# CHAPTER 6

# THE EVOLUTION OF SUPERNOVA REMNANTS IN STELLAR WIND BUBBLES

This chapter deals with the modification of the widespread component of the interstellar medium due to significant mass loss in the high-velocity winds from massive stars. Such a wind will excavate a cavity in the interstellar medium producing a low-density bubble. Thus, when a massive star explodes, the ejecta may be expanding in such a bubble.

This has several important consequences. The evolution of the surface brightness and morphology of a SNR expanding in a bubble will be different from that of the remnants expanding in a denser component of the interstellar medium. This is examined in this chapter. Another interesting consequence is for the lifetime of such supernova remnants. It is argued that these will be relatively short-lived compared to those expanding in a denser medium. If most of the remnants of type II supernovae (with massive progenitors) initially expand into such stellar wind bubbles then the standard estimates of the birthrate of SNRs will have to be significantly modified. We show that the true birthrate of SNRs could be as high as one in $\sim 35$ yr.

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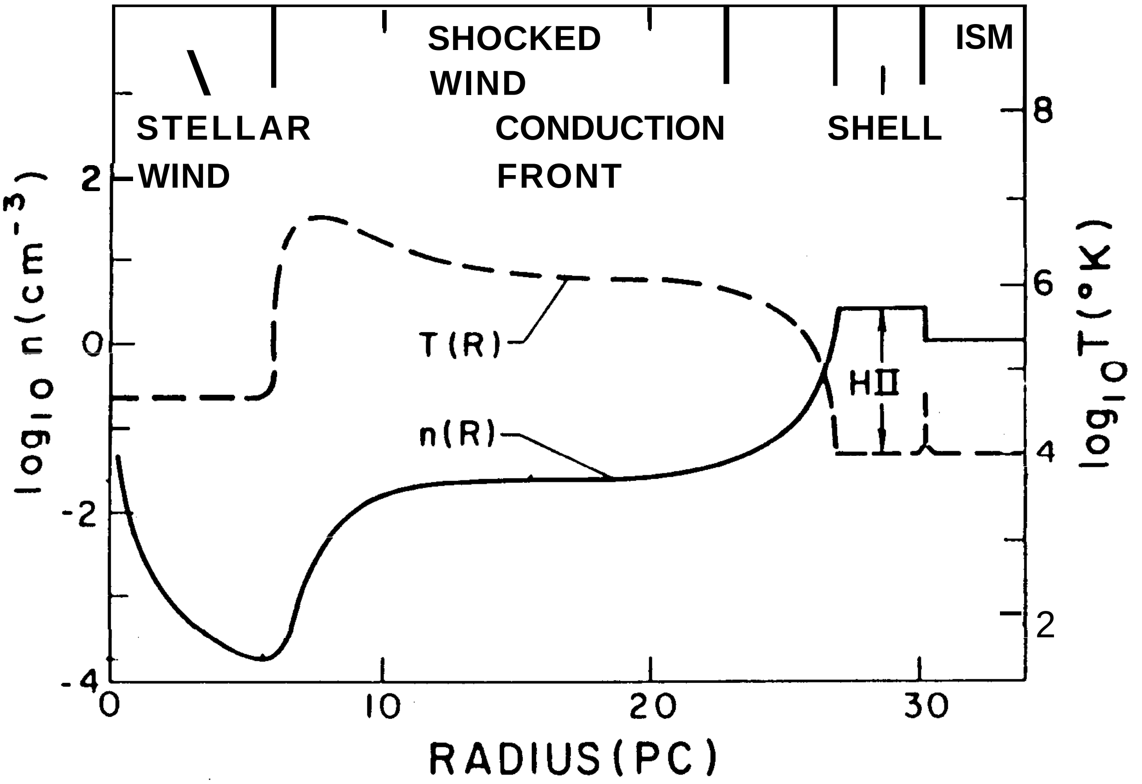
## 6.1 INTRODUCTION

In recent years it has been well established that stars lose a significant fraction of their mass by winds before they end their lives. For massive stars, the winds during the main sequence and blue supergiant phases are of such high velocity that they are expected to excavate a cavity in the interstellar medium. Such a cavity is known as the "Stellar Wind Bubble". According to current thinking, after the star explodes, for quite a while the ejecta expands not in the original ISM, but in such a low density bubble. This has important consequences for the evolution of the surface brightness of the remnant. If there is a central pulsar, this also influences the morphology of the remnant. This chapter is devoted to a discussion of this question.

In the next section we give a brief introduction to stellar wind bubbles. In section 6.3 we present results of model calculations of the evolution of SNRs in such bubbles. The existence of such low density regions in the interstellar medium (bubbles created by the pre-supernova star as well as the more widespread Coronal gas discussed in the previous chapter) has important consequences for the lifetimes of SNRs. As an illustration of this, in section 6.4 we discuss the age and the morphology of the very interesting supernova remnant MSH 15-52 which is one of the four SNRs with a central pulsar. Section 6.5 is devoted to a discussion of the birthrate of SNRs in view of the above remark.

## 6.2 THE STELLAR RIND BUBBLE

The early-type stars lose a substantial amount of mass during their Main Sequence and Blue Supergiant phases in high-velocity winds ($V_w \sim 2000-3000$ km/s). The mass loss *rates* are typically $\sim 10^{-6} M_\odot$/yr. The large mechanical luminosity carried by this high velocity wind will alter the circumstellar environment significantly. Castor, McCray and Weaver (1975), Weaver et.al. (1977), Tomisaka, Habe and Ikeuchi (1980) and McCray (1983) have discussed this matter. The primary effect of this stellar wind is to create a large expanding "bubble" of size $\gtrsim$ 10 pc around the star. The gas density in the bubble will be very low, and the temperature very high ($n \sim 10^{-2}$ atom/cc, $T \sim 10^6$ K). The typical density profile of such a bubble is sketched in fig. 6.1. Increasing amount of observational evidence for such bubbles is now



-The large-scale features of the temperature and density structure of an interstellar bubble for which $L_w = 1.27 \times 10^{36}$ ergs $s^{-1}$, $n_0 = 1$ cm$^{-3}$, and $t = 10^6$ yr. ISM means ambient interstellar medium. For a typical 0 7 1 star, the H II region would extend to $\sim 3\ R_2$.

Fig. 6.1

(From Weaver et. al. 1977)

becoming available (Georgelin et.al. 1983; van der Bij and Arnal 1986; Rosado 1986; Laval et.al. 1987 and several others). The expansion of the bubble will eventually be halted when pressure equilibrium with the surrounding matter, most likely an HII region, is achieved. If the star is not too massive, such an equilibrium will be reached before the supernova occurs. The pressure of the HII region itself will depend on whether or not it has already reached pressure equilibrium with the ISM. Table 6.1 summarizes the estimated final radius, density and temperature of the wind bubble for stars of different masses. We have used the empirical parametrization of mass loss rates and wind velocities given by van Buren (1985), and luminosities and temperatures of main sequence stars from ZAMS stellar models calculated by several authors (Becker 1981; Matraka, Wassermann and Weigert 1982; Maeder 1981; Brunish and Truran 1982; Doom 1982a,b; Chiosi et.al. 1979; de Loore, De Greve and Vanbeveren 1978). To estimate the parameters of the bubble we have used the analytic expressions of Castor, McCray and Weaver (1975) and Weaver et.al. (1977). In some cases, the bubble might stall long before the wind stops. In such cases, the actual properties of the bubble will depend on the details of the evolution of the radiative luminosity of the bubble between the stalling epoch and the termination of the fast wind phase. In the rough estimates given in table 6.1, this has not been taken into account. For the more massive stars this omission will not be a source of serious error. However, for a star of mass $\lesssim 10 M_{\odot}$, the end result nay be significantly different,

Table 6.1: Parameters of the Stellar Wind Bubble

| Mass of the star on ZAMS $(M_\odot)$ | Wind Luminosity $(10^{36}$ erg/s) | $R_f$ (pc) | $n_f$ (atom/cc) | $T_f$ (°K) | Comments |
|---|---|---|---|---|---|
| 100 | 62 | 120 | $1.1\mathrm{x}10^{-2}$ | $3.2\mathrm{x}10^{6}$ | a |
| 60 | 20 | 100 | $7.6\mathrm{x}10^{-3}$ | $2.4\mathrm{x}10^{6}$ | a |
| 30 | 2.6 | 45 | $8.7\mathrm{x}10^{-3}$ | $1.7\mathrm{x}10^{6}$ | b |
| 20 | 0.6 | 20 | $1.1\mathrm{x}10^{-2}$ | $1.4\mathrm{x}10^{6}$ | b |
| 10 | $2\mathrm{x}10^{-2}$ | 13 | $5.2\mathrm{x}10^{-3}$ | $5.8\mathrm{x}10^{5}$ | c |
| 6 | $1.3\mathrm{x}10^{-3}$ | 3 | $7.8\mathrm{x}10^{-3}$ | $3.9\mathrm{x}10^{5}$ | c |

a) Final conditions determined by Lifetime of the star

b) Final conditions determined by pressure equilibrium with HII region with $P_0/k = 15000$ cm$^{-3}$ K

c) Final conditions determined by pressure equilibrium at $P_0/k = 3000$ cm$^{-3}$ K. The values are uncertain since they depend on details of the evolution of the radiative Luminosity of the Bubble between stalling epoch and the end of fast wind phase.

since $t_{stall} << t_{MS}$ , the main sequence lifetime. We wish to mention in passing that the density profile of the bubble shown in fig. 6.1 will be modified slightly in the central region due to the slow wind during the red supergiant phase. It is not essential to take this into account for the questions to be discussed in this chapter. We shall return to a detailed discussion of the structure of the bubble near its centre in the next chapter, where we shall discuss Radio Supernovae.

The main cooling mechanism of the hot gas is conduction of heat into a relatively cold ($\sim 10^4$ K) ionised she11 surrounding the bubble, from which it is radiated away. The calculations of Weaver et.al. (1977) show that the rate of loss of energy from the hot gas reaches an asymptotic maximum of $\sim$ 0.9 times the mechanical luminosity of the stellar wind. When the wind luminosity drops, the hot region will tend to collaspe in a timescale given by the ratio of the energy content in the hot gas and the abovementioned energy loss rate. We find that in most cases the hot region will not have time to collapse before the star explodes, and hence in the next section we shall examine the effect of the expansion of SNRs in such bubbles.

## 6.3 EVOLUTION OF THE SURFACE BRIGHTNESS OF SUPERNOVA REMNANTS EXPANDING IN STELLAR WIND BUBBLES

We shall now repeat the calculations presented in chapter 5, but this time with an ambient density appropriate to a

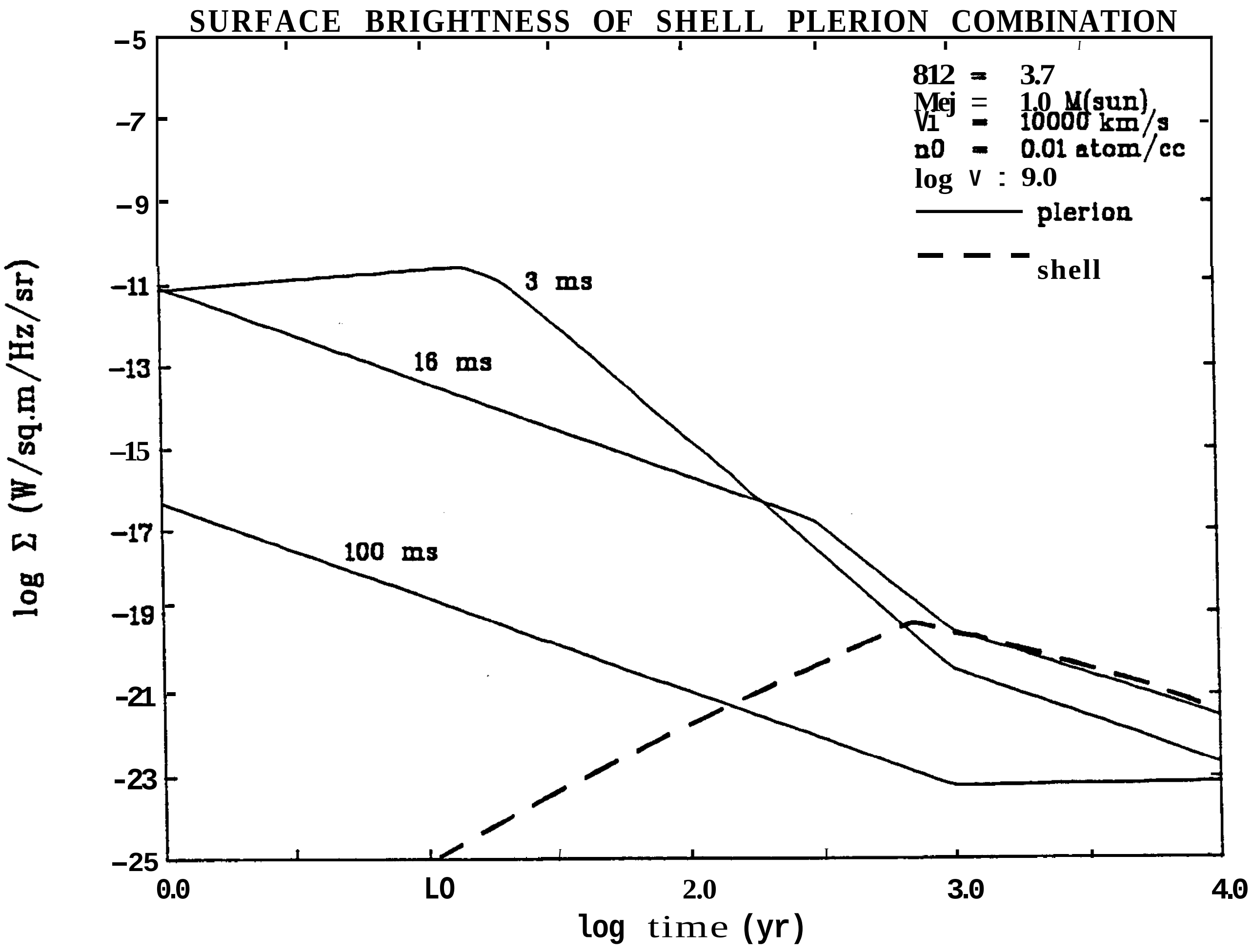


Fig. 6.2: The evolution of the surface brightness at 1 GHz of the plerionic and the shell components of supernova remnants expanding in a stellar wind bubble. The evolution of the plerionic component has been shown for three different initial rotation periods of the central pulsars. See caption of Fig. 5.4 for explanation of symbols.

bubble. The results are summarized in fig. 6.2. We have assumed an initial velocity of expansion of $10^4$ km/s and 1 $M_\odot$ for the mass in the ejecta. the evolution of the plerions for three pulsars of initial periods 3 ms, 16 ms and 100 ms are also shown. In all cases the 'pulsars were assumed to have a magnetic field of $3.7\times10^{12}$ gauss (field of the Crab pulsar). Just as in the case of the expansion into coronal gas discussed in the previous chapter, the onset of radio emission is delayed compared to an expansion in the denser intercloud medium of the standard model of the ISM. The maximum surface brightness reached is also less. As should be expected, the case discussed here is intermediate between the evolution of SNRs in the two media discussed previously.

The evolution of the plerionic component is initially similar to that in the denser medium. But since the deceleration occurs later in this medium, the plerion luminosity will continue to decay rapidly for a longer time. As a consequence when the shell emission eventually builds up, the plerionic component will be slightly less bright compared to the shell than what it would have been in the denser medium. As we have seen in chapter 5, this behaviour is more marked in the coronal gas.

## 6.4 THE SUPERNOVA REMNANT MSH 15 -52

We had occasion to remark on this supernova. remnant in chapter 3. The most intriguing aspect of this SNR is that whereas its standard Sedov age is $\sim10^4$ years (Seward et.al.

1983), the spindown age of the central pulsar is only ~1600 years. The period of the pulsar is 150 milliseconds and it has a very high field of $1.5\times10^{13}$ gauss. As was remarked in chapter 3, Blandford, Applegate and Hernquist (1983) have argued that the discrepancy between the spindown age of the pulsar and the age of the **SNR** can be understood if the field of the pulsar was built up after its birth. In this section we wish to present a model for the morphology and the observed surface brightness of this remnant without invoking this hypothesis. We wish to suggest that this interesting remnant is an example of an **SNR** expanding into a stellar wind bubble. In such a situation it is not unreasonable that it could have expanded to the presently observed large size of ~30 pc in 1600 years. Based on this scenario, we shall now present an evolutionary model for this remnant.

Let us first briefly summarize the observed features of this remnant. In the radio, this remnant has a shell morphology with hardly any central emission. In X-rays, however, there is a fairly bright plerion surrounding the pulsar. The relevant properties of this remnant are listed below:

**Table 6.2:** Observed Properties of SNR MSH 15-52

| | | | (ref.) |
|---|---|---|---|
| Angular diameter | : | 30 arcmin | (1) |
| Flux (1 GHz) | : | 70 Jy | (2) |
| $\Sigma$ of the shell region | : | $8\times10^{-20}$ W/m$^2$ /Hz/sr at 1 GHz | (1) |
| Distance | : | 4.2 kpc | (3) |
| X-ray luminosity | : | $5\times10^{16}$ erg/s/Hz at 4 KeV | (4) |

References:
(1) Caswell, Milne and Wellington 1981
(2) Weiler 1983
(3) Caswell, Murray, Roger, Cole and Cooke 1975
(4) Seward, Harnden, Szymkowiak and Swank 1984

The first attempt to model this SNR as a young object was made by Srinivasan, Dwarakanath and Radhakrishnan (1982). However, they assumed an artificial confining boundary of the plerion, within the remnant, of roughly the same size as the Crab nebula. In what follows we shall relax this, and assume that the plerion fills the whole cavity.

We shall assume that the mass ejected is $\sim 2\ M_\odot$ and that the initial velocity of expansion is $\sim$12000 km/s. These reproduce the observed size of the remnant taking into account the appropriate deceleration. With these parameters, the shell surface brightness is also well reproduced (fig. 6.3(a)). Using this expansion rate, and the presently observed field strength of the pulsar ($B_* \sim 1.5 \times 10^{13}$ gauss), the X-ray luminosity of the plerion is best fit by assuming an initial rotation period $\sim$ 6 ms for the pulsar (fig. 6.3(b)).

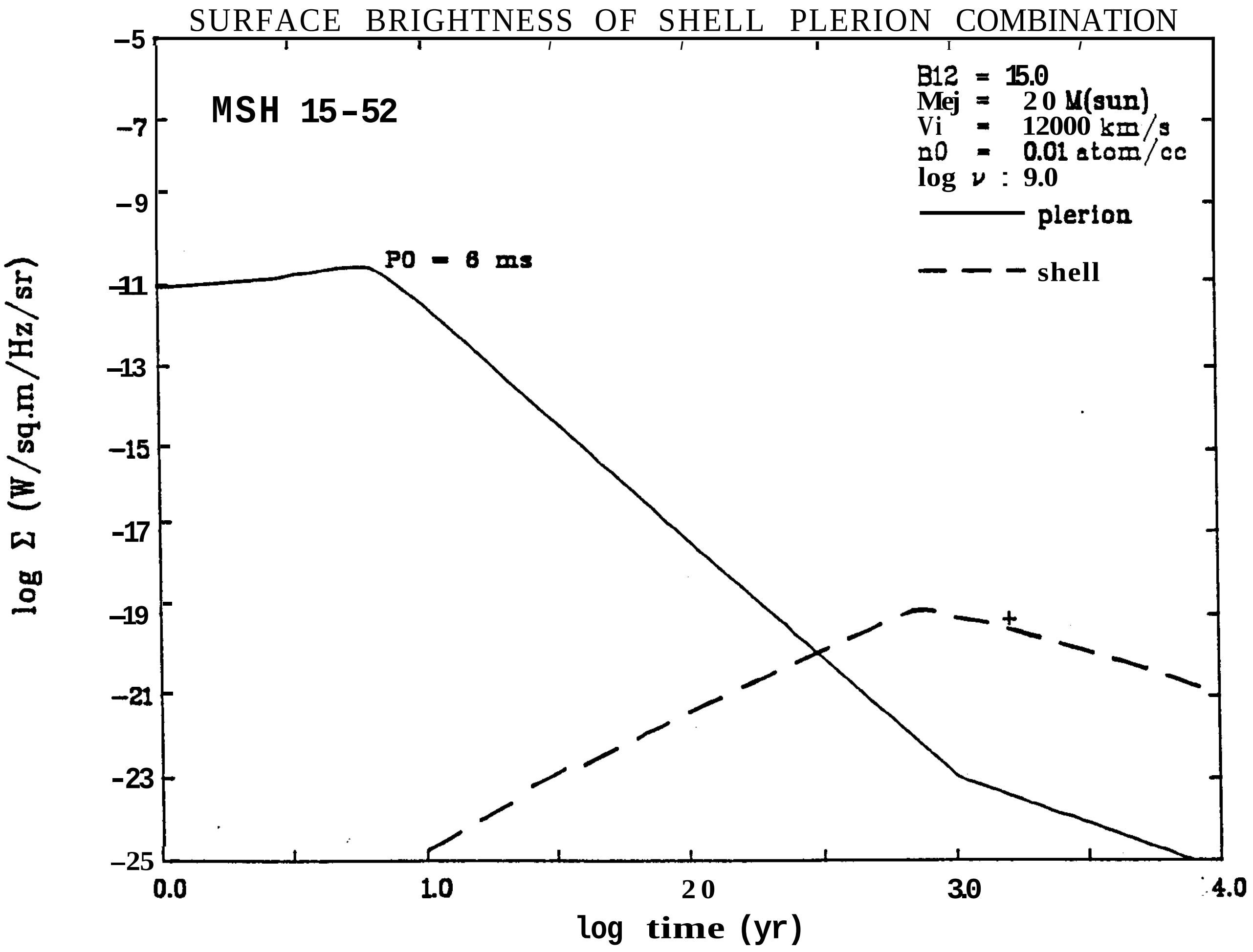


Fig. 6.3 (a): A model evolution of the radio surface brightness of the shell and the plerionic component of the supernova remnant MSH 15-52. The density assumed is appropriate for that of a stellar wind bubble. The observed value of Σ is shown by a '+' mark.

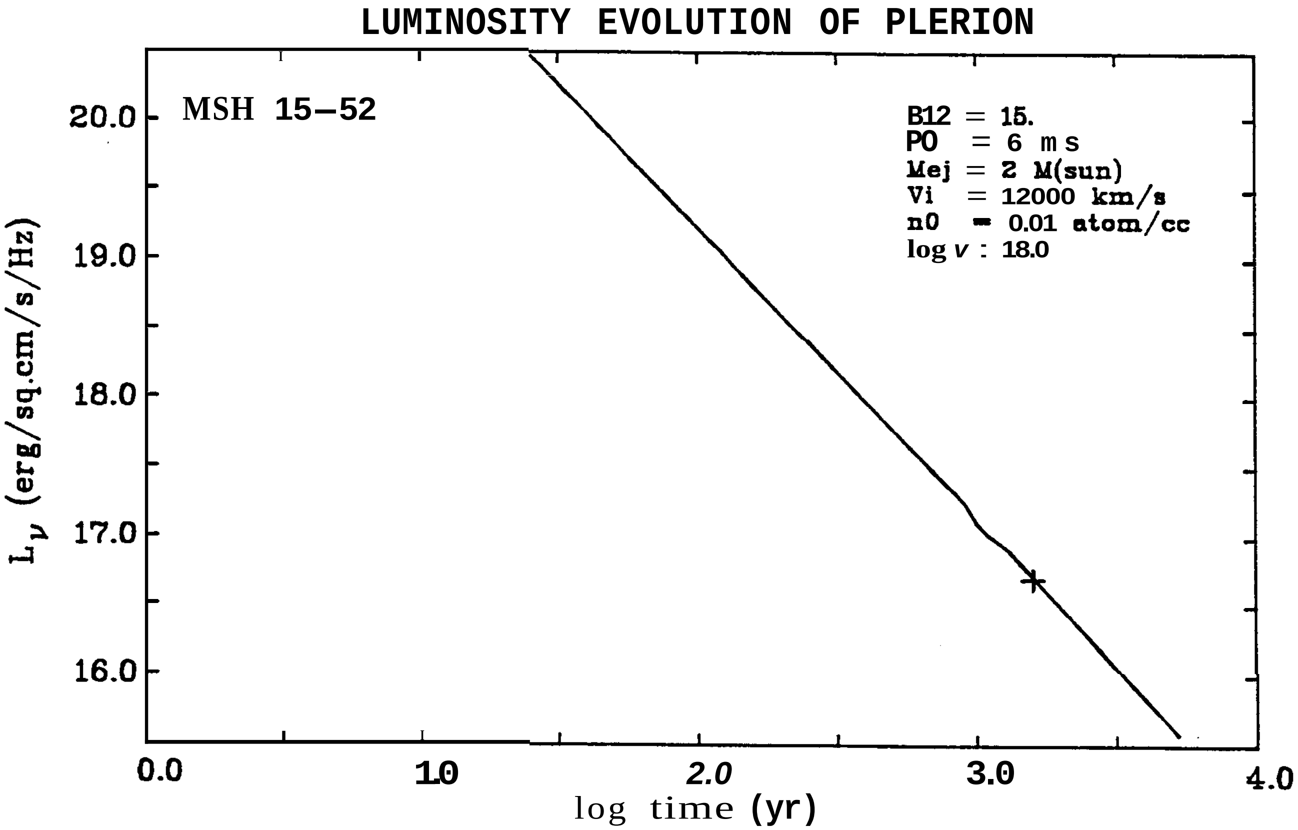


Fig. 6.3 (b): A model evolution of the X-ray luminosity of the plerionic component of the supernova remnant MSH 15-52. The observed X-ray luminosity is indicated by the '+' mark.

This estimate of initial rotation period differs from that of Srinivasan et.al. (1982) mainly because of the different assumptions involved, as we have mentioned earlier. Fig. 6.3(a) shows that the radio surface brightness of the plerion component will be $\lesssim 10^{-23}$ W/m$^2$/Hz/sr, which is below the level of detectability. This model is thus able to fit all observed properties of this SNR - its size, radio brightness of the shell, X-ray luminosity of the plerion, upper limit to the radio brightness of the plerion and the spindown age of the pulsar - in a natural way without having to invoke late turn-on of the pulsar.

## 6.5 IMPLICATIONS FOR SNR STATISTICS

It is obvious that the discussions of this chapter and section 5.5 have an important bearing on the expected lifetimes of remnants, and therefore on estimates of their birthrate. We shall now estimate the birthrate of supernova remnants by assuming that a certain fraction of them are likely to be expanding in the standard relatively high density intercloud medium, some in the coronal gas, while others may be expanding into the bubbles created by their progenitors.

The implications of SNR evolution in a low density medium have been discussed by several authors (Lozinskaya 1979; Higdon and Lingenfelter 1980; Tomisaka, Habe and Ikeuchi 1980; Srinivasan and Dwarakanath 1982). The remnants which expand in a low density medium will have a lower surface brightness at a given age, compared to the SNRs expanding in the "standard" intercloud medium. The birthrate estimates of SNRs require age estimates for known remnants. This is conventionally done by assuming, in some form, a dependence of surface brightness on age. The "standard" SNR birthrate estimate by Clark and Caswell (1976) assumes a Sedov-type expansion law for all SNRs. This is reasonable if the ambient medium has a high density $\sim 1$ atom $cm^{-3}$. However, as we noted above, a considerable fraction of supernovae must expand in the low density medium. This has to be taken into account while making an estimate of the birthrate.

We shall first attempt an estimate of the birthrate by assuming that there is no Coronal gas. The remnants will be expanding either in the standard intercloud medium or into stellar wind bubbles. Since one expects bubbles only around massive stars, which are believed to be the progenitors of type II supernovae, and since the frequency of type I and type II supernovae are roughly equal, one can make the simplifying assumption that 50% of the remnants are likely to be expanding in uniform interstellar medium with density $\sim 1$ atom/cc (referred to as the "warm" medium below), while the other half (remnants of Type II supernovae) are expanding in very low density cavities or bubbles.

According to Clark and Caswell (1976) the sample of Galactic SNRs is reasonably complete for surface brightness greater than $\Sigma = 10^{-20}$ $W/m^2/Hz/sr$ at 408 MHz. Their catalogue contains 71 shell SNRs above this limit. If $t_W$ and $t_b$ are the lifetimes of SNRs (above the limiting surface brightness) in the warm medium and the bubble respectively, then the average interval between the birth of SNRs is

$$\tau = \left[f_b t_b + (1-f_b) t_w\right] / N_{SNR}$$

where $f_b$ is the fraction of SNRs expanding in bubbles. Using $f_b = 0.5$, $n_w \sim 1$ atom $cm^{-3}$, $n_b \sim 10^{-2}$ atom $cm^{-3}$ and $N_{SNR} = 71$, we obtain

$$\tau = 37 \text{ yr} .$$

We shall now correct this estimate by making allowance for the fact that a certain fraction of SNRs outside bubbles may also be expanding in a low density medium, namely, the Coronal gas. If $f_w$ and $f_h$ are the filling factors of the warm and the Coronal gas, and $t_h$ is the lifetime of SNRs expanding in the Coronal gas, then the mean interval between the birth of SNRs is now given by

$$\tau = \left[f_b t_b + (1-f_b) \left\{f_w t_w + f_h t_h\right\}\right].$$

The birthrate estimated from the above relation is summarized in the table below:

| $f_h$ | $\tau$(yr) |
|---|---|
| 0.0 | 37 |
| 0.3 | 28 |
| 0.5 | 22 |
| 0.7 | 16 |

## *6.6* SUMMARY

In this chapter we have studied the evolution of supernova remnants expanding in bubbles created by the stellar wind of their progenitors. Our main conclusions are as follows:

1. Most remnants of type II supernovae should expand in such a low-density environment.
2. Lifetimes of these SNRs would be much shorter than for those expanding in a denser component of the ISM.
3. If the above premise is correct then it will significantly modify the "standard" estimates of the birthrate of SNRs. The arguments presented in this chapter suggest that the true birthrate could be as high as one in $\sim$ 35yr.

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