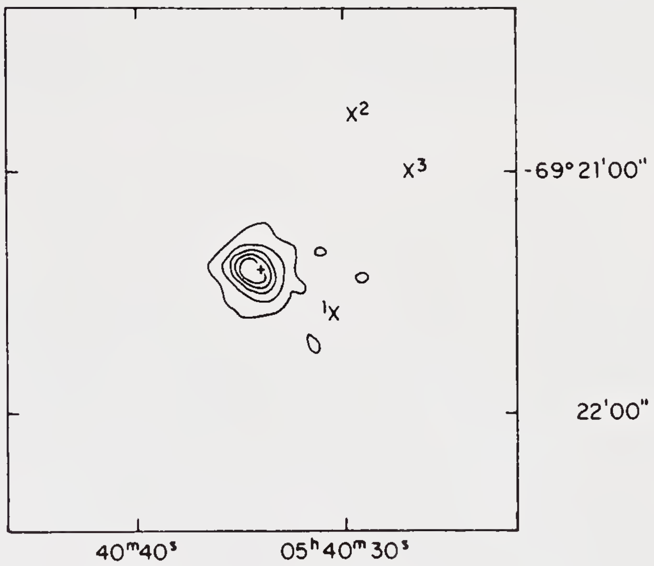

Figure 2. Einstein observatory HR I map of SNR 0540 – 69.3 obtained by Mathewson *et al.* (1983).

Optical: Different optical observations of this object have been reported by Mathewson *et al.* (1980, 1983) and Kirshner (1984). One of the important results is that the remnant is rich in oxygen. Very recent observations by Chanan, Helfand & Reynolds (1984) have revealed the presence of an optical synchrotron nebula.

The above facts strongly suggest that SNR 0540 – 69.3 is another plerion like the Crab nebula. The discovery of the pulsar appears to clinch the issue.

3. Is SNR 0540 – 69.3 another 'Crab nebula'?

Let us now examine this possibility more carefully. The observed period of the pulsar is $P = 50.2$ ms while its period derivative is $\dot{P} = 4.8 \times 10^{-13}\ \mathrm{s\ s^{-1}}$. These suggest a characteristic age $P/2\dot{P}$ of ~ 1640 yr, and a surface magnetic field of 4.9×10^{12} G, which is very close to that of the Crab pulsar (3.6×10^{12} G).

The relative size of the X-ray and radio remnants is similar to that in the Crab nebula, whereas the overall size of the remnant is roughly consistent with that of the Crab nebula, given the ratio of their respective ages. The pulsar parameters being now known, the only thing that remains to be shown is that the observed X-ray and radio luminosities of 0540 – 69.3 agree with what one would expect.

Turning to the scenario of pulsar-driven supernova remnants, as has been summarized by Srinivasan (this volume) we see that if a certain fixed fraction of the initial stored rotational energy of the pulsar goes into the kinetic energy of the expanding nebular material

$$M_{\mathrm{ej}} v^2 \propto I\omega_0^2$$

where M_{ej} is the mass in the ejecta, I is the moment of inertia of the neutron star, v is the expansion velocity of the remnant, and ω_0 is the initial angular velocity of rotation. One must remark that this expansion velocity v will be attained by the ejecta only after the initial characteristic age of the pulsar is over, and is expected to remain constant till subsequent deceleration on interaction with the interstellar medium. If the age of 0540 – 69.3 is equal to the characteristic age of the pulsar, the observed radio size implies an expansion velocity $\sim 2700\ \mathrm{km\ s^{-1}}$. Assuming the mass in the ejecta to be roughly comparable to that in the Crab nebula, the initial rotation period can be estimated to be ~ 10 ms for the pulsar. The error introduced by this nonzero initial period to the true age and hence to the estimated velocity is less than 4 per cent and this may therefore be considered quite consistent.

To calculate the expected luminosity of the nebula, we first turn our attention to X-rays. Using the formalism developed by Pacini & Salvati (1973), we have the scaling law for X-ray spectral luminosity of the nebula:

$$S_{\mathrm{X}} \propto B_*^{(6-\gamma-4\alpha)/2} P_0^{2(\alpha-2)} v^{3/4(2-\gamma)} t^{(2-\alpha-\gamma)}$$

where B_* is the surface magnetic field of the pulsar, P_0 is its initial period, v is the expansion velocity of the nebula and t its age, $\alpha = (n+1)/(n-1)$, where n is the braking index for the pulsar and γ the spectral index for the energy of injected particles.

Since the observed X-ray spectral indices of the Crab nebula and SNR 0540 – 69.3 are roughly the same, one may assume that the spectral index of the particles accelerated by the two pulsars are also roughly the same. This enables one to deduce the X-ray luminosity of 0540 – 69.3. One finds

$$S_{\mathrm{X,0540}} \simeq 0.3 S_{\mathrm{X,Crab}}.$$

Interestingly enough, this ratio is the same as the ratio of the energy loss rates of the two pulsars. This is not surprising since the high-frequency luminosity of the nebula should be directly relatable to the instantaneous pulsar energy loss rate. The X-ray luminosity of the Crab nebula in the Einstein band is $2.5 \times 10^{37}\ \mathrm{erg\ s^{-1}}$, while that of SNR 0540 – 69.3 is $\sim 1.2 \times 10^{37}\ \mathrm{erg\ s^{-1}}$ of which ~ 25 per cent comes from the pulsar. Our estimate of expected luminosity, therefore, is in reasonable agreement with the observed value. Or, in other words, the observed X-ray luminosity agrees reasonably well with what one would expect from a nebula produced by a pulsar with $P_0 \sim 10$ ms and $B_* \sim 4.9 \times 10^{12}$ G at an age of ~ 1600 yr.

Let us now estimate the expected *radio* luminosity from the pulsar bubble. Once again, we use the appropriate formula derived by Pacini & Salvati (1973). The scaling law for the radio luminosity reads as

$$S_R \propto B_*^{(3-5\gamma)/2} P_0^{2(\gamma-2)} v^{-3/4(1+\gamma)} t^{-2\gamma}.$$

The scaling from Crab predicts a radio luminosity

$$S_{R,0540} \simeq 0.04\, S_{R,Crab},$$

i.e. 4 per cent that of the Crab nebula. The observed flux, however, implies a radio luminosity nearly 75 per cent that of the Crab nebula; thus rendering the above estimate grossly discrepant.

One of the assumptions that has gone into the above estimate, and which may now be questioned is that the mass ejected was the same in 0540 as in the Crab nebula. It will be recalled that in the pulsar driven scenario the final velocity attained is determined both by the initial period of the pulsar as well as the mass in the ejecta. The inferred expansion velocity of ~ 2700 km s^{-1} could also be consistent with much shorter initial periods provided that the ejected mass was more than that in the Crab nebula. The reason for entertaining short initial periods is the following. The expression for radio luminosity shows that a shorter initial period would lead to a larger luminosity, all the other parameters being kept the same. One might thus hope to get better agreement between the observed and the predicted radio luminosities. Let us, therefore, estimate the radio luminosity by assuming that the neutron star was spinning maximally at birth. Papaloizou & Pringle (1978) have argued that the rotation period of a canonical neutron star cannot be much less than 1.5 ms. Adopting this value, one finds that the expected flux at 843 MHz can at most be ~ 26 per cent of the observed value. Thus, we are forced to the conclusion that the observed radio flux is far in excess of what one would expect from a plerion of the observed size and 1600 years of age, *regardless* of the initial period.

4. A model for SNR 0540 – 69.3

Faced with this difficulty, we suggested that the SNR under consideration is, in fact, a shell remnant with a central plerion (Srinivasan & Bhattacharya, 1984), with most of the radio flux coming from a shell which is not apparent in the MOST map because of insufficient resolution. The flux expected from a radio shell of 9 pc in diameter can be estimated using the $\Sigma - D$ relation. Although $\Sigma - D$ relation is very suspect for the galactic remnants, it is expected to be much more reliable for remnants in LMC since there is no distance uncertainty. Using the $\Sigma - D$ relation given by Mills *et al.* (1984) we find that the expected flux from the shell could account for almost *all* of the radio emission observed from 0540 – 69.3—the central plerion contributing only a few per cent to the observed flux. An attractive feature of this suggestion pertains to the observed spectral index. The observed value of $\alpha_R = -0.43$ fits in much better with a typical shell rather than a plerion which usually has a much flatter spectrum. The energy spectral index of injected particles as inferred from the X-ray spectrum of 0540 – 69.3 is $\gamma = -2\alpha_X = 1.6$, which should produce a radio spectral index $\alpha_R = (1-\gamma)/2 = -0.3$, similar to the Crab nebula. In the Crab, however, the X-ray spectrum is slightly steeper ($\alpha_X = -1.1$), presumably due to a break in the energy spectrum of the injected particles. In fact, as mentioned by Srinivasan (this volume) most galactic remnants require a break to be present in the injected particle spectrum, otherwise one ends up predicting too much X-ray luminosity. If such a break is present even in SNR 0540 – 69.3, the radio spectrum will be even flatter than $\nu^{-0.3}$, thus making the postulation of a radio shell all the more inevitable.

A natural question that would arise at this point is that if one is going to postulate a radio shell which is unresolved, why is there no attendant X-ray shell which should surely have been resolved by HR I? This can be understood by the use of X-ray $\Sigma - D$ relation for LMC SNRs as obtained by Mathewson *et al.* (1983). One expects a surface brightness $\Sigma_X \sim 7.8 \times 10^{-4}$ erg cm^{-2} s^{-1} sr^{-1} for a shell of diameter 9 pc, while the observed centrally-condensed X-ray nebula has $\Sigma_X \sim 0.12$ erg cm^{-2} s^{-1} sr^{-1}. Thus the expected surface brightness of the shell is $\sim 1/150$ that of the plerion. Hence it is conceivable that the shell will not be pronounced in the HR I image, where the minimum contour level presented is ~ 5 per cent that of the peak surface brightness.

We conclude, therefore, that SNR 0540 – 69.3 is a shell–plerion combination, like the galactic remnants MSH 15–52, G326.3 – 1.8, G29.7 – 0.3 *etc.* (see Weiler 1983).

4.1 *The Optical Ring*

Another curious feature of this remnant is a pronounced oxygen-rich annulus of mean diameter ~ 1.6 pc, as was first detected by Mathewson *et. al.* (1980) (Fig. 3). In proposing a model for the remnant, this feature must also be explained. It is tempting to

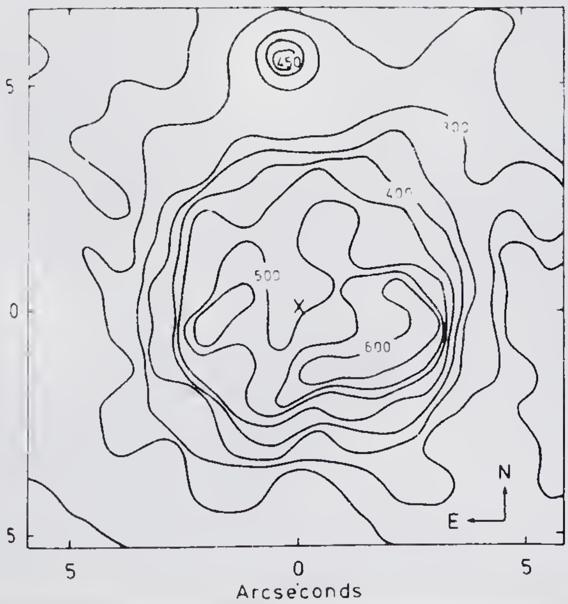

Figure 3. Isophotes of [OIII] image of SNR 0540 – 69.3, clearly showing annular emission region. (From Mathewson *et al.* 1980.)

suggest that this is, in fact, the boundary of the plerion; as has indeed been suggested by Reynolds (1985) in a slightly different model. We shall return to this presently. The main problem with such an interpretation is that it would be very difficult to reconcile the fact that the X-ray nebula is almost twice the size of this optical annulus (Fig. 4). It is, therefore, attractive to think of the following possible alternative. It is conceivable that the oxygen filaments are present at all distances from the pulsar but the 1.6 pc diameter ring is due to some enhanced excitation at this distance. Before discussing a plausible scenario for such an enhanced excitation, one must first account for such a high abundance of oxygen in the nebula.

The progenitor of this supernova might have been a massive star which had lost most of its envelope in stellar mass loss, leaving only oxygen rich core material or the model proposed for a type II supernova by Chevalier (1977) might be relevant and appropriate for the case in question. In this model the ejected mass resides in a rapidly expanding shell, as well as in a homologously expanding core material, which should be expected to be rich in heavy elements such as oxygen. It is this core material which is swept up by the pulsar wind (Reynolds and Chevalier, 1984). In analogy with the Crab nebula, one might expect to find the boundary of the pulsar bubble to be filamentary, and also to

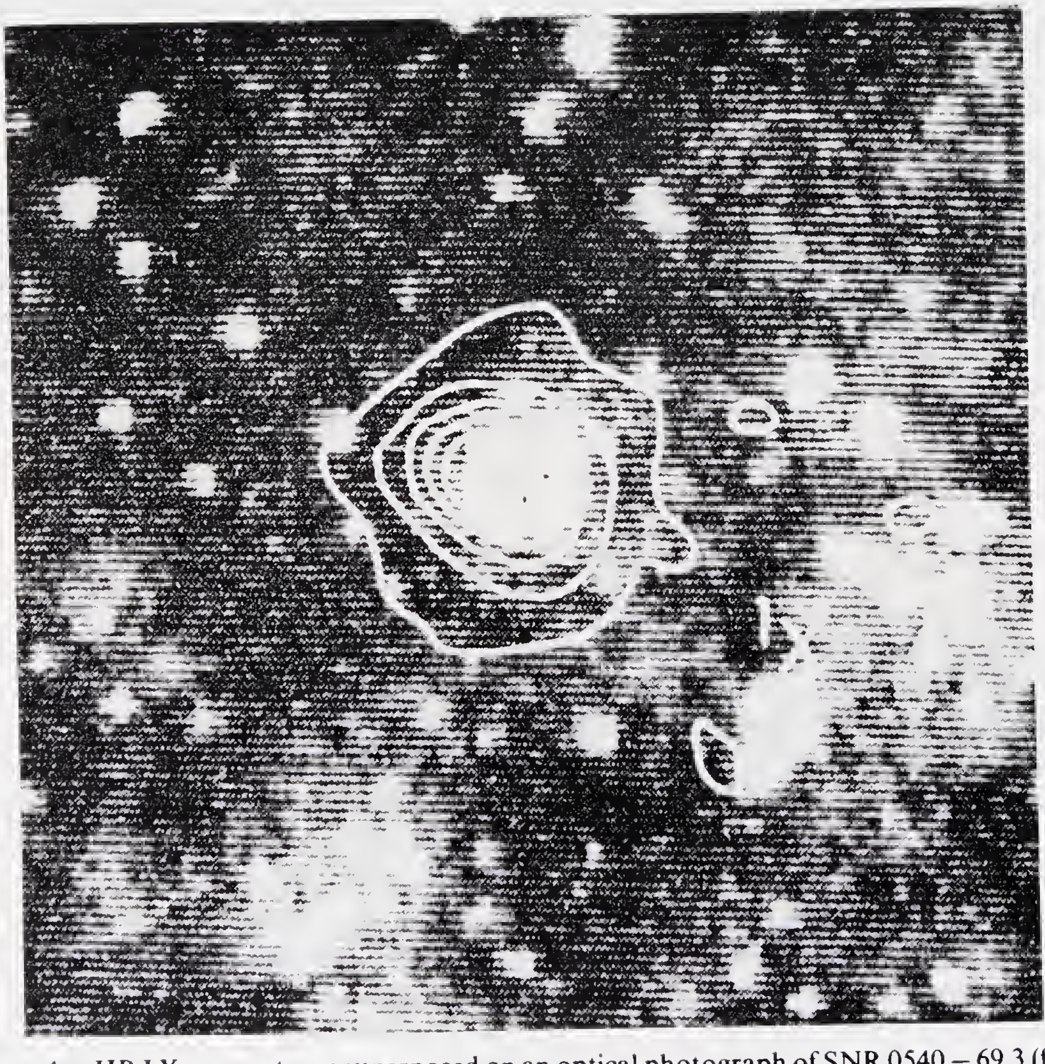

Figure 4. HR I X-ray contours superposed on an optical photograph of SNR 0540 – 69.3 (from Mathewson *et al.* 1983). The plus sign marks the centre of the [O III] ring.

find these filaments at all distances from the pulsar (Trimble, 1970). In fact, Mathewson *et al.* have pointed to an [O III] emitting filament at a distance 5 pc from the centre (Fig. 5).

We now return to the pronounced optical ring of 1.6 pc diameter. It is conceivable that a standing shock at this radius may be responsible for enhanced excitation. A natural explanation for a standing shock inside a pulsar bubble was proposed a long time ago by Rees and Gunn (1974). One expects a shock to be located at a radius where the ram pressure of the relativistic wind from the pulsar equals the built-up ambient pressure in the bubble. In fact, Rees and Gunn associated the wisps of the Crab nebula with such a shock front. A simple estimate of the shock radius R_s gives

$$R_s = R_{neb}\left(\frac{2\dot{R}_{neb}}{c}\right)^{1/2}$$

where R_{neb} and $\dot{R}_{neb}$ are the radius and the expansion velocity respectively of the nebular boundary. This formula differs from the one given by Rees and Gunn by a factor of $\sqrt{2}$ because we have taken into account the severe radiation losses by the high-energy particles and consequently a reduction in their contribution to the ambient

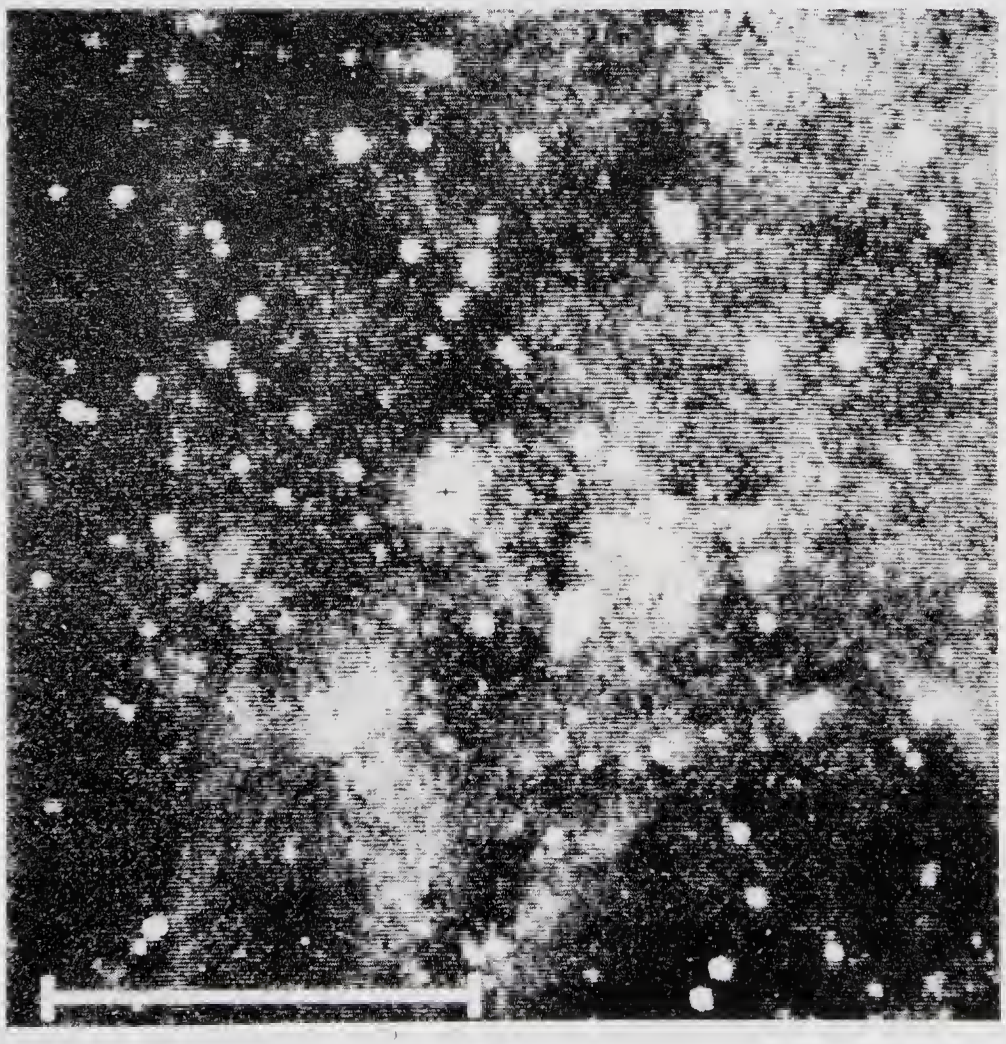

Figure 5. Optical picture of SNR 0540 – 69.3 region. The arrow at the right points to an optical filament probably connected with the SNR (Mathewson *et al.* 1983).

pressure, which now derives mainly from the built-up magnetic field. Using $R_{neb} \sim 4.5$ pc and $\dot{R}_{neb} \sim 2700\ \mathrm{km\ s^{-1}}$ we estimate a diameter of ~ 1.2 pc for this standing shock. Thus the observed size of the optical annulus is consistent with the presence of an enhanced excitation ring at R_s. This feature must in fact be filamentary, as otherwise the relativistic particles could not have propagated beyond it. A high-resolution optical image may be necessary to verify this. The observed radial velocities $V_r \sim 1200\ \mathrm{km\ s^{-1}}$ are possibly due to the bulk motion of line-emitting filaments through this excitation ring. One would naturally ask if there is such enhanced excitation near the pulsar in the Crab nebula. It appears that there is very little thermal matter near the wisp region of the Crab nebula—thus enhanced excitation at shock radius is not expected to produce strong ring-like emission, and in the published photographs of the Crab nebula taken in [O III] emission (see for example, Gull & Fesen, 1982; Clark, this volume), it is difficult to discern any such feature.

5. A different model

An alternative model for this supernova remnant has been recently proposed by Reynolds (1984). He too concludes that it is a shell-plerion combination, but there are differences in detail compared to our model. In this model, the boundary of the plerion is the [O III] emitting annulus. The radio, optical and X-ray plerions are contained

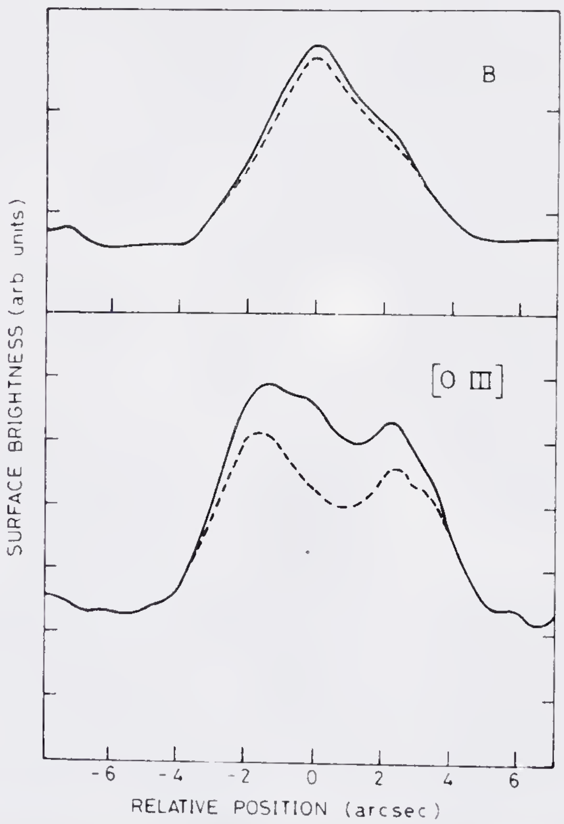

Figure 6. East-West slices through the centre of the nebula in Blue (B) filter (top) and [O III] filter (bottom). Dashed curves contain correction for unwanted contribution from line and continuum respectively. Reproduced from Chanan, Helfand & Reynolds (1984).

within this. There is an outer radio shell which is of the same size as the one suggested by us.

It is worth making a comparison of these two models. In the one proposed by us, the main difficulty is that it would predict an optical nebula larger than the X-ray nebula. Whereas the HR I observations suggest a centrally concentrated X-ray nebula of about 3 pc in diameter, according to recent observations by Chanan, Helfand & Reynolds (1984) the optical synchrotron nebula may be only ~ 2 pc in diameter. (Fig. 6). However, we feel that it may be useful to look for an extension of optical continuum at lower flux levels. A second difficulty with our model is that we predict rather luminous shell at the boundary of, or beyond the radio plerion. However, there is no clear evidence of a similar shell surrounding the Crab nebula, though there have been some suggestions (Murdin & Clark, 1981; Clark *et al.*, 1983; T. Velusamy, personal communication).

The alternative picture suggested by Reynolds also faces several difficulties. If the optical ring is the boundary of the plerions, then it is hard to understand (1) why there is a centrally condensed X-ray nebula which is $1\frac{1}{2}$ times the size of the radio plerion, and (2) why the optical nebula is as big as the radio nebula.

Reynolds suggests that the X-ray emission from outside the optical ring is not related to the synchrotron nebula, but 'contamination' from an outer X-ray shell. This is very difficult to reconcile with X-ray observations of galactic shell remnants. The question as to why there is no outer shell surrounding the Crab nebula remains a problem for this model also.

Although at present it is not possible to choose unequivocally between these two models, future observations will no doubt clarify the picture. It appears that one can say with reasonable confidence that the SNR 0540 – 69.3 is another shell–plerion combination.

According to our estimate, the initial period of the pulsar might have been ~ 10 ms. Reynolds estimates an initial period ~ 30 ms using slightly different arguments. These estimates would make the pulsar in 0540 – 69.3 very similar to the Crab pulsar. This lends support to the remark made by Srinivasan (this volume) that long-lived and bright plerions are expected only in those circumstances when the central pulsar has an initial period ~ 10–20 ms and a magnetic field $\sim 10^{12.5}$ G.

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Formation and Evolution of Neutron stars in Binary Systems

E. P. J. van den Heuvel & G. M. H. J. Habets *Astronomical Institute, University of Amsterdam, Amsterdam 1018, The Netherlands*

Abstract. In the first part of this review we summarize the observed characteristics of the various types of binary systems that contain neutron stars. For the accreting systems (X-ray binaries) we discuss the various mechanisms that can drive the mass transfer, as inferred from observational and theoretical considerations.

The second part of this review is devoted to the evolution of binary systems leading to the formation of compact objects and further to the final evolution of X-ray binaries and the possible end-products of this evolution. As to the massive binaries we especially discuss the most recent results concerning the lower mass limit for neutron star formation by direct core collapse (Habets 1985).

For the low-mass neutron-star binaries we emphasize the mounting observational evidence on the formation of neutron stars in an old stellar population by the accretion-induced collapse of old white dwarfs in close and wide binaries.

Much of the material to be discussed here has been extensively reviewed in a recent monograph (Lewin & van den Heuvel (Eds) 1983), and in recent review papers (Bradt & McClintock 1983; Joss & Rappaport 1984; McClintock & Rappaport 1984; van den Heuvel 1981, 1984) to which we refer the reader for details and general reading.

Key words: neutron stars, in binaries—binary stars, evolution—X-ray binaries—accretion

1. Observational data on compact objects in binary systems

1.1 *X-ray Binaries*

We only summarize here those points which are essential for discussing the evolution of the X-ray binaries, later in this paper. The strong galactic binary X-ray sources ($L_X \sim 10^{35}$–2×10^{38} erg s^{-1}) can roughly be divided into two groups, the massive ones ($M_s > 10\ M_\odot$) and low-mass ones ($M_s \lesssim 1 - 1.5\ M_\odot$) where M_s is the mass of the nondegenerate companion star.

The two groups are often referred to as type I and type II, the type I sources belonging to extreme stellar Population I and the type II sources being a mixture of old

Table 1. Characteristics of the two main classes of galactic X-ray sources.

Type I	Type II
1. Massive companion ($\gtrsim 10\, M_\odot$) (Optical spectrum: early-type star)	1. Low-mass companion ($\lesssim$ 1–1.5 $M_\odot$) (often: no stellar spectrum visible; accretion disc).
2. Hard X-ray spectrum; pulsating	2. Softer X-ray spectrum; non-pulsating (2 or 3 exceptions)
3. In galactic plane; young stellar population ($\lesssim 2 \times 10^7$ yr)	3. Concentrated towards galactic centre (old: mostly $5-15 \times 10^9$ yr)
4. No X-ray bursters	4. Often X-ray bursters.

disc ('bulge', 5–10 $\times 10^9$ yr) Population and extreme Population II (globular cluster sources, $\sim 1.5 \times 10^{10}$ yr). Only a few systems, such as Her X-1, do not fit into either group. Table I lists a number of important differences between the two groups. Type I sources are often regular X-ray pulsars (although also black hole candidates like Cyg X-1 and LMC X-3 belong to this group), and never show X-ray bursts. On the other hand, very few of the type II sources are X-ray pulsars (the only two exceptions are 4U $1626-67$ and GX $1+4$, see Table 3), but many of them are X-ray bursters.

Apparently, pulsars don't burst and bursters don't pulse. (With 'bursts' we mean here the normal ('type I') bursts which are due to thermo-nuclear explosions on the surface of a neutron star: *cf.* Lewin & Joss 1983). We do not mean the so-called type II bursts of the rapid burster, which presumably have a completely different origin, and may also have been seen in some massive systems, such as Cyg X-1 (*cf.* Lewin & Joss 1983).

Each of the two main groups of X-ray binaries can be further subdivided into several subclasses, as follows.

1.1.1 *Massive X-ray binaries*

These can be divided into 'standard' systems and 'B-emission' systems, which differ in a number of physical characteristics as outlined in Fig. 1 (after Rappaport & van den Heuvel 1982). Table 2 lists a number of examples of both categories. The 'standard' systems are strong and permanent sources such as Cen X-3, Cyg X-1, 4U $0900-40$, SMC X-1, *etc.*, in which the companion star (nearly) fills its Roche lobe. With the exception of 4U $1223-62$, their binary periods are $\lesssim$ 10d. The 'B-emission' systems, first recognized as a group by Maraschi, Treves & van den Heuvel (1976) tend to be transient sources with relatively unevolved (main-sequence) companion stars that are rapidly rotating B-emission stars, which are deep inside their Roche lobes. The binary periods of these systems range from $\sim$ 15d to several years. For a detailed discussion of the characteristics of the B-emission systems we refer to Rappaport & van den Heuvel (1982).

1.1.2 *Low-mass X-ray binaries*

In recent years an increasing number of the type II sources have been recognized as binaries. Table 3 lists the presently known binary periods of low-mass systems. Fig. 2

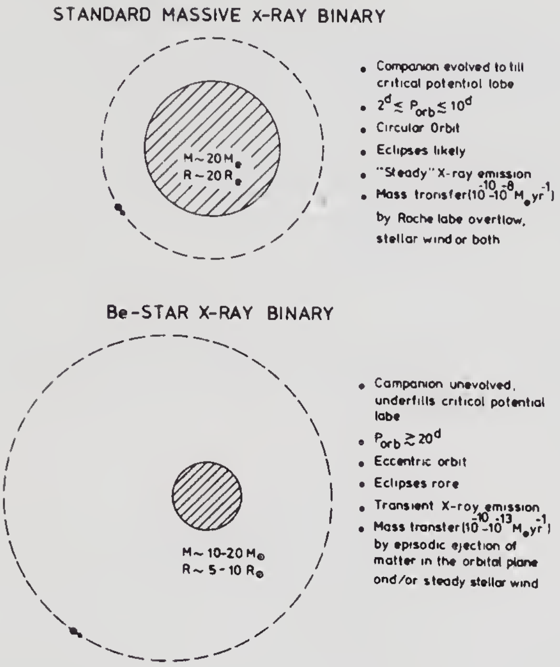

Figure 1. Schematic of a 'standard' massive X-ray binary *vs.* a Be X-ray binary system.

Table 2. The standard 'massive' X-ray binaries (top) and some examples of Be X-ray binaries (bottom).

Source	Optical counterpart	Spectral type	Pulse period(s)	Orbital period(d)	Eccentricity
LMC X − 4	Sk-Ph	07 III–V	13.5	1.408 d	$e = 0.00$
Cen X-3	Krz's star	06.5 II–III	4.84	2.087	$e = 0.00$
4U 1700 − 37	HD 153919	06.5f	. . .	3.412	. . .
SMC X-1	Sk 160	B0Ib	0.714	3.89	$e = 0.00$
4U 1538 − 52	12	B0Iab	529	3.73	$e = 0.00$
Cyg X-1	HD 226868	O9.7Iab	. . .	5.60	. . .
4U 0900 − 40	HD 77581	B0.5Ib	283	8.965	$e = 0.09$
GX 301 − 2	Wra 977	B1.5Ia	696	41.4	$e = 0.47$
4U 0115 + 63	Johns' star	Be	3.61	24.3 d	$e = 0.35$, transient
4U 0352 + 30	X Per	09.5 (III–V)e	835	580 d	Very weak, steady
A 0535 + 26	HD 245770	B0Ve	104	⩾ 18	transient
4U 1145 − 61	Hen 715	B1Vne	292	⩾ 35	Highly variable
4U 1258 − 61	MMV star	B2Vne	272	⩾ 13	Highly variable

(adapted from McClintock & Rappaport 1984) represents the orbital dimensions of these systems. The table and figure show that the low-mass systems clearly fall into (at least) two groups: those in which the orbital period is short (< 8h) such that the mass transfer can be driven by gravitational radiation losses (and/or magnetic braking) and those with longer periods (0.5d to several months), in which gravitational radiation certainly is unable to drive the mass transfer (as the timescale for orbital decay by

Table 3. Low-mass X-ray binaries with known orbital periods. The five systems in the lower part of the table have evolved companions.

Name	P_{orb}	Remark
1626 − 67	42 min	7.7s pulsar
2259 − 59	41 min (:)	7s pulsar, eccentr. orbit ($e > 0.1$)
1916 − 05	50 min	burster
1323 − 62	3 h	burster
1636 − 53	3.8 h	
1755 − 31	4.2 h	
Cyg X-3	4.8h	very large radio outbursts; small opposite radio jets
1254 − 69	4.8 h (:)	burster
1822 − 37	5.3 h	
2129 + 47	5.6 h	
1659 − 29	7.1 h	transient
0620 − 00	7.8 h	transient, K-type spectrum
Sco X-1	0.78 d	Radio source, opposite radio jets
Her X-1	1.7 d	1.2s pulsar: A-type spectrum
0921 − 63	9.0 d	F-giant
Cyg X-2	9.8 d	F-giant
GX 1 + 4	⩾ few months	118s pulsar; M6 IIIe spectrum; radio source

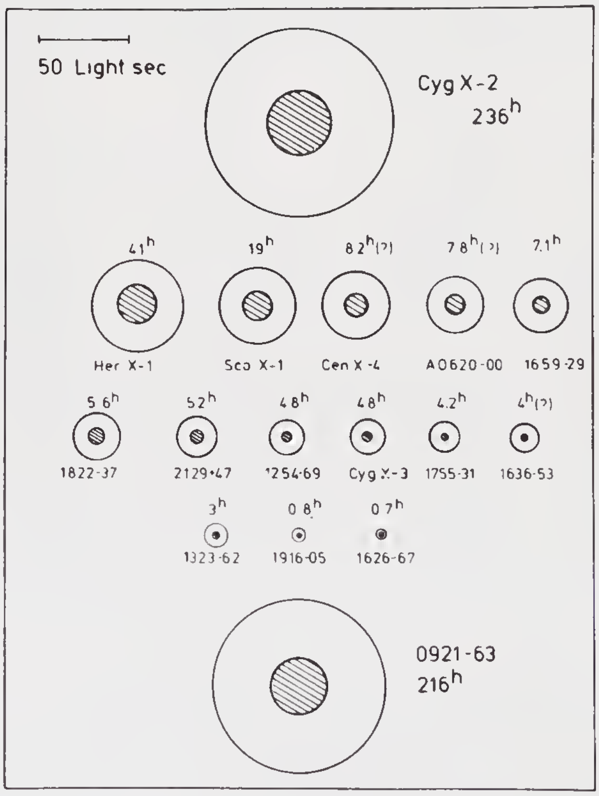

Figure 2. Orbital dimensions of the presently known low-mass X-ray binaries (adapted from McClintock & Rappaport 1984).

gravitational radiation losses is longer than the Hubble time, *cf.* Section 1.3.2. and Savonije 1983a). In these systems the mass transfer must be driven by the interior nuclear evolution of the companion. Indeed, these wider systems are the only low-mass X-ray binaries in which the stellar spectrum of a companion may be visible: examples are Cyg X-2 (F-giant), Her X-1 (A-star), GX 1 + 4 (low-mass M6 IIIe red giant). In the short-period systems no trace of the spectrum of a companion is observable: only the blue continuum and emission lines from the accretion disc are visible.

An important point is that, with a few exceptions (such as Her X-1, which has $z \sim 3$ kpc) the low-mass X-ray binaries cannot have runaway velocities larger than $\sim 50\,\mathrm{km\,s^{-1}}$, as they otherwise would, during their life-time, have travelled to distances from the galactic plane exceeding the $z < 0.6$ kpc where they are presently found.

1.1.3 *Peculiar sources with strong radio emission and mass ejection*

The strongly radio-emitting, peculiar X-ray binaries Cyg X-3, Cir X-1 and SS 433 might form a separate category (Table 4). They are characterized by occasional strong radio outbursts with a synchrotron spectrum and large IR luminosities. The 7s X-ray pulsar 1E 2259 + 59 may belong to a similar category (Fahlman & Gregory 1983). This source, Cir X-1 and SS 433 are surrounded by large supernova-like shells. The total power

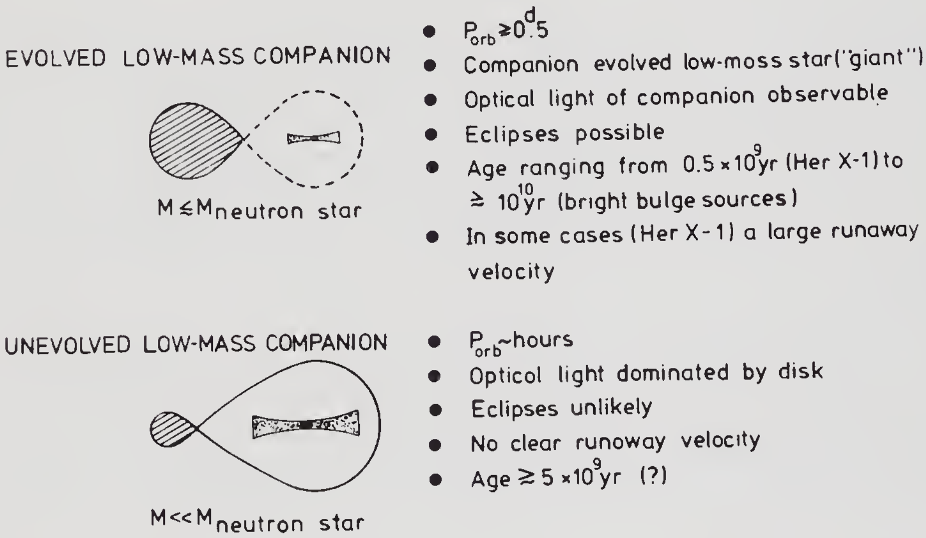

Figure 3. Schematic of the two categories of low-mass X-ray binaries: wide systems in which the mass transfer is driven by the internal evolution of the companion, and close systems in which the transfer is driven by gravitational radiation losses and/or 'magnetic braking'.

Table 4. Peculiar sources with strong radio and IR emission.

Source	Spectral type	P_{orb}	L_X/L_{opt}	z
Cir X-1	O–Be	16.6 d	10^{-2}	In galactic plane
SS 433	—	13.1 d	10^{-3}	130 pc
Cyg X-3	—	4.8 h	?	In galactic plane

(X-ray, mass outflow, *etc.*) of Cyg X-3, SS 433 and Cir X-1 is at least as large as the Eddington luminosity, suggesting that their peculiar characteristics are coupled with a very large (super-Eddington) accretion rate.

1.2 *Binary Radio Pulsars*

Four binary radio pulsars are known. Their vital data and system parameters are listed in Table 5, together with those of the 1.55 millisecond pulsar. In all these systems the companion is itself expected to be a compact star: in the case of PSR 1913 + 16 a neutron star, in the other cases a white dwarf (see van den Heuvel 1984, for an extensive review).

1.3 *Mechanisms that Drive the Mass Transfer in X-ray Binaries*

We only summarize the basics, and refer the reader to the reviews by van den Heuvel (1983) and especially Savonije (1983a) for detailed theoretical background.

1.3.1 *Massive X-ray binaries*

(i) *'Standard' systems.* In the 'standard' systems, in which the companion star (nearly) fills its Roche-lobe, the accretion may be due either to beginning Roche-lobe overflow or to capture of matter from the wind of the companion. (Basically, mass transfer by Roche lobe overflow in these systems is prone to become highly unstable, since the mass transfer takes place from the more massive to the less massive component. This soon leads to mass-transfer rates $\sim 10^{-4}$ to 10^{-3} $M_\odot$ yr^{-1}. Only during the beginning of Roche lobe overflow, when the transfer rates are below the Eddington limit, can the system be an X-ray source.)

Beginning atmospheric Roche-lobe overflow can only yield a sufficiently long-lasting (10^4–10^5 yr) phase of mass transfer at a sub-Eddington rate, if the companion star is still burning hydrogen in its core. If the companion is already beyond core hydrogen burning, its envelope will be rapidly expanding, and the mass transfer will, within a few

Table 5. Some important properties of the four binary radio pulsars and the single millisecond pulsar, together with estimates of their surface magnetic field strengths and of the masses of the companions in the binary systems.

Name	P_{orb} (d)	e	Mass function ($M_\odot$)	Most likely companion mass ($M_\odot$)	P_{pulse} (s)	B_s (G)
PSR 1913 + 16	0.32	0.617	0.1322	1.40 ± 0.05	0.059	2×10^{10}
PSR 0655 + 64	1.03	0.000	0.0712	1.00 ± 0.30	0.196	8.6×10^{10}
PSR 0820 + 02	1232	0.012	0.00301	0.2–0.4	0.865	3.3×10^{11}
PSR 1953 + 29	~ 117	< 0.01	0.00272	0.2–0.4	0.0061	2.5×10^9 (predicted)
PSR 1937 + 214					0.00155	5×10^8

thousand years grow to $\sim 10^{-3}\ M_{\odot}\ \mathrm{yr}^{-1}$, causing the X-ray source to be smothered (see Section 2.8).

As the stellar radius is relatively small during core-hydrogen burning, beginning Roche-lobe overflow can only be powering massive X-ray binaries if the orbital periods are < 4–5d. Cen X-3, SMC X-1, LMC X-4 are sources of this type. In all these systems there is clear evidence for the existence of an accretion disc as is indeed expected for Roche-lobe overflow, in view of the low velocities and large specific angular momentum of the transferred matter in this case.

In wider 'standard' systems, such as 4U 0900 − 40 ($P = 8.97$d), GX 301 − 2 (4U 1223 − 62; $P = 41.2$d) the neutron stars are expected to be accreting from the strong winds of their companions. Already the fact that both these systems have a considerable orbital eccentricity (see Table 2) makes Roche-lobe overflow unlikely here. Indeed, in neither of these systems there is optical or UV evidence for the existence of an accretion disc (the specific angular momentum in a wind is too low to expect the formation of a sizeable disc).

(ii) *B-emission x-ray binaries.* Most of these systems are transient sources, which may flare up as a strong source ($\sim 10^{36}$–$10^{38}\ \mathrm{erg\,s^{-1}}$) for a short while ($\sim$ a few weeks) and then be unobservable again for many months. In practically all cases the pulse-periods are long, ranging from 10^2 to 10^3 s (see Table 2).

As the companion stars are deep inside their Roche lobes the outbursts must be due to sudden episodes of spontaneous mass ejection from the rapidly rotating Be (meaning: B-emission) star. Indeed, all Be stars (also single ones) are observed to undergo irregular outbursts of mass ejection, which are presumably related to the very rapid rotation of these stars (*cf.* Underhill 1966).

Some of the very nearby B-emission systems are also observed to have a continuous low-level X-ray emission. X-Persei, for example, has $L_X \sim 10^{33-34}\ \mathrm{erg\,s^{-1}}$ (for more distant sources such a low-level emission would be unobservable).

This low-level emission is expected to arise by accretion from the normal wind massloss, at rates $\sim 10^{-8}$ to $10^{-9}\ M_{\odot}\ \mathrm{yr}^{-1}$ from early Be stars, sufficient to yield $\sim 10^{-12}$ to $10^{-13}\ M_{\odot}\ \mathrm{yr}^{-1}$ continuous accretion into the neutron star.

(iii) *Relation between neutron star spin and accretion mechanism; the spin history of neutron stars in massive binaries.* In the case of continuous disc accretion one expects the neutron stars to be rotating with a period close to their 'equilibrium' spin-period given by (see van den Heuvel 1977; Henrichs 1983):

$$P_{\mathrm{eq}} = (1.97\mathrm{s})(B_0/10^{12}\ \mathrm{G})^{6/7}\left(\frac{10^{-9}\ M_{\odot}/\mathrm{yr}}{\dot{M}_{\mathrm{a}}}\right)^{3/7} \tag{1}$$

where B_0 is the surface dipole magnetic field strength, and $\dot{M}_{\mathrm{a}}$ is the accretion rate (for a neutron star with $M = M_{\odot}$, $R = 10$ km).

Indeed, in systems in which there is evidence for the presence of a disc (*e.g.* Cen X-3, SMC X-1, Her X-1, 4U 1627 − 67) the pulse periods are short and, therefore, close to the expected equilibrium period. Also in these disc-fed sources continuous spin-up is observed, suggesting, according to Equation (1) a continuous slow increase in the mass accretion rate, as is also expected on theoretical grounds (Savonije 1983a). On the other hand, in the 'standard' systems with wind accretion (and no observable disc) the neutron stars rotate extremely slowly, and the same is true for practically all the B-emission systems (only two out of eleven B-e X-ray sources are short-period pulsars). Once the neutron star rotates slowly (with $P \sim 10^2$–10^3 s) accretion from a wind is not expected to be able to spin it up again. But the most important question is: what caused the very slow rotation of these neutron stars?

As the Be companion stars are still on or close to the main-sequence, and as some of these stars have masses $\sim 20\, M_\odot$ (*e.g.* X Per), their ages may be as low as 6.10^6 yr. Hence, the rotation of the neutron stars in these systems must have been slowed down from, say, $\sim 10^{-1}$ s at birth to $> 10^2$ s, within a few million years. [Periods of $\sim 10^2$–10^3 s are the equilibrium spin periods expected when they are accreting from the weak wind of their main-sequence B-e companion, van den Heuvel 1977].

Many mechanisms for rotational braking have been proposed (see the review of Henrichs 1983). Both the MHD-interaction with the weak stellar wind of the companion (Wang 1981; Wang & Robertson 1984) and interaction with a disc (Ghosh & Lamb 1978, 1979) may be able to achieve the braking. Interaction with a disc may provide braking on a very short timescale ($\sim 10^3$ yr), and is not implausible since during a mass-ejection outburst in B-emission systems very probably a temporary disc forms around the neutron star, for a period of a few weeks. In the beginning, accretion from such a disc will provide a short spin-up stage, but when the mass of the temporary disc decreases and the disc spreads out, magnetic coupling with the disc will brake the rotation of the neutron star (see Henrichs 1983). The thus-resulting spin-history of a neutron star that is born in a massive binary, is schematically depicted in Fig. 4.

1.3.2 *Low-mass X-ray binaries*

As the winds from low-mass stars are never very strong (except perhaps when the stars reach the asymptotic red giant branch) in general mass transfer by Roche-lobe overflow is required to power these strong sources.

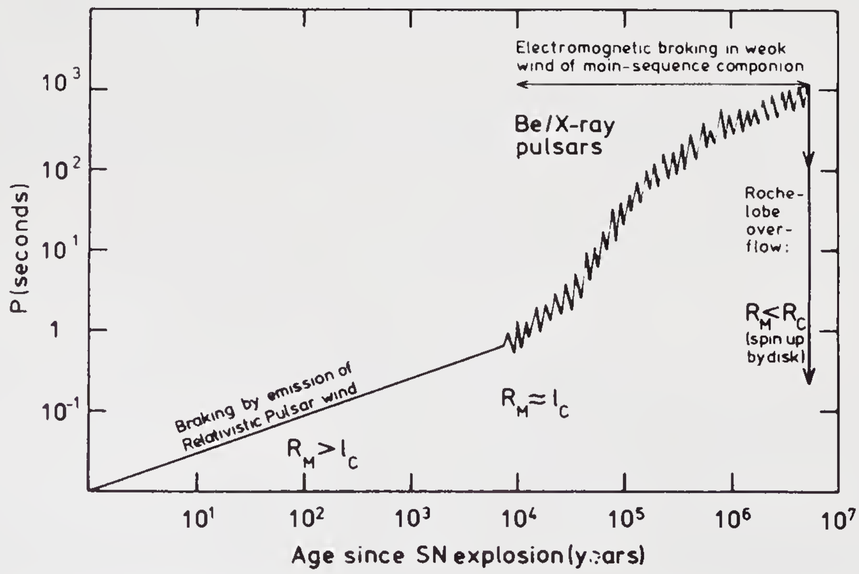

Figure 4. Suggested phases in the rotational evolution of a pulsar that is born in a massive close binary system. R_M, R_C and l_C are the radius of the magnetosphere, of co-rotation and of the light cylinder, respectively.

As the companion is always less massive than the neutron star, the mass transfer will be stable as it leads to an increase in orbital separation. (The only exception is Her X-1, where the companion has $M \sim 2\,M_\odot$; here, beginning atmospheric Roche-lobe overflow can power the source for several million years before it reaches the Eddington limit; *cf.* Savonije 1983a).

There are two mechanisms by which Roche-lobe overflow in low-mass systems can be driven (*cf.* Savonije 1983a):

(i) *Angular-momentum losses by gravitational radiation* (possibly supplemented by 'magnetic braking' (*cf.* Verbunt & Zwaan 1981). This only works for $P_{orb} < 10$ h, and yields mass-transfer rates of $\sim 10^{-11}$ to $10^{-10}\,M_\odot\,yr^{-1}$, sufficient to power sources of $\sim 10^{35}$ to 10^{36} erg s^{-1}.

The extensive calculations by Rappaport, Joss & Webbink (1982) and Rappaport, Verbunt & Joss (1983) show that even if the maximum possible magnetic braking is included, still no transfer rates larger than $10^{-9}\,M_\odot\,yr^{-1}$ can be reached. Hence, the X-ray luminosities of most of the type II sources (including the globular cluster sources) can be satisfactorily explained by this mechanism, but not the X-ray luminosities of the brightest bulge sources ($L_X = (1\text{–}3) \times 10^{38}$ erg s^{-1}: McClintock & Rappaport 1984), of which 8 are observed in our galaxy and nineteen in the bulge of M 31 (*cf.* Long & van Speybroeck 1983; Helfand 1984).

(ii) *Internal nuclear evolution of the companion star* is the only mechanism that can drive the mass transfer in low-mass systems with $P_{orb} > 0.5$d (since unevolved stars with $M < 1.4\,M_\odot$ cannot overflow their Roche-lobes in such systems). Clearly, in systems such as Cyg X-2 ($P_{orb} = 9.8$d), 2S 0921 − 63 ($P_{orb} = 9.0$d), and even in Sco X-1 ($P_{orb} = 0.78$d) the companion stars must be evolved low-mass stars (in Cyg X-2 and 2S 0921 − 63 the optical light of a F-subgiant is visible).

The evolution of binaries in which the mass-losing star is a low-mass (sub-) giant star was studied by Webbink, Rappaport & Savonije (1983) and Taam (1983). The luminosity in these low-mass ($M \sim M_\odot$) giants is generated in a hydrogen-burning shell which surrounds the degenerate helium core of low-mass ($M_{He} \simeq 0.2\text{–}0.4\,M_\odot$). During the evolution the core mass of the giant grows, and its radius and luminosity gradually increase. It is this increase in radius which, in a binary system, drives the mass transfer. During this transfer the orbit gradually widens, such that at any time the stellar radius just equals the Roche-lobe radius.

Fig. 5 represents, as an example, the evolution of a binary with an initial orbital period $P_0 = 12.5$d, an initial mass of the giant of $1\,M_\odot$ and of the neutron star of $1.3\,M_\odot$, calculated by Joss & Rappaport (1983).

(Such a system will resemble systems like Cyg X-2 and 2S 0921 − 63). The figure shows that after a brief initial episode with a mass-transfer rate of several times the Eddington limit ($\dot{M}_{Edd} \sim 2.10^{-8}\,M_\odot\,yr^{-1}$) the mass-transfer rate settles at a value of $\sim 10^{-8}\,M_\odot\,yr^{-1}$ for an interval of about 60 million years. During this time the orbital period gradually increases to ~ 120d. In the end only the helium core remains, as a $0.31\,M_\odot$ helium white dwarf (while at the onset of the mass transfer, M_{He} was $0.24\,M_\odot$).

It turns out that for systems of this type the average mass transfer rate depends (for a companion mass $M_c = M_\odot$, $Z = 0.02$), in first approximation only on the initial orbital period, roughly as:

$$\langle \dot{M} \rangle = -6 \times 10^{-10}\,(P/\text{day})\,M_\odot\,yr^{-1}. \qquad (2)$$

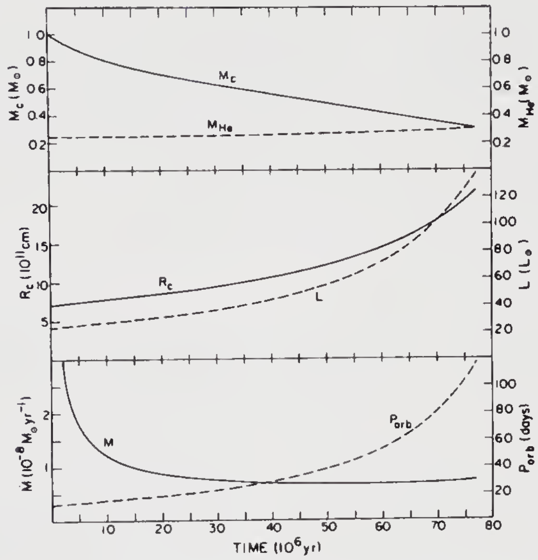

Figure 5. Evolution of a binary with a lower giant-branch secondary component of initial mass $1.0\, M_\odot$ and surface composition $X = 0.70$, $Z = 0.02$, as calculated by Joss & Rappaport (1983). Plots as functions of time: upper, total mass (M_c) and core mass of the secondary; middle, radius and intrinsic bolometric luminosity of the secondary; lower, mass accretion rate $\dot{M}$ onto the neutron star. Mass of the neutron star was taken to be $1.3\, M_\odot$.

(for other companion masses and chemical composition the relation becomes slightly different, *cf.* Webbink *et al.* 1983).

1.3.3 *Origin of the wide binary radio pulsars: evidence for accretion-induced collapse of old white dwarfs*

The orbital characteristics and companion masses of the two wide radio pulsar binaries PSR 0820 − 02 and PSR 1953 + 29 (see Table 5) very closely resemble those of systems that result from the evolution of wide low-mass X-ray binaries considered in the foregoing section, as depicted in Fig. 5. This was noticed by Joss & Rappaport (1983), Savonije (1983b) and Paczyński (1983).

One paradoxical thing with these systems is, however, that their neutron stars must be younger than $\sim 10^7$–10^8 yr (since surface magnetic fields of neutron stars decay on a timescale of $< (5$–$10) \times 10^7$ yr, (Lyne, 1981; Lyne, Manchester & Taylor 1985), whereas the systems themselves must be older than 5.10^9 yr. The latter follows from the fact that the low-mass companions, which must have started out with $M_s \lesssim 1.2\, M_\odot$, have already terminated their evolution and have become helium white dwarfs of 0.2–0.4 $M_\odot$ (see Table 5). For stars with $M < 1.2\, M_\odot$, this requires over 5×10^9 yr. Thus: we have old binaries that contain young neutron stars.

The only way out of this paradox is that the neutron stars in these systems were formed recently—during the mass-transfer process itself—by the accretion-induced collapse of a white dwarf (Helfand, Ruderman & Shaham 1983; van den Heuvel & Taam 1984; van den Heuvel 1984). (We thus imply that, at the onset of the mass transfer they still were white dwarfs). As the mass transfer in these systems lasted less than $\sim 7 \times 10^7$ yr (see Fig. 5) the neutron stars can indeed have formed quite recently and thus still have retained some magnetic field. Since this seems the only possible way out of the above-mentioned paradox, the two wide radio-pulsar binaries provide very strong observational evidence in support of the possibility that neutron stars can be formed in an old stellar population by the accretion-induced collapse of a white dwarf (as suggested first by Whelan & Iben 1973).

Moreover, just these wide systems provide particularly favourable conditions for such a collapse, as at the accretion rates of $\sim 10^{-8}\ M_{\odot}\ \mathrm{yr}^{-1}$, the hydrogen accreted by the white dwarfs will burn steadily or in weak flashes, which are unable to cause considerable mass ejection. (For further arguments: see van den Heuvel & Taam 1984; van den Heuvel 1984).

Precisely the same arguments as for these systems hold for the pulsating wide low-mass X-ray binary GX $1+4$. Here the companion still is a low-mass red giant, which also must have an age $> 5 \times 10^{9}$ yr. This system is an excellent progenitor for systems like the two wide radio-pulsar binaries (van den Heuvel 1981; Joss & Rappaport 1983).

Similar arguments apply also to the two very close—and presumably old—pulsating X-ray binaries 4U $1626-67$ (Joss, Avni & Rappaport 1978) and 1E $2259+59$ (Lipunov & Postnov 1985). (Here, the companion probably was a helium-burning helium star, which drove a white dwarf companion over the Chandrasekhar limit; see de Kool, Savonije & van den Heuvel 1985, for details).

Thus, we have at least five magnetized neutron stars in an old stellar population that provide strong evidence for the formation of neutron stars by accretion-induced collapse of old white dwarfs in binaries.

2. Formation of neutron stars in binary systems

2.1 *Introdution*

The neutron stars in X-ray binaries could either have been formed by (i) the direct collapse of the nuclearly exhausted core of an (initially) massive star, or (ii) by the accretion-induced collapse of a white dwarf in an old binary (a similar collapse might also be triggered by the coalescence of two white dwarfs in a very close white dwarf binary, *cf.* Webbink 1979, 1984; Iben & Tutukov 1984).

The first type of evolution has taken place in the massive X-ray binaries. The reason why these systems were not disrupted by the SN explosion that formed the neutron star, is that at the moment of the explosion the star had already become the less massive component of the system, as a consequence of a preceding stage of large-scale mass transfer (van den Heuvel & Heise 1972; van den Heuvel 1974). As was shown by Blaauw (1961), the system is disrupted only if more than half of the system mass is ejected in the explosion, which is not the case here. Fig. 6 depicts, as an example, the evolutionary history of a typical B-emission X-ray binary (Rappaport & van den Heuvel 1982). The various evolutionary stages are described in the figure caption. This type of close binary evolution, in which the mass transfer starts after the end of core-hydrogen burning, but before helium ignition, is called case B (in the terminology of Kippenhahn & Weigert 1967). The second neutron-star formation mechanism—by white-dwarf collapse—is expected to have taken place in most of the low-mass X-ray binaries. This is because in the direct collapse of a nuclearly exhausted stellar core always a considerable amount of mass is ejected (see next section). Taking the effects of the impact of the SN shell onto a low-mass companion in a close system into account it turns out that it is very difficult in

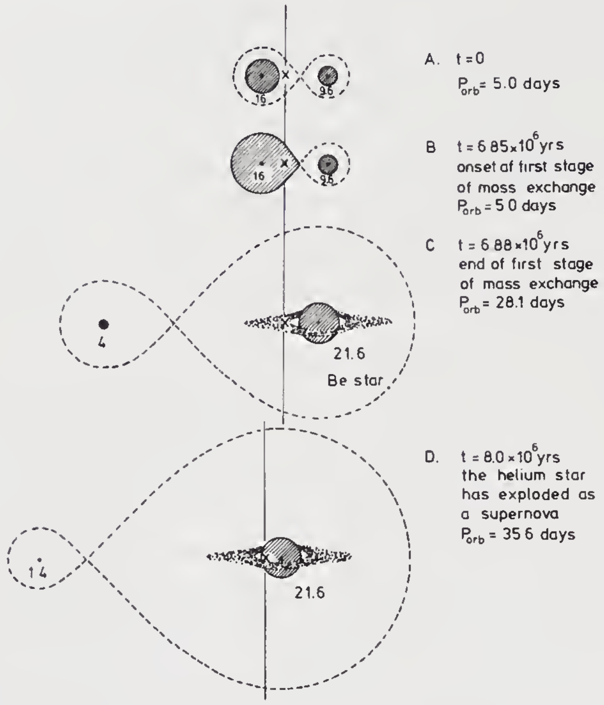

Figure 6. Conservative evolutionary scenario for the formation of a Be-X-ray binary out of a close pair of early B stars with masses of 16 $M_\odot$ and 9.6 $M_\odot$. The numbers indicate mass ($M_\odot$). After the end of the mass transfer the Be star presumably has a circumstellar disc or shell of matter associated with the rapid rotation (induced by the previous accretion of matter with high angular momentum; from Rappaport & van den Heuvel 1982).

this case to keep a low-mass companion star bound (*cf.* van den Heuvel 1978, 1981a). On the other hand, in the collapse of a white dwarf, not more than $\sim 0.1\ M_\odot$ (the mass equivalent of the binding energy of the neutron star) needs to be ejected, and disruption of the system, is in general, not expected.

2.2 *Types of Close Binary Evoluton*

We will now discuss how the type of remnant that is produced by close binary evolution, depends on the initial primary mass, mass ratio and orbital period. Fig. 7 depicts the three main types A, B and C of close binary evolution as defined in

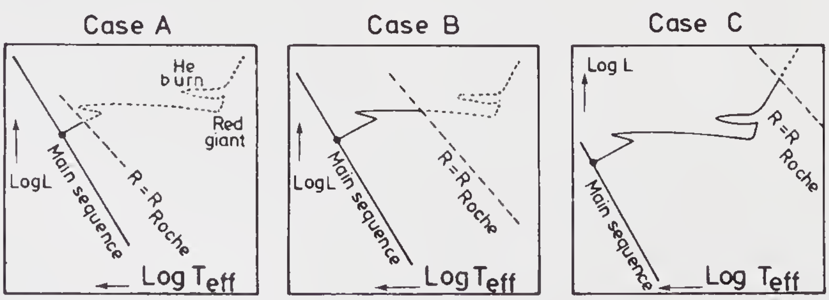

Figure 7. The three basic cases A, B and C of mass exchange in a close-binary system, as defined by Kippenhahn & Weigert (1967), illustrated on the evolutionary track of the primary star in the Hertzsprung-Russell diagram.

Kippenhahn & Weigert (1967). In case A the system is so close that the primary star already overflows it Roche-lobe before the end of core-hydrogen burning. In case C the systems are so wide that Roche-lobe overflow starts only after the end of core-helium burning. Case B is statistically most common among the known unevolved, close spectroscopic binaries. Case A is relatively rare.

The critical orbital period which separates the cases A and B, and B and C, respectively, depends on the initial mass of the primary star. M_1, and (slightly) on the initial mass ratio. Fig. 8 depicts the combinations of orbital period and primary mass for which the cases A, B and C occur, for an initial mass ratio unity (*cf.* van den Heuvel 1983; partly after Webbink 1979).

In what follows we will mainly concentrate on the results of case B evolution, as this case is very common, and its results can be described in fairly simple terms. Later on we will extend the discussions also to case C.

In case B, after the first phase of mass transfer—which takes place on a thermal timescale—only the helium core of the primary star is left. Therefore, whether or not the primary star will terminate its life as a white dwarf or as a neutron star, can be discussed simply in terms of the evolution of helium stars. It is for this reason that many authors have devoted much attention to the final evolution of helium stars (*e.g.* Arnett 1978; Nomoto 1982, 1984a, b; Habets 1985), which we will now discuss.

The correspondence between helium-core mass and initial (hydrogen-rich) primary mass can be simply expressed by analytic forms such as

$$M_{\mathrm{He}} = 0.073\,(M_1/M_\odot)^{1.42} \tag{3}$$

(van Beveren 1980; for chemical composition $X = 0.70$, $Z = 0.03$).

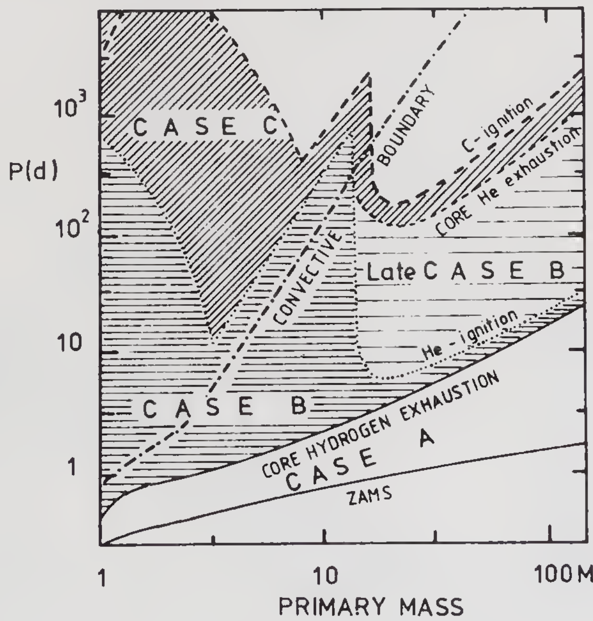

Figure 8. Types of close binary evolution as a function of primary mass and orbital period, for binaries with initial mass ratio $q = 0.5$ and $X = 0.70$, $Z = 0.03$ (partly after Webbink 1979). (The orbital periods correspond to binaries in which the primary star just fills its Roche lobe.) The cases A, B and C are defined in Fig. 7 and in the text. Above the convective boundary line the primary stars have convective envelopes at the onset of the Roche-lobe overflow. This leads to mass transfer on a dynamical timescale which presumably causes the formation of a common envelope in which the cores of the two stars will spiral-in on a very short timescale (Webbink 1979).

2.3 *The Evolution of Helium Stars*

We will review here the recent results by Habets (1985). Over-all, these results agree qualitatively well with those of other above-mentioned authors, but quantitatively they are expected to be somewhat more precise, because of the more refined treatment of convection. Habets' programme allows for growth of the convective helium core during the evolution, a feature which is not always allowed for the other programmes. Figs 9a, b represent, as an example, the interior evolution of helium stars of 3.2 $M_{\odot}$ and 4.0 $M_{\odot}$, up till neon-ignition, which occurs about 7–10 years before the final core collapse. The figures show that after the end of core carbon burning, several episodes of carbon-shell burning occur around the growing O–Ne–Mg core. (This feature is found by all authors). In the 4 $M_{\odot}$ star, the core consisting of elements heavier than helium

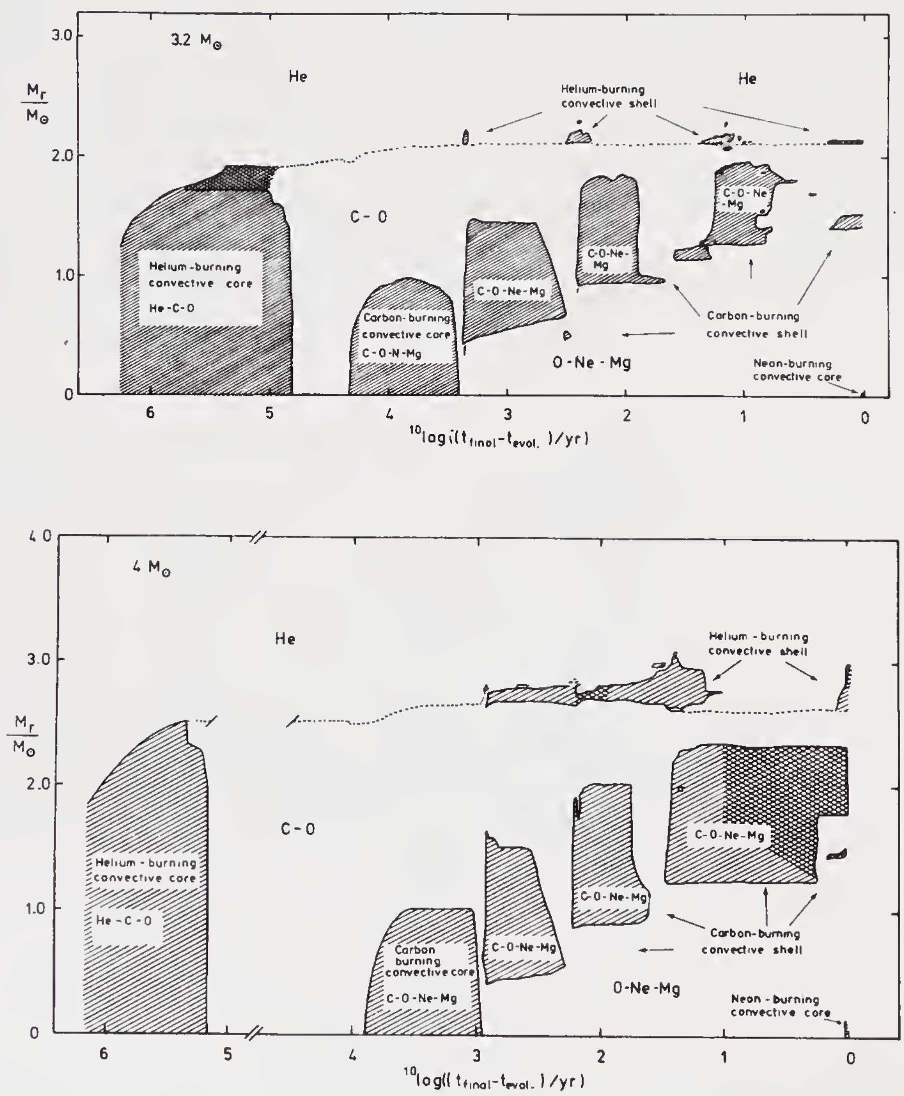

Figure 9a. The interior evolution of helium stars of 3.2 $M_{\odot}$ and (b) 4.0 $M_{\odot}$ up to neon ignition, as calculated by Habets (1985). Convective regions are hatched, semi-convective regions doubly hatched. The dashed and dotted lines indicate the regions of maximum energy generation in the helium burning shell and in the carbon-burning shell, respectively. These dashed and dotted lines are expected to be the boundaries of the C–O and O–Ne–Mg cores, respectively.

reaches a mass of 2.6 $M_\odot$, and will certainly collapse. The 3.2 $M_\odot$ star reaches a 2.2 $M_\odot$ heavy-element core, which also collapses. The outer radius of helium stars with $M > 3.5\ M_\odot$ never becomes larger than a few solar radii, before the final core collapse. Therefore, in a binary such stars will not undergo a second phase of mass transfer before they explode as a supernova.

However, for lower masses, the outer radii of helium stars may become very large during the late evolutionary stages (Paczyński 1971; Arnett 1978). This can be seen in Fig. 10 where the radius is plotted against the core mass for helium stars in the mass range 2.0 to 4.0 $M_\odot$, as calculated by Habets (1985). (The core mass is defined here as the mass inside the helium burning shell; as this core mass increases with time, the curves in Fig. 10 are, in fact, evolutionary tracks).

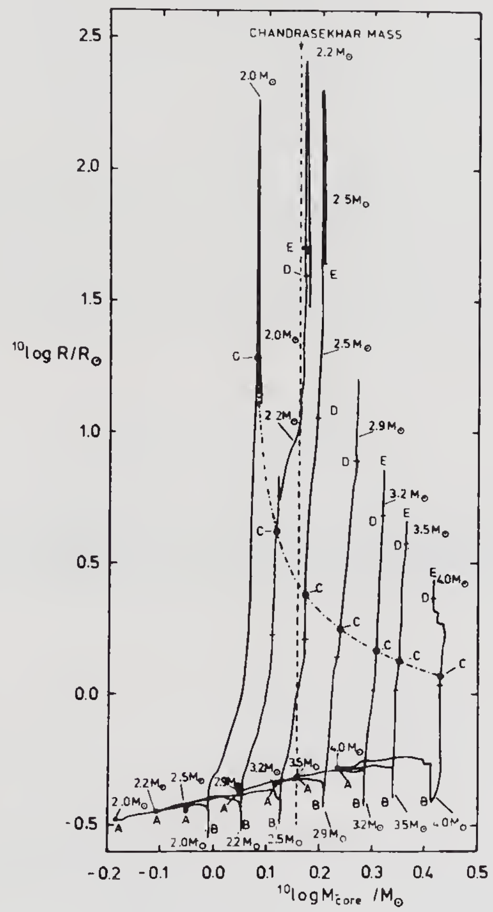

Figure 10. The cross-mass *vs.* radius relation of helium stars in the mass range 2.0 to 4.0 $M_\odot$ undergoing C-ignition and neon ignition (the 2.9 $M_\odot$ helium star was followed till very close to neon ignition); the 2.0 $M_\odot$ helium star was only followed up to the time at which the convective carbon-burning shell reaches the centre). During convective core helium burning from letter A to B) the core mass is defined as the mass of the convective helium-burning core including adjacent semi-convective regions. After convective core-helium burning the core mass is defined as the mass of the core (consisting of ^{12}C, ^{16}O, and possibly ^{20}Ne and ^{24}Mg, and some ^{4}He at the outer boundary of the core) which is limited by the helium-burning shell with maximum net energy generation. The open circles mark the onset of either central or off-centre convective core-carbon burning (at letter C). The dash-dotted curve has been drawn through these circles. The horizontal marking between B and C indicates the point where carbon burning begins in the radiative core.

2.4 *The Occurrence of a Second Phase of Mass Transfer (Case BB), and the Lower Mass Limit for Neutron-Star Formation in a Binary*

Fig. 10 shows that in a binary, helium stars with $M < 3.5\ M_\odot$ may undergo a second phase of mass transfer (so-called case BB mass transfer) as was first pointed out by Delgado & Thomas (1981).

As this reduces their mass, this second mass-transfer phase may lower the mass limit for neutron-star formation. As an example Fig. 11 shows the interior evolution of a 2.5 $M_\odot$ helium star in a binary with an orbital period of 20.29 d and a companion mass of 17 $M_\odot$ (Habets 1985). (Such a system is expected to be the evolutionary product of a binary with initial (zero-age) component masses of 13.5 $M_\odot$ plus 6.0 $M_\odot$, and an initial orbital period of 2.58 d). The figure shows that during carbon-shell burning the helium star loses about 0.3 $M_\odot$ to its companion. Since, however, the core mass grows to $\sim 1.5\ M_\odot$, and neon is ignited, this star is still expected to collapse to a neutron star. In a single helium star of 2.5 $M_\odot$ the core mass grows to 1.6 $M_\odot$, however, which shows that the occurrence of case BB mass transfer lowers the core mass, and therefore increases the lower mass-limit required for neutron-star formation in a binary system.

Habets' calculations show that the cores of helium stars in binaries with $M_{He} > 2.2\ M_\odot$ will always collapse to neutron stars (also if still a case BB mass transfer occurs). This implies that, in a case B binary, the initial (hydrogen-rich) stellar mass for reaching collapse to a neutron star is $\sim 10\ M_\odot$. For case C and for single stars this limit is lower, since in these stars the helium-core mass can still grow considerably during the later evolutionary stages, as a consequence of hydrogen-shell burning.

2.5 *Types of Remnants Produced, as a Function of Initial Primary Mass and Orbital Period*

Fig. 12 schematically represents the various types of remnants of primary stars of close binaries that can be produced, as a function of initial primary mass and orbital period,

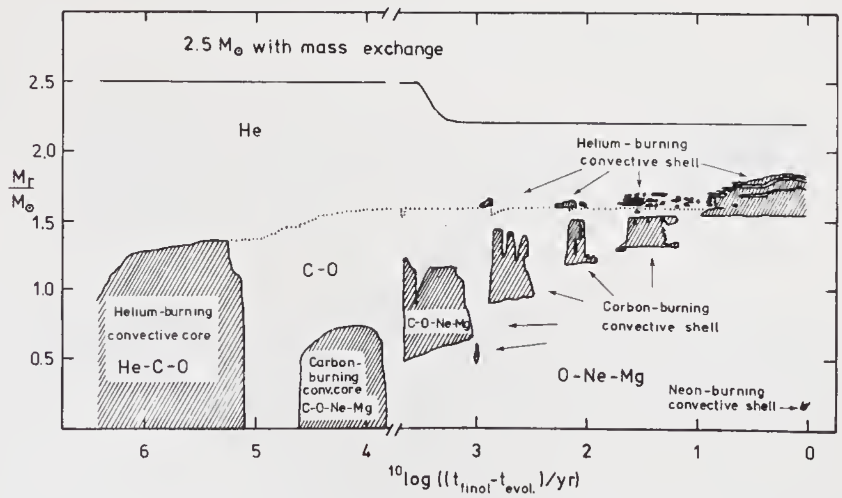

Figure 11. Interior evolution of a 2.5 $M_\odot$ helium star in a binary with a 17 $M_\odot$ companion. After carbon-shell ignition, case BB mass transfer starts and 0.3 $M_\odot$ is lost to the companion. The supernova will take place a few years after neon ignition. The meaning of the dashed and dotted lines and of the hatched region is the same as in Fig. 9.

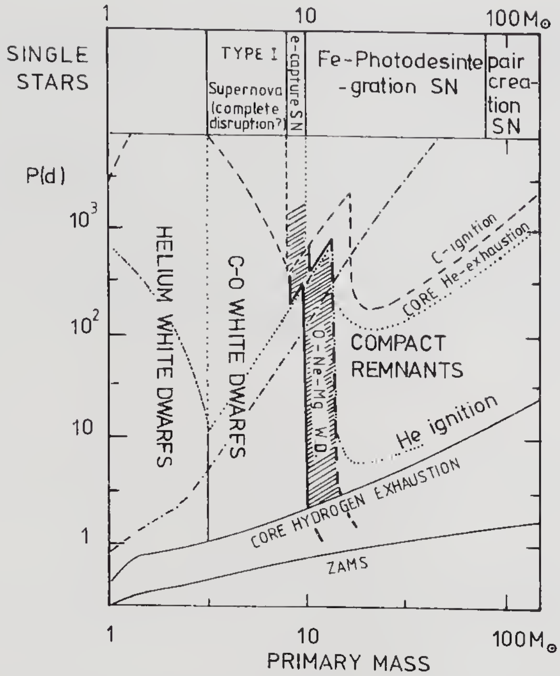

Figure 12. Classification of expected final evolutionary states of primary stars of close binaries as a function of primary mass and initial orbital period (for mass ratio 0.5 and $X = 0.70$). At the top of the figure the expected final evolution of single stars is indicated. In a subsequent phase of reversed mass-transfer CO white dwarfs may be triggered to explode as a type I supernova (complete disruption, see Nomoto 1982); old CO white dwarfs with a mass close to the Chandrasekhar limit, and O–Ne–Mg white dwarfs may be triggered by accretion to implode to a neutron star (see text).

as based on the results of Habets (1985; *cf.* van den Heuvel 1983; partly after Webbink 1979). At the top of the figure also the various types of remnants of single star evolution are indicated: these are practically to the remnants of primary stars of case C evolution, with the exception of the O–Ne–Mg white dwarfs, which (most probably) do not occur for single stars.

The figure shows the following:

1. For initial primary masses > 10–$12\ M_\odot$ (case B), $\geqslant 8$–$9\ M_\odot$ (case C) or $\geqslant 8\ M_\odot$ (single stars), respectively, a neutron star is produced, as the mass of the helium core is $> 2.2\ M_\odot$.

2. For a small range in initial primary masses below these boundaries, in the cases B and C, the remnants are white dwarfs consisting of O, Ne and Mg (products of carbon burning). In case B this occurs for initial primary masses approximately in the range 9 (± 1) to 12 (± 2) solar masses. For case C: in the range $\sim 8\ M_\odot$ to $\sim 9\ M_\odot$.

These white dwarfs are mainly the products of the later evolution of helium stars in the mass range ~ 1.9–$2.5\ M_\odot$ which lose their envelopes in a second phase—BB or CB—of mass transfer. (The above mass ranges, as depicted in Fig. 12, are approximate, as the precise values of the limits depend not solely on the initial primary mass and orbital period, but also on the initial mass ratio; the orbital period and mass ratio determine whether or not cases BB or CB of mass transfer will occur, which may slightly modify the precise values of the limiting masses. A full discussion of the various complicating factors is given in Chapter IIIc of Habets 1985).

The interesting point in Fig. 12 is especially the (rather narrow) mass range in which the remnants are O–Ne–Mg white dwarfs. When single stars produce such cores, these are still surrounded by a helium shell and a hydrogen envelope, which leads these cores to grow to the Chandrasekhar mass and to undergo an *e*-capture collapse, leaving a neutron star (*cf.* Nomoto 1984a, b; Hillebrandt 1984; Hillebrandt *et al.* 1984). In binaries, the mass transfer (case BB or CB) removes these envelopes, such that the cores may stay behind as O–Ne–Mg white dwarfs. These are interesting objects since in the case of reversed mass transfer in a binary they may be triggered by the accretion to collapse to a neutron star, as was first pointed out by Miyaji *et al.* (1980) and Sugimoto & Nomoto (1980).

2.6 *Conditions for the Occurrence of Accretion-Induced Collapse of a White Dwarf in a Close Binary*

The reaction of a white dwarf to accretion of matter depends on a number of aspects, such as (Nomoto 1982):

(i) the composition of the white dwarf, (ii) the accretion rate, (iii) the mass of the white dwarf, and (iv) the possible separation of elements during the cooling phase.

The first three aspects are expected to be the most important ones, but the fourth one might be important in very old white dwarfs. We will now consider each of these aspects in somewhat more detail.

(i) *Composition.* C–O white dwarfs (remnants of stars of 3 to 8–9 $M_\odot$ in binaries) will, when their masses increase, evolve to degenerate carbon ignition. This is expected to lead to a nuclear runaway in which part or all of the white dwarf is converted to Ni^{56}. The liberated energy of $\sim 10^{51}$ erg is sufficient to disrupt the entire white dwarf. Under some circumstances (carbon ignition in a shell) a small white dwarf remnant may be left (Taam 1980a,b; Nomoto 1982). Many authors believe that this complete or partial nuclear explosion of a C–O white dwarf is to be identified with a type I supernova (see Chevalier, this volume).

On the other hand, when O–Ne–Mg white dwarfs grow in mass, their core density may grow to the threshold for electron capture, leading to an electron-capture collapse and formation of a neutron star (see Section 2.5).

(ii), (iii) *Accretion rate and Mass.* The accretion rate is probably the most crucial parameter, as it determines whether or not the white dwarf will grow in mass. A full discussion of all the recent work on this subject and the uncertainties involved is given by Habets (1985). A brief—but rough—summary based mainly on the works by Nomoto (1982, 1984a,b) and Mueller & Arnett (1982, 1984) is as follows. At low accretion rates the accumulated hydrogen will, when its mass exceeds a critical limit, ignite and burn in a strong nuclear flash. For accretion rates $\geqslant 10^{-9}\ M_\odot\ \mathrm{yr}^{-1}$ these flashes are so strong that all (or possibly even more than all) of the accreted matter is expected to be ejected, such that no net growth of the white dwarf occurs.

(If one assumes the accreted matter to be helium, then for $M_{\mathrm{wd}} > 1.1\ M_\odot$ and low accretion rates, $< 8 \times 10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$, a thermonuclear explosion of the white dwarf can be triggered by pycno-nuclear reactions (Nomoto 1982). If the accreted matter is hydrogen, however, at this rate helium will have difficulty in building up, since (most of) the helium produced is ejected in the strong hydrogen flash; therefore deflagration may only occur here under very special circumstances).

Only for hydrogen accretion rates $> 10^{-9}$ to $10^{-8}\, M_\odot\, \mathrm{yr}^{-1}$ (depending on the white dwarf mass) the flashes are so weak that probably much of the accreted matter is retained, and a net growth in mass is possible. For $\dot{M} > 10^{-7}\, M_\odot\, \mathrm{yr}^{-1}$ the accreted hydrogen burns steadily in a shell surrounded by a red-giant like envelope. Clearly, the latter is only possible in a wide binary, as in a very close system there is not enough room for a red-giant envelope.

A carbon deflagration-explosion requires accretion rates $> 4 \times 10^{-8}\, M_\odot\, \mathrm{yr}^{-1}$, practically irrespective of stellar mass.

Let us now consider the consequences of the above results for the various types of low-mass binaries which we considered in Section 1.3.2. As mentioned in that section, in close systems ($P < 10$h) accretion rates are always $< 10^{-9}\, M_\odot\, \mathrm{yr}^{-1}$. Hence, here a net growth of the white dwarf is difficult to achieve (in view of the strength of the burning flashes). Consequently, unless the white dwarf started out with a mass very close to the critical limit for C-deflagration (or for *e*-capture collapse in the case of O–Ne–Mg white dwarfs) nothing will happen. (Only, if the white dwarf has $M > 1.1\, M_\odot$ and the accreted matter is helium, and the accretion rate is $< 8 \times 10^{-10}\, M_\odot\, \mathrm{yr}^{-1}$, C-deflagration of a C–O white dwarf might possibly occur, due to pycno-nuclear reactions, see above).

The only low-mass systems in which an accretion rate $\geqslant 10^{-9}$ to $10^{-8}\, M_\odot\, \mathrm{yr}^{-1}$ can be achieved, as required for making the white dwarf grow, are the wider ones ($P > 0.5$d) in which the mass transfer is driven by the interior nuclear evolution of the companion (see Section 1.3.2). Here the conditions for growth of the white dwarf by accretion are easily met. C-deflagration of a C–O white dwarf then required $\dot{M}_a > 4 \times 10^{-8}\, M_\odot\, \mathrm{yr}^{-1}$, which, according to Equation (2) requires an initial orbital period of about 60 days. For *e*-capture in an O–Ne–Mg white dwarf there is not such a strict limit, but in any case also here a wider ($P > 0.5$d) binary is required. Hence both C-deflagration and neutron star formation by *e*-capture collapse in an O–Ne–Mg white dwarf are preferrably expected to occur in relatively wide low-mass binaries (van den Heuvel & Taam 1984).

(iv) *Eutectic separation of oxygen and carbon in very old white dwarfs* ($> 5 \times 10^9$ *yr*). Following a suggestion of Stevenson (1980), Canal and collaborators (Canal, Isern & Labay 1980, 1982; Labay, Canal & Isern 1983; Bravo *et al.* 1983) have argued in a series of papers that during the cooling of a C–O white dwarf, the oxygen is separated from the carbon by a process of 'freezing-out', such that an old C–O white dwarf will consist of an oxygen core surrounded by a carbon mantle (see Mochkovitch 1983 for details). This situation, with oxygen in the centre, arises after $\sim 5 \times 10^9$ yr and is favourable for the occurrence of electron capture. This may even occur spontaneously, or be triggered by accretion.

An interesting aspect is that this provides a supernova-mechanism that will occur exclusively in an old stellar population, as the separation requires at least 5×10^9 yr (Mochkovitch 1983).

Another interesting aspect is, that in this way also the C–O white dwarfs, which are much more abundant in nature than O–Ne–Mg white dwarfs, may produce neutron stars. This, therefore, might considerably enlarge the reservoir of neutron-star progenitors in an old stellar population.

2.7 *Observational Evidence for Neutron-Star Formation by the Accretion-Induced Collapse of a White Dwarf: the Wide Radio Pulsar Binaries and the Bright Bulge Sources in M 31 and our Galaxy*

As mentioned in Section 1.3.3. the existence of the two wide radio pulsar binaries PSR 0820 + 02 and PSR 1953 + 29, and of the wide pulsating X-ray binary GX 1 + 4 provides very strong evidence for the formation of neutron stars by the accretion-induced collapse, since this is the only way in which the paradoxical characteristics of these systems can be explained. The fact that the conditions for the occurrence of accretion-induced collapse are most favourable just in wide systems(see Section 2.6) provides further supporting evidence.

A detailed analysis of the possible formation mechanisms for the about two dozen bright ($> 2 \times 10^{37}$ erg s^{-1}) X-ray sources within 400 pc from the centre of M 31 lead Vader *et al.* (1982) to conclude that the only conceivable way in which these systems might have been produced is: by accretion-induced collapse of a white dwarf in a low-mass binary. In combination with the fact that the high X-ray luminosities of these sources and of the $\sim$ 8 bright bulge sources ($L_X = 1$–3×10^{38} erg s^{-1}, McClintock & Rappaport 1984) in our Galaxy can only be explained by mass accretion from a low-mass giant companion (Section 1.3.2), this indicates that the neutron stars in all these systems were produced by the accretion-induced collapse of a white dwarf in a wide ($P > 0.5$ d) low-mass binary system.

Relatively wide binaries consisting of a low-mass giant and a white dwarf are well known, *e.g.* the symbiotic stars and recurrent novae such as T CrB ($P_{orb} = 227$ d). Further, double nuclei of planetary nebulae with relatively long orbital periods, and companion masses $> 1\ M_\odot$ are known (*e.g.* the nucleus of NGC 2346, which is an A5 star—$M \sim 1.8\ M_\odot$—with $P_{orb} = 15.995$ d, Ritter 1982). Such systems may later on evolve into wide low-mass X-ray binaries.

2.8 *The Final Evolution and Fate of Neutron Stars in Binary Systems*

For a recent review of this subject, in connection with the formation of the binary radio pulsars we refer to van den Heuvel (1984). The present ideas about this subject can be summarized as follows (see Table 6).

2.8.1 *Massive X-ray binaries*

Here, once the massive companion star begins to overflow its Roche-lobe, mass transfer on a thermal timescale will ensue ($\sim 10^{-3}\ M_\odot$ yr^{-1}) and the neutron star may be engulfed by the companion's envelope.

Various arguments (*cf.* van den Heuvel & De Loore 1973; Taam, Bodenheimer & Ostriker 1978; Bodenheimer & Taam 1984) indicate that the high mass transfer rate leads to a rapid spiral-in of the neutron star towards the core of its companion. Several possibilities should be distinguished here:

(i) If the core is dense, *i.e.* if the companion had already left the main sequence when the mass transfer started, one expects a very close ($P \sim$ few hours to a day) binary to result consisting of the neutron star plus the evolved core of the companion. The envelope is completely ejected.

Table 6. Fate of neutron star binaries (see text).

Type of neutron-star binary	Fate
Close massive X-ray binary ($P_{orb} < 4$–5d)	single neutron star (?) (after Thorne–Zytkow stage)
Wider massive X-ray binary ($P_{orb} > 5$d)	short-period binary consisting of: two neutron stars (eccentric orbit); or massive white dwarf and a neutron star (circular orbit); or, two runaway neutron stars.
wide low-mass X-ray binary ($P_{orb} > 0.5$d)	wide binary consisting of a neutron star and low-mass white dwarf (circular orbit).
close low-mass X-ray binary $P_{orb} < 0.5$d	close binary consisting of neutron star and a Jupiter-like object ($P \geqslant 2.5$d)
PSR 1913 + 16-system	single rapidly rotating neutron star or black hole
Neutron star plus massive white dwarf ($P < 10$h)	single rapidly rotating neutron star

If this core has a mass below the Chandrasekhar limit, this system will become a close binary consisting of a massive white dwarf and a neutron star in a circular orbit. Presumably PSR 0655 + 64 is an example. On the other hand, if the core is too massive to finish as a white dwarf, it will collapse in a second supernova event, resulting into two runaway pulsars or into a very close eccentric binary, consisting of two neutron stars. An example of the latter is PSR 1913 + 16. The above possibilities are expected to be the fate of the relatively wide massive X-ray binaries, such as the B-e X-ray binaries, Vela X-1 and 4U 1223 − 62.

(ii) Alternatively, if at the onset of the Roche-lobe overflow the companion does not yet have a dense core, *i.e.* if this star is still in the hydrogen-burning phase (which occurs for $P_{orb} < 4$–5d, see Section 1.3.1), the neutron star may spiral completely into the core of the companion.

In this case the result will either be complete dissipation of the companion star (*e.g.* if the orbital energy available is larger than the companion's binding energy) or a so-called Thorne–Zytkow (1977) star: a massive star with a neutron star in its centre. The calculations by Thorne and Zytkow show that on the outside such a star resembles a red supergiant with a radius of several astronomical units and a luminosity of $\sim 10^5 L_\odot$. Using typical wind mass-loss rates of such red supergiants ($\sim 10^{-6}$ to $10^{-5} M_\odot \mathrm{yr}^{-1}$, *cf.* Reimers 1978), this star will lose its envelope within $\sim 10^7$ yr, leaving a single neutron star. It is not clear whether this single neutron star will be a slow rotator. As the original angular momentum of the binary was deposited into the stellar envelope, the accretion of matter from this envelope onto the neutron star—a main energy source of the Thorne–Zytkow star—will presumably have kept this star in rapid rotation.

(iii) A third possibility is that the compact star is too massive to spiral into its (massive) companion's envelope. This will only be the case in black-hole binaries such as Cyg X-1. Here the large-scale mass transfer to the compact star may perhaps lead to a system resembling SS 433. Alternatively the latter system might also represent an early stage of the spiral-in of a neutron star into the envelope of a massive companion in a relatively wide binary (see van den Heuvel 1981b; Margon 1983, 1984).

2.8.2 *The fate of low-mass X-ray binaries; production of millisecond pulsars?*

In Sections 1.3.2 and 1.3.3 we already considered the fate of the wide low-mass X-ray binaries: these terminate as wide binaries with circular orbits, consisting of a neutron star and a low-mass white dwarf (see Fig. 5). The fate of the short-period (very close) systems in which the mass-transfer is driven by gravitational radiation losses and/or magnetic braking can be summarized as follows (Eggleton 1983; Savonije 1983a; van den Heuvel 1984). Gravitational-radiation losses first shorten the orbital period, but when the mass of the companion becomes $< 0.1\ M_\odot$ this star becomes degenerate (and/or fully convective) which means that its thermal equilibrium radius increases when its mass is further reduced. From the condition that this star always is filling its Roche lobe it follows that the further mass transfer causes the Roche lobe to expand, which causes the orbital period to increase (this can always be achieved by the mass transfer—due to instantaneous conservation of orbital angular momentum—since mass is being transferred from the less massive to the more massive component). Further losses of angular momentum by gravitational radiation therefore make the orbital period increase—which at the same time causes the angular momentum losses by gravitational radiation to slow down. Thus the system spirals out at a slower and slower pace while the mass of the companion decreases further and further. If gravitational radiation losses alone are operating, it takes an appreciable fraction of the Hubble time to reduce the mass of the companion to a few times the mass of Jupiter at which value the orbital period is several hours (1.2 h for a helium-rich star, see below).

An important question is whether during this spiral out the companion might be disrupted by tidal or other effects produced by the nearby neutron star. This problem is especially important as in this way a single millisecond pulsar may possibly be produced (as suggested by Alpar *et al.* 1982; Fabian *et al.* 1983; Ruderman & Shaham 1983, 1985).

A consensus among the various authors who studied this problem (Hut & Paczynski 1984; van den Heuvel 1984; Ruderman & Shaham 1985; Taam & Wade 1985; Bonsema & van den Heuvel 1985) is that disruption will never occur if the mass transfer is assumed to be conservative (*i.e.*, instantaneous conservation of system mass and orbital angular momentum when a mass element is transferred). Only if extra angular momentum losses during the mass transfer are assumed may the companion possibly be disrupted (most authors consider storage of transferred angular momentum in an accretion disc around the neutron star, from where it is—partly or totally—lost from the system). Hut & Paczynski (1984) find for a hydrogen-rich companion that even with loss of all the transferred angular momentum, this will not occur before the mass of the companion is $\simeq 0.002\ M_\odot$. For a helium companion, Ruderman & Shaham (1985) and Bonsema & van den Heuvel find a limit of 0.004 and $\sim 0.005\ M_\odot$, respectively (but within uncertainties of the assumed mass-radius relations of low-mass objects these limits are consistent with one another). Taam & Wade (1985) give the most extensive discussion of this problem. All authors find that only with very extreme assumptions (such as loss of all of the transferred orbital angular momentum) can the companion be disrupted, but only at the low companion masses mentioned above. For helium star companions it takes $> 5 \times 10^9$ yr to reach this stage. For hydrogen-rich stars, it takes more than a Hubble time to reach these low masses. Taam and Wade, Hut and Paczynski, and Bonsema and van den Heuvel conclude that it is highly unlikely that the companions will *ever* be disrupted. The systems therefore most probably end as neutron stars with a companion a few times more massive than Jupiter and an orbital period of a few hours.

In so far as one can presently judge, it seems that the two most promising remaining ways for producing a single millisecond pulsar are: either the coalescence of a double neutron-star binary like PSR 1913 + 16 (Henrichs & van den Heuvel 1983), or the coalescence of a close binary consisting of a neutron star and a massive white dwarf (such as PSR 0655 + 64, though with a somewhat shorter orbital period; van den Heuvel & Bonsema 1984).

2.9 *Some Statistical Considerations*

2.9.1. *Massive neutron-star binaries*

Above an initial primary mass of $\sim 10\ M_\odot$ (somewhat higher in some case B systems; somewhat lower in case C) practically all primary stars of close binaries terminate as neutron stars (see Section 2.5).

A detailed discussion of the statistical properties of mass ratios orbital periods, binary frequencies, *etc.* of early-type binaries is beyond the scope of this paper. For this we refer to Kraicheva *et al.* (1979), Meurs & van den Heuvel (1985) (see also van den Heuvel 1978, 1981).

From these investigations and from the high (> 50 per cent) incidence of close binaries among massive stars one expects at least some 75 per cent of all neutron stars that are produced by massive stars, to be born in (relatively close) binaries. The orbital velocities in such binaries are typically of order $\sim 10^2\ \mathrm{km\,s^{-1}}$, which is of the same order as the observed runaway velocities of most radio pulsars (Lyne 1981). The high velocities of most radio pulsars may, therefore, well be due to the disruption of the binary systems in which these pulsars were born (see van den Heuvel 1981, 1983). Since some 50 strong permanent ('standard') X-ray binaries are present in the Galaxy, and these live for $\sim 5 \times 10^4$ yr (on average) the galactic formation rate of such systems is $\sim 10^{-3}\ \mathrm{yr^{-1}}$. This implies that the strong permanent sources make only a relatively small contribution to the pulsar formation rate. On the other hand, the B-emission systems are much more abundant and may well have a formation rate of $\sim 10^{-2}\ \mathrm{yr^{-1}}$ in the Galaxy (Meurs & van den Heuvel 1985). They make a considerable contribution to the pulsar formation rate.

2.9.2 *Neutron Stars in Wide Low-Mass Binaries*

A sizeable fraction—at least between one and two dozen—of the about 10^2 strong galactic X-ray sources are in wide low-mass binaries (*e.g.*: the bright bulge sources, presumably some of the globular cluster sources, GX 1 + 4, Sco X-1, Cyg X-2, 2S 0921 − 63).

The lifetime (mass-transfer time) in these systems is typically of order $\sim 10^7$ yr, (see Fig. 5, and Webbink, Rappaport & Savonije 1983) which would imply a formation rate of these systems of at least $2 \times 10^{-6}\ \mathrm{yr^{-1}}$ in the galaxy.

The real formation rate of neutron stars in wide low-mass binaries is, however, probably considerably higher, since already 2 out of the ~ 400 known radio pulsars are in wide low-mass binaries that are remnants of such systems.

As the pulsar formation rate in the galaxy is ~ 0.01 to $0.05\ \mathrm{yr^{-1}}$ (Lyne, Manchester & Taylor 1985) this would imply a formation rate of pulsars in low-mass binaries of 0.5 to

$2.5 \times 10^{-4}\,\mathrm{yr}^{-1}$ in the galaxy which is some 10^2 times higher than the above estimated formation rate of the wide low-mass X-ray binaries.

Apparently, only a small fraction of the neutron stars born in wide low-mass binaries show up as X-ray sources. The most plausible explanation for this seems that the mass transfer rate in these systems can easily become larger than the Eddington limit (see Equation 2), such that the X-rays in such a system become smothered by the excess transferred matter—and therefore cannot be observed by us. Only if the systems start out with an orbital period < 16 d (for Population I composition) will $\dot{M}$ be below the Eddington limit, and will a bright X-ray source be observable.

It may well be that the wide low-mass systems with continuous super-Eddington mass transfer produce shells similar to W 50 (which surrounds SS 433), as the continuous super-Eddington mass transfer in these systems can go on for millions of years without the danger that the system may become unstable (de Kool, van den Heuvel & Shaver 1985).

Possibly the apparent 'SN-remnants' with axial symmetry G 357.7 − 0.1 and G 5.3 − 1.0, located in the galactic bulge (Becker & Helfand 1985; Shaver *et al.* 1985) were produced by just such systems. (Helfand & Becker 1985, pointed out that the shells may have been produced by accreting neutron stars in binaries; the wide low-mass systems seem the best candidates for this).

2.9.3 *Close low-mass x-ray binaries*

There may be some 50 such systems in the Galaxy. At their mass transfer rates of $< 10^{-9}\,M_\odot\,\mathrm{yr}^{-1}$ and companion masses of $\sim 0.5\,M_\odot$, these systems have typical X-ray lifetimes of $\geqslant 10^8$ yr. This implies a formation rate of $\leqslant 5 \times 10^{-7}\,\mathrm{yr}^{-1}$, the lowest of all known types of X-ray binaries. Hence their formation process must be a very rare one. This agrees well with the expectation that accretion-induced collapse is much more difficult to achieve in a close system than in a wide system (see Section 2.6). An alternative formation is—except in the case of the globular cluster sources—hard to imagine for these systems (*cf.* van den Heuvel 1977; Helfand *et al.* 1983).

Table 7 summarizes the rough formation rates of the various types of systems as mentioned above.

Table 7. Estimated galactic formation rates of various types of neutron star binaries, together with the suggested formation mechanisms (see text).

Type of neutron-star binary	Galactic formation rate	Formation mechanism
'Standard' massive X-ray binary	$10^{-3}\,\mathrm{yr}^{-1}$	Direct core collapse
B-emission X-ray binary	$10^{-2}\,\mathrm{yr}^{-1}$	*idem*
Wide low-mass neutron-star binary	$0.5\text{–}2.5 \times 10^{-4}\,\mathrm{yr}^{-1}$	Accretion-induced collapse of white dwarf
Close ($P < 10$h) low-mass X-ray binary	$5 \times 10^{-7}\,\mathrm{yr}^{-1}$	*idem*

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On the Meaning of Pulsar Velocities

V. Radhakrishnan & C. S. Shukre *Raman Research Institute, Bangalore 560080*

Abstract. From the observed pulsar proper-motions we conclude that most pulsars were born in and released from binary systems. A minority of pulsars belong to a class characterized by low velocities, low magnetic fields and characteristic ages in excess of 10^7 yr. These were significantly spun-up during accretion from their companions. The rest belong to the high velocity, high magnetic field class. Using a remarkable relationship between the speed at present and that in the binary orbit prior to the release of the pulsar, we deduce that such binaries must have undergone a common envelope phase of stellar evolution. Limits on masses and separations of these binary systems are derived using the proper-motion observations.

Key words: Pulsars, velocities—pulsars, magnetic fields—pulsars, progenitors—stars, binary evolution.

1. Introduction

In the literature on pulsars, much attention has been paid to their angular velocities, which provide the most stable part of their signatures. It is an interesting fact that a large number, perhaps, the majority, of theoretical studies of pulsars are based on only the angular velocities and their first derivatives, ignoring all other details of the individual pulse characteristics. In contrast, the linear velocities of pulsars have received less attention, perhaps because they are not among the characteristics which can be immediately determined. Several years of observations are necessary to measure the velocities for single pulsars, and for them it is only the proper-motions which are observed. On the other hand, it is only the *orbital* velocities which can be determined when the pulsars occur in binary systems. Thus one does not know pulsar velocities completely. Even so we wish to point out here that the linear velocities of pulsars are like signatures of their progenitors, and that much can be learnt from them. Also that the best data available at present show that pulsars were born in binary systems, and enables one to derive constraints on such binary systems indicating that they must have undergone a common envelope phase of stellar evolution. The close binary systems which we believe lead to the observed velocities are described at the end.

I

Due to the special location of the Crab pulsar, its proper motion was estimated soon after its discovery. The transverse velocity inferred by optical means was $\sim 100\ \mathrm{km\,s^{-1}}$ (Trimble 1968). On the basis of this value, as well as the derived heights of pulsars from the galactic plane, Gunn & Ostriker (1970) concluded that all pulsars must have high velocities $\sim 100\ \mathrm{km\,s^{-1}}$. They also suggested that these may be the runaway velocities from binary systems which were disrupted by the *first* supernova explosions in them. The proposal was similar to that advanced for runaway OB stars by Zwicky (1957) and Blauuw (1961).

Subsequent determinations of pulsar proper motions came from radio observations. Drifts of the pulsars scintillation patterns and analysis of pulse arrival times over several years (see references in Lyne, Anderson & Salter 1982) confirmed that pulsars indeed had proper motions of 100–200 $\mathrm{km\,s^{-1}}$. The best measurements available today are, however, due to radio interferometric observations and give a range of 10 to 370 $\mathrm{km\,s^{-1}}$ (Lyne, Anderson & Salter 1982).

On the theoretical front two other mechanisms have been proposed to explain the pulsar velocities. They are, the asymmetric supernova explosion (Shklovskiĭ 1970) and 'rocket' mechanisms (Le Blanc & Wilson 1970; Harrison & Tademaru 1975).

Asymmetric supernova explosions invoke a non-spherically-symmetric ejection of the supernova shell, which to conserve momentum must give a 'kick' to the new-born pulsar; but no detailed physical model has yet been proposed. In the 'rocket' mechanism of Harrison & Tademaru (1975), the oblique pulsar magnetic dipole is displaced from the centre of the neutron star and is skew to the rotation axis. The consequent asymmetry in the multipole radiation, propels the pulsar along its rotation axis soon after it is born.

II

Observationally, the 'rocket' mechanism can be tested by checking if the directions of motion and of the rotation axis do indeed coincide. The intrinsic linear polarization at the centre of the pulse is the projection of the rotation axis (and also of the rotating magnetic dipole axis at that instant) on the plane of the sky, according to the polar cap model of pulsar radio emission (Radhakrishnan 1969). The proper motion is also a projection of the space velocity on the plane of the sky. If two vectors coincide so must their projections. This test comparing proper motion directions to position angles of the polarization vectors at the centre of the pulses, was suggested and carried out by Morris, Radhakrishnan & Shukre (1976). These authors argued that the observations did not favour the 'rocket' mechanism, but the issue however remained clouded by two factors (Tademaru 1977). The pulse polarization in many pulsars jumped by 90° within the pulse, thus making the polarization direction uncertain. Secondly, the proper motion data itself was meagre and not of very high quality. Subsequently, Backer and coworkers demonstrated on the basis of refined polarization measurements that when allowance is made for polarization flips, all the observations fully support the polar cap model (Backer 1982). Using the excellent proper motion observations of Lyne, Anderson & Salter (1982), this test was repeated by Anderson & Lyne (1983). They have reinforced the conclusion of Morris, Radhakrishnan & Shukre (1976) that the 'rocket' mechanism is not operative in accelerating pulsars.

III

Ironically enough, while Anderson & Lyne failed to find any evidence for the directions of velocities to be as predicted by the 'rocket' mechanism which in essence invokes magnetic *multipole* moments for the purpose, they found the magnitudes of the velocities to be correlated with the derived magnetic *dipole* moments (Fig. 1). Though

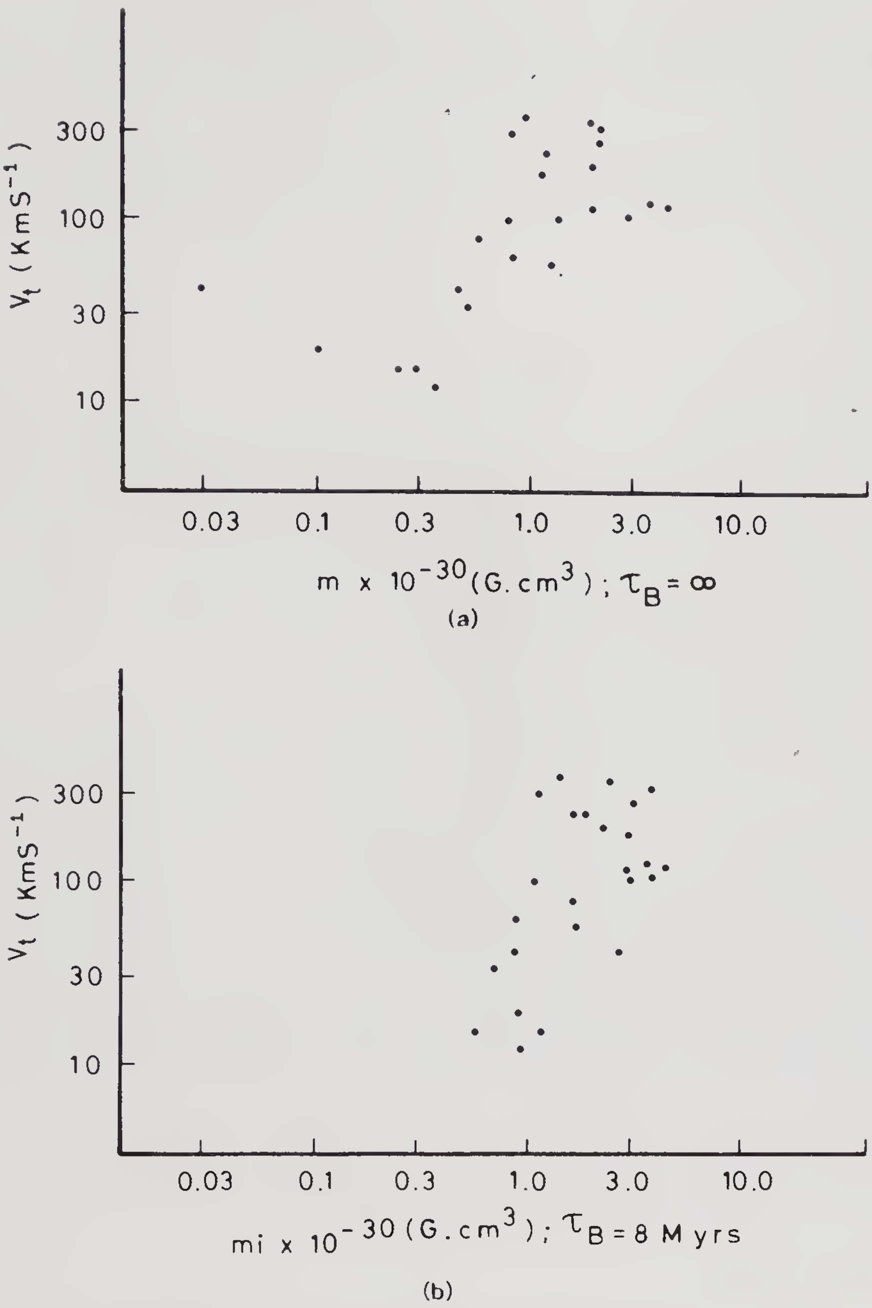

Figure 1. Transverse velocities of 25 pulsars plotted against initial magnetic dipole moments, (a) assuming no magnetic field decay, and (b) assuming exponential decay with characteristic time of 8 Myr. (From Anderson & Lyne 1983.)

they did not come to any firm conclusions on the origin of pulsar velocities, these authors suggested that the velocities are probably due to asymmetric supernova explosions, and that the asymmetry could be influenced by the magnetic dipole moment.

The possibility that the velocities could result from an asymmetric explosion governed by the magnetic field is most unlikely because the kinetic energy of a pulsar moving with 250 $km\,s^{-1}$ velocity is $\sim 10^{48}$ erg while its magnetic energy content is $\sim 10^{43}$ erg. Thus the energy stored in the dipole fields is many orders of magnitude lower than the kinetic energy of the pulsar. (This point was noted in passing by

Anderson & Lyne). Another good reason for doubting asymmetric explosions as a mechanism to produce pulsar velocities in general is the fine tuning required. The amount of energy in a supernova explosion ($\sim 10^{51}$ erg) is about two orders of magnitude higher than the kinetic energy of the pulsar. Thus, while it is true that a minute asymmetry *could* provide the energy, it would be extraordinary if the spread in asymmetry were so small as to produce the relatively narrow distribution of velocities observed.

IV

Nevertheless, the correlation found by Anderson & Lyne is there and a satisfactory explanation is required for it. Such an explanation was provided on the basis that the sample of pulsars is a mixture of two classes, one with 'high' velocities and the other with 'low' velocities (Radhakrishnan 1984; Radhakrishnan & Shukre 1985). It should be mentioned that Lyne, Anderson & Salter (1982) clearly noted that the distribution of velocities did not seem to be Maxwellian, there being excesses of both high and low values. Fig. 2 shows a plot of velocity *vs.* characteristic age which is very suggestive of a division into two groups. Those with low fields and $P/2\dot{P} \geqslant 10^7$ yr have low velocities and the high field ones have high velocities.

It was proposed by Radhakrishnan & Srinivasan (1981) and later independently by Backus, Taylor & Damashek (1982) that there must exist a class of 'recycled' pulsars which were spun-up in binary systems through accretion, and later released as single pulsars on the disruption of the binary by the second explosion. Such pulsars would have a low field due to its decay during the evolution time of the companion star, but the neutron star would still be observable as a radio pulsar due to its anomalously high spin (for the field). A necessary but not sufficient condition, which is an excellent diagnostic for such recycled pulsars, is that they must have characteristic ages $(P/2\dot{P}) \geqslant 10^7$ yr. The reason for this can be seen from Fig. 3 which is a Log B–Log P plot showing the field-period equilibrium condition or 'spin-up' line (taken from Srinivasan & van den

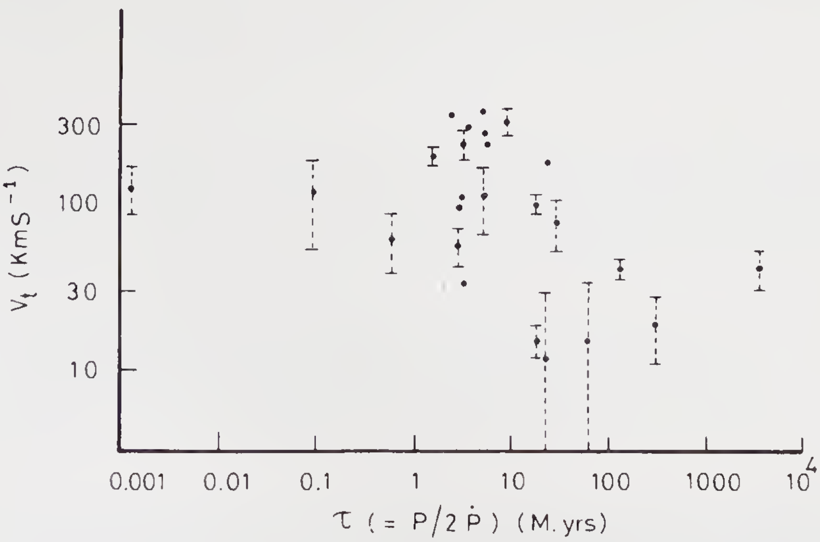

Figure 2. Transverse velocities from Lyne, Anderson & Salter (1982) plotted against characteristic age $P/2\dot{P}$—. Small error bars for some of the pulsars have been omitted from the figure for clarity. (From Radhakrishnan 1984.)

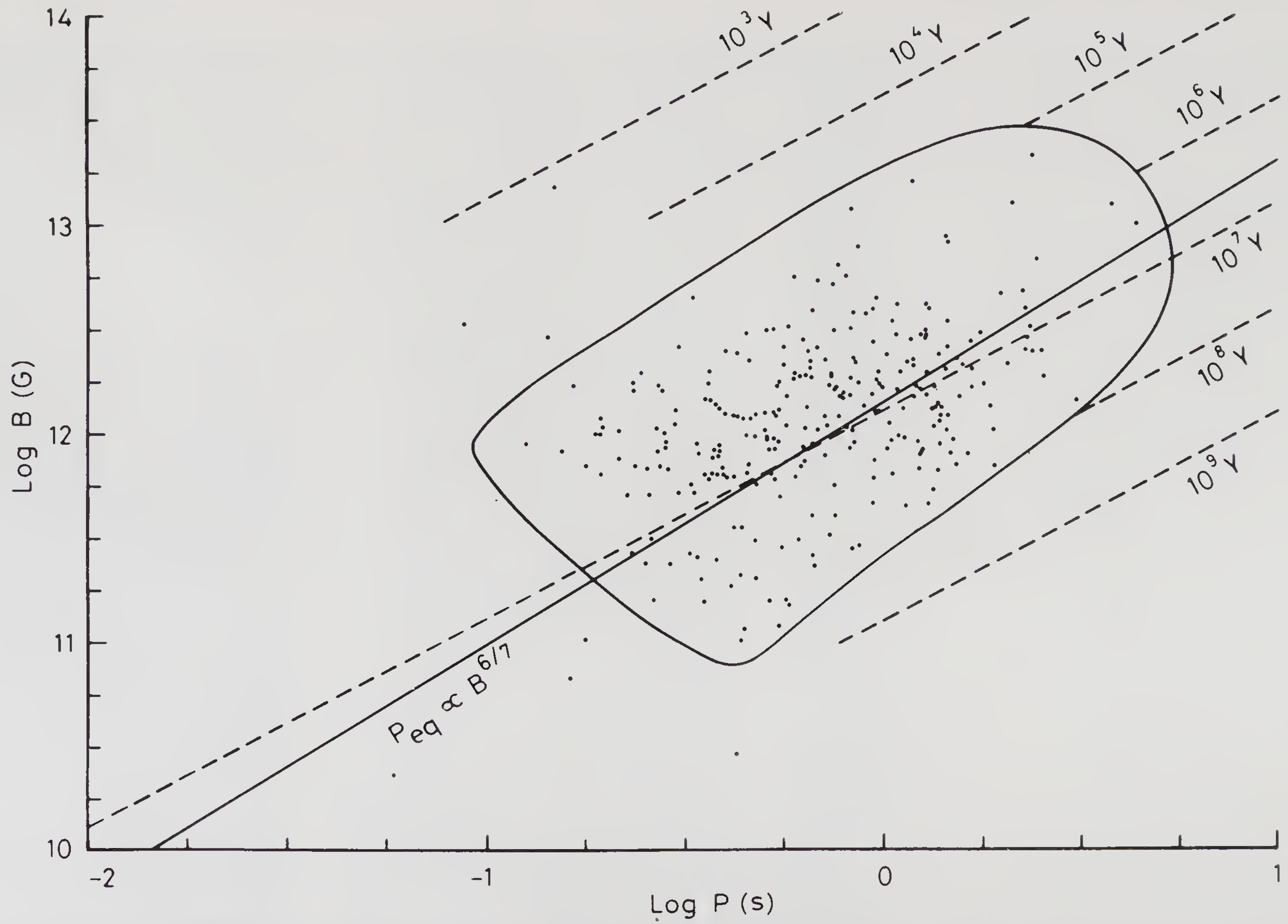

Figure 3. Plot of derived magnetic field *vs.* period for pulsars. Solid line is the field-period equilibrium condition for spin-up given by Srinivasan & van den Heuvel (1982). Broken lines are the characteristic age $P/2\dot{P}$ = constant lines. (Figure adapted from Radhakrishnan, 1982).

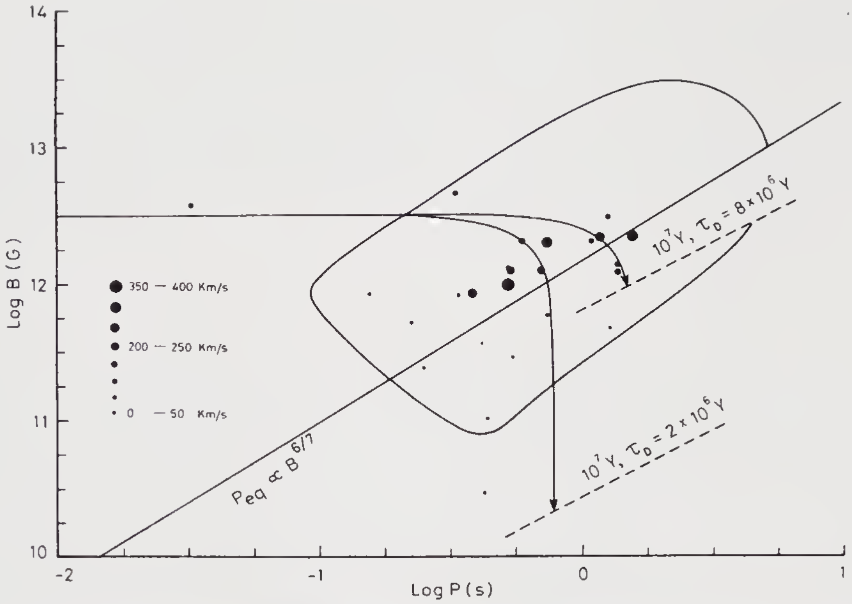

Figure 4. Plot of derived magnetic field *vs.* period for the 25 pulsars. Size of the dot reflects the magnitude of the transverse velocity of the pulsar. The straight solid line is the field-period equilibrium line. Broken lines depict age = 10^7 yr for the two indicated values of the magnetic decay timescale τ_d. Solid lines with arrows depict evolutionary tracks of a pulsar for the same two values of τ_d.

Heuvel 1982) for accretion in binaries. This line has almost the same slope as the characteristic age lines in this plot, and its position practically coincides with the age line for 10^7 yr. Therefore this provides us with the diagnostic referred to above. It is important to note that this condition is *independent* of the decay time scale for the magnetic fields.

The 26 pulsars chosen for the proper motion measurements by Lyne, Anderson & Salter (1982) were selected on the basis of positional nearness on the sky to extragalactic point sources, and not on the basis of any pulsar characteristic. For this reason, they must constitute a representative sample. It would appear therefore, that all single pulsars observed fall into two classes; a low-velocity minority, the recycled ones referred to above, and the majority with high velocities (~ 250 km s^{-1}) and high fields (as can be seen in Fig. 4).

V

It was predicted by Radhakrishnan & Srinivasan (1981) that low-field recycled pulsars will have high velocities because they were the less massive of the two stars in the pre-explosion binary system. By the same token, the fresh high-field pulsars should have low velocities. We have just seen, however, that the observations indicate the opposite. Thus, if we identify the low velocity pulsars as recycled ones, it still remains to explain the low magnitudes of their velocities. Note, however, that these velocities are too high to be attributed to random motions of single stars, and cannot be explained by assuming that pulsar progenitors are single stars. As will be seen later, such low speeds *per se* are also difficult to achieve in close binary systems in which accretion has played a role. We shall return to this point later on, and discuss now only the high-velocity class.

As noted earlier, there is no other satisfactory explanation to date for the high velocities observed, and we are left again with the only alternative that all pulsars had an origin in binary systems. At the IAU symposium on pulsars, van den Heuvel (1981) had concluded on similar considerations that the majority of pulsars were likely to come from binaries. Another indication in this direction is as follows. The majority of evolving stars today occur in binary or multiple systems (Abt & Levy 1976, 1978). The difficulty of getting rid of the angular momentum in gas clouds which are collapsing to form stars appears to strongly favour the formation of binary or multiple systems (Bodenheimer 1981). Many O and B stars which could be expected to explode later as supernovae and leave behind a pulsar are in 'runaway' binaries which acquired their velocities on the explosion of their companions (Stone 1979). Indeed, according to this author, there is little or no evidence that single stars of this category exist.

We shall therefore proceed on the assumption that all high-velocity pulsars acquire their velocities due to their release from binary systems which are disrupted by symmetric supernova explosions.

VI

Now, if pulsar velocities observed today are indeed a consequence of their having been in binary systems, what were the characteristics of those binary systems?

For this purpose let us take the pulsar velocity as it is observed today and trace backwards to the binary orbit which gave rise to it. We assume that all the supernova explosion did was to reduce the mass of the exploding star on a timescale very short compared to the orbital period, without affecting the positions and velocities of the component stars of the binary. We shall be interested in the case when the resulting orbit is unbound, *i.e.*, the amount of mass ejected by the supernova is more than half of the initial total mass of the binary. The speeds are very soon expected to approach their asymptotic values which correspond to a separation between the components large enough to allow neglect of the gravitational attraction between them. Later passage through the interstellar medium is hardly expected to affect the velocities. We thus need a relation between velocities just after (or what is the same thing, just before) the explosion and the asymptotic velocities.

Towards this aim, we must digress to mention a remarkable property of binaries which are disrupted by symmetric explosions. To an observer situated in the same frame of reference as the centre of mass of a binary system with circular orbits, a sudden expulsion of mass from one of the stars in a symmetric way leaves the speed of the remnant of this star *unchanged for all time*. Remarkably, this is true irrespective of the amount of mass lost, *i.e.*, whether as a consequence the system remains bound, or is disrupted. The reason for this surprising property can be understood in terms of a hodograph, which is a representation of the motion of a particle in velocity space just as the orbit is such a representation in coordinate space.

It is well known that the hodograph *i.e.*, the path in velocity space, is a circle in the Keplerian case, even though both the speed and direction are changing continuously as in an elliptic orbit (Goldstein 1980). Except for circular orbits, the centre of the hodograph is not at the origin. For a parabolic orbit, the hodograph is still a full circle but it passes through the origin. For a hyperbolic orbit, it shrinks to an arc bigger than a semicircle whose centre is displaced from the origin by more than its radius. If the observer is in a frame of reference whose origin is at the centre of the hodograph, clearly he will see a constant speed. The surprising thing is that when one of the stars in a binary system suddenly loses mass, the centre of mass of the remaining two-body system, whether bound or not, moves in exactly such a way in the original centre of mass frame, that the origin in velocity space continues to remain at the centre of *this* star's hodograph. The radius of the hodograph also remains unchanged. The derivation of this unexpected result is given in the Appendix.

Returning to our main objective, the implication of this extraordinary property is that the progenitor of a pulsar had precisely the *same* speed in orbit (assumed to be circular) just before the explosion, as the pulsar has today far away in space and time from this event. Let us ignore for the moment the possibility of orbits being elliptical. We can then conclude that the observed distribution of space velocities for the pulsars whose births disrupted the binaries was *exactly* the distribution of the orbital speed of their progenitors. Note that this is not true for the other object in the binary system whose mass did not undergo any sudden change. In all of the above, we have neglected the motion of the binary system as a whole before the explosion, which is a relatively minor perturbation.

Below are the formulae for the observed speeds of the pulsar and its companion in terms of the progenitor speed in the circular orbit.

$$V_{\mathrm{psr}} = V_{\mathrm{prog}} \tag{1}$$

$$V_{\mathrm{comp}} = \left[1 + (2\alpha - 1)\left(\frac{M_1 + M_2}{M_2}\right)^2\right]^{1/2} V_{\mathrm{prog}} \tag{2}$$

and

$$V_{\mathrm{prog}} = \frac{438\, M_2}{[(M_1 + M_2)a]^{1/2}}\ \mathrm{km\,s^{-1}} \tag{3}$$

with

$$\alpha \geqslant 1/2, \tag{4}$$

where M_1 is the mass of the pre-supernova object and M_2 that of the companion, in solar masses. The separation a between M_1 and M_2 is in solar radii. The fraction of the original total mass lost in the explosion is α. Equation (4) just expresses the fact that the resulting orbit is unbound. It may be noted in passing that Equation (1) in other forms has been derived before (see *e.g.*, Gott, Gunn & Ostriker 1970), but its message seems to have escaped attention so far.

VII

As noted earlier, observations provide us only with transverse velocities. To estimate the space velocities we have multiplied the data of Lyne, Anderson & Salter (1982) by $(3/2)^{1/2}$ to allow for the radial components in a statistical sense. The range of space velocities for the high-velocity pulsars thus obtained is 100–450 km s^{-1} with a mean of 270 km s^{-1}.

We can now use this to learn something about the binary systems from which these pulsars originated. The explosion which releases a pulsar as a single object can either be the first or the second explosion in the binary system. There are many systems (*i.e.*, X-ray binaries) containing a neutron star which must have clearly survived the first explosion, and at least one case (*i.e.*, PSR 1913 + 16) which survived two (we are ignoring possible neutron star formation by accretion on to white dwarfs). Still, let us consider release of the pulsar in the first explosion. Since more than one-half of the total mass has to be lost in the explosion to disrupt the binary, and assuming the mass of a neutron star to be 1.4 $M_\odot$, we have

$$M_1 \geqslant 2.8 + M_2. \tag{5}$$

This leads to

$$a \leqslant \left(\frac{438}{V_{\text{psr}}\ \text{km s}^{-1}}\right)^2 \frac{M_2^2}{2.8+2M_2} R_\odot . \tag{6}$$

It is clear that the separation required to give the observed velocities is very small (*e.g.*, consider a typical $M_2 = 5$; then $a \leqslant 5R_\odot$ for $V_{\text{psr}} = 270$ km s^{-1}. We also know that it is only in the case of very wide binaries that the individual stars can evolve just as if they were single. In such wide binaries the velocities would be clearly too low. On the other hand, if the stars were as close as required by the high velocities then mass transfer is inevitable, and the primary will become the less massive of the two before it reaches the supernova stage (Paczynski 1971; van den Heuvel 1976). The ensuing explosion cannot then unbind the system, and we will have a binary system containing one neutron star which can later become an X-ray source and/or a recycled pulsar.

Thus we must now consider the release of pulsars due to the second explosion in a binary. In this case we have the additional constraint that the mass of the companion is now $\sim 1.4\ M_\odot$. We can go to Fig. 5 which depicts, for $M_2 = 1.4$, the dependence of the separation of the stars on the total mass as given by Equation 3. Considering that speeds in the range 100–450 km s^{-1} are to be accounted for, we see that the separations have to be very small, and the dense cores of the collapsing stars have to be very compact indeed. This implies that the evolution of the binary system between the first and second SN explosions *must* go through a common envelope phase. The consequent tidal

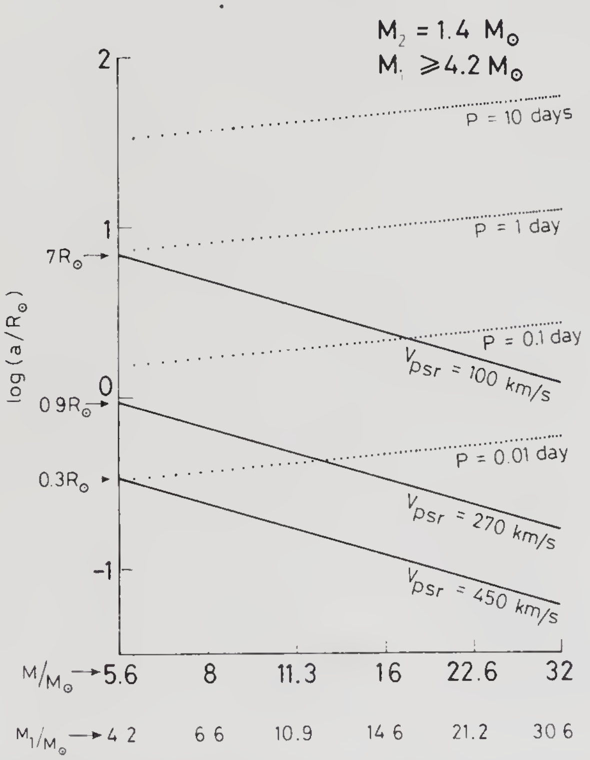

Figure 5. Plot of separation in solar radii ($a/R_\odot$) between the stars *vs.* the total mass in solar masses ($M/M_\odot$) of the binary system, for different values of V_{psr}, as derived from Equation 1. The companion neutron star mass M_2 is assumed to be 1.4 $M_\odot$. Numbers with arrows along the Y-axis indicate maximum separations appropriate for the observed range of velocities; they correspond to the minimum value of $M = 5.6\ M_\odot$ required to disrupt the binary. Dotted lines are of constant binary orbital period and are labelled by P_d, the period in days.

interactions would inescapably lead to circularization of the orbits, incidentally justifying fully our earlier assumption of circular orbits prior to the explosion.

It is interesting that our conclusion that a common envelope phase is inevitable, drawn here purely on the basis of pulsar proper motions, accords well with the conclusions of numerous studies undertaken from the point of view of stellar evolution in binaries (Tutukov 1981; van den Heuvel 1981). However, it still remains to explain the magnitudes of the observed pulsar velocities for both classes.

VIII

Binaries disrupted by the second explosion will produce two pulsars. The young one will have a lower velocity and a high magnetic field and the old recycled one a higher velocity and low magnetic field. As noted earlier, this is exactly the opposite of what is observed and is an indication that the velocities of our two classes of pulsars require different scenarios to explain them. Indeed, the low velocities are too low to follow from Equation (3) for masses appropriate for massive close binary systems.

The above contradiction is a result of our identification of low-velocity low-field pulsars as recycled ones. As one possible attempt at a unified explanation for the two classes, let us consider the possibility that the magnetic fields are low at birth and build up later with age, as has been suggested by Blandford *et al.* (1983). In such a case, it will be natural for low velocity pulsars to have low magnetic fields, since they are the young ones. The large spin-down ages ($\geqslant 10^7$ yr) for these are then just a reflection of their low fields. Now, if we take typical observed low and high velocities to be 50 and 250 $\mathrm{km\,s^{-1}}$, this is a ratio of 1:5. Through the relationships between asymptotic velocities and pre-explosion velocities (Equations 1 and 2), we can then immediately infer that the progenitor of the young pulsar is required to have a mass of $\geqslant 9\ M_{\odot}$. Such a massive pre-supernova *core* is considered unrealistic (see van den Heuvel in this volume).

We thus see that the observed pulsar velocities cannot be simply explained using the magnetic field build-up theory. Incidentally this theory also runs into difficulty when confronted with the data on the Crab pulsar. In such a theory it is easily shown that the characteristic age must always be greater than half the exponential field growth timescale. Blandford *et al.* (1983) invoke a growth time of 10^5 yr which is clearly incompatible with a characteristic age of 1000 years. If this timescale is arbitrarily assumed to be as short as 2000 years, the period of the Crab pulsar should then have changed by less than 3 ms since 1054 AD. This would raise anew the problem of the energy source of the Crab nebula, which was put to rest on the basis that the initial pulsar period was $\sim$ 16 ms. Neither can we consider the Crab Pulsar to have been the first born one in a binary so that its field could have been built up to the present value during the several million years before the second explosion. The reason is again its present observed characteristic age. If there was no accretion during the binary phase, then as mentioned just above its characteristic age must be greater than half of the field growth timescale, *i.e.*, $\sim 10^5$ yr; on the other hand, if accretion did spin it up, then as mentioned earlier in the context of recycling, its characteristic age must be $\geqslant 10^7$ yr. (We thank D. Bhattacharya for pointing out some of the above.)

IX

Consequently, we conclude that the types of evolution which lead to the low and high velocity pulsars in Fig. 3 are different. In particular, the binaries which give birth to pulsars do not produce a pair such that one of them belongs to the low velocity class and the other to the high velocity one. Nor as was noted earlier, can the low velocities be explained by assuming that pulsars originate from single stars. Therefore the magnitudes of the low velocities must be related to some special property of the binary systems which produce them.

It was proposed by Radhakrishnan (1984) that the low velocity pulsars could be explained if there occur enough binary systems consisting of a neutron star and a companion which eventually disappears in a non-explosive manner. The single neutron star left behind will then have all the characteristics of a 'low-velocity' pulsar. The spiralling-in of the neutron star (Paczynski 1976; Taam, Bodenheimer & Ostriker 1978) during the common envelope phase could result in such an outcome for certain initial conditions.

Returning to the high velocity class, the more likely result of the spiral-in is, however, an even closer binary than the initial one. Typically, the resultant binary will have a neutron star (1.4 $M_\odot$) and a He (or more evolved) star (5 $M_\odot$) in an orbit of period $\sim$ 1.5 h, corresponding to a separation of $\sim 1.2\,R_\odot$ (these numbers are based on discussions with E. P. J. van den Heuvel during and after the workshop, on the outcomes of the common-envelope evolution).

On disruption, the young pulsar will obviously have a high magnetic field. The old pulsar will also have a high magnetic field if the field decay timescale is of the order of (or longer than) the time interval between the two SN explosions. After the first SN, the He star takes $\sim 3.7 \times 10^6$ yr to overflow its Roche lobe, the spiral-in takes $\sim 10^3$ to 10^4 yr and the post spiral-in timescale for the evolved core to become an SN is at most 6×10^5 yr (for these numbers, see van den Heuvel, 1977 and these proceedings). The interval between the two SN explosions is thus $\leqslant 4 \times 10^6$ yr during which the magnetic field will hardly have decayed for generally believed values of the decay timescale.

This outcome of the spiral-in thus leads to *two* high-velocity high-field pulsars after the second SN explosion. Our high-velocity class of pulsars is then a mixture of two subclasses. If one could distinguish between them, an inverse correlation between velocities and magnetic field is predicted in this picture. As the spread in initial magnetic fields of pulsars is most probably greater than *e*, this prediction may be difficult to test. It should be pointed out here that half of these pulsars should also be 'recycled' ones. Note however that in this case accretion will not spin-up these high-field pulsars as much as it will low-field ones (see the equilibrium line in Fig. 2).

X

While concluding that binaries which produce pulsars must undergo a common envelope phase in Fig. 5, we had identified the velocities of high-field pulsars with the V_{psr} of Equation 1. This conclusion must be re-examined if the high-field pulsar sample is indeed a mixture. The data on high-field pulsars would contain both V_{psr} and V_{comp} of Equations 1 and 2, and it may not be possible to unscramble them. Due to selection effects, one or the other subclass may dominate the data. But, irrespective of the ratio, some conclusions can be drawn if both types are represented in the observed sample of high-velocity pulsars.

Fig. 6 shows both V_{psr} = const. and V_{comp} = const. lines. Any point in this plane specifies a binary system of a particular total mass and a particular separation prior to the second SN explosion. Alternatively, the system is uniquely specified also by giving

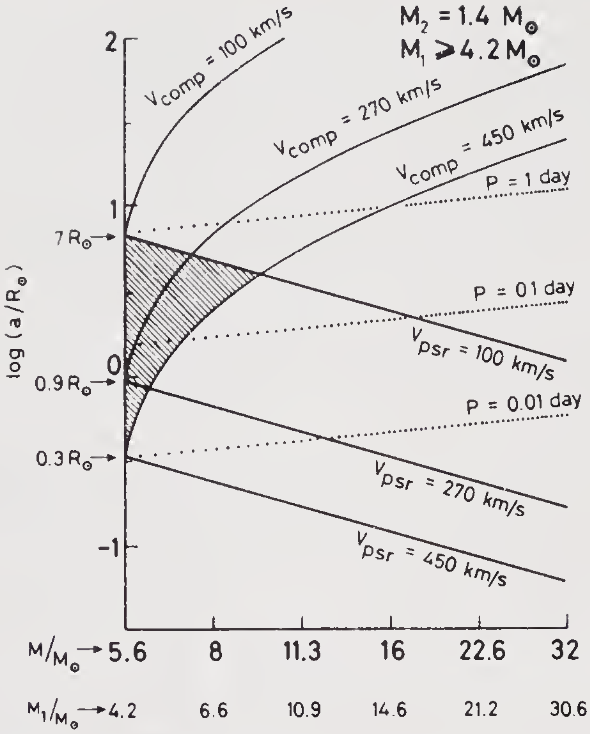

Figure 6. Same as Fig. 5 but including plots of separation $a/R_\odot$ *vs.* the total mass $M/M_\odot$ for different values of V_{comp} as derived from Equation 2. Shaded region indicates the values of a and M allowed by the proper-motion data as explained in the text.

V_{psr} and V_{comp}. The observational requirement that $100\ \mathrm{km\,s^{-1}} \leqslant V_{psr}, V_{comp} \leqslant 450\ \mathrm{km\,s^{-1}}$ restricts the relevant binary systems to the intersection of the two bands. These bands are bounded by $V_{psr} = 100, 450$ and $V_{comp} = 100, 450\ \mathrm{km\,s^{-1}}$ lines. In Fig. 5 we had considered only the V_{psr} band. We see now that the binaries in question must lie in the triangular overlap between these two bands. If smaller ranges for either V_{psr} or V_{comp} are assumed, this region will shrink further. However, even the liberal ranges of Fig. 5 put severe constraints on the binaries, *e.g.*, if $M = 8\ M_\odot$, the separation *must* lie between $2.4\ R_\odot$ and $4.8\ R_\odot$. In any case, $0.3 \leqslant a/R_\odot \leqslant 6.7$ and $5.6 \leqslant M/M_\odot \leqslant 9.5$. We conclude that pre-supernova masses must lie in the range $4\ M_\odot$ to $8\ M_\odot$.

Conclusions

Starting from the pulsar proper-motion data, we draw the following conclusions. All single pulsars were most likely born in and released from binary systems. The circumstances of their release determined their present velocities. Most of these binary systems must have undergone a common envelope phase of stellar evolution. Pulsars fall into two classes. One class consists of low-velocity pulsars which also have low magnetic fields and characteristic ages larger than 10^7 yr. These are old pulsars which were spun-up significantly during accretion from their companions. Pulsars in the other class have high velocities and high magnetic fields. They are produced in binary systems, having total masses between 5.6 and $9.4\ M_\odot$ and separations less than $7\ R_\odot$, prior to the second explosion which disrupts the system. As one of the two stars is already a neutron star, the velocity data enable us to derive limits of 4 to $8\ M_\odot$ for the pre-supernova mass of the companion.

Acknowledgements

We thank E. P. J. van den Heuvel for extensive discussions on many points relating to this work and M. Vivekanand for much help with figures.

Appendix

For Keplerian motion of two bodies of masses M_1 and M_2 we define the relative variables in the usual manner. The relative position is $\mathbf{r}$ such that in the centre of mass frame, M_1 is located at $\mathbf{r}_1 = (M_2/M)\mathbf{r}$ where $M = M_1 + M_2$. The relative velocity is $\mathbf{V}$. It is well known that the specific Lenz vector $\mathbf{\Lambda}$ is a constant of motion (Goldstein 1980), as of course is the specific angular momentum $\boldsymbol{\lambda}$ (*i.e.*, the areal velocity), where

$$\boldsymbol{\lambda} = \mathbf{r} \times \mathbf{V}, \tag{A1}$$

and

$$\mathbf{\Lambda} = \mathbf{V} \times \boldsymbol{\lambda} - \frac{GM}{r}\mathbf{r}. \tag{A2}$$

The magnitude of $\mathbf{\Lambda}$ is GMe, e being the eccentricity of the orbit.

One can write (carets denote unit vectors)

$$\mathbf{V} = \mathbf{V}_{\text{off}} + \frac{GM}{\lambda}\hat{\boldsymbol{\lambda}} \times \hat{\mathbf{r}} \tag{A3}$$

with

$$\mathbf{V}_{\text{off}} = \frac{\boldsymbol{\lambda} \times \mathbf{\Lambda}}{\lambda^2}, \quad V_{\text{off}} = \frac{GMe}{\lambda}. \tag{A4}$$

This is the equation of the relative velocity hodograph. It is clearly a circle of radius GM/λ whose centre is off-set from the origin by V_{off}.

The individual velocities depend on the reference frame and are

$$\mathbf{V}_1 = \mathbf{V}_{\text{cm}} + \frac{M_2}{M}\mathbf{V} = \mathbf{V}_{\text{off}}(1) + \frac{GM_2}{\lambda}\hat{\boldsymbol{\lambda}} \times \hat{\mathbf{r}}, \tag{A5}$$

$$\mathbf{V}_2 = \mathbf{V}_{\text{cm}} - \frac{M_1}{M}\mathbf{V} = \mathbf{V}_{\text{off}}(2) - \frac{GM_1}{\lambda}\hat{\boldsymbol{\lambda}} \times \hat{\mathbf{r}}. \tag{A6}$$

The hodographs of individual velocities are also circles, and of radii GM_1/λ and GM_2/λ, the centres of which are displaced from the origin by $\mathbf{V}_{\text{off}}(1)$ and $\mathbf{V}_{\text{off}}(2)$ respectively, where

$$\mathbf{V}_{\text{off}}(1) = \mathbf{V}_{\text{cm}} + \frac{M_2}{M}\mathbf{V}_{\text{off}}, \tag{A7}$$

and

$$\mathbf{V}_{\text{off}}(2) = \mathbf{V}_{\text{cm}} - \frac{M_1}{M}\mathbf{V}_{\text{off}}. \tag{A8}$$

In a reference frame in which $\mathbf{V}_{\text{cm}} = -(M_2/M)\,\mathbf{V}_{\text{off}}$, V_1 will be constant in time.

Let us now consider two bodies in circular orbits, one of which (say M_1) suddenly loses an amount of mass $\Delta M = M_1 - M_1' = \alpha(M_1 + M_2)$, in a spherically symmetric manner, without affecting any change in positions or velocities. For the resulting orbit the eccentricity will be

$$e' = \frac{\alpha}{1-\alpha}, \tag{A9}$$

and thus
$$V'_{\text{off}} = GM(1-\alpha)e'/\lambda' = GM\alpha/\lambda. \tag{A10}$$

The velocity of the new centre of mass in the original centre of mass frame is

$$V_{\text{cm}'} = -\frac{\Delta M}{M(1-\alpha)}\mathbf{V}_{1\text{i}}, \tag{A11}$$

where $\mathbf{V}_{1\text{i}}$ is the pre-explosion velocity of M_1 and is in the same direction as $\mathbf{V}'_{\text{off}}$. Also $V_{1\text{i}} = GM_2/\lambda$ and therefore

$$\mathbf{V}'_{\text{cm}} = -\frac{M_2}{M(1-\alpha)}\mathbf{V}'_{\text{off}}.$$

Thus in the original centre of mass frame the speed of M'_1 is constant and equal to that of M_1. If $\alpha > 1/2$ the final orbit is unbound and in this same frame the asymptotic speed of M_2 is related to that of M'_1 by

$$V_{2\text{a}} = [1 + (2\alpha - 1)(M/M_2)^2]^{1/2}\, V_{1\text{a}}, \tag{A12}$$

where
$$V_{1\text{a}} = V_{1\text{i}}, \tag{A13}$$

Note that as $\alpha > 1/2$, $V_{2\text{a}} > V_{1\text{a}}$.

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Concluding Review

L. Woltjer *European Southern Observatory, Karl-Schwarzschild Strasse 2, D-8046, Garching bei München, FRG*

In reviewing this meeting, I will not try to do justice to everything that has been said, and I will give a bit more weight to what has been discussed in the earlier days and a bit less to what has been discussed more recently.

I shall go chronologically not through the meeting, but through the supernova event. When I gave the introductory talk, I presented a somewhat negative review, since I wanted to put you in a critical mind about various things that you would hear. But now coming at the end, obviously I should not do the same thing, and I should let you go home with the conclusion that after all we know some things, and perhaps even more importantly, that there are quite a large number of things that remain to be done.

The story begins with massloss from some advanced stage of stellar evolution, and it begins there, because in supernovae, or supernova remnants, we find evidence of circumstellar matter which presumably resulted from massloss. The details of that massloss are not very well known. For example, how that matter is distributed, we do not really know. We know that generally if you have massloss, it comes off with a speed that is of the order of the escape velocity from the stellar atmosphere. But whether the speed has been constant or whether the star has shrunk and then gradually the speed has increased which would result in a ring, we do not really know. But in any case there was matter, may be rather uniform or may be filamentary already. And then some time later there happens the final collapse of the stellar object.

Virginia Trimble reviewed some of the aspects of this, and very crudely one has three different scenarios. For very large stellar masses (100 $M_\odot$) you have instabilities by electron-positron production, and for medium size masses (10 $M_\odot$) photo-dissociation of iron (which is, of course, the oldest of these mechanisms) and electron capture. Finally, at low masses you have various possibilities starting out with helium stars or with white dwarfs. To set off white dwarfs explosively, matter has to be added in an appropriate way either by massloss from a companion or by the fusion of two white dwarfs.

It is generally agreed that at the massive end of the distribution are the supernovae of type II, and at the low mass end supernovae of type I, but more detailed evidence is still largely lacking.

Anyway, as a result of the explosive event, there may or may not be a neutron star. There is some matter coming off at 10000 Km s^{-1}, and probably more at lower speed. Some of that matter is enriched in heavier elements, especially the medium heavy elements beginning with oxygen and ending in silicon, argon, *etc.*; and if you believe theory, then also much iron should come out in type I supernovae.

This is all basically single-star evolution, but there are still difficult problems: there are various convective, and pseudo-convective processes that may occur in these last phases, that are poorly understood, and I would not be surprised if the nucleogenetic yields would be much influenced in these stellar objects that have a large number of shells of different composition. Rotation has been mentioned and again for nucleogenesis it may be important, and also in deciding whether some stellar remnant remains or not, and in the symmetry of the explosion. Here, there is much that is not known, and the only way to get at it is to do a fair amount of hard work with large computers. Virginia Trimble mentioned the recent remeasurement of the $^{12}C(\alpha, \gamma)$ cross-section, which leads to the production of significantly less carbon and more oxygen. This may be very well because one sees much evidence for oxygen and not much for carbon in supernovae and remnants. But, the fact that it is possible at this late stage to have this kind of a substantial change makes one wonder how many cross-sections there are that still have to be improved, and that may affect the yields. Finally, recent discussions of diffusive separation in white dwarfs were mentioned which may change the character of the explosion and enhance the chance of having a neutron star.

If one looks at the observational side, one of the most interesting suggestions that has been made on a variety of occasions is that there exists a class of subluminous supernovae. In fact, if you just look at the seven historical ones (including Cas A), then two of these are subluminous, at least if one believes the new, lower distance for 3C 58. Taking into account that the subluminous supernovae would be seen with much more difficulty, their real frequency could be quite high. It is clear that one will have to be much more careful in the extragalactic searches for supernovae in order to find these objects. You will have to look at relatively nearby galaxies, but with very deep images. Related to this is the question whether there exist other classes of supernovae. The answer is not very obvious; there are some strange cases, but still little evidence for a whole new class. Finally, there is the long standing question as to what are really the rates of supernovae in different galaxies, and what are the environmental conditions under which supernovae are produced. Are some galaxies particularly prone to produce supernovae (Kochhar used the word 'supernovic galaxies')? It may well be, but further investigation with very carefully selected samples is needed. The answer is important, because it will give us information on what type of objects become supernovae, what their masses are, whether in ellipticals there is star formation, *etc.*

Most of what I have been talking about until now pertains to single stars, and as Radhakrishnan pointed out this morning, there is no proof really that any supernova went off in a single star. The discussion of van den Heuvel this morning has certainly shown that the binary characteristics may be absolutely dominant, even at surprisingly large separations of the components, separations at which the amount of observational evidence is still relatively limited. It is believed that on the upper main sequence something like 2/3 of the stars are binaries and, of course, it may well be even more. From what van den Heuvel told you this morning, it is very clear that the binary characteristics may have a profound effect on the amount and composition of the matter ejected by the supernova. There are various scenarios that depend on the initial mass ratio and period of the binary, and on the way in which the evolution is calculated. The simplest are conservative in mass and angular momentum, but if one looks at the details of the hydrodynamics of the flow within the Roche lobes, it is not at all easy to be sure how much of the angular momentum and of the mass comes to the other component, and how much of it is lost from the system. The cases discussed this morning are, of course, to some extent limiting cases, but to compute what really happens is a far from trivial matter, and again much hard computing will have to be done to make further progress. Then there are the other things that take away angular momentum, the gravitational radiation which puts a lower limit to the loss, and magnetic angular momentum transport, which again is difficult to calculate properly. I think the main conclusion of this morning was that below five solar masses you usually end up with white dwarfs, while above ten solar masses you get mainly neutron stars and some black holes. In between, it depends very much on the detailed scenarios, but even outside these limits other possibilities can be envisaged. Finally, it is interesting to remember that, though binary evolution already gives you a quasi-infinite number of possibilities, about fifteen per cent of all early-type stars are in triple systems. While there are phase space constraints in triple systems, which for example make the typical triple star a narrow binary with a third member at a fair distance, it is clear that there may be interesting evolutionary effects.

Returning now to the supernova explosion, the first thing that you will see is presumably a large flux of neutrinos, and possibly of gamma rays, the latter depending a bit on the density profile of the atmosphere. The neutrinos could give information on the details of the processes in the deep interior and on the energetics.

Various experiments are being planned to look for neutrinos from supernovae. Unfortunately, most of these are only able to detect supernovae in our own Galaxy, but if the high rates are correct, or if there are a large number of subluminous supernovae, there may nevertheless be some chance to see an event in the coming one or two decades. Somewhat later after the explosion the optical radiation begins to increase rapidly. However, the temperature of the radiating surface remains low, typically less than 10000 K. Some time after the maximum has passed, the light curve declines more or less exponentially in the SN I. The light curves of the SN II are globally perhaps not even that different, but with important wiggles. Also the spectra do not look as different as was initially thought, but, of course, the apparent absence of hydrogen in the SN I is important.

The mechanism for producing the light is not entirely clear. The prevalent opinion seems to be that hydrodynamic dissipation is responsible in SN II and radioactive decay in SN I. The elements responsible for the radioactive decay have been changed from time to time, but now the decay of nickel into iron is considered most important. Unfortunately, as I pointed out in my introduction, the observational evidence for iron is still ambiguous. With regard to the light curves, one should also note that the nature of the light curve depends very much on the wavelength at which you look.

A few days or months after the explosion, radio emission is observed which may be due to a pulsar as Pacini would wish it to be, with an early-formed filamentary shell around it, or probably with magnetic loops sticking out of the shell as Shklovskiĭ proposed. Alternatively, it could be due to shock acceleration as proposed by Chevalier. One of the questions coming in here is whether one also accelerates cosmic rays, which relates very much to the radioactive chronologies discussed by Cowsik. Observationally, until now there seem to have been two supernovae of type II which fit both of these models, while there has been one SN I where the Chevalier type model seems to be preferred. But, of course, to conclude from that much about the general behaviour of supernovae is very difficult, especially since the SN I seems to have been subluminous. Perhaps also there still remains a bit of a question whether the early radiation is really all synchrotron radiation. As pointed out by Weiler, what one needs in the future is a large number of supernova radio flux curves at a number of different frequencies, and VLBI observations. While this may not establish the Hubble constant, at least it may allow one to gain a better understanding of what is really going on. X-ray curves obviously are of importance, but again only one X-ray observation is available. For these things, early detection is needed, and for this the automatic searches that are being planned in a variety of places may be useful. Discussions about such searches have been going on for nearly two decades without much result to-date, but this may well change. I would, however, not be surprised if radio astronomers will waste quite an amount of observing time on objects found in the automatic searches that later turn out not to have been supernovae!

Of particular interest are the rapidly declining sources observed in M 82 which, if due to supernovae, would give an extremely high supernova rate of one every few years. It would be most worthwhile to look also for optical supernovae in M 82 and similar nearby galaxies at very faint magnitudes. Even with some ten magnitudes of absorption, you should still be able to see them.

Finally, it is worth noting that here and in the subsequent evolutionary phases one throws away one of the two parameters that one can measure, namely the spectral index of the particle spectrum. Different objects have different spectral indices. For two or three decades, one has taken that simply as information that happens to exist in the observations. But, of course, at some moment one will have to discover what the interpretation of the spectral index is, and to use it to further constrain the models. It should be predicted by a proper theory.

After the very early supernova phases, one comes to the supernova remnants. Everybody has agreed to divide these up into the shell-type ones and the Crab-like ones, even though there is some doubt if the latter really include the Crab Nebula itself. The shell-type remnants come, as Clark showed, in different classes: the hydrogen spectrum class, the oxygen spectrum class, and the more conventional ones that we have known for a long time. It is not that easy at the moment to see how many of each class there are, because the searches have been very much biased towards the last one. Probably, as more X-ray data become available, one will get a more complete inventory of young remnants, and then from the optical studies be able to see how frequent these Balmer- and oxygen-line remnants really are. There are, of course, many objects that do not look entirely like shells, and also not exactly like the Crab Nebula. So, one is tempted to introduce a class of mixed or combination remnants. I am still uncertain whether this is more than the statement that if you look at high enough resolution, supernova remnants become extremely complex. A rather spectacular case in point is the remnant (if it is really a supernova remnant!) shown by Jacqueline van Gorkom. More high-resolution maps of other remnants may well show unexpected features. Observationally, it is also important to get more and better distances from 21 cm absorption studies. It also will be important to get more proper motion data of the kind one has for the Cygnus Loop and a few other supernova remnants, to determine the distances and the structures of the shells kinematically. Also of interest are observations of the hot gas from the Fe XIV lines, but, as Clark pointed out, great care is needed to ensure that one measures that line and not something else.

With regard to the Crab Nebula, which always looms large at a meeting on supernova remnants, there were discussed here the possible segregation of helium, the very complex structure of the emission-line shell, and—by Velusamy—evidence for a possible steepening of the radio spectrum at the outer edges. Again, one would like to get a still more complete pattern of the radial velocities, but it would be important to combine these with detailed proper motion data for the same filaments in order to obtain a true three-dimensional picture of the expanding shell. In addition to the mysterious jets, the possible existence of a halo is of much importance in our understanding of this object. If there were really a substantial radio halo, the difference between the shell-type supernova remnants and the Crab Nebula would perhaps be less large than it appears to be.

Bhattacharya discussed the supernova remnant in the Large Magellanic Cloud 0540 – 69.3 showing that it looks a bit like the Crab Nebula, but at the same time pointing out the difficulty in combining the radio and the X-ray data. Much better radio pictures are obviously needed.

For the further evolution, it is important in what medium the supernova explodes. This can be the hot interstellar medium, the warm medium, a typical interstellar cloud, or a molecular cloud. Their different densities affect quite a number of things, and Dwarakanath discussed how these could affect the inferred ages and thereby the formation rates of the Crab-like supernova remnants. The same applies to the shell-type remnants just as well. These considerations are also of much importance if one wants to accelerate cosmic rays in supernova remnants, because then the speed of the expansion, and the time at which the remnant is slowed down is of much importance. Stephens in fact showed that by setting off supernovae in dense clouds, one could perhaps understand some problems relating to anti-protons in the cosmic radiation.

After the diffuse remnants have disappeared, what finally is left are the pulsars with much longer lifetimes. The radio pulsars are largely singles, and the X-ray pulsars doubles. What one would like to know is the formation rate of these objects as a function of the initial magnetic field, the initial period, and the time evolution of the magnetic field and of the period. As Radhakrishnan stressed this morning, also the velocity of the pulsars contains important information. And, of course, a satisfactory theory has to get these things right not only for the pulsars, but also for the run-away O stars which were the original basis for the whole Blaauw scenario of double stars in which one of the components blows up and the other acquires a substantial velocity. The historical development has been a bit similar to what it was in the case of the rapid process element synthesis which many seem now to have uncoupled from the supernova process, even though initially it was considered to be its most characteristic result. There seems to be now also a feeling that the run-away O stars may not derive from the Blaauw mechanism, but may result from an anisotropic explosion of the supernova itself. But, as it was pointed out here, there are still problems in having the degree of anisotropy sufficiently large. Typical initial magnetic fields of the observed pulsars seem to be mainly in the range 10^{12} to $10^{13.5}$ G. As Srinivasan argued very convincingly, the absence of large numbers of Crab-like remnants seems to indicate that the initial periods are typically larger than 50 ms. The timescale for the decay of the magnetic field seems to be of the order of a few million years. But, as Ray pointed out this morning, there are some uncertainties in particular if the thermal regeneration processes (essentially the Biermann mechanism) really would work. Also for a long time, we thought that we understood what the evolution of P as a function of time was; there again the situation is more complex, because in the binary scenarios the rate of rotation may also be increased. One therefore has to see which of the observed pulsars may have been recycled. And, finally, there is the question of the velocities which Radhakrishnan discussed this morning. Here again, one would need to have substantially larger samples, so that one will be able to see if the distribution in two groups is holding up. Other future observations which may help clarify these various problems include surveys for low period pulsars currently being planned and more complete searches for Crab-like remnants.

It was pointed out by Ramanamurti in one of the sessions that with regard to the fit to predictions in astronomy one gets away with much, with much more than in physics. The answer given to this by astronomers is ‘Well, we cannot help it, because that is the way the field works. One has to look at what there is in the universe, and then to construct some kind of interpolative theory’. I think, however, that it is a comment to keep in mind. Its importance is that it may encourage us to tighten up quite a number of things in the elaboration of theoretical models and in the connection of theoretical models with observation. Ultimately, one should aim for far more rigour in some of these problems than one has been applying to them. Nevertheless, I think it is satisfactory to see that the basic scenario of the supernova–supernova-remnant sequence is beginning to become clearer. At the same time, that scenario still has a very large number of holes in it, and I am sure that none of you will have difficulty in finding some interesting problems to work on in trying to fill in these holes.

Participants

Ajit Kembhavi *Tata Institute of Fundamental Research, Bombay*
Alak Ray *Tata Institute of Fundamental Resarch, Bombay*
K. V. K. Iyengar *Tata Institute of Fundamental Research, Bombay*
R. K. Manchanda *Tata Institute of Fundamental Research, Bombay*
Patrick Das Gupta *Tata Institute of Fundamental Research, Bombay*
S. Ramadurai *Tata Institute of Fundamental Research, Bombay*
P. V. Ramana Murthy *Tata Institute of Fundamental Research, Bombay*
Ramanath Cowsik *Tata Institute of Fundamental Research, Bombay*
Pranab Ghosh *Tata Institute of Fundamental Research, Bombay*
S. A. Stephens *Tata Institute of Fundamental Research, Bombay*
S. M. Alladin *Osmania University, Hyderbad*
P. V. Kulkarni *Physical Research Laboratory, Ahmedabad*
Pramesh Rao *Radio Astronomy Centre, TIFR, Ootacamund*
T. Velusamy *Radio Astronomy Centre, TIFR, Ootacamund*
V. R. Venugopal *Radio Astronomy Centre, TIFR, Ootacamund*
G. Swarup *Radio Astronomy Centre, TIFR, Ootacamund*
M. N. Joshi *Radio Astronomy Centre, TIFR, Ootacamund*
C. Uberoi *Department of Applied Mathematics, Indian Institute of Science, Bangalore*
Vinod Krishan *Indian Institute of Astrophysics, Bangalore*
D. C. V. Mallik *Indian Institute of Astrophysics, Bangalore*
P. K. Das *Indian Institute of Astrophysics, Bangalore*
C. Sivaram *Indian Institute of Astrophysics, Bangalore*
R. K. Kochhar *Indian Institute of Astrophysics, Bangalore*
Ch. V. Sastry *Indian Institute of Astrophysics, Bangalore*
R. C. Kapoor *Indian Institute of Astrophysics, Bangalore*
Bhaskar Datta *Indian Institute of Astrophysics, Bangalore*
T. P. Prabhu *Indian Institute of Astrophysics, Bangalore*
T. M. K. Marar *ISRO Satellite Centre, Bangalore*
S. Seetha *Technical Physics Section, ISRO Satellite Centre, Bangalore*
Ashok Jain *ISRO Satellite Centre, Bangalore*
V. K. Kapahi *Radio Astronomy Centre, TIFR, Bangalore*
S. Krishnamohan *Radio Astronomy Centre, TIFR, Bangalore*
D. K. Mohanty *Radio Astronomy Centre, TIFR, Bangalore*
V. Radhakrishnan *Raman Research Institute, Bangalore*
R. S. Arora *Raman Research Institute, Bangalore*
A. A. Deshpande *Raman Research Institute, Bangalore*
Dipankar Bhattacharya *Raman Research Institute, Bangalore*
K. S. Dwarakanath *Raman Research Institute, Bangalore*
B. R. Iyer *Raman Research Institute, Bangalore*
Joseph Samuel *Raman Research Institute, Bangalore*
S. Ramaseshan *Raman Research Institute, Bangalore*
N. V. G. Sarma *Raman Research Institute, Bangalore*
Rajaram Nityananda *Raman Research Institute, Bangalore*

C. S. Shukre *Raman Research Institute, Bangalore*
G. Srinivasan *Raman Research Institute, Bangalore*
Suketu Bhavsar *Raman Research Institute, Bangalore*
Uday Shankar *Raman Research Institute, Bangalore*
C. V. Vishveshwara *Raman Research Institute, Bangalore*
Smiles Mascaranhes *Raman Research Institute, Bangalore*
Roger Chevalier *Department of Astronomy, University of Virginia, USA*
Virginia Trimble *Astronomy Program, University of Maryland, USA*
Kurt W. Weiler *Division of Astronomical Sciences, NSF, USA*
Franco Pacini *Osservatorio Astrofisico di Arcetri, Italy*
David H. Clark *Space & Astrophysics Division, Rutherford Applied Laboratory, UK*
E. P. J. van den Heuvel *Astronomical Institute, The Netherlands*
Lodewijk Woltjer *European Southern Observatory, Germany*
Jacquiline van Gorkom *National Radio Astronomy Observatory, USA*