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On the Supernova Remnants Produced by Pulsars

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Abstract. We conclude that pulsar-driven supernova remnants (SNRs) are extremely rare objects. Indeed an analysis of the known sample of plerions suggests a very low birthrate ~ 1 in 240 years. Long-lived and bright plerions like the Crab nebula are likely to be produced only when the pulsar has an initial period ~ 10–20 milliseconds and a field ~ 10^{12} G. Such pulsars inside rapidly expanding shell remnants should also produce detectable plerions. The extreme rarity of SNRs with such hybrid morphology leads us to conclude that these pulsars must have been born with an initial period larger than ~ 35–70 milliseconds.

Key words: supernova remnants—plerions—pulsars

1. Introduction

It is 50 years since the publication of the historic paper by Baade & Zwicky (1934) in which they advanced the hypothesis that Supernovae (SN) are the result of formation of neutron stars in the centres of ordinary stars. Detailed stellar evolution calculations done in recent years have confirmed this brilliant conjecture; it is now generally accepted that this is indeed the origin of Type II Supernovae. On the other hand, according to the current consensus no stellar remnant is left behind in a Type I supernova; the star completely disrupts (see for example, Trimble 1983). In spiral galaxies of morphology similar to ours the frequency of Type I and Type II SN are roughly equal (Tammann 1974).

Though no supernova has been sighted in our galaxy since the time of Kepler, it is generally believed that they occur once in about 30 years as suggested by historical observations (Clark & Stephenson 1977a, b). At any rate, Supernovae do leave behind relatively long-lived remnants (SNRs). In all about 140 SNRs are known in the Galaxy. Most of them have the morphology of shells with hollow interiors such as Tycho, Kepler and SNR 1006. However, the best studied SNR, namely the Crab nebula, has a distinctly different morphology: it has a filled-centre appearance with no limb-brightening. For a long time, the Crab nebula was unique in this respect. Weiler (1969) and Weiler & Seielstad (1971) first drew attention to the fact that 3C58 has a morphology similar to that of the Crab. Since then, the list of such filled-centre remnants, which have come to be known as ‘plerions’, has grown to a modest number of 7 or 8 (Weiler 1983). Several others (Radhakrishnan & Srinivasan 1978, 1980a; Weiler &

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Shaver 1978; Weiler & Panagia 1980) have suggested that these plerions may, like the Crab nebula, be produced and maintained by an active central pulsar.

Even if neutron stars are associated with only Type II supernova events, it is remarkable that until recently pulsars were associated with only two SNRs, namely the Crab and Vela X, both of which, curiously, are of *filled-centre* morphology. The standard explanation for the poor pulsar–SNR association invoked statistical factors such as beaming of pulsars, interstellar smearing of the pulses, low fluxes, *etc.* (Manchester & Taylor 1977). Radhakrishnan & Srinivasan (1980a) suggested that the above-mentioned statistical arguments were unsatisfactory, since an active pulsar inside a shell remnant will produce a centrally-condensed nebula like the Crab, which should be seen from any viewing geometry. They argued 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 an active pulsar. A possible reason for this was suggested by Shukre & Radhakrishnan (1982) who proposed that a neutron star may not function as a pulsar unless its magnetic field lies in a narrow 'window' centred around the Crab value. An alternative possibility that the magnetic fields of neutron stars are built up after their birth over a long period of time has also been recently discussed in literature (Blandford, Applegate & Hernquist 1983; Woodward 1984). In this scenario the SNR would have faded away before the neutron star turned on as a pulsar.

Recently, however, a third pulsar–SNR association was found in the Galaxy, but this time the SNR MSH 15–52 had a shell morphology (Seward & Harnden 1982). There is no central radio emission surrounding the pulsar, although there is an extended X-ray synchrotron nebula. In view of this latest pulsar–SNR association one must admit the possibility that in all the shell remnants there are perhaps functioning pulsars which we do not see for the statistical reasons mentioned above, and *which do not produce plerions of sufficient surface brightness.* This might happen, for example, if pulsars inside shell remnants have relatively long periods (Radhakrishnan & Srinivasan 1983).

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 1 in 20–40 yr (Taylor & Manchester 1977; Vivekanand & Narayan 1981) are indeed consistent with the previously mentioned supernova rate, and the recent estimates of the birthrate of shell remnants of 1 in ~ 30 yr (Srinivasan & Dwarakanath 1982; Mills 1983). However, in view of the fact that a pulsar and/or a plerion has been seen in only two shell remnants (MSH 15–52 and G 326.3 –1.8) (Weiler 1983), and the general absence of point X-ray sources (Helfand 1983) within the shells, the 'agreement' between the birthrate of shell SNRs and that of the pulsars appears puzzling.

On the other hand, since one expects an active pulsar in plerions, it is important to confront the birthrate of pulsars with the birthrate of plerions. In this paper, we shall address this important question. In Section 2, we derive a birthrate for Crablike SNRs assuming that all of them are similar to the Crab nebula in every respect, namely, the pulsars powering them have the same characteristics as the Crab pulsar, and their *initial* velocity of expansion is the same as that of the Crab nebula. Given these assumptions, the relative lifetime of such nebulae will depend on the density of the interstellar medium into which they are expanding. Using a slight variant of the model of the interstellar medium given by McKee & Ostriker (1977), we derive a mean birthrate of plerions ~ 1 in 240 yr.

In Section 3, we relax the assumption that the Crab nebula is a prototype. Pulsars are allowed to have a range of initial periods and fields. But we model all the plerions in analogy with the Crab nebula, namely that *their boundaries were accelerated by the energy lost by the pulsar* (Trimble & Rees 1970). We conclude that pulsar-driven supernova explosions are very rare events, and that long-lived and bright remnants like the Crab are even more rare.

Since the conclusion from Section 2 and 3 is that Crablike supernova remnants are extremely rare, in Section 4 *we move away from the pulsar-driven scenario to the standard model in which the supernova ejecta are accelerated by a shock wave*; the pulsar plays no dynamical role. We evolve plerions produced by pulsars inside rapidly expanding shells and compare the expected number of such Plerions implied by the generally accepted pulsar birthrate with observations. This forces us to the conclusion that the initial periods of pulsars must be much greater than 20 ms.

In Section 6, we estimate the characteristics of pulsars in the historical shell SNRs. From limits on their central surface brightness we conclude that their initial periods must have been larger than ~ 35–70 ms.

2. Birthrate of crablike remnants

Weiler (1983) has listed possible and probable SNR candidates with a filled-centre morphology. Of these, some have a surrounding shell. From this list, we have selected the remnants given in Table 1 for a birthrate calculation which will be done in this

Table 1. The adopted sample of plerions.

Source	Flux (S) at 1 GHz Jy	Distance (d) kpc	Luminosity Jy kpc^2	Ref.
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[a]	2112	1
		2.6	223	4
G 326.3 − 1.8 (centre)	40	2[b]	160	1, 5
		4.6	846	
MSH 15 − 52	0.1	4.2	1.6	7, 8, 5
G 5.3 − 1.1	37	3	333	1, 6
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 (1983) we adopt a distance of 8 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. Milne & Dickel (1971)
7. Manchester & Durdin (1983)
8. Caswell, Milne & Wellington (1981)

section. A few comments are in order as to why the following remnants listed by Weiler have been excluded from our sample.

RCW 103 : No *extended* central emission is seen either in X-ray or in radio. A compact X-ray source is seen but its nature is not clear.
W 28 : There is no reliable distance estimate to the source.
W 50 : Though there is a condensed star at the centre, it is almost certainly not a standard pulsar.
CTB 80 : There seems to be some doubt as to whether the radio morphology is compatible with the identification as a plerion.
W 44 : Again, we feel that there is no clear evidence of centrally peaked emission within the shell.

Since we will be allowing for an incompleteness factor of 3, even if some of the sources we have rejected are 'legitimate' plerions it should not affect the birthrate derived.

In order to proceed with an estimate of the birthrate of plerions, one must have an evolutionary scenario for them from which one can derive their ages.

2.1 *The Evolution of Plerions*

In their pioneering paper, Pacini & Salvati (1973; hereinafter PS) discussed the evolution of the magnetic field, particle content and luminosity of the nebula produced and maintained by a central pulsar. After the initial phase, which relates to the explosion itself, there are two distinct phases of evolution:

(1) $t < \tau_0$: where $\tau_0 = P_0/2\dot{P}_0$ is the initial characteristic slowdown time of the pulsar. For the Crab pulsar $\tau_0 \sim 300$ yr.

(2) $t > \tau_0$: in this phase the nebular radius increases, the pulsar output decreases, and consequently the nebular luminosity decreases. Many of the observed properties of the Crab nebula can be successfully accounted for by this model.

PS assumed that the nebular boundary was expanding freely, even for $t > \tau_0$. This is certainly so for the Crab nebula *at the present time.* But if one wants to evolve the Crab nebula to a much older age, then one must modify the evolutionary scenario of PS to take into account the deceleration of the expansion at later times. This was first done by Weiler & Panagia (1980), and more recently by Reynolds & Chevalier (1984). Weiler and Panagia argued that the boundary of the nebula will decelerate and enter the adiabatic phase of expansion at $t \sim \tau_0$, the time when the pulsar would have lost half its rotational energy. According to them, the two youngest plerions, namely the Crab nebula and 3C 58 (probably the remnant of SN 1181) are entering, or are already in the adiabatic phase. However, in our opinion there is no immediate connection between the initial characteristic slowdown time of the pulsar and the time when the freely expanding filamentary shell will be significantly decelerated. Though the pulsar ceases to have a significant effect on the dynamics of the shell beyond $t > \tau_0$— *if ever it did*– the question of deceleration is determined by the mass in the ejecta and the density of the interstellar medium (ISM) into which it is expanding. It is generally accepted that the expanding shell will enter the adiabatic or Sedov phase only when the mass swept up far exceeds the mass ejected (Woltjer 1972). The time when this will occur depends on the mass ejected, the initial velocity of expansion, and the density of the

ISM. Since the expansion velocity of the Crab nebula (1700 km s^{-1}) is much less than the expected initial velocity of the shell SNRs($\sim 10^4$ km s^{-1}) it will take a much longer time for the former to sweep up a given amount of mass. At any rate, observations indicate that the filaments in the Crab nebula have not decelerated measurably.

In the standard model, the ISM consists of cold dense clouds in pressure equilibrium with the warm intercloud medium with a density $n_w \sim 0.3 cm^{-3}$ (Spitzer 1978). According to McKee & Ostriker (1977), however, the intercloud medium is a hot, low-density gas ($n_H \sim 0.003$ 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 ($n_w \sim 0.3$ cm^{-3}). If one accepts this picture, then one is led to the conclusion that a fraction of SNRs must be expanding in the denser medium and must therefore suffer significant deceleration. Recent analyses of the evolution of shell-type SNRs also lend support to the above picture of the ISM (Higdon & Lingenfelter 1980; Srinivasan & Dwarakanath 1982).

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 the Crab is $\sim 1\ M_\odot$ (Henry & MacAlpine 1982). If the Crab is expanding in the coronal gas, t_0 will be $\gtrsim 8000$ yr, while it will be $\gtrsim 1700$ yr if it is expanding in the denser component of ISM (at $t = t_0$ the mass swept up equals the mass ejected). For $t \gg t_0$ the radius of the nebula will increase as t^η with $\eta = 0.4$. With this modification one can easily extend the results of PS, as was done by Weiler & Panagia (1980).

In what follows we shall confine our attention to radio observations of plerions. For completeness, we give below the formulae for the radio spectral luminosity (for $\nu < \nu_c$).

$$\tau_0 < t < t_0: \qquad L_\nu \propto t^{-2\gamma} \nu^{(1-\gamma)/2}, \tag{1}$$

$$t \gg t_0 > \tau_0: \qquad L_\nu \propto t^{-2\eta\gamma} \nu^{(1-\gamma)/2}. \tag{2}$$

In Equations (1) and (2) γ is the exponent of the particle spectrum injected into the nebula by the pulsar (see PS and Weiler & Panagia 1980). The particle spectral index γ may be related to the radio spectral index a_R through the relation $\gamma = 1 + 2a_R$. For the Crab nebula, $a_R = 0.3$, implying $\gamma = 1.6$.

In Fig. 1, we have plotted Equations (1) and (2) which describe the decay of the radio spectral luminosity as a function of the age of the nebula. We have normalized the curve to the observed spectral luminosity of Crab nebula at 1 GHz. The solid curve is appropriate for the observed radio spectral index of the Crab nebula and the dashed curve for $\alpha_R \simeq 0.0$, such as for G 74.9 +1.2 or Vela X. Initially the luminosity drops as t^{-2y} and then flattens as the nebula decelerates. The sharp break in the curve is an artefact of the approximation that the remnant expands freely upto $t = t_0$ and according to the Sedov solution beyond t_0. In reality, of course, the evolution of luminosity will be described by a smooth curve. The curves labelled n_w are appropriate if the nebula were expanding in the warm, dense intercloud medium and those labelled n_H describe the evolution if it were expanding in the hot, low-density gas.

The above discussion of a smooth transition to the ISM-dominated phase ignores a subtle effect pointed out by Reynolds & Chevalier (1984). They have argued that during this transition, a reverse shock wave is likely to compress the pulsar bubble resulting in

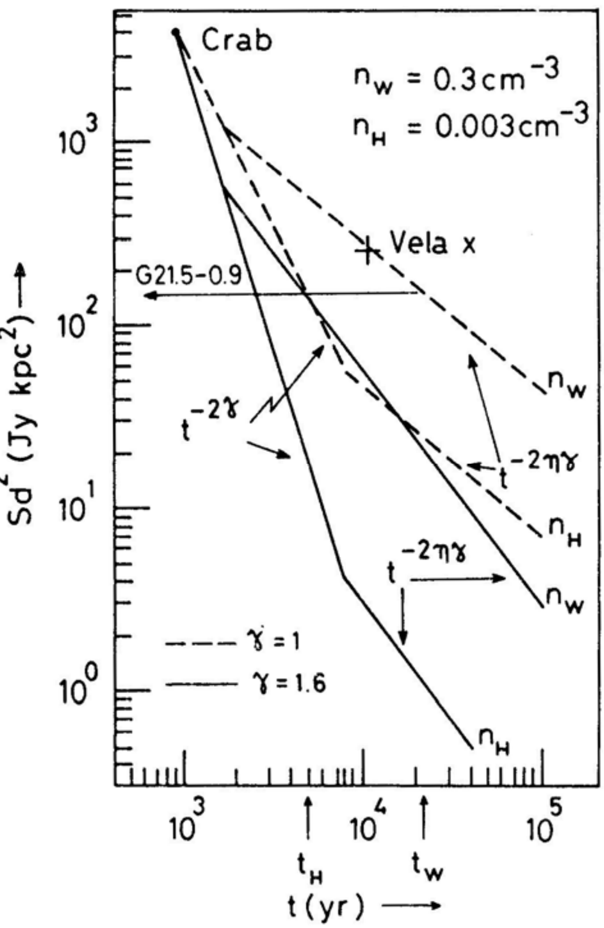

Figure 1. The secular decrease of the radio spectral luminosity of plerions at 1 GHz ($L_\nu \propto Sd^2$). The evolutionary tracks have been normalized to the luminosity of Crab nebula at an age of 1000 yr. $\gamma = 1 + 2a_R$ where α_R is the radio spectral index of the nebula; $a_R = 0.26$ for the 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 $y = 1.6$ are shown. The estimated age of G 21.5 – 0.9 is ~ 4800 yr and ~ 23000 yr in the rarer and the denser media respectively.

a discontinuous increase in the plerion luminosity. Also, in the model of Reynolds & Chevalier (1984), the plerion radius increases as $t^{0.3}$ instead of $t^{0.4}$. However, the conclusions drawn from our model will in no way be altered by the above-mentioned effects, for these further increase the lifetime of the plerion.

2.2 *Birthrate*

We will now estimate the birthrate of plerions under the following assumption, namely that *the pulsars in all of them are identical to the Crab pulsar and their expansion velocities are the same as that of the Crab nebula.*

Of the plerions listed in Table 1, the oldest one is presumably G 21.5–0.9 since except for MSH 15–52 (centre) 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 in Section 5. Of course, a source more luminous than G 21.5 – 0.9 *need not be younger if the latter is expanding in the hot medium and the former in the denser medium* (See Fig. 1) but we shall correct for this below.

It now remains to estimate the age of the least luminous source. Its age estimated from Fig. 1 (the γ=1 tracks since its spectral index is 0.0) is ~ 4800 yr (if expanding in the hot medium) and ~ 23000 yr (if expanding in the warm medium). Since not all the plerions have a spectral index of 0.0, we shall assume an 'average' value of $\alpha_R \simeq 0.15$ implying $\gamma = 1.3$. If one uses the evolutionary track corresponding to this 'average' γ, the above estimate of the age of G 21.5 – 0.9 gets modified to 3600 yr and 13000 yr, respectively. These numbers represent the lifetimes above this luminosity in the two media.

If f_H and f_w are the filling factors of hot and warm media respectively, then

$$N(>) = \frac{1}{\tau}(t_H f_H + t_W f_W); \qquad f_H + f_W = 1 \tag{3}$$

where N (>) is the number of plerions with spectral luminosities greater than that of a given source, t_H and t_w are the lifetimes in the hot and the warm media respectively and τ the mean interval between Supernovae that produce plerions. From Table 1, we see that there are 9 sources more luminous than G 21.5 – 0.9. Using this number and the age estimates t_H and t_w given above for G 21.5–0.9 Equation (3) can be simplified to read

$$\tau = (1444 - 1044 f_H)\ \text{yr}. \tag{4}$$

Though it is felt that the sample of plerions is a reasonably complete one (Weiler 1983), since most of the observed plerions are relatively close by we shall take a conservative attitude and allow for an *incompleteness factor of* 3. Thus,

$$\tau \gtrsim (481 - 348 f_H)\ \text{yr}. \tag{5}$$

This should be regarded as an *upper limit* to the birthrate. If the low-density interstellar medium has a filling factor f_H= 0.7, as suggested by McKee & Ostriker (1977), Equation (5) gives a birthrate of *one in* 240 *yr*. The filling factor for coronal gas remains a highly uncertain one. Chevalier (1978), for example, has questioned the global nature of the coronal gas. A smaller filling factor will yield a lower birthrate.

2.3 *Implications*

It should be noted that even with a very large filling factor for the coronal gas one gets a birthrate of plerions much smaller than the pulsar birthrates in the literature which lie in the range of one in 10 years to one in 40 years (Phinney & Blandford 1981; Taylor & Manchester 1977; Vivekanand & Narayan 1981). It should be emphasized that we have already allowed for an incompleteness in the sample of plerions by a factor of 3. This makes the above discrepancy a very glaring one.

The first conclusion that suggests itself is that the pulsar birthrate must be grossly in error. It has been long recognized that it could be in error due to uncertainties in the beaming factor, the interstellar electron density, selection effects in pulsar searches, *etc.* M. Vivekanand (1984, personal communication) has made a systematic study of each one of these factors and has put strong limits on the pulsar birthrate around a mean of one in ~ 40 yr. The other possible conclusion is that the evolutionary scenario used above to estimate the ages of plerions is questionable. It should be recalled that the basic assumption we have made is that Crab pulsar and the nebula are prototype objects. To be more explicit, we have assumed

(1) The initial period of *all* pulsars is the same as that of the Crab pulsar.
(2) The surface magnetic field of *all* pulsars is the same as that of the Crab pulsar.
(3) The expansion velocity of the nebular boundary, in every case, is the same as that of the Crab nebula.

In the next two sections, we shall relax all of the above three assumptions.

3. Pulsar-driven supernova remnants

As may be seen from PS, the spectral luminosity of a nebula *at a given age* depends 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. To illustrate this, we rewrite below the expression derived by PS for the radio spectral luminosity for times $t > \tau_0$ (Equation 5.7 of PS) explicitly displaying the pulsar parameters.

$$L_\nu(t) \propto B_*^{(3-5\gamma)/2} P_0^{2(\gamma-2)} V^{-3(1+\gamma)/4} t^{-2\gamma} \nu^{(1-\gamma)/2}. \tag{6}$$

In the above equation B_* is the surface magnetic field of the pulsar, P_0 its initial period and V the expansion velocity. As was mentioned before, $\gamma = 1.6$ for the Crab nebula, and the above formula will read as

$$L_\nu \propto B_*^{-2.5} P_0^{-0.8} V^{-1.95} t^{-3.2} \nu^{-0.3}. \tag{7}$$

It can be seen from Equation (7) that the dependence of the luminosity on the pulsar field and the velocity of expansion 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 and its pulsar are prototypes.* We discuss this point in greater detail below.

3.1 *Expansion Velocity of Plerions*

One of the most remarkable aspects of 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 and the magnetic field frozen into it pushed out the remaining mass and accelerated it to the present velocity. It was through such arguments that one was able to estimate the initial period of the Crab pulsar (Trimble & Rees 1970; PS; Bees & Gunn 1974). It is natural, therefore, to assume 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 while it still had a dynamical effect on it. Let $E_0^R = \frac{1}{2} I \omega_0^2$ be the initial stored rotational energy of the pulsar. Here I is the moment of inertia of the neutron star and ω_0 is the initial angular frequency of rotation. Within the initial characteristic slowdown time $\tau_0 = P_0/2\dot{P}_0$, the pulsar would have dumped approximately half this energy in the form of relativistic particles and magnetic field. If M_{ej} is the mass accelerated, then the velocity imparted to it by the pulsar can be estimated from the relation

$$\tfrac{1}{2} M_{ej} V^2 \simeq \tfrac{1}{2} E_0^R \tag{8}$$

In what follows *we shall assume that the mass ejected in all cases is roughly the same as in the Crab nebula, and hence the expansion velocity* $V \propto 1/P_0$.

3.2 *The Initial Characteristics of the Pulsars*

Although it is believed that the initial period of the Crab pulsar was 16 ms, according to conventional wisdom most pulsars at birth will be spinning much more rapidly with $P_0 \sim$ a few milliseconds. *For the present we shall adopt the conventional viewpoint that the initial period of pulsars can be anywhere between* 1 *to* 20 *ms with equal probability.*

In the previous section we assumed that all pulsars have the same surface magnetic field as that of the Crab pulsar. However, one knows that there is a wide distribution in the derived magnetic fields of pulsars, which range from 10^{11}–$10^{13.5}$ G and there are strong reasons to believe that very few pulsars have magnetic fields very much less than $10^{12.5}$ G *at birth* (Radhakrishnan 1982). The pulsars with $B < 10^{12}$ G are presumably several millions of years old and consequently their field would have decayed. If this were not the case, it is very hard to understand why no pulsar has been found with a field less than the Crab value and whose period is < 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. [The binary pulsar PSR 1913 + 16 and the two recently discovered millisecond pulsars are believed to have low fields and short periods because of their evolution in binary systems (Radhakrishnan & Srinivasan 1981; Radhakrishnan & Srinivasan 1982)]. In the calculations to follow, *we shall therefore assume that 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.*

3.3 *The Evolution of the Nebula*

We are now ready to discuss the evolution of the luminosity of such pulsar-driven nebulae. Combining Equations (6) and (8) one gets

$$L_\nu \propto B_*^{(3-5\gamma)/2} P_0^{(11\gamma-13)/4} t^{-2\gamma} \nu^{(1-\gamma)/2}. \tag{9}$$

It will be recalled that this formula is valid only for $t > \tau_0$. As long as one stuck to the initial period of the Crab pulsar and its magnetic field, one was mainly interested in this phase. But since we will now allow pulsar periods and fields to take a range of values we will need the full evolutionary curve, both for $t < \tau_0$ and $t > \tau_0$.

This is shown in Fig. 2 where we have compared the evolution of the radio luminosity of different nebulae with the central pulsars having different fields and initial periods. Since we are now dealing with pulsar-driven nebulae *we have taken into account the acceleration of the nebular boundary during* $t < \tau_0$. In this phase, the expansion velocity of the nebula is not constant and is proportional to $t^{1/2}$; consequently a slight modification of the formulae given in PS is needed. Since this is fairly straightforward

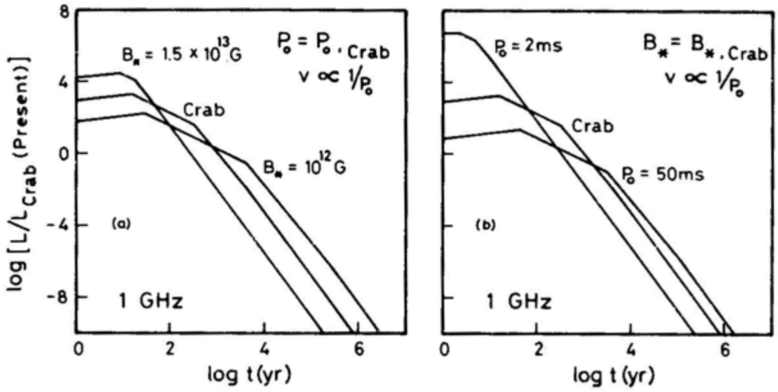

Figure 2. The evolution of radio spectral luminosity for pulsar-driven SNRs, in units of the present value for the Crab nebula, (a) The evolutionary tracks of two such nebulae powered by pulsars with the same initial period as the Crab pulsar, but with differing magnetic fields, are compared with the evolution of the Crab nebula, (b) Here the pulsars are assumed to have the same magnetic field but different initial periods.

we refer to Maceroni, Salvati & Pacini (1974) and Reynolds & Chevalier (1984) for further details. It will be seen from the figures that nebulae of the same age can have widely differing luminosities depending upon the characteristics of the central pulsar. The same information is displayed in a more concise form in Fig. 3. 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 *same luminosity* at a given age. In Fig. 3a, the different contours correspond to different luminosities but the same age, whereas in Fig. 3b, different contours correspond to different ages for the same luminosity. It is clear from Figs 2 and 3 that it is not meaningful to assert that nebulae with luminosities greater than that of a given one

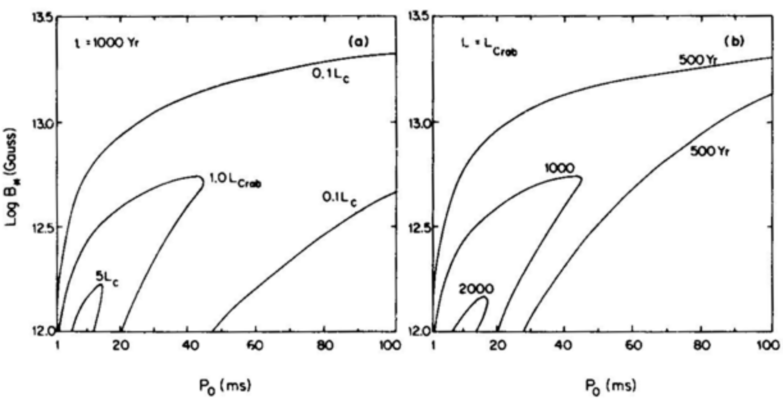

Figure 3. Contours of constant luminosity for pulsar-driven SNRs are shown in the $B_* - P_o$ plane; here B_* is the surface magnetic field and P_o the initial period of the pulsars. All pulsars born on a given contour will have the same luminosity at a specified age. (a) The three contours correspond to three different luminosities (measured in 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.

are necessarily younger, as was assumed in Section 2. We already saw the case of MSH 15 – 52 in which hardly any central radio emission was found even though it is of roughly the same age as the Crab nebula! Thus, if we relax the assumption made in Section 2, namely that the Crab pulsar and its nebula are prototypes, it is not possible to estimate the ages of plerions and therefore their birthrates.

3.4 *Expected Number of Plerions*

What one can ask is the following. Given a pulsar birthrate, and range of initial periods and magnetic fields, how many nebulae does one expect to see with luminosities above a specified value.

One has to now set 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/l0th 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 Ay are unlikely to have been missed in surveys at frequencies around 1 GHz. It must be kept in mind that the plerions are likely to be more or less uniformly distributed in the inner Galaxy and that this flux limit corresponding to $L = 0.1\ L_{\mathrm{Crab}}$ refers to an extreme distance of 20 kpc. Therefore in what follows we shall take 0.1 L_{Crab} as the luminosity cut-off above which one should, in principle, be able to detect all sources in the Galaxy.

In Fig. 4, we have plotted several contours all corresponding to the above-mentioned

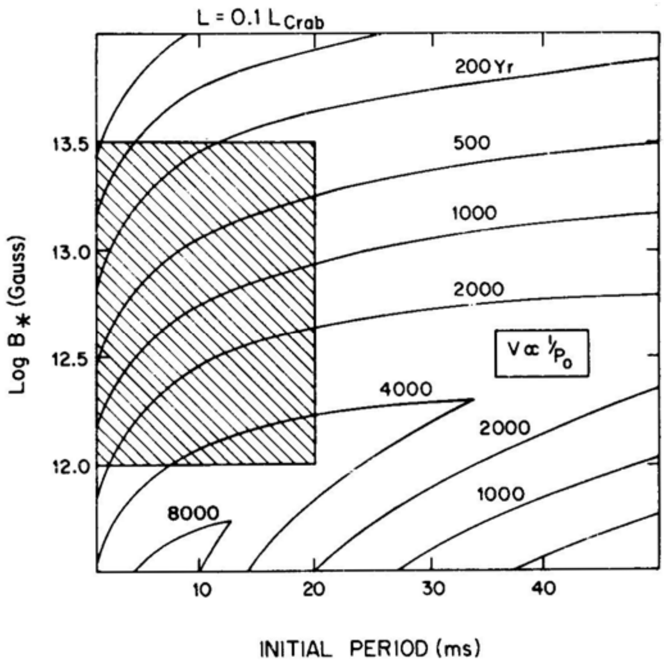

Figure 4. Pulsar-driven plerions. The contours of diffrent ages for a luminosity of 0.1 L_{Crab}. In estimating the expected number of plerions with luminosities greater than the above-mentioned value we have assumed that pulsars are born anywhere inside the shaded region (see Section 3).

luminosity, namely, 0.1 L_{Crab}. The labels on them represent the duration for which the nebulae are more luminous than the specified value, or in other words, their *lifetimes.* 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

$$N(>) = \frac{1}{\tau}\int_0^\infty t f(t)\,\mathrm{d}t. \tag{10}$$

Here $f(t)$ dt is the probability that the nebula will have a lifetime between t and t + dt. This formula is analogous to Equation (3) of Section 2. As we discussed above, the lifetime of the nebula depends on the initial parameters of the pulsar.

We shall assume a pulsar birthrate of 1 in 40 years, and that they are born with periods anywhere between 1 to 20 ms and log B_* (G) between 12 to 13.5 with equal probability.

Let $P(> t)$ be the probability that a nebula will have a *lifetime greater* than t. This is related to $f(t)$ we introduced in Equation (10) through

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

or

$$f(t) = -\frac{\mathrm{d}P(> t)}{\mathrm{d}t}. \tag{11}$$

Let $a(t)$ be the area enclosed by the contour corresponding to age t and *within* the area A specified above in the plane (the hatched area in Fig. 4). Then, clearly,

$$P(> t) = a(t)/A. \tag{12}$$

From Fig. (4) and Equation (10), we find that there should be 35 nebulae whose luminosities are greater than 1/10th that of Crab nebula, or in other words, whose fluxes should be greater than 1 Jy *even if placed at* 20 *kpc.* However, as can be seen from Table 1 there are at most 4 objects with luminosities above 0.1 L_{Crab}. There is, of course, a remote possibility that the sample is grossly incomplete, but this is extremely unlikely (see Weiler 1983). Thus we are once again faced with a gross discrepancy between the pulsar birthrate and the observed number of Crablike supernova remnants. There is, of course, the possibility that pulsar birthrates available in the literature are seriously in error. But it is very unlikely that this is so by a factor of eight! Another possibility is that most pulsars are born with fields less than 10^{12} G or greater than $10^{13.5}$ G, or that their initial periods are much greater than 20 ms. The former may be ruled out since it is inconsistent with pulsar observations (Radhakrishnan 1982). The latter possibility must be taken seriously.

The most straightforward conclusion that one might draw is that *pulsar-driven supernova explosions,* such as SN 1054 A.D., *are very rare events.* This conclusion has also been arrived at independently by Bandiera, Pacini & Salvati (1984), Reynolds & Chevalier (1984) and Weiler (1983). It must be remarked that this conclusion is consistent with the one drawn above, namely, that the initial periods of pulsars might be much greater than 20 ms. Pulsars with such long initial periods will have very little stored rotational energy and in addition will take a very long time to get rid of it ($\tau_0 \propto P^2_0/B^2_*$). Hence they are unlikely to have any dynamical effect on the mass surrounding the newly born neutron star.

According to the standard picture of Supernovae the energy of the explosion is not derived from the stored rotational energy of the central pulsar but rather from a shock wave driven by the core bounce during the formation of the neutron star (Arnett 1980). The velocity of the shell is determined by the strength of the shock wave and the mass in the envelope, and is expected to be ~ 10,000 km s^{-1}. It is immediately obvious that a pulsar in the centre of such a rapidly expanding shell will produce a much weaker plerion. In the next section we shall discuss this scenario.

4. Pulsars inside rapidly expanding shells

We shall assume a typical expansion velocity of 10,000 km s^{-1} for the shell and a pulsar birthrate of 1 in ~ 40 yr. Once again, we shall allow the initial periods of pulsars to lie anywhere in the range 1–20 ms and their fields between 10^{12} to $10^{13.5}$ G. Since we have now decoupled the velocity of the shell from the initial period of the pulsar, the formulae derived in PS can once again be used to calculate the luminosity of the central nebula produced by the pulsar, as a function of its age. We shall now estimate the number of such plerions with luminosities greater than 0.1 $L_{\text{Crab.}}$

In Fig. 5, we have plotted contours corresponding to the luminosity mentioned above for different ages. Following the procedure outlined in detail in Section 3, we arrive at the following conclusion. *There should be at least* 16 *plerions with luminosities greater*

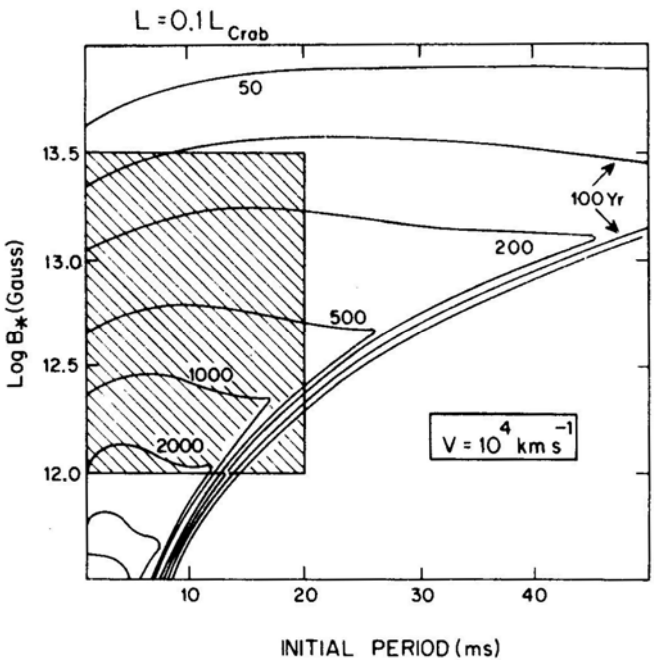

Figure 5. Plerions produced by pulsars inside standard shell SNRs expanding with a velocity 10^4 km s^{-1}. Once again the contours correspond to a luminosity of 0.1 LCrab. In Section 4, we have estimated the number of such plerions allowing the initial parameters of the pulsars to lie anywhere in the shaded region.

than 0.1 L_{Crab} *inside rapidly expanding shells.* This number will be even greater if the velocity of the shell is smaller than the assumed value of 10^4 km s^{-1}.

Although this number is less than the 35 predicted in the pulsar-driven scenario, the discrepancy with observations is even more glaring. From Table 1 we see that there are only four plerions above our luminosity limit. Of these, Crab clearly does not 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! This can of course be reconciled with a much lower pulsar birthrate. But once again we reject it. We also reject the possibility that no stellar remnant is left behind in Supernovae that produce well-defined shells for the following reasons. For one thing, a pulsar *has* been detected in a standard shell (MSH 15 – 52). Even if the Type I Supernovae do not leave behind stellar remnants but well-defined shells, one still expects pulsars in at least half the shell SNRs, since the frequency of Type II Supernovae, which are believed to leave behind neutron stars, is roughly equal to the frequency of Type I Supernovae (Tammann 1974). The only alternative is to say that all pulsars are born in a very different scenario, such as the instability of accreting white dwarfs. Though this is a very distinct possibility, van den Heuvel & Taam (1984) have argued that pulsars born in such a manner will belong to a very different class and will be a minority.

We feel that the only resolution is the following. Namely, that the majority of pulsars are born outside the region we have considered in the B_*–P_o plane. This implies relatively long initial periods ($P_0 \gg 20$ ms), contrary to conventional wisdom, and/or fields $> 10^{13.5}$ G or $<10^{12}$ G. We have already remarked that the statistics of pulsars is inconsistent with initial fields less than 10^{12} G and only a small fraction have fields greater than 10^{13} G (Radhakrishnan 1982). *Thus the only viable conclusion is that the initial periods of pulsars must be much greater than* 20 *ms.* It will be seen from Equation (7) that the dependence of the luminosity on the initial period is weaker than on the initial velocity of expansion. Consequently, the initial periods must be *substantially greater* than 20 ms, since increasing the expansion velocity of the boundary of the pulsar bubble from ~ 10^3 km s^{-1} to 10^4 km s^{-1} has not resolved the issue! The situation will be much worse in some current models of Supernovae (Chevalier 1977; Reynolds & Chevalier 1984) in which the pulsar bubble always expands with a relatively small velocity irrespective of the velocity of the expanding shell. These models will constrain the lower limit on the initial period much more.

5. The case of MSH 15–52

This is the third pulsar-SNR association in the Galaxy. Although the standard age of the shell is very large (~ 10^4 yr) compared to the characteristic age of the pulsar (1600 yr), the age derived from the Σ-t relation given by Srinivasan & Dwarakanath

(1982) is in excellent agreement with the pulsar age, thus confirming the pulsar–SNR association (Srinivasan, Dwarakanath & Radhakrishnan 1982). There is of course a possibility that it is an accidental superposition, as has been suggested by van den Bergh & Kamper (1984). But in this section we shall assume that the pulsar is in fact associated with the SNR.

Despite its young age, there is hardly any radio emission surrounding the pulsar (Manchester & Durdin 1983) but there is a pronounced X-ray nebula. Srinivasan, Dwarakanath & Radhakrishnan (1982) argued that the observed X-ray and radio luminosities are consistent with an initial period of the pulsar ~ 70 ms. They assumed that there was an inner shell which contained relativistic particles and which was expanding with a velocity similar to the filaments in the Crab nebula. In their paper, published soon after the discovery of the pulsar, the X-ray luminosity of the plerion was taken to be ~ 1/15th that of the Crab nebula. More recent estimates, however, give a value ~ 1/100 (Seward *et al.* 1984). This would modify the estimate of the initial period to ~ 115 ms, given the same assumptions, implying an age of 660 years for the pulsar and an average expansion velocity for the shell of ~ 24 000 km s^{-1}, an unacceptably large value. Hence we reject this estimate for the initial period.

As was already emphasized by Srinivasan, Dwarakanath & Radhakrishnan (1982), the assumption of an inner shell is a serious one. We now feel that it is more likely that the boundary of the plerion is the observed shell itself. This is the scenario discussed in Section 4.

Using the formalism of PS, we have calculated the evolutionary track for the radio and X-ray spectral luminosities appropriate for an expansion velocity ~ 10000km s^{-1} (as suggested by the characteristic age of the pulsar). These are shown in Fig. 6. It can be seen that the radio luminosity will be almost 10^4 times smaller than that of the Crab nebula for a whole range of initial periods. The predicted

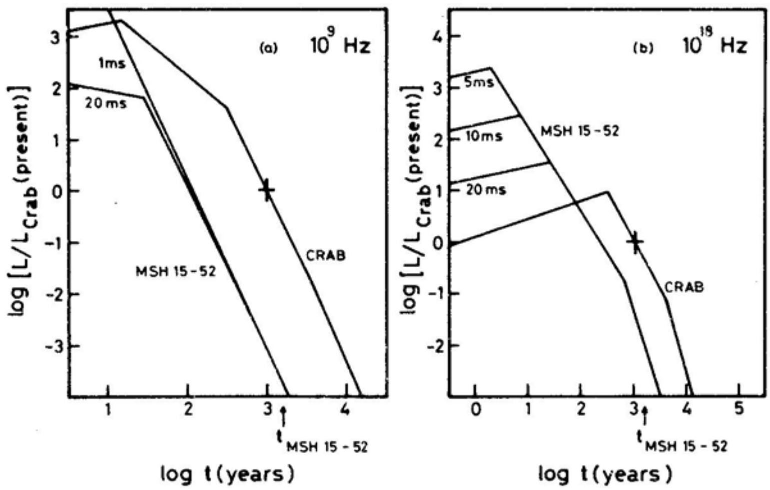

Figure 6. The expected luminosity of the central plerion in MSH 15–52 for several possible initial periods of the central pulsar. The measured magnetic field strength of the pulsar and an expansion velocity of 10^4 km s^{-1} were used; (a) refers to the radio and (b) to the X-ray luminosity; both are plotted in units of the present luminosity of the Crab at the respective frequencies. Shown for comparison are the evolutionary tracks of the Crab nebula.

X-ray luminosity ~ 10^{-2} that of the Crab nebula is also in good agreement with the observed value.

We see from Fig. 6 that the predicted luminosity of the plerion is very insensitive to the initial period of the pulsar; consequently we cannot draw any conclusions in this regard, as was done by Srinivasan, Dwarakanath & Radhakrishnan (1982) who used formulae appropriate for $t \lesssim \tau_0$.

6. 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 remnants (Clark & Stephenson 1977a; 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? None of these shells show significant emission from the centre From the published maps, one can get an *actual* estimate of the central emission only for the case of Kepler. The brightness temperature in the central region is less than 2 K, while the limb has an average brightness temperature ~ 10 K. Central emission at such a low level is consistent with an optically thin shell whose thickness is, say, 1/5 the radius. But by attributing all of it to a possible central plerion, one can get an *upper limit* to its luminosity. From this we can put bounds on the parameters of a central pulsar. In the case of the other remnants, since no central emission is detected, one can get weaker limits on the pulsar parameters by postulating a central plerion with a surface brightness l/5th the average value for the remnant. Since we know the ages of these remnants, we can estimate their average expansion velocities. The fluxes and distances used are summarised in Table 2. In Fig. 7, we have plotted for each of these remnants contours corresponding to $\Sigma_{\text{plerion}} = f\,\Sigma_{\text{average.}}$ The meaning of these contours is the following. Consider the one labelled 'Kepler'. If there is an active pulsar in its centre, then it could not have had an initial period and a field in the region enclosed by the contour. We have also included RCW 103, since there is a point X-ray source inside it. Its age was estimated to be 740. yr using the Σ–t relation given by Srinivasan & Dwarakanath (1982). It should be remarked that for all the remnants except Kepler the limit on the excluded region for the pulsar is very weak; one has been generous in admitting a central plerion with as large a surface brightness as $f\,\Sigma_{\text{average.}}$ *A more realistic value for the central surface brightness will increase the excluded region considerably,* bringing them closer to the contour for Kepler. We see from Fig. 7 that if there are pulsars in these remnants, they must all have fields significantly greater than 10^{13} G or lie to the right of the contours. Although one is dealing with a very small sample of historical remnants, it is striking that the conclusion is quantitatively similar in each case. Hence this may be statistically significant and suggest that pulsars in all the shells must have been born outside such an excluded region. In a prescient paper, Pacini (1972) arrived at the remarkable conclusion that the hollowness of the historical shells is consistent with the presence of very high field pulsars in them (~ 10^{14} G). This may indeed be so in specific cases. But this cannot apply to the majority of shells for the following reason. In Fig. 7 we have shown a histogram of the distribution of pulsar fields at birth. This has been derived from Fig. 13 of Radhakrishnan (1982). It is seen that very few pulsars have fields greater than 10^{13} G. This would imply that for the

Table 2. Historical shells considered.

Source	Distance d kpc	Angular diameter arcmin	Size pc	Age yr	Average velocity of expansion km s^{-1}	$\frac{L_{Plerion}{}^{*}}{L_{Crab}}$	Ref.
SNR 185	2.5	39	28	1800	7800	< 0.016	1, 2
SNR 1006	1.3	34	12.8	980	6500†	< 0.002	1, 3
RCW 103	3.3	9.4	9	740[a]	6000	< 0.014	1, 4
Kepler	3.5[b]	3.2	3.3	380	4300†	$\lesssim$ 0.012	1, 5, 6
Tycho	3	7.9	6.9	410	8400†	< 0.026	1, 7, 8, 9

* Luminosity attributed to a possible central plerion.

[a] This is not a historical remnant. Nevertheless it is an important one for our discussion since a point X-ray source has been detected in it. We have estimated its age using the Σ–t relation given by Srinivasan & Dwarakanath (1982).

[b] Danziger & Goss (1980) have significantly improved upon the standard estimate of $d \sim 10$ kpc.

† These average velocities tend to be much greater than the measured values (Hesser & van den Bergh 1981; van den Bergh & Kamper 1977; Kamper & van den Bergh 1978). It is conceivable that these remnants have decelerated in recent times.

References:

1. Clark & Caswell (1976)
2. Caswell, Clark & Crawford (1975)
3. Milne (1971)
4. Caswell *et al.* (1980)
5. Danziger & Goss (1980)
6. Gull (1975)
7. Duin & Strom (1975)
8. Gorenstein, Seward & Tucker (1983)
9. Storm, Goss & Shaver (1982)

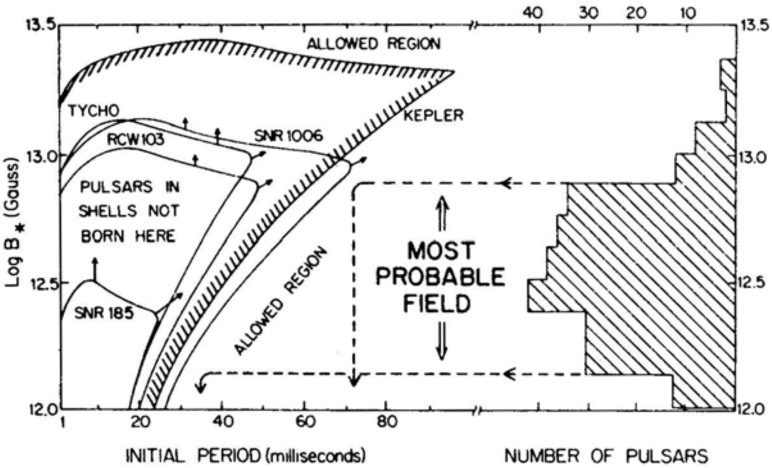

Figure 7. Pulsars inside the historical shells. The contours correspond to surface brightness of an assumed central plerion equal to fth the average surface brightness of the SNR; the appropriate ages and expansion velocities inferred from their sizes were used. If pulsars in these shells were born inside 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.

majority of pulsars that could be there in shells the period at birth must have been longer than 35–70 ms. We wish to regard this as a lower limit for the initial periods since the analysis was done not on the basis of measured fluxes from their centres, but on the basis of upper limits on them. Since the shell SNRs constitute more than 80 per cent of the sample of SNRs, *the above conclusion applies to the majority of all pulsars.*

7. Another way out?

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 in at least roughly half of them (produced by Type II Supernovae). We have then attempted to put constraints on the initial characteristics of the pulsars consistent with the absence of pronounced plerions in the shells.

There is however an alternative way out of this dilemma, and that is to say that there are neutron stars in all young SNRs, but not substantially endowed with fossil fields, and therefore not functioning as pulsars. A variety of mechanisms have been recently suggested for thermally driven magnetic field generation in neutron stars after their birth (Woodward 1978, 1984; Blandford, Applegate & Hernquist 1983 and references therein). According to the latter the timescale to build up the magnetic field to typical values observed in pulsars is ~ 10^5 yr. Long before this the SNRs would have faded away. It would appear that this scenario neatly explains the small number of SNRs of hybrid morphology. Two pulsars, however, are an embarrassment to the above picture, *viz.,* the Crab pulsar and PSR 1509 – 58 in MSH 15–52 (in the latter case a field of

1.5×10^{13} G has been presumably built up in at most ~ 9000 yr). Blandford, Applegate & Hernquist (1983) have suggested that in a rapidly rotating neutron star one may be able to tap the rotational energy to generate additional heat flux, thus enabling a rapid build-up of the field. Woodward (1984) has suggested that initially the magnetic fields of neutron stars may be built up by a Hall-field-limited battery effect. In this mechanism a saturation field which is proportional to the angular frequency of rotation (ω) will be built up in a timescale which will be proportional to ω^{-1} (Roxburgh 1966).

If such field build-up mechanisms are taken seriously, the fact that there are very few shell SNRs with central plerions seems to suggest that the neutron stars in them are unlikely to have been born spinning rapidly. For, otherwise, they will build up strong magnetic fields before the SNR disappears (like in MSH 15 – 52). It therefore seems to us that even if the magnetic fields of neutron stars are built up *after* their birth, one is forced to the conclusion that the majority of them must be born spinning slowly.

8. Conclusions

1. Our analysis of the sample of Crablike supernova remnants indicates that they are extremely rare objects. At present, only 7 or 8 such objects are known in the Galaxy, even though over 120 SNRs of shell morphology have been detected. In analogy with the Crab nebula and Vela X, it is reasonable to suppose that they are all powered by a central pulsar but whose beams are presumably missing us. If one assumes that all of them are remnants of Supernovae similar to SN 1054 AD, then the observed number of plerions yields a birthrate of 1 in ~ 240 yr. This is in fact an upper limit since we have allowed 7 out of 10 explosions to occur in the extremely low-density coronal gas component of the interstellar medium. Remnants expanding in this medium will have a very short life-time and hence will increase the estimated birthrate. A smaller filling factor for the coronal gas than the one we have assumed will further drastically reduce the birthrate quoted above.

2. In analogy with the remnant of SN 1054 AD, we have assumed in Section 3 that the boundaries of all plerions are accelerated by the central pulsar, but allowed the initial periods and fields to have any value in a domain $1 \lesssim P_0 \lesssim 20$ ms and $10^{12} \lesssim B_* \lesssim 10^{13.5}$ G. It was found that given a pulsar birthrate of one in 40 years, there should be about 35 nebulae with luminosities greater than 0.1 L_{Crab}. But in the sample of plerions, only four satisfy this criterion. Hence the majority of pulsars must be born outside the domain mentioned above, implying initial periods much greater than 20 ms. We dismiss the possibility of the majority having fields outside the range considered as inconsistent with pulsar observations. The alternative is to say that only in rare cases the pulsar accelerates the nebular boundary. Even if it does, only when the rare combination of 10 ms $\lesssim P \lesssim$ 20 ms and $B_* \sim 10^{12}$ G obtains, can the pulsar driven nebula be expected to be 'long-lived' and 'bright'. The particular nature of the Crab nebula must be understood in terms of the Crab pulsar having just these characteristics as surmised by Pacini (1972) a long time ago.

3. If the energy of the supernova is not derived from the pulsar, then it must be derived from the energy released in the formation of the neutron star. Hence we have studied the evolution of the luminosity of pulsar-produced nebulae inside rapidly expanding shells. Even in this case one should find 16 plerions with luminosities greater than 0.1 L_{Crab} inside standard shell SNRs. But there is not even a single such example.

Of the three sources (other than the Crab nebula) above this luminosity limit none show the expected X-ray shell or limb brightening in the radio. We conclude from this that pulsars inside shell SNRs must have initial periods substantially greater than 20 ms to be consistent with observations.

4. We have estimated the characteristics of pulsars in the historical shells from (generous) limits on the surface brightness of associated plerions (Fig. 7). In all cases, the bounds are similar, forcing us to the conclusion that pulsars in shell SNRs are born with periods greater than 35–70 ms. This provides strong support for the conclusion arrived at by Vivekanand & Narayan (1981) from an analysis of the periods and period derivatives of pulsars that the majority of them make their 'appearance' with periods $\gtrsim 100$ ms.

These conclusions once again raise but leave unanswered the fundamental question as to what determines when pulsars play a role in the acceleration of the nebular boundary.

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References

Arnett, W. D. 1980, *Ann. NY. Acad. Sci.,* **336,** 366.
Baade, W., Zwicky, F. 1934, *Phys. Rev.,* **45,** 138.
Bandiera, R., Pacini, F. , Salvati, M. 1984, *Astrophys. J.,* (in press).
Becker, R. H., Helfand, D. J., Szymkowiak, A. E. 1982, *Astrophys. J.,* **255,** 557.
Becker, R. H., Szymkowiak, A. E. 1981, *Astrophys. J.,* **248,** L23.
Blandford, R. D., Applegate, J. H., Hernquist, L. 1983, *Mon. Not. R. astr. Soc,* **204,** 1025.
Caswell, J. L, Clark, D. H., Crawford, D. F. 1975, *Austr. J. Phys., Astrophys. Suppl. No.* 37, 39.
Caswell, J. L, Haynes, R. F., Milne, D. K., Wellington, K. J. 1980, *Mon. Not. R. astr. Soc,* **190,** 881.
Caswell, J. L., Milne, D. K., Wellington, K. J. 1981, *Mon. Not. R. astr. Soc,* **195,** 89.
Caswell, J. L, Murray, J. D., Roger, R. S., Cole, D. J., Cooke, D. J. 1975, *Astr. Astrophys.,* **45**,239.
Chevalier, R. A. 1977, in *Supernovae,* Ed. D. N. Schramm, D. Reidel, Dordrecht, p. 53.
Chevalier, R. A. 1978, *Mem. Soc astr. ItaL,* **49**, 497.
Clark, D. H., Caswell, J. L. 1976, *Mon. Not. R. Astr. Soc,* **174,** 267.
Clark, D. H., Stephenson, F. R. 1977a, *Mon. Not. R. astr. Soc,* **179**, 87p.
Clark, D. H., Stephenson, F. R. 1977b, *The Historical Supernovae,* Pergamon Press, Oxford.
Danziger, I. J., Goss, W. M. *l9W,Mon. Not. R. astr. Soc,* **190,** 47p.
Duin, R. M., Strom, R. G. 1975, *Astr. Astrophys.,* **39**, 33.
Gorenstein, P., Seward, F., Tucker, W. 1983, in *IAU .Symp.* 101: *Supernova Remnants and their X-ray Emission,* Eds J. Danziger & P. Gorenstein, D. Reidel, Dordrecht, p. 1.
Green, D. A., Gull, S. F. 1983, in *IAU Symp.* 101; *Supernova Remnants and their X-ray Emission,* Eds J. Danziger & P. Gorenstein; D. Reidei, Dordrecht, p. 335.
Gull, S. F. 1975, *Mon. Not. R. astr. Soc.,* **171**, 237.
Helfand, D. J. 1983, in *IAU Symp.* 101: *Supernova Remnants ana their X-ray Emission,* Eds J. Danziger & P. Gorenstein, D. Reidei, Dordrecht, p. 471.
Henry, R. B. C, MacAlpine, G. M. 1982, *Astrophys. J.,* **258,** IL

Hesser, J. E., van den Bergh, S. 1981, *Astrophys., J.,* **251,** 549.

Higdon, J. C, Lingenfelter, R. E. 1980, *Astrophys., J.,* **239,** 867.

Kamper, K. W., van den Bergh, S. 1978, *Astrophys. J.,* **224,** 851.

Kazes, I, Caswell, J. L. 1977, *Pulsars,* Freeman, USA.

Maceroni, C, Salvati, M., Pacini, F. 1974, *Astrophys. Space Sei.,* **28,** 205.

Manchester, R. N., Durdin, J. M. 1983, in *IAU Symp.* 101: *Supernova Remnants and their X-ray Emission,* Eds J. Danziger & P. Gorenstein, D, Reidel, Dordrecht, p. 421.

Manchester, R. N., Taylor, J. H. 1977, *Pulsars,* Freeman, USA.

McKee, C. F., Ostriker, J. P. 1977, *Astrophys. J.,* **218,** 148.

Mills, B. Y. 1983, in *IAU Symp.* 101: *Supernova Remnants and their X-ray Emission,* Eds J. Danziger & P. Gorenstein, D. Reidel, Dordrecht, p. 551.

Milne, D. K. 1971, *Austr. J. Phys.,* **24,** 757.

Milne D. K., Dickel, J. R. 1971, *Nature Phys. Sei.,* **231,** 33.

Pacini, F. 1972, in *The Physics of Pulsars,* Ed. A. M. Lenchek, Gordon & Breach, London, p. 119.

Pacini, F., Salvati, M. 1973, *Astrophys. J.,* **186,** 249 (PS).

Phinney, E. S., Blandford, R. D. 1981, *Mon. Not. R. astr. Soc,* **194,** 137.

Radhakrishnan, V. 1982, *Contemp. Phys.,* **23,** 207.

Radhakrishnan, V., Srinivasan, G. 1978, paper presented at *Asian-South-Pacific Regional Meeting in Astronomy,* Wellington, unpublished.

Radhakrishnan, V., Srinivasan, G. 1980a, */. Astrophys. Astr.,* **1,** 25.

Radhakrishnan, V., Srinivasan, G. 1980b, */. Astrophys. Astr.,* **1**, 47.

Radhakrishnan, V., Srinivasan, G. 1981, paper presented at *2nd Asian-Pacific Regional Meeting IAU,* Bandung.

Radhakrishnan, V., Srinivasan, G. 1982, *Current Sei.,* **51,** 1096.

Radhakrishnan, V., Srinivasan, G. 1983, in *IAU Symp.* 101: *Supernova Remnants and their X-ray Emission,* Eds J. Danziger & P. Gorenstein, D. Reidel, Dordrecht, p. 487.

Rees, M. J., Gunn, J. E. 1974, *Mon. Not. R. astr. Soc,* **167,** 1.

Reynolds, S. P., Chevalier, R. A. 1984, *Astrophys. J.,* **278,** 630.

Roxburgh, I. W. 1966, *Mon. Not. R. astr. Soc,* **132**, 201.

Seward, F. D., Harnden, F. R. 1982, *Astrophys. J.,* **256,** L45.

Seward, F. D., Harnden, F. R., Szymkowiak, A., Swank, J. 1984, *Astrophys. J.,* **281,** 650.

Shukre, C. S., Radhakrishnan, V. 1982, *Astrophys. J.,* **258,** 121.

Spitzer, L. 1978, *Physical Processes in the Interstellar Medium,* Wiley-Interscience, New York.

Srinivasan, G., Dwarakanath, K. S. 1982, *J. Astrophys. Astr.,* **3,** 351.

Srinivasan, G., Dwarakanath, K. S., Radhakrishnan, V. 1982, *Current Set,* **51,** 596.

Strom, R. G., Goss, W. M., Shaver, P. A. 1982, *Mon. Not. R. astr. Soc,* **200,** 473.

Tammann, G. A. 1974, in *Supernovae and Supernova Remnants,* Ed. C. B. Cosmovici, D. Reidel, Dordrecht, p. 155.

Taylor, J. H., Manchester, R. N. 1977, *Astrophys. J.,* **215,** 885.

Trimble, V. L., Rees, M. J. 1970, *Astrophys. Lett.,* **5,** 93.

Trimble, V. 1983, *Rev. mod. Phys.,* **55,** 511.

van den Bergh, S., Kamper, K. W. 1977, *Astrophys. J.,* **218,** 617.

van den Bergh, S., Kamper, K. W. 1984, *Astrophys. J.,* **280,** L51.

van den Heuvel, E. P. J., Taam, R. E., 1984, *Nature,* **309,** 235.

Vivekanand, M., Narayan, R. 1981, *J. Astrophys. Astr.,* **2,** 315.

Weiler, K. W. 1969, *PhD Thesis,* California Institute of Technology.

Weiler, K. W. 1983, in *IAU Symp.* 101: *Supernova Remnants and their X-ray Emission,* Eds J. Danziger & P. Gorenstein, D. Reidel, Dordrecht, p. 299.

Weiler, K. W., Panagia, N. 1980, *Astr. Astrophys.,* **90,** 269.

Weiler, K. W., Seielstad, G. A. 1971, *Astrophys. J.,* **163,** 455.

Weiler, K. W., Shaver, P. A. 1978, *Astr. Astrophys.,* **70,** 389.

Woltjer, L. 1972$_S$ *A. Rev. Astr. Astrophys.,* **10,** 129.

Woodward, J. F. 1978, *Astrophys.* J.,**225,** 574.

Woodward, J. F. 1984, *Astrophys.*J.,**279,** 803.