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THE EVOLUTION OF NONTHERMAL SUPERNOVA REMNANTS. II. CAN RADIO SUPERNOVAE BECOME PLERIONS?

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ABSTRACT

We discuss the evolution of pulsar-driven supernova remnants. It is shown that the early stages closely resemble the phenomenon of radio supernovae and that one can establish a direct evolutionary link between the two classes of objects. Light curves are obtained in the radio and the X-ray ranges under simple assumptions about the injected spectrum. The derived relations between surface brightness and diameter, both at low and at high frequencies, are compared with the observational data.

Subject headings: nebulae: supernova remnants — radiation mechanisms — radio sources: general — X-rays: sources

I. INTRODUCTION

In a previous paper (Pacini and Salvati 1973, hereafter Paper I), two of us investigated the evolution of supernova remnants powered by a central pulsar. Following standard pulsar electrodynamics we assumed a continuous injection of magnetic energy and relativistic particles into a remnant expanding with constant velocity. We then derived, as a function of time, the internal magnetic field strength, the energy distribution of the particles, and the resulting synchrotron luminosity.

An obvious consequence of Paper I was the expectation of a large flux of nonthermal radiation from the site of supernova explosions, beginning some time after the optical event. Apart from the possibility of internal or circumstellar absorption, one would then expect in particular a strong radio emission lasting for a time of the order of the initial slowing-down time scale of the central pulsar, which would then be followed by a gradual decay. This expectation holds for all supernovae giving birth to a pulsar, i.e., according to our present theoretical understanding, for Type II supernovae.

Unfortunately at the time of Paper I, only two remnants (Crab Nebula and Vela) were known to contain a neutron star, and therefore it was not possible to compare theory and observations in a fair number of objects. Furthermore, until recently, no radio emission had been detected from the site of several recent supernova explosions (see, e.g., de Bruyn 1973; Brown and Marscher 1978; Ulmer *et al.* 1980; Cowan and Branch 1982).

The situation has now changed because one has recognized the existence of several galactic remnants which closely resemble the Crab Nebula and are probably driven by a central (as yet undetected) pulsar, the so-called plerions (Weiler and Panagia 1980; Weiler 1983). Furthermore the increase in sensitivity achieved in radioastronomy over the last decade has led to the discovery of some time-variable, very strong, compact radio sources coinciding with the location of recent Type II supernova explosions, the so-called radio supernovae (Gottesman *et al.* 1977; Goss *et al.* 1973; Allen *et al.* 1976; Weiler *et al.* 1981, 1983).

These developments have caused a renewed interest in the study of pulsar-driven supernova remnants (Weiler and Panagia 1980; Reynolds and Chevalier 1984), and it has been suggested that radio supernovae may represent the very early manifestation of newly born plerions (Pacini and Salvati 1981). Although this interpretation is still controversial (for a different point of view see Chevalier 1982), it is clearly worthwhile to reconsider the evolution sketched in Paper I and to apply it to the presently available observations in order to see, for instance, whether a genetic connection between radio supernovae and plerions is a tenable hypothesis.

We recall at this point that Allen *et al.* (1976) already discussed a possible connection between radio supernovae and pulsars. Similarly Marscher and Brown (1978) considered in some detail the same problem taking into account time-dependent opacity effects and various modes of particle production. Their approach, however, was not suited to the investigation of the long-term evolution.

In the present paper we shall adopt the treatment of our Paper I with some partial modifications. These are as follows:

1. In the case of very fast pulsars, we will consider the possibility that the initial slowing down is due also to the emission of gravitational waves.
2. We will approximate the dynamical effect of the interstellar matter by assuming that the latter is swept up in a thin shell (see eq. [2] below); then the expansion takes place with constant velocity only at the beginning, while at later times the classical Sedov solution applies. The pressure of the relativistic fluid is not included.
3. We will assume that the upper limit for the energy of the injected particles varies with the maximum potential drop in the neutron star magnetosphere, i.e., the square of the rotation frequency (Goldreich and Julian 1969). This translates into $\mu = \frac{1}{2}$ in equation (4) below.
4. We will take into account synchrotron reabsorption in the very early life of the source. An optically thick regime is inevitable because of the very strong initial magnetic field.

We will however neglect possible internal or circumstellar absorption from thermal matter. This is a very controversial point, since a uniform distribution of ionized matter resulting from the explosion would prevent the escape of radio emission for some 10^2 years, as emphasized by Chevalier (1982) and by Reynolds and Chevalier (1984). On the other hand, the evidence concerning the Crab Nebula and some theoretical arguments suggest that a scenario based on uniform expansion is a

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large oversimplification, and that a supernova envelope pushed by a young and energetic pulsar is likely to fragment very early into filaments, possibly because of Rayleigh-Taylor instabilities (Bandiera, Pacini, and Salvati 1983). This would guarantee the existence of transparent lines of sight from the observer to the central nonthermal bubble.

We assume that the emission is due to the synchrotron process over the entire spectrum, but we consider primarily the properties of the radio range and only marginally those at much higher frequencies. Indeed in our calculations we assume that the injected electron spectrum has a well-defined spectral index, constant over the whole energy range, the actual value for this index being inferred from the radio observations. Clearly, a pure power law with a single exponent is a very rough approximation if we want to extend our results to very distant spectral domains. As a consequence, even taking into account the evolutionary changes which introduce breaks in the energy distribution of the particles, we will only be able to describe properly the radio emission (§ II), although we will also make tentative statements concerning the high-energy emission of either young or evolved plerions (§ III). In the final section, § IV, we will consider the relation between surface brightness Σ and diameter D, stressing the differences between plerions and shell-type supernova remnants.

II. NONTHERMAL RADIO EMISSION FROM PLERIONS

As already mentioned, in recent years several extragalactic supernovae have been detected in the radio band, some time after the optical outburst. Their properties are reviewed by Weiler *et al.* (1983) (see also Pennington and Dufour 1983; van der Hulst *et al.* 1983). All detections refer to Type II supernovae, while a similar search for Type I's has been so far unsuccessful.

Although the information concerning these sources is still very limited and, in particular, we lack a long-term light curve, the following points are well established:

1. The radio emission is nonthermal and (at least in the best studied cases) delayed with respect to the optical outburst.
2. The radio emission lasts at a level stronger than Cas A for several years, possibly more than 10 or 20. If this lifetime is common among radio supernovae, a frequency of one Type II every 30 years would entail the existence of a radio supernova every one to three galaxies.
3. The energetics involved in these sources imply an internal energy input greater than 10^{38}–10^{40} ergs s^{-1} in the form of relativistic electrons with Lorentz factors higher than 10^2.

In Table 1 we have listed the observational properties of the presently known radio supernovae: flux at 6 cm (in mJy); distance (in Mpc); spectral index; absolute radio luminosity. In addition we have computed the equipartition energy content and the corresponding requirements for the rate of energy input averaged over the lifetime of the sources. Finally, under the assumption that this input is provided by a pulsar similar to PSR 0531, we have listed the required pulsar periods. We stress that the quoted energetics represent absolute minima because of the equipartition assumption and because we have neglected expansion and radiation losses. The quoted pulsar periods should therefore be regarded as upper limits.

Of course the presence of a central pulsar is by itself only an assumption. Two different interpretations of the origin of the radio emission have indeed been proposed. According to Chevalier (1982), the nonthermal flux originates outside the expanding remnant, and the particles are accelerated when the shell interacts with circumstellar material. The alternative model (Pacini and Salvati 1981; Shklovskii 1981) postulates the existence of a central pulsar which produces in its surroundings a nonthermal bubble, the future plerion. Although a detailed analysis of the radio evolution over an extended time is required to discriminate between the two models (see Salvati 1983), only the latter interpretation will be considered here.

Without going into the details of the computations, we intend to review the basic equations which describe our model.

$$-\dot{\omega} = A\omega^3 + B\omega^5 \quad \text{(braking law for the pulsar)} . \tag{1}$$

The first term is the usual dipole-like torque, and from PSR 0531 one deduces $A = 3.5 \times 10^{-16}$ s. In order to account for gravitational radiation losses, we have also added a quadrupolar term which depends on the equatorial ellipticity ϵ, $B = 1.8 \times 10^{-14}\epsilon^2$ s^3 (for motivations and effects of this term, see Bandiera, Pacini, and Salvati 1983). Gravitational losses are not very important, except for a neutron star rotating with an initial period close to the break down limit; in these cases our numerical simulations assume $\epsilon = 10^{-4}$.

The above differential equation can be solved as

$$2A^2 t = B \times \ln\,[\omega^2/\omega_0{}^2] + A[(1/\omega^2) - (1/\omega_0{}^2)] + B \times \ln\,[(A + B\omega_0{}^2)/(A + B\omega^2)] \, . \tag{1a}$$

The time dependence of ω is found by inverting equation (1a), so that the power transferred to the nebula in the form of magnetic field and energetic particles is $L = IA\omega^4$, where I is the star's moment of inertia. Let us remember the behavior of L in the case of negligible gravitational losses, $L = L_0/(1 + t/\tau)^2$ where $\tau = 1/(2A\omega_0{}^2)$ is the intial pulsar lifetime.

$$dR/dt = v_0/(1 + R^3/R_{\rm eq}{}^3)^{1/2} \quad \text{(expansion law for the nebula)} . \tag{2}$$

The nebula starts with the initial expansion velocity v_0, but it is decelerated by the ram pressure of the interstellar matter in such a way as to keep constant the total kinetic energy. $R_{\rm eq}$ is the radius of the sphere containing an amount of interstellar matter comparable to the ejected mass (typically $R_{\rm eq} \approx 10^{19}$ cm). At this stage we are neglecting possible dynamical effects of the relativistic bubble on the expanding envelope. This is because a sizable fraction of the energy lost by the pulsar may go into gravitational waves in the case of very fast neutron stars. Also, if there is a strong magnetic pressure, this may lead to Rayleigh-Taylor instabilities, and the dynamical treatment would then become much more complicated and outside our present scope.

$$d(B^2R^4)/dt = 6pLR \quad \text{(evolution law for the magnetic field)} . \tag{3}$$

Here we have assumed that a constant fraction p of the energy lost by the pulsar goes into building the plerion magnetic field.

$$j = W \times (L/L_0)^{1-(2-\gamma)\mu}E^{-\gamma} \quad \text{for } E < E_{\rm max} = q \times (L/L_0)^{\mu} \quad \text{(injected particle spectrum)} . \tag{4}$$

The constant W is determined by assuming that the remaining fraction of pulsar input, $1 - p$, goes into relativistic electrons. Note that equation (4) holds only for $\gamma < 2$; particle spectra as flat as this are indeed suggested by the observational evidence on plerions (Weiler and Panagia 1980). In our calcu-

TABLE 1

SUMMARY OF OBSERVED AND DERIVED PROPERTIES OF RADIO SUPERNOVAE

SN	Galaxy	Reference Time after Maximum (days)	Observed Flux at 6 cm (mJy)	Distance (Mpc)	Observed Spectral Index	Absolute Radio Luminosity (ergs s^{-1})	Equipartition Energy (ergs) [ν min = 10^8 Hz: ν max = 10^{11} Hz]	Average Input Power (ergs s^{-1})	Required Pulsar Period (ms)	References
1957d......	NGC 5236	8553	2.50 (20 cm)	4	1 (assumed)	7×10^{34}	5×10^{47}	6×10^{38}	31	1
1970g......	NGC 5457	852	4.60 (21 cm)	7	1 (assumed)	4×10^{35}	6×10^{46}	9×10^{38}	28	2
1979c......	NGC 4321	1212	5.54	16	0.49	9×10^{36}	2×10^{48}	2×10^{40}	12	3, 4
1980k......	NGC 6946	463	1.07	5	0.56	2×10^{35}	2×10^{46}	6×10^{38}	32	3
1981j	NGC 4258	609	0.50	6.6	1.06	1×10^{35}	2×10^{46}	4×10^{38}	33	5

REFERENCES.—(1) Cowan and Branch 1982. (2) Allen *et al.* 1976. (3) Weiler *et al.* 1983. (4) K. W. Weiler 1983, private communication. (5) van der Hulst *et al.* 1983. This is the anonymous supernova in NGC 4258, which we have christened 1981j for ease of reference.

lations $\mu = \frac{1}{2}$ and q is approximately scaled from PSR 0531, $q \approx q_{0531} \times (L_0/L_{0,0531})^\mu$.

$$d[1/(ER)]/dt \propto B^2/R \quad \text{(single particle evolution)}\,. \tag{5}$$

The energy losses are due both to adiabatic expansion and to synchrotron radiation.

$$n = \int j_i(E_i{}^2 R_i)/(E^2 R) \times dt_i \quad \text{(evolution of the particle distribution)}\,. \tag{6}$$

The value of n at a given energy E and at a given time t is the sum of the particles contributed at different times t_i, with the right E_i so as to evolve into E exactly at time t. Here equation (5) is used in calculating the evolutionary tracks.

$$S_\nu \propto BEn \quad \text{(evolution of the nebular luminosity)}\,. \tag{7}$$

Here the so-called monochromatic approximation is used (see Paper I). Fixing the frequency of observation, the corresponding electron energy is derived from $\nu \propto BE^2$.

We have integrated numerically these equations in a variety of cases in order to obtain the evolution of the electromagnetic spectrum emitted by a plerion. The actual numerical solution depends on a number of model parameters, such as the neutron star magnetic field B_0, the initial rotation period P_0, and the initial expansion velocity v_0. Rather arbitrarily, we ignore here the possibility of a large dispersion in B_0 and take a universal value by normalizing to PSR 0531. We use instead P_0 and v_0 for a classification of our model into four general categories:

1. A fast rotating pulsar ($p_0 \approx 1$ ms, close to the breakdown limit) pushing against a remnant which expands as slowly as the Crab ($v_0 \approx 10^8$ cm s^{-1}); this we label case FS (=Fast pulsar, Slow remnant).

2. A pulsar rotating much more slowly ($P_0 \approx 10$–20 ms, comparable to the inferred value for PSR 0531) inside a remnant with canonical Type II velocity ($v_0 \approx 10^9$ cm s^{-1} as deduced from optical spectra); case SF (= Slow pulsar, Fast remnant).

3 and 4. The two "antipodal" cases SS and FF.

In the following it will become apparent that examples of these various cases may have already been found. Also of importance is the assumed value of the injected particle spectral index, γ, which affects the plerion radio luminosity in combination with $E_{\max}$. Our models below correspond to different γ's, chosen so as to achieve approximate consistency with the broad-band radio and X-ray properties of some standard examples.

Figure 1 shows the light curves at 6 cm expected for different plerions, labeled FF, SF, and SS and compares them with the observational evidence. The models exhibit an initial flux rise, basically due to a decreasing synchrotron opacity. This is followed by a phase of almost constant luminosity which lasts for a time comparable to the pulsar slowing-down time scale. Finally, there is a marked flux decrease at later times when the injection rate has declined and the evolution of the source is dominated by adiabatic and radiation losses.

In particular the curves labeled FF and SF are fitted to the radio data on SN 1979c and SN 1980k, respectively, but take into account the X-ray observations as well (see below); furthermore, the choice of a fast expansion is consistent with the optically measured velocity.

Curve SS, instead, has been fitted to the present-time flux and slope of the Crab Nebula and is intended to prove the

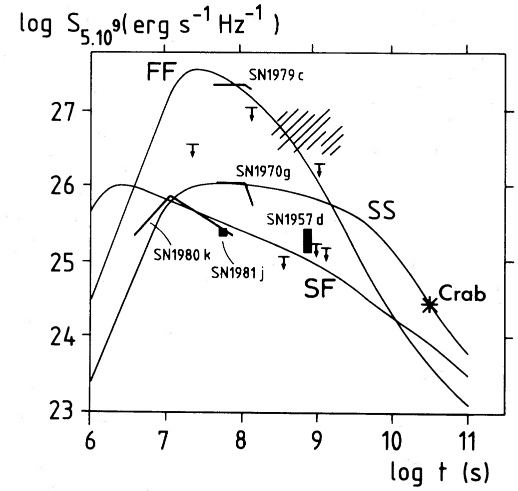

FIG. 1.—Comparison of the theoretical light curves in the cases SS, FF, and SF with some actual measurements or upper limits for radio supernovae. Curve SS refers to a slowly expanding remnant ($P_0 = 17$ ms; $\gamma = 1.5$; $v_0 = 1.5 \times 10^8$ cm s^{-1}). Curve FF assumes instead $P_0 = 1$ ms, $\gamma = 1.4$, and $v_0 = 10^9$ cm s^{-1} and allows for gravitational radiation losses. Curve SF has been computed with $P_0 = 20$ ms, $\gamma = 1.8$, and $v_0 = 10^9$ cm s^{-1}. The observations (cf. references given in Table 1) are labeled with the supernova name, and the asterisk marks the normalization point (Crab Nebula). Only the most stringent available upper limits are shown individually, while the remaining ones are represented globally by the hatched area: they are derived from de Bruyn (1973), Brown and Marscher (1978), Ulmer *et al.* (1980), and Cowan and Branch (1982).

continuity between radio supernovae and fully developed plerions from the standpoint of "typical" peak fluxes.

The agreement with the flat portion of the light curve of SN 1970g has to be regarded as accidental. Indeed, the abrupt decline of this source at age ~4 years could hardly be explained in any plerionic model without invoking additional "ad hoc" assumptions, and it is more reminiscent of the expectations of the shock model.

No clearly established example of case FS is available yet; however, if the nuclear radio source in M82 (Kronberg and Biermann 1983) were interpreted as a radio supernova undetected in the optical, its properties would be suggestive of an FS plerion.

We stress the fact that we have only attempted to describe the long-term general evolution and have not proposed any detailed modeling of the light curve over an interval of months or a few years. In fact, the short-time behavior may be affected by such local phenomena as residual variable opacity and absorption by filamentary matter. A continuous monitoring of radio supernovae over a substantial time span will eventually rule out one of the competing models. At any rate, we can draw from Figure 1 the following conclusions:

1. The light curve expected from evolving plerions can roughly match both the radio supernova phase and the later evolutionary stages.

2. The upper limits set by the lack of detection of several supernovae in the post-outburst phase do not contradict the evolutionary scheme which we are considering.

3. Most of the known radio supernovae (with the exception of SN 1979c) do not require the presence of a very active and fast pulsar but rather the existence of an object like PSR 0531.

Here we would also like to note that, as in the optical range, in the radio range one is also somewhat surprised by the lack of

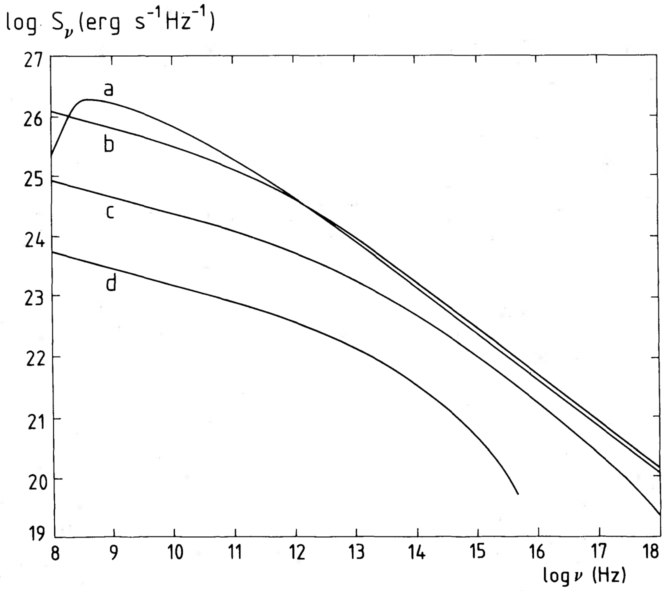

FIG. 2.—The history of the electromagnetic spectrum of a Crab-like plerion (SS case) at ages 10, 100, 1000, and 10,000 years for curves a, b, c, and d, respectively.

young plerions with age, say, around 100 years in our own Galaxy. Such plerions should be easily detectable at a distance 20,000 pc, their flux on Earth would be of order 10 Jy, and they would appear as slowly decaying point sources. One may actually wonder whether such objects would have been recognized as supernova remnants in the surveys or perhaps confused with extragalactic sources. An alternative possibility, suggested by Reynolds and Chevalier (1984), is that they are obscured by the surrounding thermal matter for about 200–300 years. However, we feel that the problem would basically remain unchanged, just considering the fate of the plerions born in the last 500 years.

III. REMARKS ABOUT THE HIGH-FREQUENCY EMISSION

From the standpoint of principle, our model could also be used for making predictions about the plerions' properties at high frequencies, say in the X-ray band, provided that they too are of synchrotron origin. However, as we have anticipated in § I, the assumed injection spectrum is oversimplified. Having been chosen to fit the radio data, this spectrum may be expected to perform weakly in a completely different spectral region. On the other hand, this assumption is made not only for the sake of simplicity but also because there are no valid arguments which can guide a different choice.

A direct comparison between the observed spectrum of the Crab Nebula and curve c of Figure 2 would show a discrepancy above the radio frequencies, the computed values being in excess by about a factor of 3 in the optical, and even more in the X-ray. Clearly this implies some intrinsic bending in the injected particle distribution.

In view of the simplicity of the underlying assumptions, we do not regard the discrepancy as a failure of the model and consider the high-frequency predictions as a useful source of qualitative information. We thus give in Figures 2, 3, and 4 the overall electromagnetic spectrum at certain specified times for the plerion parameters used in Figure 1, that is, for parameters suitable to the Crab, SN 1979c, and SN 1980k, respectively. The three light curves at $\nu = 2.4 \times 10^{17}$ Hz ($=1$ keV) are shown in Figure 5.

The early time portions of these curves have been checked against the measured X-ray value (SN 1980k) (Canizares, Kriss, and Feigelson 1982) or upper limit (SN 1979c) (Palumbo *et al.* 1981) during the fitting procedure, and an order of magnitude agreement has been obtained. Note that the X-rays follow the evolution of the pulsar input more closely than the radio, peaking at around the initial pulsar slowing-down time scale and then declining more abruptly. Because of the different radiative lifetimes relevant to the two spectral domains, radio emission can be due to relatively old electrons, whereas only fresh particles can produce the X-rays.

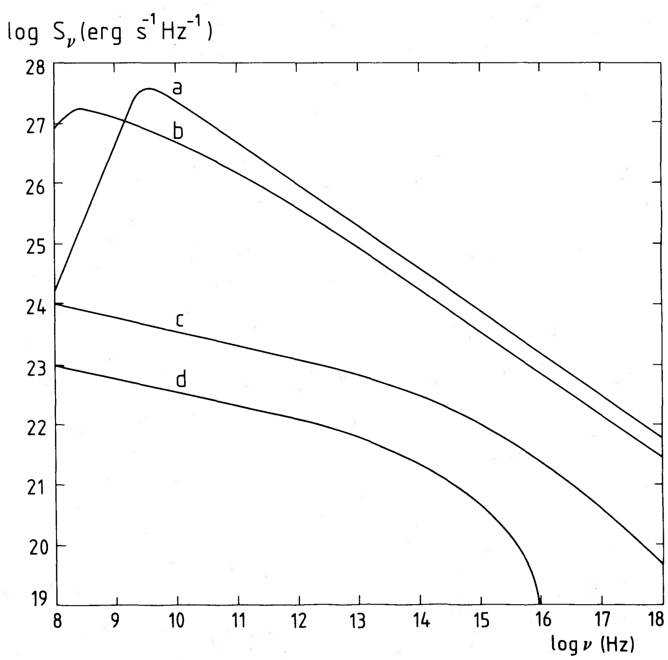

FIG. 3.—The electromagnetic spectrum for a FF plerion at ages 1, 10, 1000, and 10,000 years for curves a, b, c, and d, respectively.

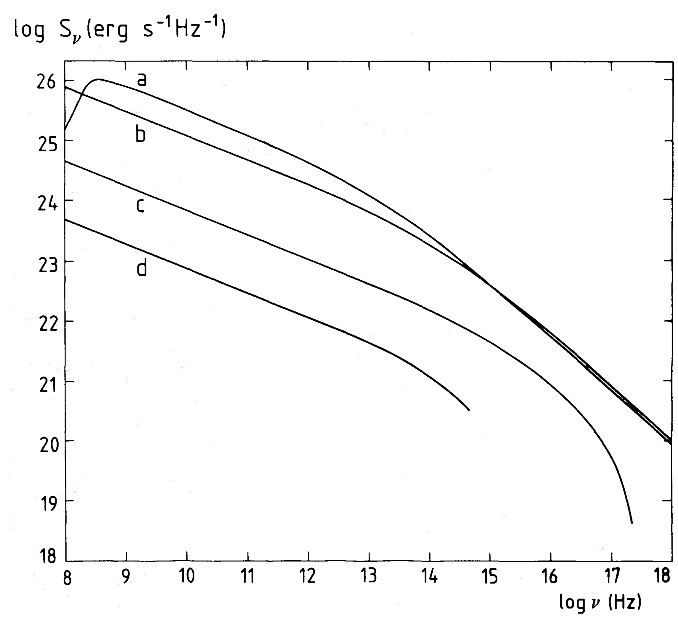

FIG. 4.—The electromagnetic spectrum for a SF plerion at ages 1, 10, 1000, and 10,000 years for curves a, b, c, and d, respectively.

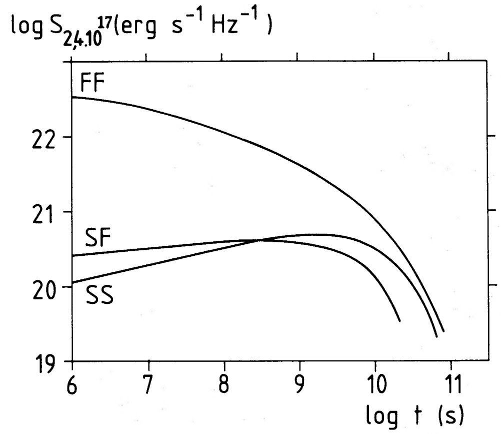

FIG. 5

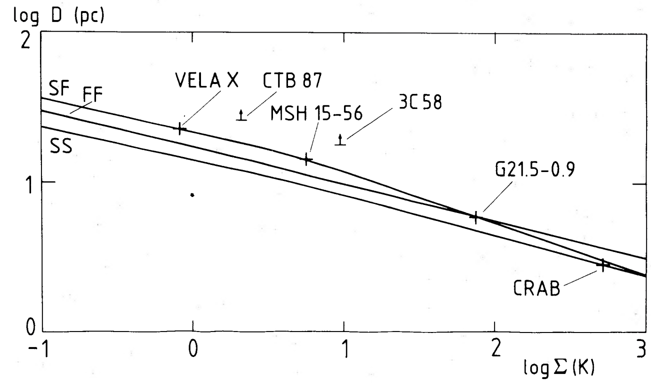

FIG. 6

FIG. 5.—Expected X-ray light curve at 1 keV for models SS, FF, and SF

FIG. 6.—Comparison of the observed Σ-D plot for plerions at radio frequencies with the model prediction for the three cases SS, FF, and SF.

IV. THE SURFACE BRIGHTNESS–DIAMETER RELATIONSHIP

A classical way of comparing theory and observation in the field of SNRs is the relationship between the surface brightness Σ and the diameter D. Independently of the assumed model, the very notion of a Σ-D implies that all the objects in the sample represent different evolutionary stages corresponding to identical initial conditions. We know this is not the case for plerions—take, for instance, the peculiar expansion velocity of the Crab Nebula—hence the following considerations must be applied to the entire class, rather than to single objects.

In the absence of energy input, if only adiabatic losses are important, $\Sigma \propto D^{-2-2\gamma}$ (see, e.g., Shklovskii 1968). With the particle indices appropriate to plerions, the exponent is about -5; on the other hand, the available data for uncontroversial members of the class—taken from Weiler and Panagia (1980) and reported in Figure 6—indicate a rather shallower dependence, between D^{-3} and D^{-4}. This is suggestive of a non-negligible pulsar contribution, i.e., of a long pulsar lifetime which in turn implies a relatively slow initial rotation.

Note the agreement between the above considerations and the implications of Figure 1, where SN 1979c stands out as an exceptional occurrence and less energetic events appear more common. The three curves shown in Figure 6 correspond to the same three parameter sets; while SN 1980k extrapolates satisfactorily to the whole class, the model fitted to SN 1979c gives too short a pulsar lifetime and too steep a dependence.

It is important at this point to mention that the customary arguments used to attribute an age to supernova remnants on the basis of the Σ-D relation may fail in the case of plerions and lead to a discrepancy between the derived age and the pulsar $P/\dot{P}$. This is the situation occurring for MSH 15−52 and the associated pulsar PSR 1509 (Seward and Harnden 1982; Manchester, Tuohy, and D'Amico 1982). As already noted by Srinivasan, Dwarakanath, and Radhakrishnan (1982), this discrepancy could be eliminated by assuming a Crab-like pulsar inside a high-velocity remnant.

The same procedure to establish a Σ-D relation can be repeated for the X-rays. Here the particle lifetime is much shorter, and, at variance with the radio, the effect of an incipient decline of the pulsar input should be immediately apparent. Indeed the X-ray data show $\Sigma \propto D^{-5}$ for plerions, in rough agreement with our expectations.

However, we will refrain from a deeper discussion of this point because we feel that our treatment of the X-ray emission can only offer qualitative results. Apart from the above mentioned unrealistic assumption of a spectral index constant up to X-ray energies, another crucial point becomes the assumption of a high-energy cutoff proportional to P^{-2}. This may lead, in the case of plerions containing an evolved pulsar, to a situation where the nonthermal output is dominated by the thermal X-ray emission resulting in the Sedov phase from the interaction with the interstellar medium.

V. CONCLUSIONS

In this paper we have shown that our present understanding of pulsar electrodynamics allows us to establish a plausible genetic link between radio supernovae and plerions. Evolutive tracks with standard plerion parameters define the luminosity and the time scale ranges covered by the observed radio supernovae and do not conflict with the available upper limits. The same tracks also translate into a theoretical Σ-D relation which describes with reasonable accuracy the present-day radio plerions. Pulsars appear to be born with relatively long rotational periods in the majority of cases so that the effect of injection is discernible also in well-evolved plerions. The behavior of the nonthermal X-rays still requires a better quantitative model. A more elaborate dynamical description of the remnant and of the injected relativistic fluid would greatly improve our understanding in this area.

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REFERENCES

Allen, R. J., Goss, W. M., Ekers, R. D., and de Bruyn, A. G. 1976, *Astr. Ap.*, **48**, 253.
Bandiera, R., Pacini, F., and Salvati, M. 1983, *Astr. Ap.*, **126**, 7.
Brown, R. L., and Marscher, A. P. 1978, *Ap. J.*, **220**, 467.
Canizares, C. R., Kriss, G. A., and Feigelson, E. D. 1982, *Ap. J.* (*Letters*), **253**, L17.
Chevalier, R. A. 1982, *Ap. J.*, **259**, 302.
Cowan, J. J., and Branch, D. 1982, *Ap. J.*, **258**, 31.

de Bruyn, A. G. 1973, *Astr. Ap.*, **26**, 105.
Goldreich, P., and Julian, W. H. 1969, *Ap. J.*, **157**, 869.
Goss, W. M., Allen, R. J., Ekers, R. D., and de Bruyn, A. G. 1973, *Nature Phys. Sci.*, **243**, 42.
Gottesman, S. T., Broderick, J. J., Brown, R. L., Balick, B., and Palmer, P. 1972, *Ap. J.*, **174**, 383.
Kronberg, P. P., and Biermann, P. 1983, in *IAU Symposium 101, Supernova Remnants and Their X-ray Emissions*, ed. J. Danziger and P. Gorenstein (Dordrecht: Reidel), p. 583.
Manchester, R. N., Tuohy, I. R., and D'Amico, N. 1982, *Ap. J.* (*Letters*), **262**, L31.
Marscher, A. P., and Brown, R. L. 1978, *Ap. J.*, **220**, 474.
Pacini, F., and Salvati, M. 1973, *Ap. J.*, **186**, 249 (Paper I).
———. 1981, *Ap. J.* (*Letters*), **245**, L107.
Palumbo, G. G. C., Maccacaro, T., Panagia, N., Vettolani, G., and Zamorani, G. 1981, *Ap. J.*, **247**, 484.
Pennington, R. L., and Dufour, R. J. 1983, *Ap. J.* (*Letters*), **270**, L7.
Reynolds, S. P., and Chevalier, R. A. 1984, *Ap. J.*. **278**, 630.
Salvati, M. 1983, in *IAU Symposium 101, Supernova Remnants and Their X-ray Emissions*, ed. J. Danziger and P. Gorenstein (Dordrecht: Reidel), p. 177.
Seward, F. D., and Harnden, F. R. 1982, *Ap. J.* (*Letters*), **256**, L45.
Shklovskii, I. S. 1968, *Supernovae* (London: John Wiley and Sons).
———. 1981, *Pis'ma Astr. Zh.*, **7**, 479 (*Soviet Astr. Letters*, **7**, 263).
Srinivasan, G., Dwarakanath, K. S., and Radhakrishnan, V. 1982, *Current Sci.*, **51**, 896.
Ulmer, M. P., Crane, P. C., Brown, R. L., and van der Hulst, J. M. 1980, *Nature*, **285**, 151.
van der Hulst, J. M., Hummel, E., Davies, R. D., Pedlar, A., and van Albada, G. D. 1983, *Nature*, **306**, 566.
Weiler, K. W. 1983, in *IAU Symposium 101, Supernova Remnants and Their X-ray Emissions*, ed. J. Danziger and P. Gorenstein (Dordrecht: Reidel), p. 299.
Weiler, K. W., and Panagia, N. 1980, *Astr. Ap.*, **90**, 269.
Weiler, K. W., Sramek, R. A., van der Hulst, J. M., and Panagia, N. 1983, in *IAU Symposium 101, Supernova Remnants and Their X-ray Emissions*, ed. J. Danziger and P. Gorenstein (Dordrecht: Reidel), p. 171.
Weiler, K. W., van der Hulst, J. M., Sramek, R. A., and Panagia, N. 1981, *Ap. J.* (*Letters*), **243**, L151.

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