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CONSTRAINTS ON A PUTATIVE PULSAR IN SN 1987A

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ABSTRACT

We assume that all the energy loss of the putative pulsar in SN 1987A would contribute to the luminosity of the remnant, which acts like a bolometer. The bolometric luminosity of SN 1987A provides an upper bound on the pulsar's rate of energy loss. An isolated pulsar spinning down by magnetic dipole radiation alone with initial rotation periods of 10–30 ms, as extrapolated for galactic young pulsars, can have a luminosity below the bolometric bound if either the magnetic field is weak, $B \sim 10^9$–10^{10} G, or if it is so strong that the pulsar luminosity decays rapidly, $B \sim 10^{16}$ G.

Subject headings: pulsars: general — stars: neutron — supernovae: individual (SN 1987A)

1. INTRODUCTION

The observed Balmer absorption lines class SN 1987A as a Type II supernova. The identification of the pre-supernova star, the neutrino flux detected at the time of the explosion, the evolution of the optical light curve, and the observations of the emission of soft gamma rays all confirm this classification. Therefore, it is expected that a neutron star lies at the center of the remnant. Simulations of the neutrino output in core collapse leading to a black hole differ strongly from the Kamiokande neutrino detections, which agree with several neutron star models (Burrows 1988). Any detection of a neutron star formed in SN 1987A would arouse great interest since the properties of very young neutron stars are largely unknown. Searches for pulsed emission from the remnant have yielded no results (Ögelman et al. 1990). A claimed pulsar period of 2.14 ms has been discussed by Middleditch et al. (2000). A synchrotron nebula would indicate a young pulsar even if its beam does not sweep our direction, so that a pulsed signal is not received. No synchrotron nebula has been detected in the remnant of SN 1987A, with a *Chandra* upper limit of 5.5×10^{33} ergs s^{-1} to the luminosity of a central X-ray source (Park et al. 2003).

The newborn neutron star is characterized by its initial rotation rate and magnetic dipole moment. It will spin down, generating radiation and accelerating charged particles at the expense of its rotational energy. The power output of the neutron star is the luminosity of a rotating dipole, regardless of the detailed processes by which the dipole emission is converted to the energy of charged particle acceleration and high-enegy electromagnetic radiation. The remnant is optically thick to the radiation emitted by the young pulsar. Thus, the remnant will act as a bolometer, absorbing and reprocessing the pulsar luminosity. Most of the remnant's central luminosity is in the optical, IR, and UV bands, exceeding its X-ray luminosity by several orders of magnitude. The observed bolometric luminosity of the remnant is dominated and well fitted with the radioactive decay luminosity, so the contribution from the pulsar must be a small admixture. We shall assume that the pulsar loses energy as an isolated rotating dipole, of constant magnetic dipole moment, without any other torques (as would arise, for example, from the presence of a fallback disk). We use the bolometric luminosity to place bounds on the dipole emission of the putative pulsar and on its birth properties.

2. ESTIMATION OF THE PULSAR'S BIRTH PROPERTIES

The spin-down of the pulsar by dipole radiation follows from

$$I\Omega\dot{\Omega} = L_{\rm dip} = \frac{2\mu^2\Omega^4}{3c^3}, \qquad (1)$$

where I is the moment of inertia of the neutron star, Ω is the star's rotation rate, and μ is its magnetic moment. The solution for the luminosity is

$$L_{\rm dip}(t) = L_0(1 + t/t_0)^{-2} \qquad (2)$$

in terms of the initial luminosity $L_0 = (2/3)\mu^2\Omega(0)^4/c^3$. The timescale t_0 is the initial energy-loss timescale of dipole radiation,

$$t_0 = E_0/L_0 = \frac{3Ic^3}{4\mu^2\Omega(0)^2}, \qquad (3)$$

where $E_0 = \frac{1}{2}I\Omega(0)^2$ is the initial rotational energy.

The bound provided by the observed bolometric luminosity at time t is $L_{\rm dip}(t) < L_{\rm bol}(t)$. Using equation (2) and substituting for L_0 and t_0, we obtain

$$\left[1 + \frac{4\mu^2\Omega(0)^2 t}{3Ic^3}\right]^2 > \frac{2\mu^2\Omega(0)^4}{3c^3L_{\rm bol}(t)}. \qquad (4)$$

Expressing the inequality in terms of the initial period P_0 and magnetic moment μ and taking the square root leads to

$$\left(P_0^2 + \frac{16\pi^2\mu^2 t}{3Ic^3}\right) > \frac{4\pi^2\mu}{[3/2c^3L_{\rm bol}(t)]^{1/2}}. \qquad (5)$$

Completing the square in terms of μ and normalizing, we obtain the constraint

$$\frac{P_0^2}{P(t)^2} + \frac{[\mu - \bar{\mu}(t)]^2}{\bar{\mu}(t)^2} > 1. \qquad (6)$$

Thus, the allowed values of the magnetic moment μ and

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initial period P_0 must lie outside an ellipse in the P_0-μ plane, with

$$\bar{P}(t) = \left[\frac{I\pi^2}{2tL_{\rm bol}(t)}\right]^{1/2}, \tag{7}$$

$$\bar{\mu}(t) = \frac{(6c^3)^{1/2}I}{8t[L_{\rm bol}(t)]^{1/2}}, \tag{8}$$

as shown in Figure 1. For initial rotation periods $P_0 < \bar{P}$, the dipole luminosity is less than the observed $L_{\rm bol}(t)$, either because the magnetic moment is small or the magnetic moment is large enough that the dipole luminosity has decreased rapidly. For $P_0 > P$, the initial rotation rate is slow enough that the pulsar's luminosity at time t is less than $L_{\rm bol}(t)$ for all values of the magnetic moment.

As the observed bolometric luminosity decays rapidly with time, the forbidden ellipse in the P_0-μ plane expands, as indicated by equations (5) and (6). Thus, in a data set $L_{\rm bol}(t)$ extending to $t = t_{\rm max}$, it is the lowest luminosity $L_{\rm bol}(t_{\rm max})$ that yields the tightest constraint, encompassing the constraints imposed by all earlier observations. The bolometric luminosity observed for over 10 yr is fitted quite well by a series of exponential decays corresponding to the radioactive decays of ^{56}Co, ^{57}Co, ^{44}Ti, ^{22}Na, and ^{60}Co (Timmes et al. 1996). Bouchet et al. (1991) have compiled the bolometric luminosity evolution in the IR, optical, and UV bands for days 14–432 after the supernova. An initial hump is followed after 130 days by an exponential decay of time constant $\tau \cong 110$ days, corresponding to the decay of ^{56}Co (see Bouchet et al. 1991, Fig. 3), with a slight increase in the rate of decay after $t = 300$ days. At later times the bolometric luminosity can be fitted with a sum of slower decays. At 3346 days the bolometric luminosity $L_{\rm bol} = 2.1 \times 10^{36}$ ergs s^{-1}, fitting on a curve corresponding to the decay of ^{44}Ti (Balberg et al. 1999). Later data taken by the *Hubble Space Telescope* Wide Field Planetary Camera and Wide Field Planetary Camera 2 give *UBVRI* magnitudes corrected by subtraction of the ring contribution in the SN 1987A images (Soderberg, Challis, & Suntzeff 1999). We use the latest observations reported in this work, deriving a bolometric luminosity $L_{\rm bol} = 3 \times 10^{34}$ ergs s^{-1} from the *UBVRI* magnitudes at 4339 days, using a distance of 55 kpc for the Large Magellanic Cloud. The magnitudes were converted to luminosities using the standard bandwidths and conversion formulae for the *UBVRI* bands (Padmanabhan 2001).

Figure 1 shows the results using these late data. We obtain a characteristic period P ($t = 4339$ days) of 21 s; thus, a pulsar born with a longer rotation period would remain below the bolometric luminosity limit no matter what its magnetic dipole moment is. The characteristic magnetic moment $\bar{\mu}$ ($t = 4339$ days) is 2.4×10^{34} G cm^3 for a neutron star with moment of inertia $I = 10^{45}$ gm cm^2. For initial periods P_0 of 10, 15, or 30 ms, we find that two alternatives are allowed. The magnetic dipole moment is either less than 2.8×10^{27}, 6.4×10^{27}, or 2.5×10^{28} G cm^3, respectively, for these initial periods, or it is greater than $\cong 2\bar{\mu} = 4.8 \times 10^{34}$ G cm^3. For a slow initial rotation rate, e.g., $P_0 = 0.3$ s, we find $\mu < 2.5 \times 10^{30}$ or $\mu > 2.4 \times 10^{34}$ G cm^3. For a pulsar born with a 2 ms rotation rate, $\mu < 1.1 \times 10^{26}$ or $\mu > 2.4 \times 10^{34}$ G cm^3.

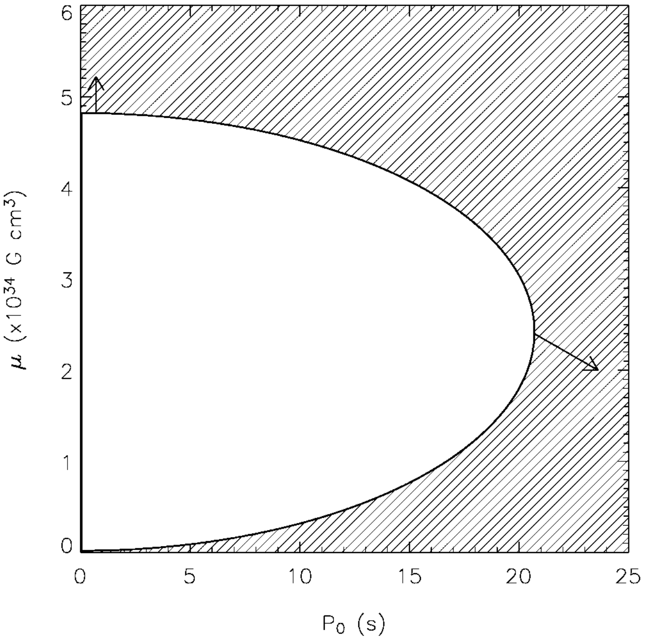

FIG. 1.—Initial period P_0 and dipole magnetic moment μ of the putative pulsar allowed by the bolometric luminosity of SN 1987A must lie in the shaded region exterior to the ellipse shown. The semiminor axis $\bar{\mu}$ and the semimajor axis P are determined by $L_{\rm bol}(t)$ at each observation time t. As $L_{\rm bol}(t)$ decays exponentially, the extreme points of the ellipse move as indicated by the arrows, so that the ellipses at later times completely include the ellipses at earlier times, and the tightest constraint is provided by the latest observations. The ellipse shown corresponds to the latest observations published by Soderberg et al. (1999).

3. DISCUSSION

By using the bolometric luminosity of the central remnant in SN 1987A, one can obtain interesting constraints on the properties of the neutron star at birth. The constraints on initial rotation period and on magnetic dipole moment are not independent of each other. To place the options in context, let us recall the possibilities presented by the conventional interpretation of the radio pulsar population.

Regarding the initial periods, the population of "fresh" normal radio pulsars (as distinct from the "recycled" binary and millisecond radio pulsars; Alpar et al. 1982; Radhakrishnan & Srinivasan 1982) implies $P_0 \sim 10$–30 ms, by extrapolation from the youngest pulsars. An alternative suggestion, particularly for the possible pulsar in SN 1987A, is that it was formed by a core merger (Chen & Colgate 1995; Middleditch et al. 2000). The pulsar is expected to have an initial period in the millisecond range, and millisecond pulsars in general can be young objects according to this scenario.

The suggestion that some pulsars are born with slow rotation rates to explain the distribution in the P-$\dot{P}$ diagram has proved difficult to check conclusively because of a complex of selection effects and has led to conflicting results. Slow initial rotation rates are not supported by the later work (Lorimer et al. 1993). The distribution in the P-$\dot{P}$ diagram can be obtained if pulsars are born with short initial periods of 10–30 ms and evolve under varying torques that include contributions other than the dipole radiation torque at some epochs in the pulsars' evolution. This is supported by the observation of braking indices less than the dipole braking index $n = 3$ (Kaspi et al. 2001) and ages that differ significantly from the characteristic age $P/2\dot{P}$ of dipole spin-down (Gaensler & Frail 2000).

The dipole magnetic moments of the majority of radio pulsars are on the order of 10^{30} G cm^3 ($B \sim 10^{12}$ G). There is no evidence for decay of the magnetic moment during the normal radio pulsars' active lifetimes (Bailes 1989; Bhattacharya et al. 1992). There are a few pulsars in the tail of the distribution, with dipole magnetic moments in the 10^{31} G cm^3 range (Camilo et al. 2000; Morris et al. 2002; McLaughlin et al. 2003) and surface dipole magnetic fields in the magnetar range, higher than the quantum critical field $B_c \equiv (m_e^2 c^3)/(e\hbar) = 4.4 \times 10^{13}$ G. PSR J1847−0130 (McLaughlin et al. 2003) has the highest dipole moment, $\mu = 9.4 \times 10^{31}$ G cm^3, corresponding to a dipole magnetic field of 9.4×10^{13} G on the magnetic equator and 1.9×10^{14} G on the poles. These pulsars lie in the upper right-hand corner of the P-$\dot{P}$ diagram, among the anomalous X-ray pulsars (AXPs) and the soft gamma-ray (burst) repeaters (SGRs) for which the magnetar model has been developed (see Thompson 2000 for a review). While the magnetar model successfully addresses many properties of the SGRs and AXPs, the period clustering and the presence of radio pulsars with periods and inferred magnetic dipole moments similar to those of AXPs and SGRs has motivated another class of models involving fall-back disks and a combination of dipole radiation and disk torques (Alpar 2001; Chatterjee, Hernquist & Narayan 2000; Ekşi & Alpar 2003). In these models the magnetic moments of AXPs, SGRs, and pulsars, such as PSR J1847−0130, can be in the conventional 10^{30} G cm^3 range. The absence or presence and mass of such disks introduces a third neutron star parameter at birth, in addition to P_0 and μ. We shall assume here that the possible pulsar in SN 1987A has no disk or a light enough disk mass that its early evolution is determined by magnetic dipole radiation, as must be the case for the typical radio pulsars. An analysis of the present bolometric luminosity constraints allowing for fall-back disks in the initial conditions will be the subject of separate work.

Inferred dipole magnetic moments of 10^{27}–10^{28} G cm^3 are typical of the observed millisecond pulsars. The recycling hypothesis (Alpar et al. 1982; Radhakrishnan & Srinivasan 1982) is supported by the locations of binary and millisecond pulsars in the P-$\dot{P}$ diagram and particularly by the discovery of millisecond rotation periods from low-mass X-ray binaries (Wijnands & van der Klis 1998), of which now five are known. These links, as well as the abundance of millisecond and binary pulsars in globular clusters, suggest that the radio pulsars with such weak inferred magnetic dipole moments are from an old population. The possible pulsar in SN 1987A is not expected to have a magnetic moment on the order of 10^{28} G cm^3 if only old pulsars can have such weak fields. However, if the pulsar was born as a result of a core merger, allowing it a millisecond period at birth, then the magnetic field could be weak. Another possibility is that pulsars are born with weak initial magnetic fields, and the dipole magnetic fields of conventional $\mu \sim 10^{30}$ G cm^3 pulsars and magnetars are generated subsequently on timescales longer than the 16 yr time span of SN 1987A observations (see Reisenegger 2003 for a review and Michel 1994 for applications to the possible pulsar in SN 1987A).

Allowing all pulsar birth scenarios with appropriate choices of initial periods, we found that for 10, 15, and 30 ms initial periods, the upper limits on weak initial magnetic moments are 2.8×10^{27}, 6.4×10^{27}, or 2.5×10^{28} G cm^3. With the assumption of a slow rotator, say, with an initial period of 0.3 s, it was found that the constraint at the weak field end was not very stringent, $\mu < 2.5 \times 10^{30}$ G cm^3. If the pulsar was born from a core merger, with an initial period of 2 ms, then the upper limit on a weak magnetic moment is as low as $\mu < 1.1 \times 10^{26}$ G cm^3.

For all choices of initial period considered above, if the initial magnetic moment is not weak, and if the putative pulsar is spinning down under a constant magnetic dipole radiation torque, without field generation, we conclude that the putative pulsar has a magnetic dipole moment μ greater than 2.4×10^{34} G cm^3. If weak initial magnetic moments can be ruled out for all young pulsars, then we find that the possible pulsar in SN 1987A has to be a strong magnetar. If that is the case, then we may need to change our strategy for detecting the putative pulsar and look for its transient features, such as bursts observed from anomalous X-ray pulsars and soft gamma-ray repeaters, if the uniting property of all these sources is the possession of magnetar fields.

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