Mon. Not. R. astr. Soc. (1989) **237**, 1033–1036

Supernova SN 1987A: rotation rate of the central pulsar

Harish C. Bhatt and Bhaskar Datta *Indian Institute of Astrophysics, Bangalore 560034, India*

Accepted 1988 November 1. Received 1988 November 1; in original form 1988 September 1

Summary. Using available observational data on supernova SN 1987A, we derive firm quantitative lower limits on the rotation period of the central pulsar (assuming the pulsar luminosity to power the supernova light curve). We also demonstrate that pulsars born in type II supernovae are, in general, unlikely to be fast pulsars.

1 Introduction

The detection of neutrinos from supernova SN 1987A (Bionta *et al.* 1987; Hirata *et al.* 1987) is generally accepted to be indicative of the formation of a neutron star (Burrows 1988). The subsequent detection (Barthelmy *et al.* 1988; Matz *et al.* 1988) of gamma ray lines from SN 1987A characteristic of ^{56}Co decay and the exponential decay of the light curve (Catchpole *et al.* 1987a, b) with a time-scale similar to ^{56}Co decay half-life after about 120 days after the explosion suggest that the energy source is ^{56}Co radioactive decay. The unusual behaviour of the SN 1987A light curve during the first few months has also been suggested as being due to a central pulsar providing the energy (Ostriker 1987). The energy transferred by the pulsar to the surrounding nebula will cause the supernova light curve to level off at some asymptotic value after the radioactive contribution has declined sufficiently, depending on the relative magnitudes of the pulsar luminosity and the radioactive energy. The observed luminosity therefore provides an upper limit of the central pulsar luminosity. As the light curve has not shown any sign of levelling off even after more than 400 days since the explosion, the luminosity of the central pulsar must be low, and the pulsar must not be rotating rapidly. Using available observational data, we derive quantitative lower limits on the rotation period of the central pulsar. We also show that pulsars born in type II supernovae are, in general, unlikely to be fast pulsars.

2 Theoretical considerations

For an observed bolometric luminosity L_0 of the supernova, we can write,

$$L_{PSR} \leqslant L_0, \tag{1}$$

where $L_{\rm PSR}$ is the luminosity of the central pulsar. Following Ostriker & Gunn (1971),

$$L_{\rm PSR} = L_{\rm i}(1+2t/\tau_{\rm i})^{-2} \quad (2)$$

$$L_{\rm i} = 2B^2R^6\Omega_{\rm i}^4/3c^3 \quad (3)$$

$$\tau_{\rm i} = 3c^3 I/(2B^2R^6\Omega_{\rm i}^2). \quad (4)$$

Here B is the surface dipole magnetic field and R, I and $\Omega_{\rm i}$ are the radius, moment of inertia and the initial angular speed of the pulsar, respectively. Values of B, R and I that are typical of pulsars give $\tau_{\rm i} \sim 4P^2(\mathrm{ms})$ yr. Therefore, for $t \sim 1$ yr the factor $2t/\tau_{\rm i}$ can be neglected for most plausible values of P, and we can write

$$L_{\rm PSR} \simeq L_{\rm i} \leqslant L_0. \quad (5)$$

So, the initial rotation period ($P_{\rm i}$) of the pulsar will satisfy

$$P_{\rm i} \geqslant 2\pi(1.5\, c^3 L_0)^{-1/4} B^{1/2} R^{3/2}. \quad (6)$$

On day 134 after the explosion, the visual magnitude of SN 1987A was $V=4.4$ and the bolometric luminosity $L_0 = 10^{41.5}$ erg s^{-1} (Catchpole *et al.* 1987a, b). Therefore,

$$P_{\rm i} \geqslant 5.75\times10^{-3} B_{12.5}^{1/2} L_{41.5}^{-1/4} x^{3/2} \ \mathrm{s}, \quad (7)$$

where $B_{12.5}$ is the surface magnetic field strength in units of $10^{12.5}$ G, $L_{41.5}$ is the luminosity in units of $10^{41.5}$ erg s^{-1} and $x = R/10$ km. The visual brightness has been declining continuously since then. By 1988 April 22 it declined to $V=7.4$. The visual magnitude is a measure of the bolometric luminosity, as the colours $(B-V)$ for most type II supernovae after about 100 days look similar (Barbon, Ciatti & Rosino 1979; Hamuy *et al.* 1988) at $\simeq +0.7$, implying a small, constant bolometric correction. Therefore, we can assume that the bolometric luminosity of SN 1987A has also fallen by 3 mag from day 134 to 424. Since $P_{\rm i}$ falls as $L^{-1/4}$, we can write

$$P_{\rm i} \geqslant 11.47\, x^{3/2} \ \mathrm{ms}, \quad (8)$$

where we have taken for B the canonical value $10^{12.5}$ G. Equation (8) sets a rough lower limit on the rotation period of the central pulsar.

3 Results and conclusions

The total binding energy (W) of the remnant neutron star in SN 1987A can be estimated using the neutrino flux data, choosing a neutrino-cooling model and a distance estimate (Kahana, Cooperstein & Baron 1987; Sato & Suzuki 1987):

$$W = \begin{cases} (2.0\pm0.5)\times10^{53}\ \mathrm{erg} \\ (1.7-3.4)\times10^{53}\ \mathrm{erg} \\ (1.2-5.3)\times10^{53}\ \mathrm{erg}. \end{cases} \quad (9)$$

Structural parameters of neutron stars can be calculated, for a given equation of state, by integrating the relativistic hydrostatic equilibrium equations. For a set of six representative equations of state of neutron star matter (Pandharipande 1971; Bethe & Johnson 1974; Walecka 1974; Canuto, Datta & Kalman 1978; Friedman & Pandharipande 1981; Kutschera & Pethick 1986), we have calculated W as a function of R. This gives us, corresponding to equation (9), $1.0 \leqslant x \leqslant 1.5$. Equation (8) then implies the following range for the lower limit of $P_{\rm i}$: 11.47–21.08 ms. This provides a first estimate of the minimum rotation rate of the central pulsar in SN 1987A. If the luminosity of SN 1987A declines further in the coming months, the lower limit on the period will correspondingly increase. Therefore, the above range of values will represent firm lower limits on P_i.

The limit derived above can be improved if the explanation of the initial rise in the light curve of SN 1987A is in terms of the radiactive decay of ^{56}Co. If t_d and t_e are the diffusion and expansion times, then the bump can be understood as being due to energy stored in a region within the supernova photosphere till $t_d \simeq t_e$, which happens at about 100 days after the explosion. This stored energy, as a function of time, will be given by

$$E(t)=\int_0^t L(t')\,dt'=\int_0^t L_i \exp(-t'/\tau)\,dt=\tau L_i[1-\exp(-t/\tau)]. \tag{10}$$

At about 120 days after the explosion, the brightness of SN 1987A had declined exponentially with τ in a similar manner to ^{56}Co decay time-scale, and (Catchpole *et al.* 1987a, b)

$$E(t=134\ \text{day})=6.4\times 10^{48}\ \text{erg}. \tag{11}$$

Equations (10) and (11) give

$$L_i \simeq 9.5\times 10^{41}\ \text{erg s}^{-1}. \tag{12}$$

For $t=424$ days (i.e. 1988 April 22) we then theoretically expect

$$L(t=424\ \text{day})\simeq 2.2\times 10^{40}\ \text{erg s}^{-1}. \tag{13}$$

On the other hand, the luminosity of SN 1987A on day 424 that can be inferred from the observed $V=7.4$ is 2×10^{40} erg s^{-1} (assuming the spectral energy distribution to be the same as on day 134 when $V=4.4$ and $L_0=10^{41.5}$ erg s^{-1}). Thus, the observed luminosity on day 424 agrees with the value given in equation (13) to within 10 per cent. Therefore, the pulsar luminosity contribution to the supernova luminosity is at most a tenth of the observed luminosity, so that

$$L_{PSR} \leqslant 2\times 10^{39}\ \text{erg s}^{-1}, \tag{14}$$

which would then give

$$P_i \geqslant 40.67\text{–}74.75\ \text{ms} \tag{15}$$

for the same values of B and x adopted earlier.

There are four other type II supernovae for which light curves beyond 100 days exist. These are SN 1969L, 1970G, 1979C and 1980K, for which the absolute magnitudes $(M_v)_0$ and colours $(B-V)_0$ corrected for extinction are given by Barbon *et al.* (1979). At the least level down to which these have been observed, $(M_v)_0$ and $(B-V)_0$ values are: -12.3 and 0.45 (SN 1969L), -12.2 and 0.05 (SN 1970G), -12.4 and 0.25 (SN 1979G) and -12.1 and 0.70 (SN 1980K). Applying bolometric corrections (which turn out to be small, $\lesssim 0.2$ mag) corresponding to the observed $(B-V)_0$ colour and appropriate to supergiants, the absolute bolometric magnitudes m_{bol} are: -12.2 (for SN 1969L), -12.2 (for SN 1970G), -12.4 (for SN 1979C) and -12.1 (for SN 1980K). Taking $m_{bol}=-12.2$ as the representative value, the bolometric luminosity level to which these supernovae have been oberved to have declined is 1.9×10^{40} erg s^{-1}, which is nearly the same as in the case of SN 1987A. It has recently been noted (Young & Branch 1988) that the light curve of SN 1987A resembles that of the likely type II SN 1909A, the observed luminosity of the latter at the faintest level being similar to the earlier mentioned four type II suypernovae. *Thus, light curves of type II supernovae for which observational data beyond 100 days exist are quite similar, all attaining a low luminosity level* ($\sim 2\times 10^{40}$ *erg s*$^{-1}$). Since this observed feature is in agreement with theoretical models of type II supernovae (see, e.g. Woosley 1987), it is reasonable to expect it to be generally true of all type II supernovae. Hence, the conclusion that emerges is that pulsars born in type II supernovae are not likely to be fast pulsars (for which a binary accretion spin-up is the likely scenario; see Alpar *et al.* 1982; Radhakrishnan & Srinivasan 1982; Fabian *et al.* 1983). It may be relevant to recall here that the extrapolated initial spin period of the Crab pulsar is ~17 ms, which reinforces the above conclusion.

Low luminosities of pulsars in supernovae could also be due to (as suggested by the referee): (i) the pulsar initial magnetic field being weak (and built up later by a battery mechanism, see, e.g. Urpin & Yakolev 1980; Blandford, Applegate & Hernquist 1983) or (ii) a quenching of the pulsar emission, even if the magnetic field is high, by accretion from the inner envelope or from a binary companion. In the latter case, the accretion rate must be rather large for any effective quenching. The details of either scenario are, however, not yet fully understood. We have taken here the prevalent standard view that initial dipole magnetic field strengths of pulsars are $\sim 10^{12.5}$ G. Continued observations of nearby supernovae to as faint magnitudes as possible would be desirable.

References

Alpar, M. A., Cheng, A. F., Ruderman, M. A. & Shaham, J., 1982. *Nature,* **300,** 728.
Barbon, R., Ciatti, F. & Rosino, L., 1979. *Astr. Astrophys.,* **72,** 287.
Barthelmy, S., Gehrels, N., Leventhal, M., MacCallum, C. J., Teegarden, B. J. & Tueller, J., 1988. *IAU Circ. No. 4593.*
Bethe, H. A. & Johnson, M. B., 1974. *Nucl. Phys.,* **A230,** 1.
Bionta, R. M. *et al.,* 1987. *Phys. Rev. Lett.,* **58,** 1494.
Blandford, R. D., Applegate, J. H. & Hernquist, L., 1983. *Mon. Not. R. astr. Soc.,* **204,** 1025.
Burrows, A., 1988. Preprint.
Canuto, V., Datta, B. & Kalman, G., 1978. *Astrophys. J.,* **221,** 274.
Catchpole, R. M. *et al.,* 1987a. *IAU Circ. No. 4485.*
Catchpole, R. M. *et al.,* 1987b. *Mon. Not. R. astr. Soc.,* **229,** 15P.
Fabian, A. C., Pringle, J. E., Verbunt, F. & Wade, R. A., 1983. *Nature,* **301,** 222.
Friedman, B. & Pandharipande, V. R., 1981. *Nucl. Phys.,* **A361,** 502.
Hamuy, M., Suntzeff, N. B., Gonzalez, R. & Martin, G., 1988. *Astr. J.,* **95,** 63.
Hirata, K. *et al.,* 1987. *Phys. Rev. Lett.,* **58,** 1490.
Kahana, S. H., Copperstein, J. & Baron, E., 1987. *Phys. Lett.,* **196,** 259.
Kutschera, M. & Pethick, C. J., 1986. *Nucl. Phys.,* **A455,** 664.
Matz, S. M., Share, G. H., Leising, M. D., Chupp, E. L., Vestrand, W. T., Purcell, W. R., Strickman, M. S. & Reppin, C., 1988. *Nature,* **331,** 416.
Ostriker, J. P. & Gunn, J. E., 1971. *Astrophys. J.,* **184,** L95.
Ostriker, J. P., 1987. *Nature,* **327,** 287.
Pandharipande, V. R., 1971. *Nucl. Phys.,* **A174,** 641.
Radhakrishnan, V. & Srinivasan, G., 1982. *Current Science,* **51,** 1096.
Sato, K. & Suzuki, H., 1987. *Phys. Lett.,* **196,** 267.
Urpin, V. A. & Yakolev, D. G., 1980. *Soviet Astr.,* **24,** 425.
Walecka, J. D., 1974. *Ann Phys.,* **83,** 491.
Woosley, S. E., 1987. *Astrophys. J.,* **318,** 664.
Young, T. R. & Branch, D., 1988. *Nature,* **333,** 305.