CHAPTER 7

RADIO SUPERNOVAE AND THEIR FUTURE EVOLUTION

In recent years strong radio emission has been detected from some supernova outbursts in external galaxies. This has raised the following questions:

1. What is the mechanism of this prompt radio emission, and
2. Whether the radio emission from (old) supernova remnants is a continuation of this process.

The two suggestions made in the literature are critically discussed in this chapter and we come to the conclusion that it is most likely that (in the majority of cases) the emission originates in the circumstallar matter. Hence in order to answer the second question raised above we examine the secular evolution of the radio emission in this model. **Our main conclusion is that in most cases the prompt emission (namely, the radio supernova) will fade away in a timescale ~50 pears. Radio emission will build up once again a few centuries later.**

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7.1 INTRODUCTION

In the previous chapter we have seen that according to the generally accepted model of radio emission from shell supernova remnants, the remnants remain radio quiet until the mass swept up from the interstellar medium becomes roughly equal to the ejected mass. This also seems to explain rather neatly the absence of supernova remnants younger than Cas A (age $\sim$ 300 yr) in our Galaxy. In recent years, however, strong radio emission has been detected from several extragalactic supernovae soon after the optical maximum (Weiler et.al. 1986). Such a prompt emission is not expected in the standard models. In this chapter we shall discuss later evolution of the radio emission from supernovae and its statistical implications. In the next section we shall summarize the observed properties of radio supernovae. In section 7.3 we discuss the proposed models for the radio emission and the evolution of radio luminosity expected from these models.

7.2 RADIO SUPERNOVAE

The first supernova to be detected at radio frequencies was SN 1970g in M101 (Gottesman et.al. 1972). After the commissioning of the VLA, radio emission has now been detected from six (excluding SN1986j: van Gorkom et.al. 1986) extragalactic supernovae within ten days to one year of the optical maximum, and in two cases radio emission has been found from the sites of SN outbursts that occurred ~30 years ago (Cowan and Branch 1985). Observed properties of these "radio supernovae" (RSN) are summarized in table 7.1. It is evident that they are very strong radio sources, the peak luminosities being 15-300 times that of the youngest known, and most luminous, galactic SNR Cassiopeia A (The luminosity of the RSN 1986j is ~1500 times that of Cas A. However, no optical information is yet available to ascertain whether it was indeed a conventional supernova). Out of the eight radiosupernovae detected so far, two are of type I (SN 1983n and SN 19841). They are distinct from the other RSNs in the rapid rate of decay of their radio luminosity ($L \propto t^{-1.6}$). Among the rest, the decay rates of SN 1979c, SN 1980k and SN 1981k have been measured, and all of them show a slower decline of radio flux ($L \propto t^{-0.7}$). It is interesting to note that if these typeII RSNs continue to decay no faster than the present rate, their luminosities after a few hundred years will be comparable to the galactic SNRs of similar ages (fig. 7.1).

Table 7.1: Properties of Radio Supernovae

			Observed Radio Maximum at 6 cm				Radio	Rate of
SN Name	SN Type	Distance (Mpc)	Age (yr)	Flu (mJy)	Spectral Luminosity in 10^{25} erg/s/Hz	Ratio to Cas A	Spectral index a $S \propto \nu^{a}$	Flux decline β $S \propto t^{\beta}$
SN1950b	**II?**	7	30	0.5	3	5	-0.4	
SN1957d	**II?**	7	23	1.9	10	15	-0.25	
SN1970g	II	7.2	1.4	2.5	10	15	-0.7 ±0.1	
SN1979c	II-L	17	1.2	8.3	200	250	-0.72±0.05	-0.71±0.08
SN1980k	II-L	7	0.4	2.6	10	15	-0.50±0.06	-0.65±0.10
SN1981k	II?	6.6	0.5	2	10	15	-0.91±0.07	-0.73±0.06
SN1983n	**I-SL**	7	0.08	18.5	100	125	-1.03±0.06	-1.59±0.08
SN1984l	**I-SL**	24	0.14	0.7	40	60	-1.0 ±0.02	-1.5 ±0.3

(Adapted from Weiler et.al. 1986)

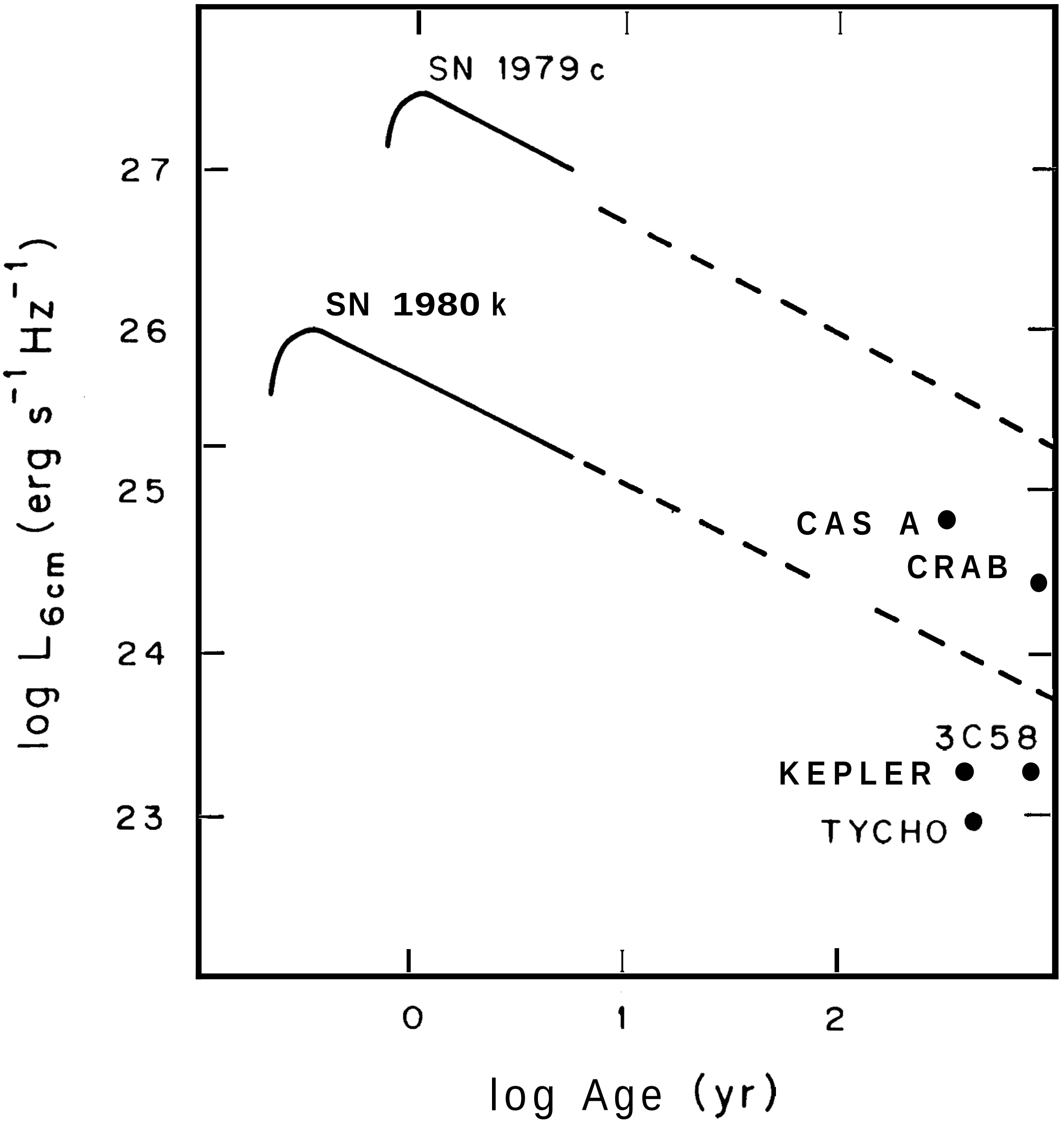

Fig. 7.1: Luminosity vs. age of young Galactic supernova remnants (filled circles) and extragalactic radio supernovae SN 1979c and SN 1980k. The measured radio light curves of these supernovae are shown as solid lines, and the broken lines are extrapolations.

This, therefore, raises the following question: If indeed the radio emission in the SNR phase is a gradual "fade out" of very strong emission of radiosupernovae, then

why are the bright young SNRs of intermediate age not seen?

If all type II supernovae are strong radio emitters, then with a galactic SN rate of one in ~ 20 yr, one would expect to see at least ten SNRs younger and more luminous than Tycho or Kepler's remnant. But there is only one such remnant (namely, Cas A) in our Galaxy.

There can be two possible explanations for the absence of such luminous young SNRs:

i) Radio emission from supernovae must be a rare phenomenon,

ii) The radio emission in the SNR phase is **not** a simple continuation from the Radio supernova phase. The radio emission of the supernova probably dies after a few decades, and is regenerated after a few centuries.

The answer depends, of course, on the origin of the radio emission from the supernova.

7.3 MODELS FOR RADIO SUPERNOVAE

The models that have been proposed for radio supernovae can be divided into two main categories. One of them relies on the interaction of the supernova ejecta with the circumstellar medium (Chevalier 1982a). This has been called the "mini-shell" model. The other model invokes a pulsar-produced nebula for this early emission (Pacini and Salvati 1981). This is known as the "mini-plerion" model.

7.3.1 The Mini-plerion Model

In this model a central pulsar is responsible for the radio emission from the supernova (Pacini and Salvati 1981; Shklovskii 1981; Bandiera, Pacini and Salvati 1984). According to this model, the pulsar born in the supernova explosion supplies the magnetic field and relativistic particles in the expanding cavity. Synchrotron radiation from these relativistic particles is responsible for the observed radio emission. In other words, the radio emission from a supernova is due to a mini "Crab nebula".

However, there are several difficulties with this picture. The most serious one is that the pulsar nebula is likely to be hidden for more than a decade due to free-free absorption in several solar masses of ejecta surrounding it (Reynolds and Chevalier 1984). This problem can, however, be avoided if the ejecta fragments very soon due to a Rayleigh-Taylor instability. For fragmentation to take place within a few months of the SN outburst, the central pulsar must be a very powerful one, which requires a very short initial rotation period: $\sim$ 1 ms (Bandiera, Pacini and Salvati 1983). But such fast pulsars are rare, as argued in chapter 2. Also, as we shall discuss in the next chapter, the supernovae in which such powerful pulsars are born will be characterized by peculiar light curves; but among the observed supernovae such light curves are rare.

One may now ask, if indeed pulsar nebulae are responsible for the early emission, what will be the future evolution of these objects? Bandiera, Pacini and Salvati (1984) have investigated the evolution of the mini plerion model in detail and they conclude that the radio supernovae will gradually evolve into plerions like the Crab nebula. Herein lies the second difficulty with the model.

A distinguishing feature of all known plerions is their relatively flat radio spectral index $\alpha_R \lesssim 0.3$ $(S_\nu \propto \nu^{-\alpha_R})$, as opposed to supernova remnants of the shell type, which have a radio spectral index $\alpha_R \sim 0.5$. Almost all radio supernovae have spectra much steeper than conventional plerions. The only two RSNs that have relatively flat spectra are SN 1950g $(\alpha_R \sim 0.25)$ and SN 1957d $(\alpha_R \sim 0.4)$. Therefore, gradual evolution of the RSNs into plerions will also require flattening of their spectral index with time, for which' no evidence exists at present.

A more serious difficulty with this evolutionary scenario is that it predicts very luminous young plerions in the intermediate stage. We have argued in chapter 2 that the paucity of such young bright plerions suggests that most pulsars must be born with relatively long 050 ms) rotation periods. But "mini plerions" as luminous as radio supernovae can only be produced by pulsars with initial rotation periods

$\lesssim 20$ ms. Thus, if we accept this picture of radio emission from supernovae, we must conclude that a Radio Supernova must be a very rare phenomenon, the frequency of occurrence being equal to the birthrate of bright plerions. In chapter 2 we have argued that in not more than 10% of the cases will a newly born pulsar be able to produce a bright plerion like the Crab nebula. This would mean that only ~10% of SN events are expected to produce strong radio emission.

However, from the relatively scanty data available on Radio supernovae, it appears that the fraction of radio-quiet supernovae may not be so low. In fact, Weiler et.al. (1986) suggest that almost all TypeII supernovae may be radio emitters*. If so, then a mini-plerion cannot be responsible for the radio emission in all cases. This leads us to the second model for this radio emission.

7.3.2 The Mini-shell Model

This model attributes the radio emission from supernovae to the interaction between the supernova ejecta and pre-existing circumstellar medium (Chevalier 1982a,b;1984). As we have outlined in the previous chapter, Gull's work shows that the expansion of supernova ejecta into a uniform-density ISM results in the development of a region where the sense of local "gravity" (due to deceleration of the expansion) is opposite to that of the density gradient. Such a region is

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*No strong radio emission has, however, been detected from the peculiar TypeII supernova SN1987A till the time of writing, i.e. till about three months after the outburst.

Rayleigh-Taylor unstable, and turbulent convective cells form. In this region particles can be accelerated by the stochastic Fermi mechanism (Scott and Chevalier, 1975; Cowsik and Sarkar, 1984), and the magnetic field amplified. Rough equipartition is achieved between the energies in turbulent cells, relativistic particles and magnetic fields, each being $\sim$ 1% of the total kinetic energy.

In Gull's (1973) picture, the onset of turbulence occurs only when significant deceleration takes place; this happens when the mass swept up from the ambient medium exceeds the ejected mass. Chevalier (1982a,b) has argued, however, that the Rayleigh-Taylor instability in the shocked material develops even in the early phase of expansion (when swept up mass is not significant), if the expanding stellar envelope has a power law density profile. He has obtained similarity solutions for SN ejecta with a density profile $\rho_{SN} \propto r^{-n}$ expanding into a circumstellar medium with a density profile $\rho_{CSM} \propto r^{-s}$. If the circumstellar medium is generated by stellar wind from the SN progenitor, then $s=2$. The value of n is expected to be $\sim$ 12 for type II SN (see Chevalier 1982b and references therein), while for an exploding white dwarf, which is expected to produce a type I SN, $n \sim 7$ (Chevalier 1982c, 1984). Assuming that the energy densities in relativistic particles and magnetic field in the shocked matter are proportional to the postshock thermal energy, good fits to the radio light curves can be obtained (Chevalier 1982b, 1984). The fits for type I supernovae are in fact very good (see

Weiler **et.al.** 1986; Panagia, Sramek and Weiler, 1986).

Long-term Evolution Of The Mini-shell Model

We shall now examine what should be the long-term evolution of the mini-shell model. Since the luminosity of the radio supernova depends on the density of the ambient matter in which the blast wave propagates, the evolution of the radio emission must be related to the structure of the circumstellar matter. As we remarked above, the radio supernova models proposed by Chevalier assume a r^{-2} density profile for the circumstellar matter (CSM), as is expected for a steady unconfined stellar wind. This profile is reasonable for the distance the blast wave would traverse in a few years of time. To investigate the long-term evolution, one requires a knowledge of the density distribution on larger scales.

The Circumstellar Matter

The immediate environment of a pre-SN star consists of stellar wind material shed during the red supergiant phase. Typical mass loss rates from red supergiant stars are $\dot{M} \sim 10^{-6} M_\odot/yr$, with typical velocities $V_W \sim 10$ km s^{-1} (see Dupree 1986, for a recent review). If we assume the duration of the red supergiant phase to be typically $\sim 10^5$ yr, then the extent of the unconfined wind material would be $\sim$ 1pc. If the red supergiant phase lasts for a longer time, the ambient pressure of the interstellar medium ($P_0/k \sim 3000$ cm^{-3} K) will confine the red supergiant wind matter to within a similar radius. If the ambient ISM is the standard "intercloud medium", the sound velocity in the ISM is of the same order as the expansion velocity of the red giant wind. In this situation the density of the stellar wind matter at the confining radius will be nearly the same as the density of the surrounding ISM. The evolution of the young SNR in such a medium will be more or less continuous between the CSM interaction phase and the ISM interaction phase, i.e., a radio supernova would gradually evolve into a older SNR.

However, as we have discussed in the previous chapter, the rather massive stars which are responsible for type II supernovae are likely to produce hot, low density bubbles around themselves due to the strong winds during their main sequence and blue supergiant phases. The distance upto which the red supergiant wind (RGW) material extends will then depend on the pressure of the hot bubble. If the bubble interior has a pressure equal to that of the ISM, the RGW material will extend upto a parsec or so, provided the red supergiant stage lasts for at least $\sim 10^5$ yr. A higher bubble pressure will confine'theRGW matter within a smaller .radius (e.g. bubble pressure $(P_0/k) \sim 15000$ cm^{-3} K will confine the red giant wind matter within $\sim$ 0.5 pc). The important point, of course, is that outside the RGW matter there will now be a very low density region. A typical density profile of the circumstellar matter is sketched in fig. 7.2.

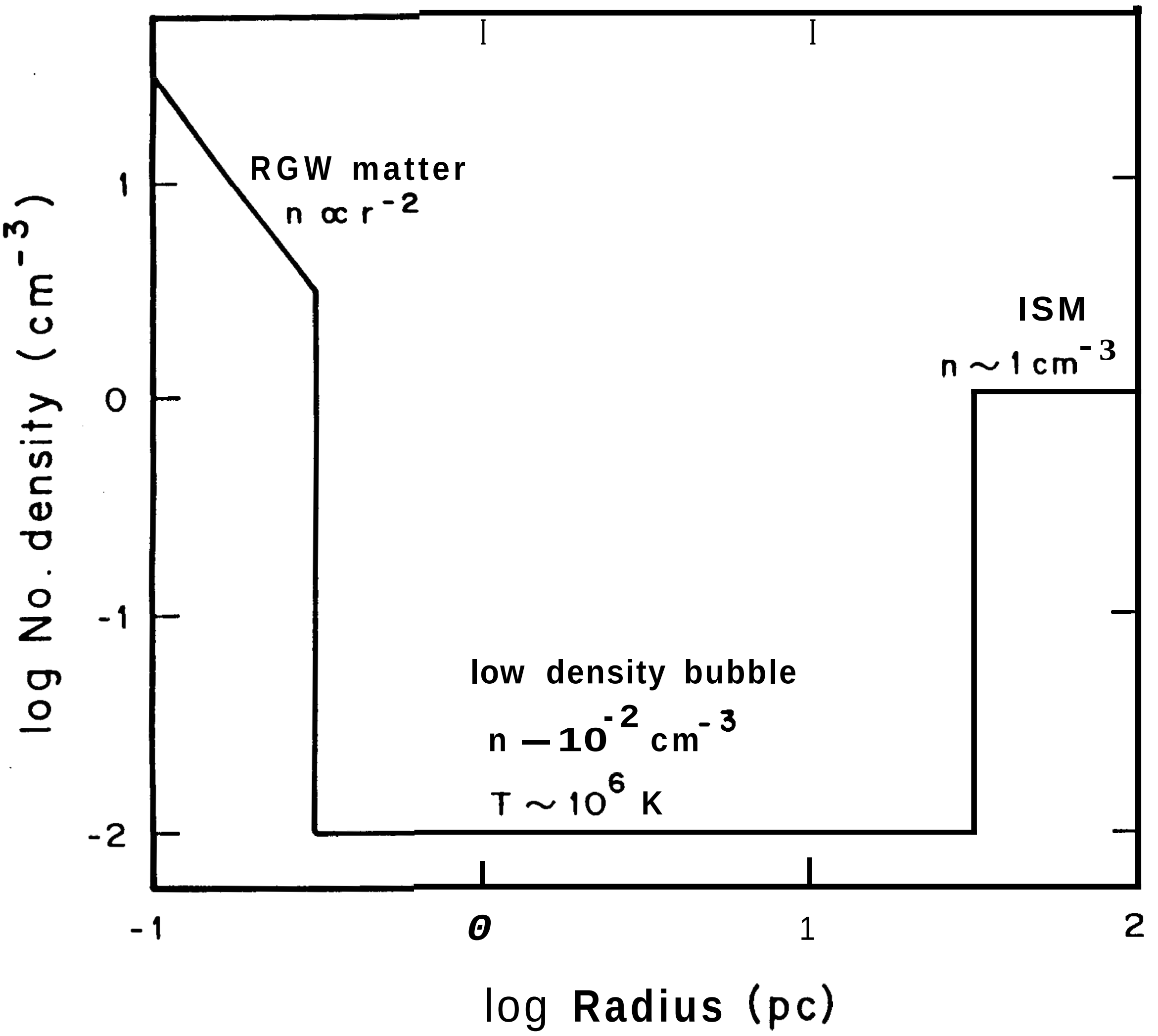

Fig. 7.2: The density profile of a stellar wind bubble, including the slow Red Giant Wind (RGW) matter shed by the pre-supernova star.

SNR Evolution In Circumstellar Medium

Given this density profile around the pre-SN star, we can follow the evolution of the RSN/young SNR. In the beginning the SN ejecta is going to expand into the $\rho \propto r^{-2}$ RGW matter. During this phase we shall see a radio supernova as described by Chevalier (1982a). With an expansion velocity $\sim 10^4$ km s^{-1}, the RGW matter will be completely swept up in $\sim$ 50-100 yr. Till then the RSN luminosity will follow the $\sim t^{-0.7}$ law. After the power law RGW is all swept up, the SNR will start expanding freely into the low density bubble region. Since the convective instability will no longer be active, the relativistic particles and the magnetic field will suffer severe adiabatic losses. As a result, the luminosity of the SNR will drop very rapidly ($L_\nu \propto t^{-2\alpha} \nu^{(1-\alpha)/2}$), and soon after the power law matter has been swept up, the SNR will disappear below the detection limit. One should, however, note that the mini-shell model requires a rather strong mass loss rate to explain the very bright radio supernovae. In fact, model fits to the radio emission from SN 1979c, an exceptionally bright radio SN, requires mass loss rates for the pre supernova star to be as high as $\sim 10^{-4} M_\odot$ /yr! This probably indicates a "superwind" phase for a very brief period before the SN occurred. The blast wave is likely to sweep it up in a much smaller time, probably within a decade, after which the radio luminosity should show a sharp decline (see Weiler et.al. 1986).

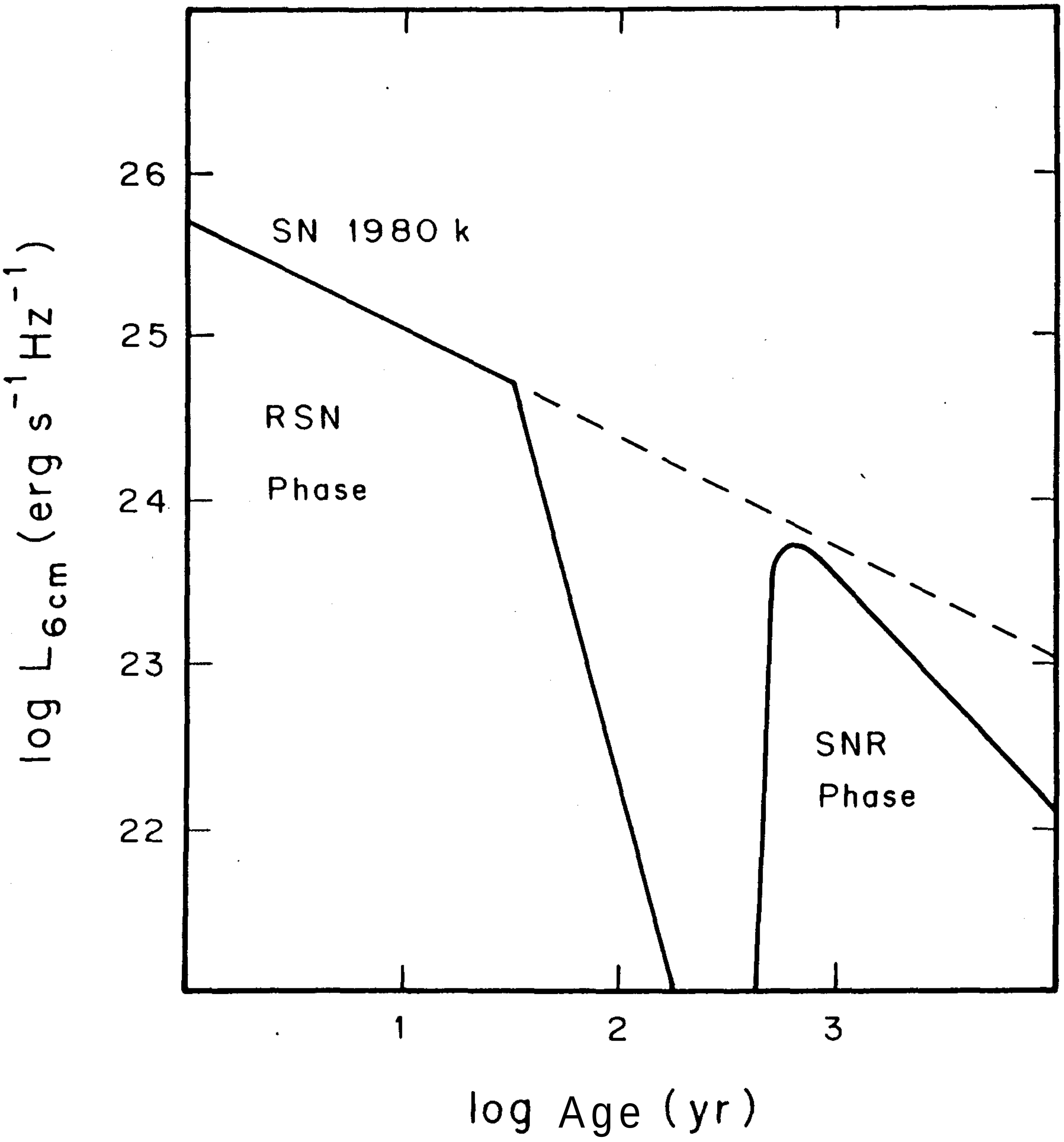

Fig. 7.3: The expected evolution of a supernova remnant expanding in a stellar wind bubble. The Radio Supernova (RSN) phase lasts as long as the expansion occurs in the central 'red giant wind (RGW) matter shown in fig. 7.2. The luminosity rises again when the supernova remnant (SNR) decelerates in the tenuous bubble interior.

Later evolution of the SNR will be similar to that described by Tomisaka, **Habe** and Ikeuchi (1980). To summarize briefly, the free expansion of the SNR will continue, and the SNR will remain "radio quiet", till enough matter is gathered from the bubble to make it slow down. When deceleration becomes significant, "convection" will again set in, reviving the radio emission à la Gull (1973). A scaling of Gull's models to $n \sim 10^{-2}$ yields a maximum luminosity in the SNR phase similar to that of Tycho's remnant, and the age at maximum to be ~ 500 years. Thus between ~ 50 to ~ 500 years of age the SNR will be invisible. Fig. 7.3 summarizes the expected evolution of the radio luminosity.

7.4 SUMMARY AND CONCLUSIONS

1. If the radio emission from supernovae is caused by the synchrotron nebula produced by a fast pulsar, the radio supernovae would later evolve into bright "plerions". The absence of bright plerions in our galaxy suggests that such occurrences must be very rare (less than 10%).

2. It is likely that in most of the cases, interaction between the SN ejecta and the circumstellar matter is responsible for the radio emission in the supernova phase. The circumstellar medium of massive pre supernova stars consists of red giant wind matter extending up to ~ 0.5-1 pc inside a low density "bubble" ($n \sim 10^{-2}$ atom cm^{-3}) of radius ~ 30 pc. This bubble is created by the fast stellar wind during the main sequence

and blue supergiant phases of the star. Normal interstellar medium exists outside this bubble. The radiosupernova phase lasts till the red giant wind matter is swept up in ~ 50-100 yr, following which the radio emission rapidly decays below the detection limit. The radio emission is regenerated in the SNR phase, at an age ~500 yr, when the blast wave decelerates. The radio quiet phase between 50-500 yr explains why luminous young SNRs are absent in the Galaxy.

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