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Does SN 1987A Contain a Rapidly Vibrating Neutron Star?

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If the recently reported 0.5 ms period pulsed optical signal from the direction of SN 1987A[1] originated in a young neutron star, its interpretation as a rotational period has difficulties. First, the upper bound on the present luminosity of 1987A will limit such a rotating star's surface magnetic field to $\leq 10^9$ G. Unless this field rises to 10^{12} G in a time of $\sim 10^3$ yrs, because of the emergence of a presently buried field or from magnetothermal generation [2], such a low field marks this event as very different from the Crab supernova as well as from those explosions responsible for the half-dozen other pulsar/supernova remnant associations. Second, such a high rotation rate without triaxial instability may place too severe a constraint on the equation of state of nuclear matter [3]. Here we point out that a remnant radial oscillation of a neutron star, excited in the supernova event, may survive for several years and has the expected (gravitationally red-shifted) period. Heavy ions at the low density stellar surface, periodically shocked by the vibration, will efficiently produce sharp pulses of optical cyclotron radiation in a surface field of $\sim 10^{12}$ G. These pulses may be only negligibly modulated by a (much slower) stellar rotation because of the nearly isotropic emission mechanism and the strong gravitational bending of light rays[4,5]. We discuss below some details of this model. We do not discuss here a mechanism for the reported 8 hr modulation[1], which may be the result of timing noise in much the same way that spurious quasi-sinusoidal modulations have appeared in period timing analyses of older pulsars[6].

Neutron star vibrations have already been discussed at some length in the literature [7,8]. From dimensional considerations the fundamental radial mode period is expected to be of order $P \sim (G\rho)^{-1/2} \sim 10^{-3}$ s with ρ the mean neutron star density. Typical neutron star models[8] with $M \sim 1M_\odot$ and $R \sim 10^6$ cm give periods close to 4×10^{-4} s with no sensitivity to the exact central density. This vibrational period is close to that observed when corrected for the gravitational red shift ($4. \times 10^{-4}(1 - 2GM/Rc^2)^{-1/2} \sim 5 \times 10^{-4}$ s). Non-radial and higher order radial modes would be damped on timescales of ≤ 1 yr[7,8,9] from gravitational, neutrino, and electromagnetic radiation. According to Finzi and Wolf [10], the major damping source for the fundamental radial mode is the URCA neutrino emission process, which gives a damping time $\sim 10^2$ yrs. However, this timescale could be reduced dramatically by two effects:

(1) "Exotic" enhancement of the weak interactions, the main source of the radial vibration damping. These include central π-condensates, or quark matter [11,12]. Confirmation of our modell may rule out the presence of these in the putative neutron star produced by SN 1987A, unless the neutrino emission they can give is suppressed by superfluid energy gaps.

(2) Enhancement of gravitational radiation from coupling to non-radial vibrations. Such coupling will arise when the underlying spherical symmetry is broken, *e.g.*, if the neutron star is rotating. For a neutron star with a uniform density, Chau[13] calculated the rotation-dependent gravitational radiation damping time to be $\sim 2 \times 10^3 \ P^4$ yrs, where P is the rotation period in seconds. Our model would then require a slowly rotating neutron star, with $P \geq 10^{-1}$ sec. With such a period, a 10^{12} G field does not cause the neutron star spin down power to exceed the current supernova luminosity.

The optical radiation cannot originate in a region larger than a light-travel size of 150 km. Furthermore, because the reported presence of strong first and

second harmonics indicates a sharp pulse, the size of the emission region should be much smaller than this, implying emission very close to the stellar surface. For a pulse luminosity $\geq 5 \times 10^{35} \mathrm{ergs}^{-1}$ (18th magnitude[1] at a distance of 55 kpc) any thermal emission must occur at a temperature $T > 10^6 K$; upper limits on the X-ray emission from the supernova[14] constrain the emission process to be nonthermal.

If a radiating particle of charge Z emits energy E per vibration period, the observed pulse luminosity from an optically thin surface region would require

$$E/Z \geq 8 \text{ MeV}. \tag{1}$$

If optically thick only at optical frequencies, it requires $E \geq 10^2$ MeV. If electron synchrotron radiation were responsible for the optical emission, the magnetic field would have to be

$$B \sin \alpha \leq 3.5 \times 10^5 (\frac{8MeV}{E})^2 \epsilon \text{ Gauss} \tag{2}$$

to produce optical emission, where ϵ is a typical photon energy in eV and α is a typical electron pitch angle. This extreme constraint on B suggests, instead, that the radiation arises from cyclotron radiation from stellar surface heavy ions, Fe^{+Z} for example. These will produce optical cyclotron radiation (at much higher fields) with a typical photon energy of

$$\epsilon \sim 3B_{12}\frac{2Z}{A} \text{ eV}, \tag{3}$$

where B_{12} is the magnetic field value in units of 10^{12} Gauss and A is the atomic number of the ion. [While curvature radiation by an electron could fall in the optical band, this mechanism, generally, has a very low efficiency ($\sim \frac{e^2}{c\hbar}\frac{\hbar\omega}{mc^2} \sim 10^{-7}$) compared to that of synchrotron emission.]

In this ion cyclotron emission model, condition (1) requires the energy of Fe^{+26}, for example, to be $\geq .2$ Gev per ion; the column density is then $\sim 2 \times$

$10^{22}E_{\mathrm{Gev}}^{-1}$ cm^{-2}. Fully stripped energetic but nonrelativistic Fe ions (or He^{++} or protons) can give strong cyclotron optical emission in a field $B \sim 10^{12}$ Gauss. We propose that these ions can be given the needed velocities as the radial vibration steepens into a shock when it reaches the small densities and scale heights at the stellar surface. These strong shocks occur at 0.5 ms intervals, just after the surface reaches its maximum outward speed, and can accelerate particles to velocities of order 10^{10} cm/sec [15]. Just after the shock the kinetic energy (~ 4 Gev per ion) carried by ions will dominate that carried by electrons. Because of the short travel time for the shock passing through the surface of the neutron star and the short ion cyclotron lifetime ($\leq 10^{-5}$ sec), a sharp pulse is expected within each cycle. Furthermore, since the emission is concentrated around the ion gyration frequency, the vibration shocked surface can gives a reasonably efficient conversion of internal vibration energy to optical radiation.

The total luminosity of SN 1987A sets a lower limit to the neutron star rotation period of $\geq 20\,B_{12}L_{38}^{-1}$ ms, where L$_{38}$ is the supernova luminosity in 10^{38} erg/s. As noted above, our model requires $P \geq 10^{-1}$ sec. As the cyclotron emission occurs in a magnetic field which varies over the surface of the star, one expects a modulation at the stellar rotation period. However, the amplitude of this modulation may be rather small because of the isotropic energy input from the vibration, the fairly isotropic geometry of cyclotron emission, and the strong gravitational bending of the emitted light rays [4,5].

Future period observations should test our model. The period of the neutron-star vibration should not increase significantly with time although the luminosity will decrease as the vibration is damped; the rotation period of the star should be found to be $\geq 10^{-1}$ s. The optical pulse spectrum should be significantly different from that of the Crab pulsar, which originates from a very different mechanism. The frequency corresponding to the peak emission in the SN 1987A

optical pulsar spectrum could be used to estimate the magnetic field at the surface of the neutron star (see Equation (3)). Observations in other wavelength bands are highly desirable. The detection of X-rays from the neutron star before the vibration dies out could provide important input to our understanding of the origin of the optical light.

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