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On the Morphology of Supernova Remnants with Pulsars

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Abstract. One of the intriguing aspects of supernova remnants is their morphology. While the majority of them look like hollow shells, a few, called plerions, are centrally filled like the Crab nebula, and some have a shell-plerion combination morphology. The centrally-filled component in these remnants is believed to be powered by a central pulsar. In this paper we present results of model calculations of the evolution of surface brightness and morphology of supernova remnants containing pulsars. We discuss how the morphology of a supernova remnant will depend on the velocity of expansion, the density of the ambient medium into which it is expanding, and the initial period and magnetic field strength of the central pulsar.

Key words: Supernova remnants, evolution—Supernova remnants, morphology—plerions—pulsars.

1. Introduction

Detailed radio observations over the past two decades have established that there are at least three distinct types of supernova remnants (SNRs). The vast majority of them have the appearance of hollow "shells" with hardly any central emission (*e.g.* Tycho's SNR, SNR 1006 etc.). Another class of SNRs are centrally-filled with no limb brightening. These have come to be known as "plerions", the Crab nebula is a prime example of this morphology. The third category contains SNRs of a "hybrid" nature—a shell surrounding a centrally condensed nebula. These are commonly referred to as "combination remnants". The SNR G 326.3–1.8 is an example of this class. Of the ~ 150 SNRs so far identified in our galaxy the relative numbers in the above three categories are roughly in the ratio 10:1:1 respectively (Weiler & Sramek 1988; Green 1988).

The reason for the occurrence of the three distinct types of SNRs has been debated in the literature. It is now widely accepted that a filled-centre nebula is powered by a central pulsar, although in many cases the pulsar may not be beamed towards us. A pronounced shell emission is believed to be the result of the interaction of the supernova ejecta with the interstellar medium. By extension, the presence of an active pulsar at the site of the supernova explosion would naturally account for the hybrid

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appearance of some SNRs. This still leaves unaccounted why the majority, viz. the shells, have hollow interiors. The explanation often invoked is that the shells and the plerions are the remnants of different types of supernova. Shklovskii (1980) suggested that plerions are produced by type II supernovae which leave behind pulsars, while shells are the result of type I supernovae which according to current models leave no stellar remnants. Although it is reasonable to associate plerions with supernovae that leave behind pulsars, it is not obvious that the hollow shells do not harbour central pulsars. In any case, it is difficult to identify the majority of shells with type I supernovae for the following reason. Recent studies of supernova statistics indicate that the Galactic rates of supernovae of type Ia, type Ib and type II are in the ratio 3:4:11 (van den Bergh, McClure & Evans 1987). If the progenitors of type Ib supernovae are massive stars as argued by van den Bergh (1988) then they, too, might leave behind neutron stars. Thus, the hollowness of the interiors of most SNRs can not, in all cases, be attributed to the absence of central neutron stars.

This led Radhakrishnan and Srinivasan (1983) to argue that the hollow shells should be understood in terms of their central pulsars having rather long initial periods. Srinivasan, Bhattacharya & Dwarakanath (1984) showed that the paucity of luminous plerions is, indeed, consistent with most pulsars being born spinning rather slowly. Although the hollow shells and the hybrid SNRs found a natural explanation in this scheme, the intriguing question as to why the classical plerions like the Crab nebula, 3C 58 etc. show no limb brightening remained open. Could it be that the plerions and the shells are merely manifestations of different stages of evolution of SNRs with central pulsars? Although such a suggestion was made by Lozinskaya (1980) it has not been examined in detail.

In this paper we wish to report the results of a simple model calculation which elucidates this question. Our aim is to obtain a qualitative understanding of the general trends of evolution, rather than to build detailed quantitative models. The problem we have studied is the following. Let there be an active pulsar at the centre of an expanding shell of supernova ejecta. The relativistic wind from the pulsar will produce a central synchrotron nebula, and the interaction of the ejecta with the interstellar medium will result in radio emission. By assuming these two components to evolve independent of each other, the radio morphology of the SNR at various times can be inferred by comparing the surface brightness of the shell and that of the central plerion. In the next section the analytical method adopted to compute the surface brightness of the two components is briefly outlined. In Section 3 the results for a Crab-like central pulsar are discussed. The dependence of SNR morphology on the characteristics of the central pulsar is discussed in Section 4. It has now become quite clear from observations that supernova remnants may expand in media of different densities, and also have different blast energies. The role of the ambient density in determining the surface brightness and morphology of a supernova remnant is discussed in Section 5.

2. The approach

The morphology of a supernova remnant which has both shell and plerionic components of emission depends on the relative surface brightness of the two. To study the evolution of the morphology, therefore, we have followed the evolution of both these components of composite SNR models, in which the shell emission forms at the outer edge of the plerionic nebula.

2.1 *The Plerionic Component*

A detailed theoretical model for the evolution of a pulsar-produced nebula was first constructed by Pacini & Salvati (1973). They derived analytical results for the evolution of the spectral luminosity of a uniformly expanding spherical bubble in which a central pulsar continuously injects magnetic field and relativistic particles. We have used the same formalism in our model calculations, with modifications appropriate for a bubble that undergoes deceleration at late times due to interaction with the surrounding medium. According to this model, the surface brightness of the plerion at a given time is determined by: (a) the initial period P_0 and the magnetic field B of the pulsar, and (b) the expansion velocity $v(t)$ of the nebula. Detailed analytical expressions for the luminosity evolution in the decelerated phase can be found in Reynolds & Chevalier (1984) and Bhattacharya (1987). A more accurate numerical treatment of this phase has been made by Bandiera, Pacini & Salvati (1984), and also Reynolds & Chevalier (1984). For the present model calculations, we feel that it is sufficient to follow the analytical approach.

2.2 *The Shell Component*

The radio emission of the shell component is believed to originate due to the interaction of the supernova ejecta with the interstellar medium. Unfortunately, no reliable analytical method exists for the computation of the evolution of the radio luminosity. The first quantitative model for the radio emission of a shell remnant was due to Gull (1973). He studied the numerical evolution of hydrodynamical models of supernova remnants, and showed that a certain fraction of the blast wave energy goes into turbulence at the interface between the shocked interstellar matter and the supernova ejecta. These turbulent cells can amplify the magnetic field by stretching and twisting the field lines, and also accelerate relativistic particles by the "Fermi process". Under the assumption that an equipartition is reached between the energy densities in turbulence, magnetic field and relativistic particles, one may then calculate the evolution of the radio luminosity of the shell. The surface brightness at a given time will be a function of the ejected mass M_{ej}, the ambient density n_0 and the blast energy $E_{tot} \equiv \frac{1}{2} M_{ej} v_i^2$, where v_i , is the initial velocity of expansion. This model explains fairly well the evolution of radio luminosity of young supernova remnants like Cas A and Tycho's SNR (Gull 1973,1975; Braun, Gull & Perley 1987). Detailed models of particle acceleration, if included, also leads to similar results (Scott & Chevalier 1975; Cowsik & Sarkar 1984). It is likely that in some cases shock acceleration may also be an important source of relativistic particles in the shell. Unfortunately there is as yet no complete theory for the origin of these high-energy particles. In this paper we have used Gull's models to estimate the radio luminosity of the shell component of the SNR.

To build the final model, we have combined the evolution of the shell and the plerionic components with a common expansion velocity. The SNR is assumed to be a spherical bubble of radius R at a time t, where

$$R(t)=v_i t \qquad \text{if} \quad M_{sw}(t)<M_{ej}$$

and

$$R(t)=v_i t_0 (t/t_0)^{0.4} \qquad \text{if} \quad M_{sw}(t)>M_{ej}.$$

Here M,(t) is the swept up mass: $M_{sw}(t)=\frac{4\pi}{3}R^3(t)n_0\, m_p$, and t_0 is the time at which $M_{sw}(t)=M_{ej}$; m_p is the proton mass. This model for expansion is based on asymptotic slopes, and is admittedly crude. The $t^{0.4}$ expansion law is appropriate for the so-called Sedov phase of evolution, but numerical calculations (*e.g.* Fabian, Brinkmann & Stewart 1983) show that the Sedov phase begins when $M_{sw} \gtrsim 5M_{ej}$, and is fully established only after $M_{sw} > 19M_{ej}$. This is likely to introduce an uncertainty of a factor ~ 2 in the estimate of to mentioned above. The shell emission is assumed to be confined to within a thickness $\Delta R = \delta \cdot R(t)$ at the outer edge. In the calculations reported here, we have used a constant value of $\delta = 0.2^{\dagger}$. The cavity interior to the shell is assumed to be filled by the plerionic nebula.

It should be mentioned that due to the simple relation adopted between the expansion rate of the shell and the plerionic components of the remnant, this model cannot treat the case of a large amount of slow-moving material in the interior of the supernova ejecta, a scenario discussed in detail by Reynolds & Chevalier (1984).

As mentioned above, we are interested in studying the evolution of the SNR for different values of blast energy (E_{tot}), ambient density (n_0) and ejected mass (M_{ej}). However, Gull's (1973) calculations were done for a particular choice of these parameters. To use these results for other values of E_{tot}, n_0 and M_{ei}, we adopted the following scaling procedure:

(a) From the results presented graphically by Gull (1973), we expressed the dimensionless quantities E_{rel}/E_{tot} and $B_s(M_{ej}ln_0E_{tor})^{1/2}$ as a function of the dimensionless mass ratio parameter x, defined as $x= \frac{4\pi}{3}R^3(t)m_p n_0 /M_{ej}$, where E_{rel} is the energy content in relativistic particles, B_s the magnetic field in the shell region and m_p the proton mass. These relations were expressed in best-fit polynomial form.

(b) From the radius *vs* time relation in our model we computed $x(t)$, and using the above relations we obtained $E_{rel}(t)$ and $B_s(t)$ for any desired value of E_{tot}, n_0 and M_{ej}. These were then used to compute the radio luminosity of the shell component as a function of time.

The relativistic particles responsible for the synchrotron radiation from both the shell and the plerionic components were assumed to be injected with a power-law energy distribution of the form $N(E)\propto E^{-\gamma}$, with the value of γ chosen to be 1.6 for the plerionic component (in analogy with the Crab Nebula), and 2.3 for the shell component (as in an average shell remnant).

Given the assumptions and the method outlined above, one can now follow the evolution of the surface brightness of the idealized composite SNR. We compute, as a function of time, the surface brightness of the plerionic component averaged over the

†This estimate of shell thickness is likely to be poor in late phases of the evolution, and when the pulsar power is small. In reality, the relative size of the pulsar bubble and the outer shock may vary with time in a complicated manner, as suggested by Reynolds & Chevalier (1984). However, we shall adopt the (simpler) model described above, in order to keep the problem tractable.

projected “disc”, and that of the shell component averaged over the projected bright “ring” at the edge of the plerionic “disc”.

3. Results

Fig. 1 illustrates the evolution of the surface brightness for the following parameters.

initial velocity = 10^4 km s^{-1}

density of ISM = 1 atom cm^{-3}

initial period of PSR = 16 ms

magnetic field = 3.7×10^{12} G

The parameters of the pulsar have been chosen to be that of the Crab pulsar, often assumed to be the prototype of a young pulsar. Again, the initial velocity of the ejecta and the density of the ISM are “standard-values”. As expected, the surface brightness of the shell (broken line) increases to reach a maximum at a time ~ t_0 when deceleration sets in. The rapid decline at t > 3000 yr is an artefact of the extrapolation of the polynomial fit to Gull’s models. The evolution of the plerion is shown as the solid line. The change of the rate of decline of the surface brightness at $t = t_0$ and $t = \tau_0 (\equiv P_0 / 2\dot{P}_0)$, the initial characteristic slow-down timescale, are due to the deceleration of the walls of the cavity and the decline in the pulsar luminosity respectively. In reality the transition between these different phases will be smooth and gradual.

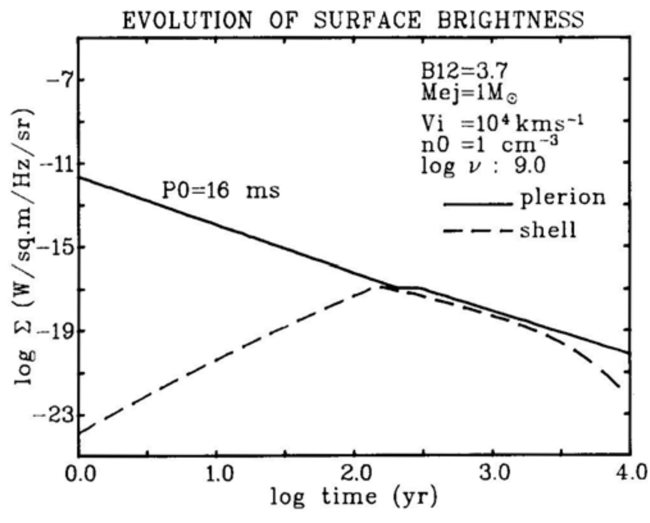

Figure 1. Evolution of the 1 GHz surface brightness of the plerionic component (solid line)and the shell component (dashed line) of a supernova remnant harbouring a Crablike pulsar and expanding in a uniform medium of density 1 Hatom cm^{-3}.10^{12} B12 gauss is the surface dipole magnetic field of the pulsar and P0 is its initial rotation period. Mej is the mass in the ejecta, Vi the initial velocity of expansion, and n0 the density of the ambient medium, ν is the assumed frequency of observation in Hz. A fairly strong shell component is expected, resulting in a combination morphology of the remnant. The rapid drop of the shell surface brightness at ages exceeding ~ 3000 yr is an artifact due to the extrapolation of the polynomial relations used to fit Gull’s (1973) models.

As we see from this figure, once the shell emission builds up to its peak value its surface brightness remains comparable to that of the central plerionic component. Thus, after a few hundred years the remnant will have a combination morphology. Although the surface brightnesses plotted in Fig. 1 have been computed at 1 GHz, the morphology will be roughly the same also at lower observing frequencies. Quantitatively, the ratio of the surface brightness of the shell to that of the plerion will be larger at lower frequencies owing to the fact that the spectral index of the shell is usually larger than that of the plerion.

The most striking feature of the above figure is that although the central pulsar has the same period and magnetic field as the Crab pulsar, the morphology of the remnant is very different from that of the Crab nebula which shows no pronounced limb brightening. In our opinion, the reason for this is the following. One of the most remarkable properties of the Crab nebula is its very small expansion velocity ~ 1700 km s^{-1}. All available evidence indicates that the ejecta have not yet decelerated; if anything, there was a post supernova acceleration of the filaments. To see the effect of such a small initial velocity of expansion on the morphology of the remnant we have repeated the calculations for a slowly expanding remnant and the results are shown in Fig. 2. We see that in this case even after the shell builds up, its surface brightness will be about two orders of magnitude smaller than that of the plerion. A recent lunar occultation observation of the Crab nebula (Agafanov *et al.* 1987) confirms the earlier observations that the spectrum steepens significantly near the outer edge of the nebula. The surface brightness of this steeper spectral component is ~ 1 per cent that of the relatively flat spectrum plerion. This is consistent with the expectations based on Fig. 2.

To summarize, our calculations indicate that bright plerions like the Crab and 3C 58 which show hardly any limb brightening may be the remnants of rather low

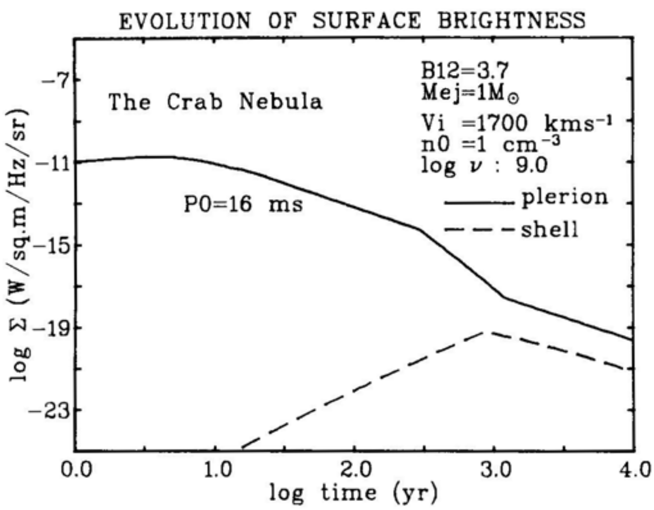

Figure 2. Evolution of the shell and the plerionic components of the Crab nebula, expanding with a small velocity ~ 1700 km s^{-1}. The plerionic component dominates the emission at all times; the maximum contribution of the shell component being ~ 1%, in agreement with recent lunar occultation observations (Agafanov et al. 1987) of the Crab nebula. See caption of Fig. 1 for explanation of legends.

energy Supernovae. The paucity of such objects is consistent with the fact that the estimates of the kinetic energy of the ejecta in most extragalactic Supernovae is ~ 10^{51} ergs, rather than 10^{49} ergs estimated for SN 1054 from the Crab nebula. In view of this, in the remainder of the discussion we shall adopt the standard value of $E_{\text{tot}} \sim 10^{51}$ erg.

4. Dependence of the morphology on pulsar parameters

Although the kinetic energy of the ejecta in most Supernovae may be a Standard number, the parameters of the pulsar and the interstellar medium into which the ejecta expand are not. First we will discuss how the morphology of an SNR depends on the properties of the central pulsar.

Even though the Crab pulsar is often taken to be the prototype of young pulsars there is mounting evidence that this may not be so. A careful analysis of the statistics of plerions (Srinivasan *et al.* 1984) and a study of the distribution of the periods and period derivatives of pulsars (Vivekanand & Narayan 1981; Narayan 1987) both suggest that the majority of pulsars may be born with rather long spin periods compared to the Crab pulsar. In addition the distribution of the derived magnetic fields of pulsars reveals a spread of over two orders of magnitude. As was mentioned before, both the initial period and the magnetic field have an important influence on the surface brightness of the plerions produced by the pulsars. This is illustrated in the next two figures. In Fig. 3 the surface brightness of the plerions produced by pulsars with three different initial periods is compared with that of the shell; the blast energy and the density of the interstellar medium are the same as in Fig. 1 (10^{51} erg and 1 atom cm^{-3} respectively). As can be seen, the central nebula produced by a 100 ms pulsar never gets nearly as bright as the shell. Such remnants, once they build up, will have the morphology of a hollow shell. Interestingly, this is nearly true even if the initial period of the pulsar is very small. The nebula produced by a 3 ms pulsar, though very bright initially, will become less luminous than that produced by a 16 ms pulsar. Consequently, the remnant will have a combination morphology with a dominant shell component. The reason for this is that a very fast pulsar deposits most of its energy rather quickly when the size of the cavity is rather small. Because of this the adiabatic losses are more severe and reduce the energy content at late times considerably. Consequently, the luminosity of the plerion is less than that of, for example, a 16 ms pulsar. At lower frequencies the shell will be even brighter relative to the plerion. Thus only when the initial characteristics of the central pulsar are similar to that of the Crab pulsar will the remnant have a hybrid radio morphology with a strong plerionic component. If the initial period of the pulsar is very small, then the pressure of the pulsar bubble will *accelerate* the ejecta, increasing the kinetic energy of expansion. This will result in the shell component being even brighter relative to the plerion.

Fig. 4 shows the evolution of the surface brightness for three different values of the surface magnetic field of the pulsar; the initial period is assumed to be 16 ms for all the pulsars. We see that if the surface magnetic field of the pulsar is very large then at late times the plerion it produces becomes less bright than one produced by a pulsar with a lower magnetic field. Again the basic reason is more severe adiabatic losses at early times. However, if the magnetic field is *very* small then the plerion never builds up to a

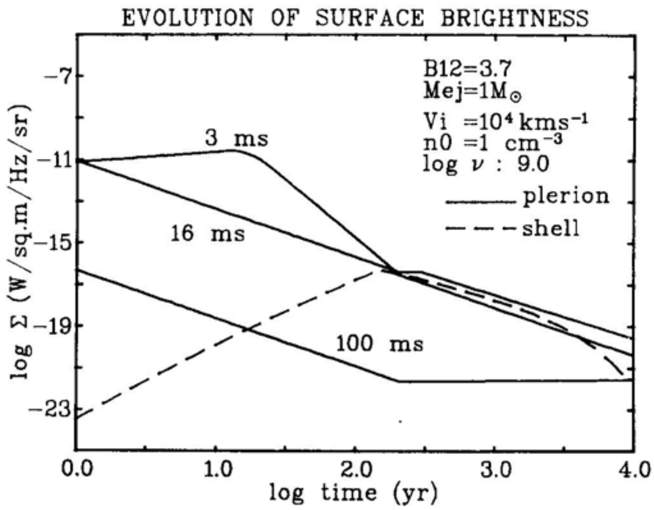

Figure 3. Dependence of the SNR morphology on the initial spin period of the central pulsar. Plerionic components produced by pulsars with initial periods 3, 16 and 100 ms are shown. An ambient density of 1 H atom cm^{-3} has been assumed. The ratio of the surface brightness of the plerion to that of the shell attains a maximum value when the timescale for the ejecta to decelerate matches the initial spindown timescale of the central pulsar. See caption of Fig. 1 for explanation of legends.

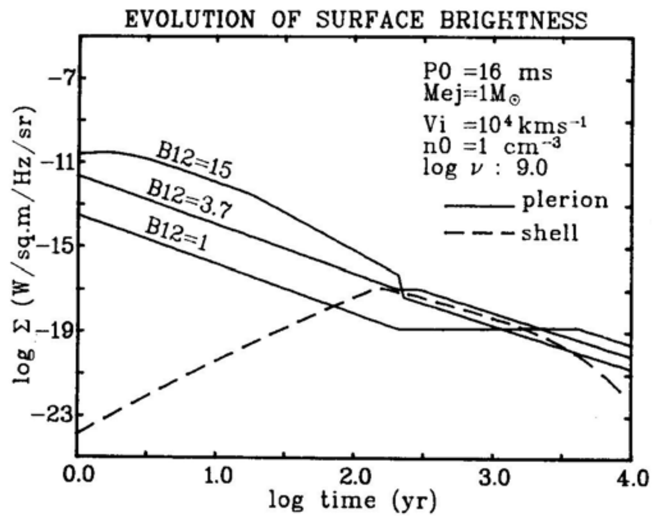

Figure 4. Evolution of the shell and the plerionic component of an SNR for three different values of the magnetic field of the central pulsar. See caption of Fig. 1 for explanation of legends.

high enough surface brightness to compete with the shell. Thus as in the case with different initial periods, the remnant is expected to have a hybrid morphology with a strong plerionic component only if the magnetic field of the central pulsar has a value similar to that of the Crab pulsar ($\sim 4 \times 10^{12}$ G).

The evolutionary model considered above is relevant for the early phase of development of supernova remnants, upto an age of $\sim 10^4$ yr. When the remnant becomes very old, many other physical processes may significantly influence its morphology. For example, it has been suggested (Shull, Fesen & Saken 1989) that in remnants of age $\gtrsim 10^5$ yr, the pulsar may move and catch up with the decelerated shell, and re-energize it by supplying relativistic particles. The resultant morphology in this case may turn out to be quite complicated, CTB 80 being an example.

5. The role of the interstellar density

One of the major factors determining the evolution of supernova remnants is the density of the ISM into which it expands. Traditionally, in this context it is generally assumed that the particle density of the ISM is of the order of 1 atom cm^{-3}. There is mounting evidence that this not a good assumption.

The standard model of the ISM that emerged from 21 cm observations is the so-called "two component" model in which small cool clouds are in pressure equilibrium with a warm diffuse intercloud medium of density $n_0 \sim 0.3$ cm^{-3} (Spitzer 1978). It is this intercloud medium in which most supernova remnants are assumed to evolve. While the existence of such a warm medium is well established, its filling factor is still very controversial. Recent ultraviolet and X-ray observations (Rogerson *et al.* 1973; Jenkins & Meloy 1974; York 1974; Cowie & Songaila 1986) have revealed the presence of a medium of much lower density and higher temperature ($n_0 \sim 3 \times 10^{-3}$ atoms cm^{-3}, $T \sim 10^6$ K). The existence of such a "Coronal gas" had, in fact, been predicted by Spitzer (1956). According to some authors (*e.g.* McKee & Ostriker 1977) this gas may have a filling factor ~ 70 per cent, but this, too, is very uncertain and controversial. Nevertheless it is important to examine how a supernova remnant will evolve in such a low density medium. It has been poirted out by several authors (Lozinskaya 1979; Srinivasan & Dwarakanath 1982 and several others) that a shell remnant expanding in a low-density medium will turn on later, and its peak luminosity will be smaller compared to one expanding in a denser medium. A low-density ambient medium also has an important effect on the plerion. Since deceleration will set in much later, the adiabatic losses of the energy in relativistic particles and magnetic fields will be severe for much longer.

Quite apart from the coronal gas there are reasons to expect that some fraction of Supernovae with massive progenitors may go off in low-density regions. In recent years it has been established that massive stars lose a significant amount of mass by means of high-velocity stellar winds. Such a stellar wind is expected to excavate a cavity in the original interstellar medium. The interior of such a bubble is likely to have a density ~ 0.01 atom cm^{-3} and its radius can be $\gtrsim 10$ pc (Weaver *et al.* 1977). If such a bubble remains stable till the star eventuall, explodes, then the ejecta will initially expand in a low-density medium before encountering the interstellar medium.

Keeping all this in mind we have repeated the evolutionary calculation for lower values of the ambient density. Fig. 5 shows the model evolution in a stellar wind bubble with the characteristics mentioned above. As expected, the shell emission turns on later, and the peak surface brightness is smaller than that in Fig. 3. In spite of this the plerionic component does not dominate at late times. This is a direct consequence of the free expansion phase lasting longer in a low density medium. This trend will be the same, of course, in the coronal gas.

Fig. 5 also illustrates the fact that at a given age a supernova remnant expanding in a low-density medium is much less bright than its counterpart in a higher-density medium. Consequently, given a detection limit for surface brightness, the lower the ambient density, the shorter will be the observable lifetime of the supernova remnant. This has an important implication for the derived birthrates of the supernova remnants and we will discuss this a little later.

The morphology of a supernova remnant expected under different conditions is briefly summarized in Table 1. As we can see, very fast pulsars produce very bright plerionic nebulae which at late times evolve into shell remnants. Crab-like pulsars, on the other hand, produce long-lived and bright plerions. For standard explosion energies (~ 10^{51} erg) such plerions are expected to be surrounded by shell components of comparable brightness.

After the shell emission builds up, the relative contrast between the brightness of the shell and that of the plerionic component (and hence the final morphology of the SNR) is not as strongly dependent on the ambient density as the surface brightness itself is. The highest value of $\Sigma_{\rm plerion}/\Sigma_{\rm shell}$ obtains when the initial spindown timescale τ_0 of the central pulsar roughly equals the deceleration timescale t_0, which is different in different media. If the central pulsar is fast, and if the remnant is expanding in a low-density medium, the shell component will become more dominant at late times. However, since in a low-density medium the lifetime of a supernova remnant is small, and the shell turns on later, this late phase of evolution will be detectable only for a short time; consequently for most of its lifetime the remnant will have a plerionic appearance. It seems therefore that while a shell or a combination morphology of a supernova remnant may be expected under a wide variety of circumstances, there appear to be only two ways to make a purely plerionic nebula: either the kinetic energy of expansion must be very low—like in the Crab nebula, or the ambient medium must

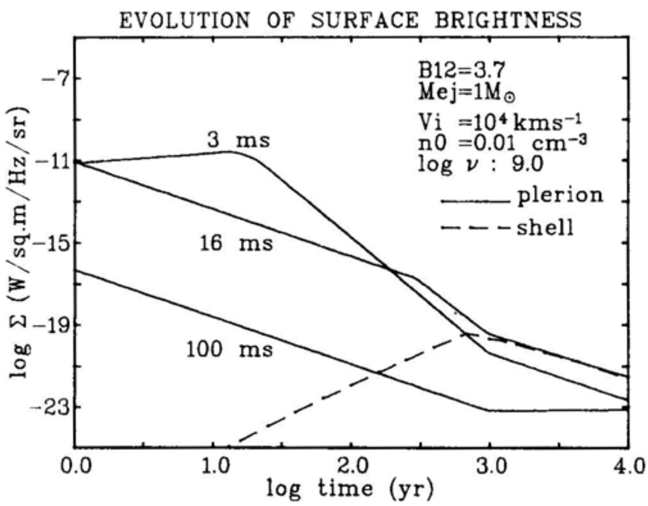

Figure 5. Same as Fig. 3, but for an ambient density of 0.01 H atom cm^{-3}, appropriate for a stellar wind bubble. The shell emission turns on later, and reaches a smaller peak surface brightness than in Fig. 3. Yet the plerionic component does not dominate at late times because of the prolonged phase of free expansion during which adiabatic losses are severe. See caption of Fig. 1 for explanation of legends.

Table 1. SNR morphology expected under different conditions.

Pulsar's initial spin		Strong Explosion $E_{tot} \sim 10^{51}$ erg	Weak Explosion $E_{tot} \sim 10^{49}$ erg
Fast	($P_0 \lesssim 5$ ms)	Very bright plerion ⇒ Shell	"Pulsar-driven" bright plerion ⇒ shell
Medium	($P_0 \sim 20$ ms)	Bright plerion ⇒ combination	Bright plerion
Slow	($P_0 \sim 100$ ms)	Weak plerion ⇒ shell	Weak plerion ⇒ combination

have a very low density, which will keep the morphology "plerionic" for most of the detectable lifetime of the SNR. Of course, the characteristics of the central pulsar must be appropriate for producing a strong plerionic component.

6. Discussion

We wish to illustrate a few specific cases where the morphology and the surface brightness (or the limit to it) of supernova remnants seem to be best understood in terms of their evolution in media of low density.

6.1 *Absence of SNRs around Young Pulsars*

In a recent high frequency survey by Clifton & Lyne (1986) three pulsars with spindown ages ~ 20,000 yrs were discovered (PSR1737–30, PSR1800–21, and PSR 1823–13). A subsequent sensitive search with the VLA for supernova remnants around these pulsars have placed stringent upper limits on the surface brightness of possible emission surrounding these pulsars (Braun, Goss & Lyne 1989). Using our simple model it is possible to estimate the expected surface brightness of the supernova remnants around these pulsars for different values of the ambient density. We find that in all the three cases the limit of the surface brightness set by the VLA observations can be reconciled only if the ambient density is assumed to be less than or equal to 0.01 atom cm^{-3}, for standard values of the explosion energy.

6.2 *The Supernova Remnant MSH 15-52*

Another likely case of evolution in a tenuous medium is that of the supernova remnant MSH 15–52. This remnant harbours a pulsar (PSR 1509–58) with a spindown age of ~ 1600 years, but has a rather large diameter (~ 30 pc). The standard "Sedov" age of the SNR is ~ 10^4 yr (Seward *et al.* 1984). In radio the remnant has the morphology of a hollow shell, but there is a bright X-ray plerion surrounding the pulsar. The relevant properties of this SNR are listed in Table 2.

Table 2. Properties of SNR MSH 15–52.

		Ref.
Angular Diameter	: 30 arcmin	1
Flux (1 GHz)	: 70 Jy	2
Σ of the shell region	: 8×10^{-20} W m^{-2} Hz^{-1} sr^{-1} at 1 GHz	1
Distance	: 4.2 kpc	3
X-ray luminosity of the plerion	: 5×10^{16} erg s^{-1} Hz^{-1} at 4 keV	4
PSR 1509–58		
Period	: 150 ms	5
Period derivative	: 1.54×10^{-12} s s^{-1}	5
Derived Magnetic Field	: 1.5×10^{13} gauss	
Spindown age	: 1600 yr	

References:
1 Caswell, Milne & Wellington 1981
2 Weiler 1983
3 Caswell, Murray, Roger, Cole and Cooke 1975
4 Seward, Harnden, Szymkowiak and Swank 1984
5 Weisskopf et al. 1983

Different explanations offered for the discrepancy between the apparent ages of the pulsar and the supernova remnant include:

1. chance superposition of the pulsar on the supernova remnant (van den Bergh & Kamper 1984),
2. late turn-on of a ~ 10^4-year-old neutron star as a pulsar due to magnetic field growth (Blandford, Applegate & Hernquist, 1983), and
3. a fast expansion of the SNR to its presently observed size in ~ 1600 years (Srinivasan, Dwarakanath & Radhakrishnan 1982; Seward *et al.* 1984).

The last alternative requires a low ambient density around the supernova. This is, in fact, quite likely since this SNR is in the vicinity of a complicated OB association indicating that the progenitor of the supernova might have been a massive star with a strong stellar wind, which could have created a large low-density bubble around itself.

We wish to argue that all the gross properties of this supernova remnant are consistent with the hypothesis that it initially expanded in a low-density stellar wind bubble. If the density of the external medium is 0.01 cm^{-3}, then the observed size of the remnant can easily be reconciled with an age ~ 1600 years if the mass ejected was ~ 2 $M_\odot$ and the initial expansion velocity ~ 12000 km s^{-1}. The expected surface brightness of the shell is also consistent with this choice of initial parameters (see Fig. 6). What remains to be explained is why there is no detectable radio plerion although there is a fairly luminous X-ray plerion. As has been argued before, the clue resides in the initial rotation period of the pulsar. We see from Fig. 7 that the observed X-ray luminosity can be well understood if the initial period was ~ 6 ms. Given such a fast pulsar in a rapidly expanding cavity the low radio surface brightness of the plerion is to be expected. As can be seen from Fig. 6, the expected radio surface brightness will be < 10^{-23} Wm^{-2} Hz^{-1} sr^{-1}, well below the level of detectability. Of course, given that this is a very-high-field pulsar, even a somewhat slower pulsar will produce a weak radio plerion (see Fig. 4). Therefore, in our opinion, the only reasonable way to

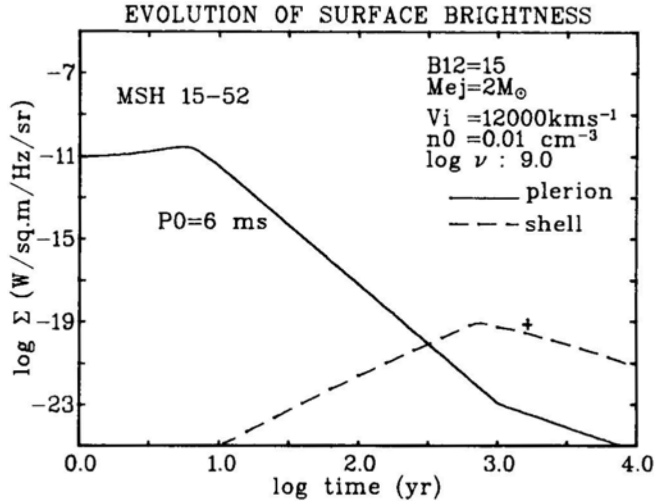

Figure 6. A model evolution of the shell and the plerionic components of the supernova remnant MSH 15–52. It is assumed that the remnant is expanding in a stellar wind bubble. The observed value of Σ is shown by a " + " mark. See caption of Fig. 1 for explanation of legends

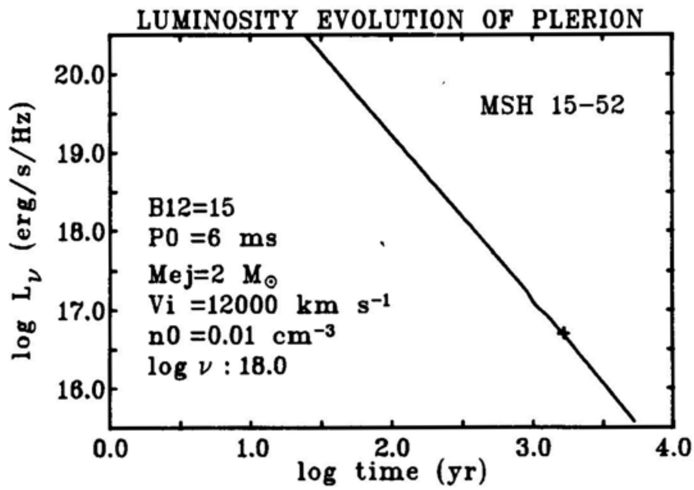

Figure 7. A model evolution of the X-ray luminosity of the plerionic component of the supernova remnant MSH 15–52. The observed X-ray luminosity is indicated by the " + " mark. See caption of Fig. 1 for explanation of legends.

reconcile a bright X-ray plerion and the absence of a radio plerion is to invoke an initial rapid expansion phase.

7. Conclusions

The important points that emerge from the above discussions are:

1. In many cases the morphology of a SNR harbouring a pulsar is likely to be that of a hollow shell. Indeed, the conditions in which a detectable plerionic component is

expected are quite restricted. Thus, the hope that the presence of a pulsar in a SNR should be revealed by means of the plerion it creates (Radhakrishnan & Srinivasan 1980) may, in most cases, not be realized in practice. An immediate implication of this is the following.

2. A good fraction of shell SNRs may, in fact, have pulsars in them, and more and more of them will be classified as combination remnants as the dynamic range of the observations improve in the future.

3. The SNR Birthrate: An obvious implication of the above is that the birthrate of shell SNRs must be nearly equal to the pulsar birthrate, if not more. There has been a long-standing controversy in this regard. While the present estimate of the pulsar birthrate is about one in ~ 40 years (see, *e.g.* Narayan 1987), the "standard" estimate of SNR birthrate is one in ~ 80 years (Clark & Caswell 1976).

A possible resolution of this disagreement is suggested by another important point raised in the above discussion. We have seen that in some cases the observed characteristics of supernova remnants have to be understood in terms of the ambient medium being of rather low density. It has also been argued that in a good fraction of cases a supernova is expected to go off in a low-density medium, namely, the interior of a stellar wind bubble created by the progenitor star. Some SNRs should also evolve in the very tenuous coronal gas.

As has been discussed by many authors (*e.g.* Lozinskaya 1979; Higdon & Lingenfelter 1980; Tomisaka, Habe and Ikeuchi 1980; Srinivasan and Dwarakanath 1982), and also pointed out above, a low ambient density significantly reduces the detectable lifetime of a supernova remnant, and appropriate allowance has to be made for this in deriving the birthrate of SNRs. This can be done in the following manner (see Lozinskaya 1979). If f_w and f_c represent the "filling factors" of the "warm" medium (of density ~ 0.3 atom cm^{-3}) and the coronal gas (of density ~ 3×10^{-3} atom cm^{-3}) respectively ($f_w + f_c = 1$), and f_b represents the fraction of SNRs expanding in stellar wind bubbles, then the inverse birthrate τ_{SNR} would be given by:

$$\tau_{SNR} = [f_b t_b + (1 - f_b)(f_w t_w + f_c t_c)]/N_{SNR}$$

where N_{SNR} is the number of shell SNRs (since most of the evolved remnants are expected to have a shell morphology) detected above a certain limit of surface brightness, and t_w, t_c and t_b are the "lifetimes" of these SNRs above this level of surface brightness in the corresponding media. According to Clark & Caswell (1976), the sample of galactic supernova remnants is reasonably complete above a surface brightness $\Sigma = 10^{-20}$ W m^{-2} Hz^{-1} sr^{-1} at 408 MHz. Their catalogue contains 71 shell SNRs above this limit. Using our models, we estimate the lifetimes t_w and t_b above this limit to be ~ 5300 yr and ~ 850 yr respectively. A supernova remnant evolving in the coronal gas would never become brighter than this limit, and the value of t_c can be taken to be zero. If the fraction of SNRs evolving in stellar wind bubbles is insignificant, *i.e.* $f_b \simeq 0$, then the inverse birthrate τ_{SNR} derived from the above expression lies in the range 76–23 yr for a corresponding range of 0–70 per cent for the filling factor f_c of the coronal gas. On the other hand, if we assume that ~ 50 per cent SNRs evolve in stellar wind bubbles, for example (*i.e.* $f_b \sim 0.5$), then τ_{SNR} will lie in the range 43 to 17 yr for f_c in the above range.

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