Reports

When Will a Pulsar in Supernova 1987a Be Seen?

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The means by which a pulsar might be detected in the remnant of supernova 1987a in the Large Magelanic Cloud is examined. One possibility is that the slower-than-radioactive decay typically seen in the type II light curves is itself the sign of powering by the underlying pulsar, with the decline representing not the spinning down of the pulsar but rather the declining nebular opacity that would allow increasing amounts of the energy to escape as gamma rays. The test of this hypothesis (if the supernova conforms to type II expectations) would be to look for the "missing" energy in the form of those gamma rays that escape from the remnant instead of powering it.

A PULSAR IN A NEW SUPERNOVA might be detected through direct observation of the pulsed radiation or through evidence of the pulsar power output (pulsed or the relativistic wind) contributing to the nebular luminosity. Bahcall, Rees, and Salpeter (*1*) early on made such estimates. Now, Ostriker (*2*) argues that the remnant may soon brighten to more than its maximum as a supernova owing to powering by the pulsar. Detection of pulsed emission depends on how the remnant obscures the pulsar and how it generates a competing background, which are straightforward to assess on dimensional grounds. One hopes, of course, that the beam sweeps close enough to the earth for detection, although pulsed detection is not expected to be the first sign of a pulsar, as we will see. The possibility of collapse to a black hole can therefore be tested as well. In contrast, detecting a role in energizing the supernova requires understanding the evolution of remnants without pulsars. Woosley *et al.* (*3*) have calculated light curves similar to supernova (SN) 1987a that show an exponential radioactive-powered decay starting from a luminosity of 2.5×10^{41} ergs/sec after 1.5×10^{7} seconds.

Up to now, the initial spin and magnetic field of a new pulsar have been unknown and study of SN 1987a might reveal these characteristics. Also early detection would test suggestions that pulsars undergo a delayed turn-on [most supernova remnants do not have pulsars associated with them (*4*)] if the magnetic fields are thermoelectrically generated (*5*). The neutrino pulse associated with SN 1987a (*6, 7*) strongly indicates that a neutron star was indeed formed.

Our baseline model for the pulsar has instead the same magnetic field as the Crab pulsar ($B_0 \approx 4 \times 10^{12}$ G) and an initial rotation period of 10 msec. Ruderman (*8*) points out that such a pulsar with a period exceeding about 10 msec would deposit too much energy in the existing remnant. The magnetic dipole spin-down power output (*4*) would then be $L_0 = 5.6 \times 10^{40}$ ergs/sec, with a total available rotational energy 2×10^{50} ergs for a canonical moment of inertia of 10^{45} g cm^2. The characteristic spin-down time at birth would then be $\tau = 112$ years, where the total power output (L) is

$$L = L_0\tau^2/(t + \tau)^2 \qquad (1)$$

with t the time since the event, a linear decay for $t \ll \tau$ of about 2% per year.

Given the quasi-exponential decay of type II supernova (half-life of about 2 months), the light curve will quickly decay to below such a pulsar power output. The obvious question is whether the pulsar will thereafter sustain the luminosity. The Crab pulsar now appears to maintain its nebula, the power apparently coming from a shocked relativistic wind. For the above numbers, the pulsar luminosity will be reached in about 10 months after the explosion, more or less is argued by Ostriker (*2*).

Pulsar interaction with the remnant has been modeled by Rees and Gun (*9*) and Kennel and Coroniti (*10, 11*). The expectations (*12*) are illustrated in Fig. 1 and are (i) electrons accelerated to high Lorentz factors $(\gamma) \approx 3 \times 10^{6}$; (ii) a large magnetic field owing to compact size; (iii) synchrotron photons with much higher energies; and (iv) Compton boosted photons ($\approx 10^{13}$ eV) from interaction of energetic electrons with thermal photons filling the interior.

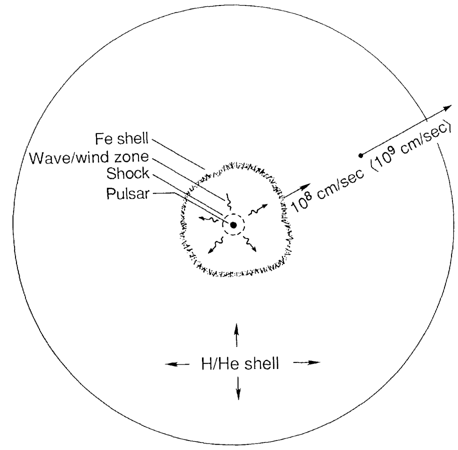

Fig. 1. Cross section of the remnant showing expanding hydrogen/helium (H/He) shell with an average velocity of 10^9 cm/sec, the inner iron shell expanding about ten times more slowly. Within the latter will be the pulsar wind/wave zone, a shock transition at perhaps 0.1 times the iron shell radius, and the pulsar. The scales are uneven to show full system.

The surface field of the neutron star should drop off with radius as $1/r^3$ out to the light cylinder distance $R_L \approx 5 \times 10^7$ cm ($R_L = c/\Omega$; where the rotation rate is $\Omega = 628$ rad/sec). The magnetic (wind) field then drops as $1/r$ out at the inner edge of the expanding ejecta shell, which we will simply assume to move at a velocity of roughly $V = 10^8$ cm/sec. Thus the magnetic field in the nebula (in gauss) is

$$B_{neb} = B_0a^3/R_LVt \approx 1.6 \times 10^7/t \qquad (2)$$

A somewhat larger field could result from accumulation of field lines or shock compression. In the Crab nebula, electrons and positrons with $\gamma \approx 3 \times 10^6$, spiraling on the nebular magnetic field lines, emit radiation of energy $\gamma^2 hf_c$ where $hf_c = 11.5\ B_{12}$ keV (B_{12} in units of 10^{12} gauss) where h is Planck's constant and f_c is the cyclotron frequency of the particles, giving photon energies above

$$E_{sync} = 2 \times 10^{11}\ \text{eV}/t \qquad (3)$$

or 23 keV after 100 days. The Crab spectrum has a power-law dependence extending to high energy gamma rays, cutting off somewhat below E_{sync}. Inverse Compton scattering will undoubtedly be important early on and produce $\approx 10^{13}$ eV gamma rays, but after 100 days the interaction probability is only about 10^{-4}, providing relatively little energy transport.

Photons from the shocked wind will also excite the surrounding remnant while it is opaque. Initial optical opacity is largely due to Thomson scattering by electrons, possibly augmented later by dust condensing from the cooling ejecta. Unit optical depth

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Table 1. Energetic photon optical depths (in units of grams per square centimeter) and times to transparency for hydrogen (H) and iron (Fe).

Energy (MeV)	Depth (H)	Time (H)	Depth (Fe)	Time (Fe)
0.01	2.60	720 days	0.00562	109 years
0.1	3.39	630 days	2.91	1750 days
1.0	7.94	410 days	16.8	730 days
10	31.1	210 days	34.0	510 days
100	68.0	120 days	23.4	620 days

for Thomson scattering in ionized hydrogen is 0.25 g/cm^2. The column density for 15 solar masses of hydrogen expanding at 10^4 km/sec is $10^{16}/t$ sec^2 g/cm^2, and after 2×10^8 seconds (6.3 years) the nebula should start to become transparent. (The nebula becomes translucent much earlier.) The opacity is significantly lower for more energetic photons, with optical depths increasing to about 8 g/cm^2 at 1 MeV (*13*) as shown in Table 1, until pair production becomes important beyond about 300 MeV. Thus the nebula becomes transparent to gamma rays early on. The role of the slower moving inner shell of heavy elements is more important because the cross sections are comparable or larger than hydrogen and the shell expands more slowly. A solar mass of iron moving at 10^3 km/sec has a column density 6.7 times larger than the hydrogen shell, giving corresponding longer times to transparency, especially for x-rays (see Table 1). Because this shell should be Rayleigh-Taylor unstable (witness, for example, the filamentary network of the Crab Nebula), the opacity along our line of sight may depart significantly from such estimates.

On average, the shell should beome progressively thinner to hard gamma rays at early epochs (possibly as soon as 120 days but certainly after 620 days) and ultimately be optically thin after about 6 years [unless copious amounts of dust form at a critical time of about 280 days (*14*)]. Thus, detecting steady emission of gamma rays from the pulsar powered nebula seems a promising possibility. If, as in the case of the Crab, the pulsed gamma ray intensity from the pulsar is a reasonable fraction ($\approx$10%) of the nebular output, photon counting techniques could be used to pull the pulsar signal out of background. One would then need an excess of 10^2 counts per time bin and at least 10 bins to give 10^3 counts over one day, requiring a total acquisition rate of 0.01 count per second. By contrast, 10^{40} ergs per second per decade of gamma rays at 55 kpc corresponds to a counting rate of 0.015 count per second per square centimeter at 1.0 MeV. For a Crab-like energy spectrum (approximately equal energies per decade), the counting rate at 100 MeV, which should be detectable first, will be 100 times less. Such low counting rates require long observing times, which complicates the data analysis owing to the changing rotation rate (linear decay terms become important in a few hours, quadratic terms become important in a few days, and so forth), and this is further complicated by the necessity to search for the unknown period. Observation of unpulsed continuum gamma rays (from sources other than Co^{56}) seems diagnostic for the presence of the pulsar. Detection of pulsed gamma rays seems less certain, but important to provide an early determination of the spin period.

Optically, the existence of an active pulsar should be signaled by a leveling off of the light curve, well before the nebula starts to become optically thin ($\approx$ 6 years) and one can hope to see optical pulsations. The nebula will become transparent to infrared and radio waves somewhat earlier, but unfortunately we have no reliable theory to predict what fraction of the spin-down energy appears as pulsed radio emission, or how it will be distributed spectrally. Typical pulsars emit only about 10^{-5} of their energy at radio wavelength and comparable upper limits exist for the optical part of the spectrum. The Crab and Vela pulsars are even less efficient radio emitters, and for some reason the pulsed optical spectrum of the Crab drops precipitously as one goes into the infrared (*15*), so we have not even an observational basis for predicting infrared behavior (possibly important given the uncertainties in dust formation rates). The nebular emissions themselves constitute a strong (and at early epochs, unresolved) background source (expansion at 10^4 km/sec corresponds to about 40 milliarcseconds per year). For a pulsed optical signal 10^{-5} that of the total, one needs an excess of 10^{10} counts per time bin and, with 10 bins to give 10^{11} counts, requiring months of data acquisition to pull the signal out of the nebular background.

Any radio pulses will be strongly smeared by the nebula itself. The average electron concentration scales as $1.8 \times 10^{31}/t^3$ cm^{-3} so the nebular plasma frequency will fall below 50 MHz (for example) after 2.85 years, but even then the scattering on inhomogeneities will be huge. The dispersion measure for the above electron concentration will be $5.5 \times 10^{21}/t^2$ and will exceed 10,000 pc/cm^3 (unless reduced by recombination) until about 23 years after birth, a likely limit for de-dispersal even at that future date. The nebular radio emission itself is of great interest, given the uncertainty over whether radio synchrotron emission comes from pulsar injection of comparatively low energy electron-positron pairs that simply radiate away that energy, or from electrons reaccelerated by the pulsar wind (*10, 11*).

Apart from gamma ray observations, pulsar powering of the light curve should be seen well before direct detection of a pulsar. Have such effects on the light curve already been detected in other type II supernova? Although SN 1987a is a type II supernova, type I supernovae are also thought to be powered in their late phase by radioactive (78.8-day half-life) Co^{56} emission of nuclear gamma rays and also some positrons (*16*). Observation of type I supernovae (*17*) gives a half-life of 54.8 days, close but not equal to that of Co^{56} (the near coincidence of the radioactive half-life with the supernova mean-life can cause confusion). The discrepancy is attributed to the declining gamma-ray opacity of the shell, which causes progressively less energy to be converted to light (*18*).

The decay of type II supernovae like SN 1987a do not follow such a simple decline even though the same radioactive power source is presumed. Typically, type II supernovae decay about half as fast as the type I's (*19*). Thus during the period that most type II's have been followed ($\approx$1 year), they decay slower than the radioactivity. If radioactive decay is indeed the power source, one would expect that they would eventually decay at least as fast as the radioactivity or faster (like the type I's). As noted above, energy released by the pulsar should at some point take over from radioactive decay, consequently the light curve should cease to decay so rapidly and at some point should be powered primarily by the pulsar. Thus the generally observed slow decline of type II may itself be diagnostic of the presence of a pulsar. In contrast, Ostriker and Gunn (*20*) proposed that the entire supernova event be the result of the pulsar formation event, and by implication the long-term behavior as well. However, they expected the luminosity to drop until the wind zone emission moved into the optical, 5 to 10 years by their estimate (we put that epoch at more like 10^3 years, the age of the Crab nebula) after which a dramatic increase was predicted, a possibility now open to verification. Later work (*21–23*) was mainly preoccupied with fitting the peak luminosity part of the light curves to pulsar powering. Our hybrid suggestion is that the peak luminosity is related to Ni^{56} decay and only the long-term decline is pulsar-powered.

Alternatively, a slow decline could be due to other effects (interaction of ejecta with unusually dense surroundings, for example); in that case, one must ask what the long-term behavior of type II's is, because eventually pulsar activation should become apparent just as it has for the Crab nebula. Branch and Cowan (*24*) have, for example, detected a radio source as bright as Cas A only 26 years after SN 1961v (*25*). Observationally, there is the selection effect that most of these events are observed in distant galaxies and can only be followed down for a limited period. The expectation that the remnant will continue to fade may also bias observational effort after about 6 magnitudes of fading (*19, 25, 26*). For a typical type II supernova, excitation by a central pulsar would not be expected after 6 magnitudes of decay unless the spin-down power exceeded 5×10^{39} ergs/sec. Because SN 1987a is starting off a factor 50 to 100 times dimmer, it could reach the pulsar luminosity threshold much sooner, yet 7 magnitudes of decline would be required even before SN 1987a could be powered by a pulsar of typical 10^{12} Gauss magnetic field and entirely plausible 20-msec period. Thanks to its proximity, SN 1987a should be observable over a much larger magnitude range. A change of 20 magnitudes would take at least 4.0 years at the Co^{56} decay rate and flattening at this point would indicate powering by even a common 0.24-second pulsar. A dramatic leveling off of the light curve is therefore expected within a few years, possibly as soon as 10 months after birth of SN 1987a.

The illustrative estimates presented here can obviously be adjusted to accommodate different initial pulsar spin and magnetic field strengths, and different masses and expansion velocities of the inner heavy element shell and outer hydrogen-helium shell. Given the richness of these parametric dependences, it is possible that some of the variability of the type II supernovae light curves may have a natural explanation in terms of pulsar powering, at least at late times. In summary, we suggest that the existence of a Crab-like pulsar in SN 1987a would make itself known through detection of unpulsed (and possibly pulsed) hard gamma rays within about a year, accompanied by a deviation of the optical light curve from that predicted from Co^{56} decay (*27*). An early interpretation pointing to a pulsar is the possible excitation of nearby matter by a jet from the remnant (*28*), which would indicate a high pressure interior breaking out or intrinsic jet formation (*29*).

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A Substantial Bias in Nonparametric Tests for Periodicity in Geophysical Data

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A nonparametric test that has been used to conclude that extinction rates are periodic with a period of 26 million years is shown to be substantially biased toward this conclusion, regardless of whether or not the data are periodic in origin (and, indeed, regardless of the actual period if they are in fact periodic). The test is shown to be sensitive to measurement error of a type expected with these data (early recording of extinctions due to missing fossil specimens, the "Signor-Lipps effect"), and it is shown that because of the unequal spacing in time, such models may be expected to produce statistically significant but artifactual periods of (in this case) exactly 26 million years over the span of time actually used.

THERE HAS BEEN CONSIDERABLE INTEREST in recent years in the analysis of time series data in the geophysical sciences, with the goal of determining whether patterns, particularly periodic patterns, can be detected that depart significantly from what might be expected from a

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