RADIO AND X-RAY EMISSION FROM NEWLY BORN REMNANTS

Marco Salvati
Istituto di Astrofisica Spaziale - CNR
C.P. 67 00044 Frascati Italy

ABSTRACT

Radio and X-ray observations of SN 1979c and SN 1980k offer a unique opportunity of monitoring the transition from supernovae to remnants. By means of the two-frequency radio light curves, we test the hypothesis that these objects are surrounded by circumstellar matter, originated in a presupernova wind, and derive the relevant parameters. Then we use the absorption-corrected light curves to test the various proposed models. SN 1980k appears to be powered by a canonical shock, while SN 1979c is a good plerion candidate. An optical pulsar could still be detected at its location.

1. INTRODUCTION

While the physical connection between Supernovae and Supernova Remnants has always been obvious, until very recently these two phenomena were dealt with in rather independent contexts. The reason was the lack of direct experimental information on the intermediate phases, through which an exploding star develops into an expanding remnant. This gap now begins to be bridged because of the detection of radio emission at the sites of SN's 1970g, 1979c, and 1980k, and of X-ray emission at the site of SN 1980k. In all cases the detection first occurred only a few months after maximum light; the underlying objects, then, granted their kinship to the classical SNR's, must be in a very early, embryonic stage, characterized by length and time scales several orders of magnitude less than the conventional ones. It should be noted that the association of the X-ray flash from SN 1980k with a SNR-like phenomenon is model dependent (Canizares et al., 1982). On the other hand, the evidence collected about the radio emission strongly suggests that the basic physical mechanisms involved here are the same which we invoke for the classical SNR's.

A complete discussion of the embryonic stage of SNR's should take into account the numerous observations carried out at the sites of recent Supernovae, 10 to 100 years after maximum light, which however have given

J. Danziger and P. Gorenstein (eds.), Supernova Remnants and their X-Ray Emission, 177–182.

only upper limits (de Bruyn, 1973; Brown and Marscher, 1978; Cowan and Branch, 1982); also, there is at least one member of a new class of objects which show many similarities to the ones under discussion, but whose parent explosions, if any, have gone undetected (Kronberg et al., 1981). Here, instead, we will limit our analysis to SN's 1979c and 1980k, which are by far the best observed cases and the only ones to constrain significantly the theory. Most of the emphasis will be placed on the assessment of the competing models referred to in the following, and on the discussion of the near-future behavior to be expected of the sources. The very extensive radio data have been obtained by Weiler et al. (1983), who generously allowed their use in advance of publication. General information on the Supernovae themselves, as well as reference to related works, can be found in Panagia et al. (1980) and Panagia (1982), respectively.

2. POSITION OF THE PROBLEM

Upon inspection of the two-frequency light curves obtained by Weiler et al. (1983) one notices several distinctive features, such as the different switch-on time at different frequencies, the rapid onset followed by a plateau or a slow decline, the steady variation of the observed spectral index. The most obvious interpretation is that both sources have experienced a steady decline of optical thickness in the radio range. The required opacity is very likely due to free-free absorption in a shell of circumstellar matter, with a higher density than the general interstellar medium. In the case of SN 1979c, independent evidence for the existence of such matter is provided by UV emission lines (Panagia, 1982; Fransson et al., 1982). Further evidence can be drawn from the fact that embryo SNR's appear to be associated with Type II Supernovae, whose progenitors are believed to be red giants with a dense, low-velocity wind. The wind parameters which are obtained under this hypothesis are quite reasonable (see below), and may be looked at as an a posteriori justification.

As for the energy supply in magnetic fields and relativistic particles, two basic models have been proposed. It is conceivable that the newly born remnants are a small scale version of classical shells like Tycho or Kepler (Chevalier, 1981, 1982): the equipartition energy deduced from the radio observations is only 1 percent of the shock-driven turbulent energy. It is equally conceivable that the newly born remnants are a small scale version of the so-called plerions, of which the Crab Nebula is the prototype (Pacini and Salvati, 1981): this approach assumes that a pulsar is the primary energy source, and attributes the observed radiation to a bubble of relativistic fluid (electrons and fields) inflated by the pulsar within the supernova material. Note that the pulsed radio emission is expected to be negligible, even at the shortest pulsar periods; but the rotational energy can be made larger than the equipartition energy, and there are no difficulties in stockpiling the latter inside the bubble. A crucial problem with the plerion model is the enormous opacity of the supernova ejecta (Bahcall et al., 1970); this is overcome if the relativistic fluid bulges out of the stellar debris (Shklovskii, 1981), or if an effective filamentation process begins operating at sufficiently early times; the observed filamentary structures in classical remnants only suggest that the time scales of the process are shorter than several hundred years.

The shell model and the plerion model are most easily distinguished by means of their time behavior: it is obvious that in the latter case the continuing activity of the pulsar prevents a rapid decline of the luminosity, until the rotational energy reservoir becomes depleted; this feature will form the basis of the following analysis (Panagia, private communication). We assume: a) that the opacity is due to CSM, and the CSM was provided by a steady presupernova wind: hence the density scales as $n \propto r^{-2}$, and the optical depth as $\tau \propto r^{-3}$; b) that the dynamical influence of a possible pulsar is negligible, and the radius of the ejecta follows a self-similar law as discussed by Chevalier (1982): for the sake of definiteness, we set the envelope profile exponent equal to 12, so that $R \propto t^{0.9}$, and $\tau \propto t^{-2.7}$; c) that in a given object the intrinsic spectral index α is time independent. A certain value of α defines the intrinsic flux ratio at the observed frequencies; then, comparison with the measured ratio gives the value of τ at that time. Since the time dependence of τ is determined by our assumptions to within a normalization factor, A, the only free parameters are A and α, which we find by ordinary χ^2 techniques. A is related to the CSM density and to the presupernova mass loss rate; more important still, its knowledge allows us to correct the observed flux at a fiducial frequency, and to compare its intrinsic time behavior with model predictions.

The light curve to be expected from a shell-type source is taken from Chevalier (1982), with a minor correction to relate the typical electron energy to the shock velocity. In the plerion case, one must distinguish between two alternatives: the low field, slow pulsar case, where the synchrotron lifetime is longer than the expansion time; and the high field, fast pulsar case, where the opposite is true. The predicted light curves are taken from Pacini and Salvati (1973), corrected for a non-linear expansion. One has

$$\begin{aligned} F &\propto t^{-(0.1+1.4\alpha)}\,\nu^{-\alpha} && \text{shell} \\ F &\propto t^{(0.15-0.85\alpha)}\,\nu^{-\alpha} && \text{plerion, } \nu < \nu_b \\ F &\propto t^{(0.85-0.85\alpha)}\,\nu^{-\alpha} && \text{plerion, } \nu > \nu_b \end{aligned} \tag{1}$$

The break frequency which divides the two plerionic regimes evolves as

$$\nu_b \propto t^{-2}\,B^{-3} \propto t^{0.55} \tag{2}$$

Its normalization coefficient contains information on the bubble magnetic field, hence, indirectly, on the rotational energy loss and initial period of the pulsar. Additional information is provided by the X-ray observations, and by the early portions of the radio light curves, where only single-frequency measurements are available, and the optical depth has to be extrapolated from later times.

3. RESULTS AND DISCUSSION

When the outlined procedure is applied to SN 1979c, one finds a satisfactory fit for the τ-vs-time curve; if t is measured in days, and the optical thickness is referred to ν = 5 GHz, the best fit parameters are

$$A = 4.6\ 10^{6} \qquad \alpha = 0.67 \qquad (3)$$

A is easily transformed into a density profile and a presupernova mass loss rate

$$n = C\ r^{-2}\ \mathrm{cm}^{-3} \qquad C = 9.0\ 10^{37}\ v_{o9}^{1.5}\ \mathrm{cm}^{-1}$$

$$\dot{M} = 3.5\ 10^{-5}\ v_{w6}\ v_{o9}^{1.5}\ M_{o}\ \mathrm{yr}^{-1} \qquad (4)$$

where v_{o9} is the velocity of the ejecta at a reference time $t_o = 3\ 10^{6}$ s, in units of 10^9 cm s^{-1}; and v_{w6} is the wind velocity in units of 10^6cm s^{-1}.

The problems with this particular object arise when one tries to fit the corrected light curve to the theoretical models of Eq.1. The curve, either corrected or uncorrected, exhibits statistically significant irregularities which cannot be reproduced by any power law; the best which can be done is to account for the general trend, and under this respect the best performing model is a plerion with a fast pulsar inside, $\nu > \nu_b$. The fast pulsar condition implies that the spectral index unperturbed by synchrotron losses is equal to $\alpha - 0.5 = 0.17$: spectra as flat as this are peculiar to plerionic remnants (Weiler and Panagia, 1980). Furthermore, the requirement that ν_b be smaller than 1.5 GHz for at least 1200 days is a severe constraint on the pulsar period. The exact upper limit is a sensitive function of the plerion volume, that is, of the ejecta velocity and of the bubble filling factor; our best guess is between a few and several milliseconds, which implies an average optical magnitude $<$ $<$ 22 according to the canonical scaling (Pacini, 1971). Since ν_b is an increasing function of time, one expects a change in spectral slope and time slope, as prescribed by Eq.1; later still, when the pulsar initial lifetime is elapsed, the energy supply will start to decline, and the source will be switched off with the expansion time scale. If both events were actually observed, one could evaluate separately the pulsar period and the plerion volume.

Now we turn to SN 1980k, and in analogy with Eqs.3 and 4 we find

$$A = 5.6\ 10^{4} \qquad \alpha = 0.38 \qquad (5)$$

$$C = 9.9\ 10^{36}\ v_{o9}^{1.5}\ \mathrm{cm}^{-1}$$

$$\dot{M} = 3.8\ 10^{-6}\ v_{w6}\ v_{o9}^{1.5}\ M_{o}\ \mathrm{yr}^{-1} \qquad (6)$$

With the given α, a satisfactory fit to the corrected light curve is obtained with the shell model: apart from opacity effects, and at variance with SN 1979c, the radio flux from SN 1980k is declining at a substantial rate, and the plerion model could work only if the pulsar power input were declining as well. A Crab-like pulsar rotating at the breakdown period, P ∿ 0.5 msec, would indeed have a lifetime of about one month, but would also be so energetic that some exotic and unmistakable manifestations should be observed.

A further argument in favor of the shock interpretation is that classical shell-type remnants have a spectral index distribution with a median value of precisely 0.4. It is then natural to interpret the X-ray emission from SN 1980k in analogy with classical remnants, i.e. as a thermal emission from shock-heated material (Chevalier, 1982). It might be noted that a similar shock and a similar emission process is unavoidable in SN 1979c, which is surrounded by an even thicker CSM cocoon; X-ray observations were carried out at comparable post-outburst times, with negative results (Palumbo et al., 1981). If the expansion velocity is assumed to be the same, and if the small difference due to the slightly discrepant ages is neglected, the luminosity should scale as the τ coefficient A; however, the result exceeds the measured upper limit by almost an order of magnitude. A possible remedy, may be only a partial one, is the assumption that v_o had a lower value in SN 1979c.

The same considerations can be repeated for the radio emission: the shock system surrounding SN 1979c is likely to be the site of instabilities and energization processes as well as SN 1980k, so that the plerion emission must be contaminated by a shell emission. The scaling law for a universal value of α is

$$F \propto t^{-(0.1+1.4\alpha)}\ \nu^{-\alpha}\ D^{-2}\ A^{0.25(3+\alpha)}\ v_o^{0.25(13+19\alpha)} \tag{7}$$

and the shell component at, say, t = 800 d is comfortably smaller than the observed total, especially if the effect of a different v_o is included. A qualitative support to this picture is found by extrapolating the τ curve and by deriving the corrected light curve even at very early times, for which only high-frequency measurements are available. SN 1980k nicely follows the best-fit power law which describes the later, two-frequency measurements. SN 1979c, instead, has an intrinsic flux definitely higher than the best fit, and the discrepancy decreases smoothly with increasing time until it disappears around day 600. It is certainly disturbing that the higher intrinsic flux, if real, would conspire with opacity in such a way as to give an almost constant observed flux. But it is nonetheless appealing to interpret the early-time excess as a shell component, which then faded and became dominated by a time-steady plerion component.

If the analogy between the two objects were complete, one would expect in the near future a flattening of the SN 1980k light curve, in correspondence with the taking over of a plerion. Until then, however, the place to search for an extragalactic optical pulsar would be the site of SN 1979c.

We gratefully acknowledge very interesting discussions with N. Panagia, F. Pacini, and R. Bandiera.

REFERENCES

Bahcall, J.N., Rees, M.J., and Salpeter, E.E.: 1970, Astrophys. J. 162, p.737
Brown, R.L., and Marscher, A.P.: 1978, Astrophys. J. 220, p.467
Canizares, C.R., Kriss, G.A., and Feigelson, E.D.: 1982, Astrophys. J. 253, p.L17
Chevalier, R.A.: 1981, Astrophys. J. 251, p.259
Chevalier, R.A.: 1982, preprint
Cowan, J.J., and Branch, D.: 1982, Astrophys. J. 258, p.31
de Bruyn, A.G.: 1973, Astron. Astrophys. 26, p.105
Fransson, C., Benvenuti, P., Gordon, C., Hempe, K., Palumbo, G.G.C., Panagia, N., Reimers, D., and Wamstekers, W.: 1982, NORDITA preprint 82/24
Kronberg, P.P., Biermann, P., and Schwab, F.R.: 1981, Astrophys. J. 246, p.751
Pacini, F.: 1971, Astrophys. J. 163, p.L17
Pacini, F., and Salvati, M.: 1973, Astrophys. J. 186, p.249
Pacini, F., and Salvati, M.: 1981, Astrophys. J. 245, p.L107
Palumbo, G.G.C., Maccacaro, T., Panagia, N., Vettolani, G., and Zamorani, G.: 1981, Astrophys. J. 247, p.484
Panagia, N.: 1982, Proc. 3rd IUE European Conf., to be published
Panagia, N., et al.: 1980, M.N.R.A.S. 192, p.861
Shklovskii, I.S.: 1981, Pis'ma Astron. Zh. 7, p.479 (Sov. Astron. Lett. 7, p.263)
Weiler, K.W., and Panagia, N.: 1980, Astron. Astrophys. 90, p.269
Weiler, K.W., Sramek, R.A., van der Hulst, J.M., and Panagia, N.: 1983, this volume, p. 171.