Supernova 1993J: a veiled pulsar in a binary system?

Enrico Ramirez-Ruiz\textsuperscript{1} and Aldo M. Serenelli

School of Natural Sciences, Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540, USA.

\textsuperscript{1}Chandra Fellow.

ABSTRACT

The recent report of a binary companion to the progenitor of supernova 1993J may provide important clues for identifying the nature of the nascent compact object. Given the estimates of the progenitor mass, the potential power source is probably a pulsar rather than an accreting black hole. If there is a pulsar, one would expect the rotational luminosity to be stored and reprocessed by the supernova remnant, but no pulsar nebula has yet been seen. The lack of detection of an X-ray synchrotron nebula should be taken as strong evidence against the presence of a bright pulsar. This is because absorption by the surrounding supernova gas should be negligible for the light of the companion star to have been detected. A model is developed here for the luminosity of the pulsar nebula in SN 1993J, which is then used to predict the spin-down power of the putative pulsar. If one exists, it can be providing no more than \(\sim 6 \times 10^{39} \text{erg s}^{-1}\). With an initial rotation period of 10-30 ms, as extrapolated from young galactic pulsars, the nascent neutron star can have either a weak magnetic field, \(B \leq 10^{11}\) G, or one so strong, \(B \geq 10^{15}\) G, that its spin was rapidly slowed down. The companion star, if bound to the neutron star, should provide ample targets for the pulsar wind to interact and produce high-energy gamma-rays. The expected non-pulsed, GeV signal is calculated; it could be detected by current and future experiments provided that the pulsar wind velocity is similar to that of the Crab Nebula.

Key words: pulsars: general – stars: supernovae – supernovae: individual (SN 1993J) – gamma rays: theory – radiation mechanisms: non-thermal

1 INTRODUCTION

Supernova 1993J was discovered on 28 March 1993 in the spiral galaxy M81 (at a distance of 3.63 Mpc; Freedman et al. 1994). Although it is factor of 65 further away than SN 1987A, it is relatively close for a SN and has been the subject of intense observational campaigns in a number of wavelengths regions (Chevalier 1997, and references therein). Shortly after the explosion, its spectrum was found to contain hydrogen lines - a type II supernova - but within a few weeks strong helium lines developed. The spectrum looked then more like a type Ib supernova, as though the envelope of hydrogen had lifted to reveal a helium layer (Filippenko et al. 1993). This, together with the observed peculiarities observed in the lightcurve, led many to conclude that the dying star, identified as a non-variable red supergiant in images taken before the explosion (Aldering et al. 1994), must have lost a considerable amount of its outer envelope of hydrogen gas to a companion before it exploded (Nomoto et al. 1993; Podsiadlowski et al. 1993; Woosley et al. 1994). But no companion had been seen until recently when the brightness of SN 1993J dimmed sufficiently that its spectrum showed the features of a massive star superimposed on the supernova (Maund et al. 2004).

Given the estimates of the progenitor mass, the remnant is probably a neutron star rather than a black hole (Nomoto et al. 1993; Podsiadlowski et al. 1993; Woosley et al. 1994), and the neutron star is generally expected to manifest as a pulsar. The newly born 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. We expect the reprocessing of rotational energy to produce a bright flat-spectrum synchrotron nebula, but this soft emission has not been observed.

Here we developed a simple shocked wind model for the luminosity of the pulsar nebulae in SN 1993J (Section 2), which is then compared with the current luminosity limits in order to place bounds on the dipole emission of the nascent neutron star and its birth properties (Section 4). We also investigated the impact of the soft photon field radiation of the binary companion on the central pulsar wind (Section 3), along with the types of observation that would help to unambiguously demonstrate whether or not the system is disrupted as a result of the supernova. Our conclusions are discussed in Section 4.
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2  A MODEL FOR THE PULSAR NEBULA IN SN 1993J

Neutron stars formed in core collapse SN explosions are thought to emit radiation as pulsars, the Crab (Rickett & Seiradakis 1982) being the canonical example. Pulsars are generally presumed to lose rotational energy by some combination of winds of relativistic particles and magnetic dipole radiation at the frequency of the neutron star’s rotation. In the generic pulsar model, the field is assumed to maintain a steady value, and the luminosity declines as the spin rate slows down (Shapiro & Teukolsky 1983). The spindown law is then given by \( \Omega(t) = \Omega_0(1 + t/t_\Omega)^{-1/2} \), so that \( \dot{L}_\Omega(t) = L_{\Omega,0}(1 + t/t_\Omega)^{-2} \), where \( t\Omega \approx 10^5 \) s \( L_{\Omega,0}B_{p,15}^{-2}P_{0,-3}^{-2}R_6^{-6} \) is the characteristic time scale for dipolar spindown, \( B_{p,15} \approx B_p/(10^{15} \text{G}) \) is the dipolar field strength at the poles, \( R_6 \approx R/10^6 \text{cm} \) is the radius of the light cylinder, \( P_{0,-3} \) is the initial rotation period in milliseconds, and \( L_{\Omega,0} \approx 10^{39} \text{erg s}^{-1} B_{p,15}^2 P_{0,-3}^{-4} R_6^6 \).

The power output of the pulsar is typically assumed to be \( L_{\Omega} \), regardless of the detailed process by which the dipole emission is converted to the energy of charged particle acceleration and high-energy electromagnetic radiation. The pulses themselves, even when seen in the gamma-rays, constitute an insignificant fraction of the total energy loss. Large fraction of the power output, on the other hand, goes into a bubble of relativistic particles and magnetic field surrounding the pulsar (Chevalier & Fransson 1992). This bubble gains energy from the pulsar, and loses it in synchrotron radiation losses and in doing work on the surrounding supernova gas, sweeping it up and accelerating it.

2.1  Hydrodynamic Evolution

The density structure of the supernova gas is determined by the initial stellar structure, as modified by the explosion (Arnett 1988). The density structure has been relatively well determined for models of SN 1987A – it shows an inner flat profile outside of which is a steep power-law decrease with radius (e.g. Shigeyama & Nomoto 1990). Chevalier & Soker (1989) approximated the velocity profile by an inner section \( \rho_i = A r^{-m} e^{m-3} \) and an outer section \( \rho_o = B r^{-n} e^{n-3} \), where \( m = 1 \) and \( n = 9 \) for SN 1987A. The two segments of the density profile are assumed to be continuous and they intersect at a velocity \( v_i \). For an explosion with total energy \( E \) and mass \( M_t \), one has

\[
v_i = \left[ \frac{2(5 - m)(n - 5)E}{(3 - m)(n - 3)M_t} \right]^{1/2},
\]

where

\[
A = \frac{(n - 3)}{(n - m)} \left[ \frac{(3 - m)(n - 3)M_t}{2(5 - m)(n - 5)E} \right]^{(3-m)/2} \frac{(3 - m) M_t}{4 \pi}.
\]

SN 1987A was an unusual type II supernova because of its small initial radius. This is in contrast to SN 1993J where the early lightcurve indicated that the progenitor star was more extended, about ten times larger than that of SN 1987A. The lack of a plateau phase in this case is attributed to the low mass of the hydrogen envelope, about 0.1 to 0.6 \( M_\odot \) (Nomoto et al. 1993; Podsiadlowski et al. 1993; Woosley et al. 1994), although the initial stellar mass was probably \( \sim 15 M_\odot \). Woosley et al. (1994), for example, estimated that the final presupernova star \(^1\) had a helium and heavy element core of \( \sim 3.7 M_\odot \), a low density hydrogen envelope of \( 0.2 M_\odot \), and a radius of about 4.3 x 10\(^{13} \) cm.

The core collapse of the progenitor of 1993J resulted in the deposition of about \( 3 \times 10^{50} \) erg of kinetic energy per solar mass (Woosley et al. 1994). The expanded density profile shows an outer steep power-law region with \( n \sim 9 \) and an inner, relatively flat region (Blinnikov et al. 1998 and Fig. 4 therein). The bend in the profile occurs at a velocity of \( \sim 2000 \) km s\(^{-1} \). The inner density profile is clearly not a single power law in \( r \). However, it is likely that hydrodynamic instabilities, similar to those believed to occur in SN 1987A (e.g. Fryxell et al. 1991), lead to mixing and smooth out any sharp features in the density profile. Thus, a reasonable smooth, flat inner profile may be a good approximation. In the outer parts of the density structure, on the other hand, radiative transfer effects are more important for the explosion of an extended star and can lead to the formation of a dense shell in the outer layers. The shell is, however, expected out in the steep power-law region of the density profile, where the pulsar bubble is not likely to reach. In what follows, we assume \( m = 1 \) or 2 and \( n = 9 \).

The first stage of evolution involves the interaction of the pulsar bubble with the inner density structure. With the assumptions that the pulsar luminosity is constant during this phase (i.e. \( t_{\text{age}} \leq t_\Omega \)) and the supernova gas is swept up into a thin shell of mass \( M \) and velocity \( v \), the radius of the pulsar bubble can be written as (Chevalier & Fransson 1992)

\[
r_p = \left[ \frac{(3 - m)(5 - m)^3 L_{\Omega}}{4 \pi A(9 - 2m)(11 - 2m)} \right]^{1/2} \frac{t^{(6-m)/(5-m)}}{t},
\]

where \( r_p \propto v \propto M_t^{-1/2} E_{(3-m)/2}(5-m) L_{\Omega}^{1/2}(5-m) \). The shell velocity is \( v = [740 L_{\Omega,39} E_{51}^{1/4} M_t^{-1/2} t_{\text{age},11}^{1/4}, 270 L_{\Omega,39} E_{51}^{1/6} M_t^{-1/2} t_{\text{age},11}^{1/6}] \) km s\(^{-1} \) for \( m = [1, 2] \), where \( M_t = M_t/5 M_\odot \), \( E_{51} = E/10^{51} \) erg, \( L_{\Omega,39} = L_\Omega/10^{39} \) erg s\(^{-1} \), and \( t_{\text{age},11} = t_{\text{age},11} \) yr. The density transition velocity is \( v_i = [5100, 6300] E_{51}^{1/2} M_t^{-1/2} \) km s\(^{-1} \) for \( m = [1, 2] \), so it is likely that the shell remains within the inner part of the density profile.

The density of the uniform gas shell is \( \rho \approx [5 \times 10^{-19} L_{\Omega,39}^{1/4} E_{51}^{1/4} M_t^{5/2} t_{\text{age},11}^{1/4}, 4 \times 10^{-15} L_{\Omega,39}^{2/3} E_{51}^{-5/6} M_t^{11/3} t_{\text{age},11}^{-1/3}] \) g cm\(^{-3} \) for \( m = [1, 2] \), where \( \rho \propto M_t^{1/2} E_{(5-m)/2}(5-m) L_{\Omega}^{-m/(5-m)} \). The presence of the companion implies that the supernova gas should be

\(^1\) This model was derived from a 13 \( M_\odot \) main-sequence star that lost most of its hydrogen envelope to a nearby companion (0 \( M_\odot \), initially 4.5 AU).
transparent to optical radiation (i.e. the optical depth to electron scattering should be less than unity), which gives \(E > 10^{39} M_{1.5}^2 \Omega_{11}^{-2} \) for \(m = 1\) and \(L_\Omega \geq 10^{40} E_{51}^{-2} M_{1.5}^{-9/2} \Omega_{11}^{-7} \) erg s\(^{-1}\) for \(m = 2\).

For X-ray energies \(\geq 10\) keV, electron scattering also provides the main opacity. However, in this case the bound electrons contribute as well as the free ones, so that the optical depth is always given by electron scattering irrespectively of the degree of ionization. At lower X-ray energies \(\epsilon \geq 3\) keV, photoionization provides additional opacity (Bahcall et al. 1970) and may delay the time at which the envelope becomes transparent by an additional factor \(\sim 5(\epsilon/1\text{keV})^{-3/2}\) (this estimate is for a predominantly neutral envelope of pure hydrogen). The delay is somewhat larger if the envelope is rich in heavy elements. The matter that is swept up by the pulsar bubble is subject to Rayleigh-Taylor instability and may form filaments (Vishniac 1983). The optical depth to electron scattering could then be much less if the envelope is sufficiently irregular that some lines of sight to the pulsar traversed relatively little envelope mass. Under such favourable circumstances, the opacity of the envelope is a less serious problem (except at late times when grain formation may occur in the supernova ejecta and dust absorption could significantly increase the opacity at visual wavelengths).

Radio measurements suggest that any pulsar nebula in the center of SN 1993J is fainter than \(\approx 10^{36}\) erg s\(^{-1}\) (Bietenholz et al. 2003). The material immediately surrounding the putative pulsar is, however, expected to be totally opaque until

\[
\tau_{\text{II}} \sim 1 = \begin{cases} 
2 \times 10^7 E_{51}^{-1/2} M_{1.5} T_4^{-3/4} \nu_9^{-1} \text{yr} & \text{for } m = 1 \\
10^4 L_{53}^{-1/7} E_{51}^{-1/2} M_{1.5}^{-9/14} T_4^{-9/14} \nu_9^{-6/7} \text{yr} & \text{for } m = 2 
\end{cases}
\]

at which time the radio flux (\(\nu_9 = \nu/1\text{GHz}\)) will suddenly appear. Here \(T_4 = T/10^4\) K is the temperature of the swept-up material. The lack of detection of a synchrotron nebula at radio wavelengths should not be taken as strong evidence against the presence of a bright pulsar (Bahcall et al. 1970). On the other hand, the lack of an X-ray nebula indicates that, if one exists, its radiative power must be less than \(L_X \approx 2 \times 10^{38}\) erg s\(^{-1}\) (Zimmermann & Aschenbach 2003).

### 2.2 Emission Model

A compelling model for the optical/X-ray properties of the Crab Nebula was developed by Rees & Gunn (1974). In this model, the central pulsar generates a highly relativistic, particle dominated wind (with Lorentz factor \(\gamma_w\)) that passes through a shock front and decelerates to match the expansion velocity set by the outer nebula. The emission from the pulsar bubble is thought to provide a larger luminosity source than the radiative shock front itself (Chevalier & Fransson 1992). The wind particles acquire a power-law energy spectrum of the form \(N(\gamma) \propto \gamma^{-p}\) (for \(\gamma \geq \gamma_m\), where \(\gamma\) is the particle Lorentz factor and \(\gamma_m\) is its minimum value) in the shock front and radiative synchrotron emission in the down stream region (Chevalier 2000). Under the basic simplification that the emitting region can be treated as a one zone (i.e. no spatial structure in the nebula), and assuming that a balance between injection from the shock front and synchrotron losses is established, the number of radiating particles at a particular \(\gamma\) is given by \(N(\gamma) = 2p^{-1} \gamma^{-2} \Omega_{11}^{-2} L_{\Omega}\gamma^{-(p+1)}\) (Chevalier 2000), where \(B\) is the magnetic field in the emitting region, and \(\beta = 1.06 \times 10^{-15}\) cm\(^3\) s\(^{-1}\).

In what follows, it is assumed that the energy density in the emitting region (which is approximately determined by the shock jump conditions) is divided between a fraction \(\epsilon_e\) in particles and a fraction \(\epsilon_B\) in the magnetic field. These efficiency factors are constrained by \(\epsilon_e + \epsilon_B = 1\). With this assumption, the magnetic field in the emitting region is \(B = (6\epsilon_B L_{\Omega}/r_s^2)\), where \(r_s\) is the shock wave radius. The electron energy is radiated at its critical frequency \(\nu(\gamma) = \gamma^2 (q_eB/2\pi mc^2)\), where \(q_e\) and \(m\) are the electron charge and mass, respectively. If the electrons and positrons cool rapidly by synchrotron radiation, as thought to be the case for the Crab Nebula, the luminosity produced from the pulsar power is given by \(L_{\nu} = \phi(p)\epsilon_{\epsilon}^{-1} \epsilon_{B}^{(p-2)/4} \gamma_w^{-2} r_s^{-2} \Omega_{11}^{-2} L_{\Omega}^{-2} (p+2)/4 \nu^{-p-1}\) (Chevalier 2000), where \(\phi(p) = \frac{1}{2} \left(\frac{p-1}{p} \right)^{p-1} \left(\frac{p+2}{4}\right)^{p-2} \Omega_{11}^{-2} \gamma_w^{-2} r_s^{-2} \Omega_{11}^{-2} L_{\Omega}^{-2} (p+2)/4 \nu^{-p-1}\), and \(r_s = 2.8 \times 10^6\) cgs units. If the particle spectrum is similar to that of the Crab Nebula (\(p = 2.2\)), the X-ray luminosity \((\nu = 10^{18}\) Hz\) becomes

\[
\nu L_{\nu} \approx 5 \times 10^{37} \epsilon_{\epsilon}^{6/5} \epsilon_{B}^{1/20} \gamma_w^{11/50} \Omega_{11}^{-1/10} \nu_{18}^{21/20} \Omega_{11}^{-1/10} \text{ erg s}^{-1},
\]

where cgs units are used. We note that the X-rays from a putative pulsar nebula in SN 1993J with \(L_{\Omega} \sim 10^{39}\) erg s\(^{-1}\) could provide the additional energy input required to reproduce the observed H\alpha luminosity at ~350 days (Houck & Fransson 1996).

The above relation can be used to predict the spin-down power, \(L_{\Omega}\), of the putative pulsar in wind nebula where a pulsar has not yet been observed (Chevalier 2000). In the case of SN 1993J, the value \(r_s\) can be determined by the condition that the envelope should be transparent to optical radiation (Section 2.1). The need for a particle dominated shock suggests that \(\epsilon_e \geq 0.5\). We set \(\epsilon_B = \epsilon_e = 0.5\), although there is little dependence to \(\epsilon_B\). The value of \(\gamma_w\) is difficult to constraint. Here we use \(\gamma_w \sim 3 \times 10^6\), the value typically assumed for the Crab Nebula (Kennea & Coroniti 1984). A better estimate of \(\gamma_w\) is given in Section 3. When these parameters are substituted into equation (4), the XMM upper limit of \(L_X \approx 2 \times 10^{38}\) erg s\(^{-1}\) (0.3-10 keV; Zimmermann & Aschenbach 2003) yields \(L_{\Omega} \leq 2 \times 10^{39}\) erg s\(^{-1}\). On the basis of the ASCA data, Kawai et al. (1998) found the relation \(\log L_X = (33.42 \pm 0.20) + (1.27 \pm 0.17) \log (L_{\Omega}/10^{40})\), where \(L_X\) is the nebular luminosity in the 1-10 keV range, from which we estimate \(L_{\Omega} \leq 5 \times 10^{39}\) erg s\(^{-1}\). This estimate is in fair agreement with our predicted value.
3 THE ROLE OF BINARITY

At the time of the explosion, the progenitor of 1993J has a mass of 5.4 $M_{\odot}$ (with a helium-exhausted core of 5.1 $M_{\odot}$), the secondary has a mass of 22 $M_{\odot}$. The orbital period of the system is $\sim$ 25 yr, and the companion has an orbital velocity of $\sim$ 6 km s$^{-1}$ (Maund et al. 2004). There may have been a large kick imparted by the explosion mechanism, and that would be very interesting to study, but barring that, let us assume the companion star is bound in an eccentric orbit with the newly born pulsar$^2$. The bulk of the pulsar energy $L_{\Omega}$ would be primarily in the form of a magnetically driven, highly-relativistic wind consisting of $e^-$, $e^+$ and probably heavy ions with $L_{\nu}$ $\simeq \zeta L_{\Omega}$ and $\zeta \leq 1$.

Under the assumption, the relativistic wind (which is likely to be undisturbed by the presence of the binary companion$^3$ since $L_{\Omega} \gg v_{\infty}^2 m_e c^2$) would escape the compact remnant while interacting with the soft photon field of the companion with typical energy $\theta_* = kT_e/(m_e c^2) \sim 3 \times 10^{-6}$ (Maund et al. 2004). The scattered photons whose energy is boosted by the square of the bulk Lorentz factor of the magnetized wind (i.e. $\gamma_* = 2\gamma_0^2 \theta_* \sim 6 \times 10^6 \gamma_w^2$) propagate in a narrow $\gamma_w^{-1}$ beam owing to relativistic aberration. The rate of energy loss of a relativistic particle moving in a radiation field with an energy density $w_\nu \simeq L_\nu/4\pi a^2 c$ is about $m_e c^2 d\gamma/dt \simeq -w_\nu w_\nu \gamma_w^2$ in the Thompson limit (Landau & Lifshitz 1975). Here $L_\nu \sim 10^9 L_{\odot}$ is the luminosity of the optical star and $a$ is the binary separation ($a \sim 25$ AU $\sim 200 R_*$; Maund et al. 2004). The total luminosity of scattered hard photons $L_{1}$ is then equal to the total particle energy losses in the course of motion from the pulsar to infinity $L_1 = L_w \frac{\dot{a}}{a^2} \simeq 1 - (1 + \zeta)^{-1}$, where

$$\zeta = \frac{\gamma_0 \sigma_T L_w}{4\pi m_e c^3} \sim \left(\frac{\gamma_0}{3 \times 10^6}\right) \left(\frac{L_w}{10^{10} L_{\odot}}\right) \left(\frac{a}{200 R_*}\right)^{-1}$$

(6)

denotes the efficiency in extracting energy from the relativistic outflow (Chernyakova & Illarionov 1999). The resulting radiation pressure on electrons in the ejecta will brake any outflow whose initial Lorentz factor exceeds some critical value $\gamma_{\text{lim}} = (\frac{a}{200 R_*})^{1/2} \sim 3 \times 10^2 L_{\text{lim}}^{1/2}$, converting the excess kinetic energy into a directed beam of scattered photons. With $\gamma_0 \sim \gamma_{\text{lim}}$, equation (5) yields $L_{\Omega} \leq 6 \times 10^{39}$ erg s$^{-1}$.

As the stellar companion emits a black body spectrum, of effective temperature $\theta_*$, the local photon energy density is given by

$$n(r, \varpi) = \frac{2\pi}{h^3} \left(\frac{m_e c^2}{h}\right)^2 \left(\frac{R_*}{a}\right)^2 \varpi^2 \left[\exp(\varpi/\theta_*) - 1\right],$$

(7)

where $\varpi$ is the soft photon energy in units of $m_e c^2$. The scattered photons are boosted by the square of the Lorentz factor so that the local spectrum has a black body shape enhanced by $\gamma_w^2$. As can be seen in Fig. 1, the resulting spectrum is the convolution of all the locally emitted spectra (i.e. $\int_{-\infty}^{\infty} dn_{\nu}(r, \varpi)$) and it is not one of a blackbody. Note that Klein-Nishina effects are important for incoming photon energies such that $\theta_* \varpi \gtrsim 1$. The maximum energy of the scattered photons in this regime is $\gamma_0^2 m_e c^2$.

We note that the total luminosity emitted by the relativistic outflowing wind through the Compton-drag process in the direction of the observer could be highly anisotropic and may change periodically during orbital motion for an eccentric (or a highly inclined) orbit. The time dependence, in this case, will be very distinctive and such effects should certainly be looked for.

4 DISCUSSION

Despite presumptions that a neutron star may have been created when the progenitor star of SN 1993J exploded and its core collapsed, no pulsar has yet been seen. If one exists, its radiative power must be less than $L_{\Omega} \approx 6 \times 10^{39}$ erg s$^{-1}$ or lower if the pulsar nebula has a high radiative efficiency. The well-known Crab pulsar and its nebula for comparison, put out $2 \times 10^{39}$ erg s$^{-1}$; and originally, when it was spinning faster, the luminosity might have been seven times greater still. Fig. 2 shows the pulsar spin-down luminosity divided by 4$t$ times the square of the distance, the total pulsar energy output at Earth. The ten gamma-ray pulsars (including candidates) are shown as large circles. The solid curves show the dipole emission of the putative pulsar in 1993J (at $t \sim 11$ years) for various assumptions regarding its initial period and magnetic field strength. The 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 spin-down luminosity below $\sim 6 \times 10^{39}$ erg s$^{-1}$ (see shaded region in Fig. 2) only if either the magnetic field is relatively weak $\lesssim 10^{11}$ G or if it is so strong (i.e. $\gtrsim 10^{15}$ G) that the pulsar luminosity decays rapidly. If weak magnetic moments could be ruled out in the near future by X-ray and infrared observations, then we find that, if undetected, the putative pulsar in SN 1993J could be a magnetar.

With a spectrum similar to that of the Crab (see Fig. 2), the pulsed emission is likely to be below the detection limit of current instruments and may deprive us of the opportunity to witness the emergence of a gamma-ray pulsar in the immediate future. GeV radiation with luminosities high enough to be detected with ARGO$^4$, and the Veritas$^5$ experiment now under construction, could be produced by the interaction of the pulsar wind with the soft photon field of its companion provided that the system remains bound and $\gamma_w \gtrsim 10^7$ (i.e. similar or larger to than inferred for the Crab pulsar). Its detection will surely offer important clues for identifying the nature of the progenitor and possibly constraining whether or not kicks have played an important role.

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$^2$ The binary is likely to remain bound after the supernova explosion provided that the kick velocity $\lesssim 90$ km s$^{-1}$ (Brandt & Podsiadlowski 1995).

$^3$ Here $v_{\infty}$ and $M_w$ are the velocity and mass-loss rate of the stellar companion.

$^4$ http://argo.na.infn.it/

$^5$ http://veritas.sao.arizona.edu/
If there is not a neutron star in SN 1993J, could there be a black hole instead? Had matter fallen back onto the nascent neutron star (with mass of $1.4\ M_\odot$) on a timescale of 100 seconds to a few hours after the explosion, enough mass may have been accreted to push the object over the minimum thought to be necessary for the creation of a black hole. Matter would continue to accrete onto the black hole, but the resulting radiation would be trapped in the outflow so that the escaping luminosity would be small. Because the cores of massive stars increase with initial stellar mass, this picture would be more plausible if the initial mass of the SN 1993J progenitor star, $\sim 15\ M_\odot$, were close to the mass limit above which stars collapse directly to black holes (e.g. Fryer 1999).

Even if the neutron star is rotating only slowly or has a weak magnetic field, one would expect surrounding material to fall back onto it, giving rise to a luminosity $\lesssim L_{\text{Edd}} \sim 3 \times 10^{39}\ \text{erg s}^{-1}$ (see Fig. 1). The remaining possibility of a weak pulsar with little surrounding mass will be difficult to rule out. The thermal emission from a newly formed neutron star gives a luminosity of $\sim 3 \times 10^{34}\ \text{erg s}^{-1}$. The neutron-star emission should have a characteristic soft X-ray emission, but its detection will be arduous. If future observations fail to identify a pulsar in 1993J, then the youngest pulsar that we know will still be PSR J0205+6449 (Camilo et al. 2002), associated with SN 1181.

ACKNOWLEDGEMENTS

This work was stimulated by conversations with M. J. Rees and S. Smartt. Discussions with J. Bahcall and R. Chevalier are gratefully acknowledged, as is helpful correspondence from the referee Ph. Podsiadlowski. This work is supported by the W.M. Keck foundation (AMS) and NASA through a Chandra Postdoctoral Fellowship award PF3-40028 (ER-R).

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Figure 1. Representative spectra produced by the interaction of the pulsar wind with the radiation of the stellar companion. The luminosity of the gamma-ray emission $L_\gamma$ is shown for $\gamma_w = 10^2, 10^3, 10^4, 10^6$ (dashed lines). The spectra of the Crab and Vela pulsars are shown for comparison (adapted from Thomson 2003).
Figure 2. Pulsar observability as measured by the spin-down energy seen at Earth. Small dots represent pulsars with no gamma-ray emission, while large filled symbols show all known gamma-ray pulsars (including candidates; Thompson 2003). The power-output of the pulsar wind, at the distance and age (here assumed to be 11 years) of SN 1993J, is shown for $B = 10^{11}$, $10^{12}$, $10^{13}$, $10^{14}$ and $10^{15}$ G (from left to right) as a function of the assumed initial period. The putative pulsar in SN 1993J, spinning down by magnetic dipole radiation alone, can have a wind nebula X-ray luminosity below the XMM limit if $L_{\Omega} \leq 6 \times 10^{39}$ erg s$^{-1}$ (shaded region).