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EMISSION FROM THE SUB-MILLISECOND PULSAR IN SN 1987A

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Abstract

We consider the production and emission of high energy particles from the submillisecond pulsar, newly discovered in SN 1987A. We also discuss the emission of very high energy gamma rays and other electromagnetic radiation from the pulsar surface and magnetosphere including possible pleirons and cavities.Constraints are put on some of the current models of particle acceleration in pulsars. The evolution of such pulsars and their contribution to the high energy cosmic ray background is studied.

<u>Introduction</u> The recent detection of a submillisecond optical pulsar in SN 1987A (i.e. optical variations between magnitude 18 and 19 detected with a 1968.629 Hz periodicity [Lindley 1989] with a period $P \approx 0.5$ ms, surprised many pulsar theorists as it was commonly supposed that pulsar are born as slow rotators and with high magnetic fields. The dipole field at the surface of the present pulsar would be $B < 10^9$ G typical for a millisecond pulsar. With the optical luminosity scaling as B^4P^{-10}, this would make it $\sim 3^{10} \sim 5.8 \cdot 10^4$ times brighter than the millisecond pulsar at optical wavelengths, i.e. sixteen magnitude brighter. The X-ray flux should also be correspondingly larger by the same factor, i.e. at least $\sim 6 \cdot 10^{33}$ ergs/s. For a similar $\dot{P}$, it would have an ellipticity $y < 10^{-9}$ and emit gravitational waves at a frequency of $\sim$ 3938 Hz and $3^6 \sim 700$ times that of the millisecond pulsar. It was gratifying that the detection of the neutrino burst implied about $\sim 3 \cdot 10^{53}$ ergs being released in neutrinos of all flavours which is the typical binding energy of a neutron star. So one would have expected a pulsar rather than a black hole remnant. Of course the angular momentum of a giant star conserved through collapse to a neutron star would have been enough to create a millisecond pulsar. If it formed by the coalescence of two protoneutron stars [Sivaram 1982], their individual binding energies $\approx 10^{53}$ ergs would be liberated in ν emission within two seconds. Their fusion by emission of gravitational radiation would have taken about 9 secs. with an accompanying burst $\sim 2 \cdot 10^{52}$ ergs of gravitational radiation with frequency

$\sim 2\cdot 10^3$Hz. If nuclei are accelerated and injected into supernova ejecta in the early stages, they may generate high energy gamma rays and ν's via pion production. The main part of galactic cosmic rays is considered to be generated in supernova shock fronts through the Fermi mechanism with multiple scatterings in upstreams and downstream of the shock front with a power law energy spectrum. But this mechanism cannot accelerate protons and nuclei much above about 10^{15}ev [Sivaram 1987] and another type of source for still higher energies is required which very probably would be the newly formed pulsars. As an illustration a pulsar with a 10 ms period and a magnetic field $\approx 10^{12}$G, has a polar cap potential energy drop of $\approx 10^{17}$ev and so is capable of accelerating charged particles to at least this energy. This cap potential scales as $\sim P^{-2}$ and for $P \approx 1$ ms could reach 10^{19}ev. Again as indicated by Cyg X-3 observations an early phase pulsar can generate proton beams with energies $\approx 10^{17}$ev interacting with matter to produce ultra high energy gamma rays and ν's with $E > 10^{17}$ev.

Energy outflow and production of high energy particles

Total liberation rate of rotational energy [Sivaram 1987] due to dipole magnetic field is

$$L \approx 4\cdot 10^{43}\text{ergs/s}\cdot \left[B/10^{12}\right]^2 \left[R/10^6\text{cm}\right]^2 \left[P_o/1\ \mathrm{ms}\right]^{-4} \qquad (1)$$

For the present pulsar this gives $\approx 6\cdot 10^{38}$ergs/s. Here the rotational energy about same as gravitational binding energy. The Goldreich-Julian rate of particle flux [Goldreich 1969] defined by:

$$\dot{N}_{GJ} \approx B_o R_o^3 \Omega^2/ec \approx 10^{37}\left[B/10^{12}\right]\left[R_o/10^6\text{cm}\right]^3 1/(P/1\ \mathrm{ms})^2 \text{part/s} \qquad (2)$$

which for the present pulsar is $\approx 5\cdot 10^{34}$ particles/s. This gives a E_{max} of particle average energy as:

$$E_{max} \approx 10^{19}\text{ev}\cdot\left[B/10^{12}\text{G}\right]\left[P_o/1\ \mathrm{ms}\right]^{-2}\left[R_o/10^6\right]^3 \qquad (3)$$

which works to $\approx 5\cdot 10^{16}$ev for this pulsar. But for $P_o < 10$ ms due to curvature radiation E_{max} is about an order of magnitude lower. If there exist turbulent magnetic field $> 10^{-2}$G in the ejecta, the charged particles with $E_{max} < 10^{17}$ev can be trapped. Similarly the Gunn-Ostriker mechanism [Gunn 1969] gives an

$$E_{max} \sim 10^{17}\text{ev}\ (P/1\ \mathrm{ms})^{-4/3}\cdot(B/10^{12})^{2/3} \qquad (4)$$

with similar results of $E_{max} \approx 10^{16}$ev for the present case. The above relations eqs.(1-4) seem to indicate that this newly formed submillisecond pulsar is not capable of accelerating paticles to much above ~ 10^{16}ev if above models apply. So the highest energy cosmic rays ~ 10^{19} or 10^{20}ev should be produced by some other sources. However it could still produce about $5\cdot10^{34}$particles/s at energies ≈ 10^{16}ev. A birth rate of such pulsars in our galaxy at rate of $\approx 10^{-2}yr^{-1}$, would give rise to a maximal background flux of $\approx 10^{-12}cm^{-2}s^{-1}$ of such particles in a diffusion time scale. The high energy protons produced with energies $\approx 10^{16} \div 10^{17}$ev would interact with ejecta producing ν's and high energy γ-rays, i.e.for a monoenergetic proton beam with energy E_o, energy distribution of γ-rays generated by π^o decay is [Taylor 1976]:

$$N_\gamma(E)dE \propto (1 - E/E_o)^{3.5}d\ lnE \quad \text{with maximum at } E \approx 0.2\ E_o$$

The c-s's for the various processes pp leading to π^o,γ's etc are known and if λ_p^{-1}, λ_γ^{-1} are mean free paths of protons and γ-rays and $\eta_{\pm o}$ are multiplicity of pion production rate at source, the fluxes of protons, ν's or γ's satisfy differential eqs.of the type:

$$dF_p/dr = - \lambda_p(r)F_p \ , \qquad dF_\nu/dr = \eta_\pm\lambda_p(r)F_p\ d\tau$$

with solutions of the form $I_\nu(t) = \eta_\pm\left[1 - \exp\left[-(t_c/t)^2\right]\right]$

$t_c = \left[3M\sigma_{pp}/4\pi m_p\right]^{1/2} \eta/V_{shell}$ etc $\eta \approx 0.5$. Similar equations for high energy neutrino production. The fact that no muons were detected from the high energy ν's several months after the explosion enables an upper limit to the fluxes to be put of < 10^{41}ergs/s for total power in high energy particles. Similarly observed flux of line γ-rays gives a limit of < $5\cdot10^{38}$ergs/s for the γ-ray luminosity. The velocity of light cylinder for this pulsar ~ c/Ω is ≈ 20 km, too close to the pulsar surface. The low magnetic field would give a low Alfven radius. This may invalidate some of the usual models of particle acceleration. If the internal energy is partly supplied by decay of ^{56}Co with heating rate:

$$L_{Co}(t) = L_{Co}e^{-t/\tau_o} \ , \ \tau_o = 113.7\text{days}, \quad L_{Co} = 10^{42}\left[M_{Co}/0.01M_\odot\right]\text{erg/s}$$

$W_\bullet$ evolves as: $\tau_o^2L_{Co}/t\left[1 - (1 + t/\tau_o)e^{-t/\tau_o}\right]$

For $t << \tau_o$, cavity radius increases as $R = (L/L_{Co})^{1/3} Vt$ and the mass of $M(L/L_{Co})$ has been evacuated to form cavity. For $t >> \tau_o$, shocked shell will be formed at epoch

$$t_s \approx 1.5 \frac{L_{Co}/10^{42} \text{ ergs s}^{-1}}{(L/10^{40})^{2/7} M^{8/7} (V/500)^{6/7}} \text{ yrs}$$

This is about the time when nuclear γ-rays become transparent to inner ejecta. Peak frequency of synchrotron radiation estimated as $\nu_m \approx 10^8 (G/10^6 ev)^2$Hz where G is the electron energy. Corresponding photon energy for inverse Compton scattering is $\approx 10^{1.67}$Mev in the hard X-ray or γ-ray region which would confirm sufficiently strong magnetic field in cavity. Also general relativistic effects would be large. There would be different temperature distribution at pole and equator due to rapid rotation. Roughly

$$T(R,\vartheta_{eq})/T(R,\vartheta_{pole}) \simeq \frac{\left[1 + (a/R)^2 (1 - 2R_s/R)^{-1}\right]^{1/2}}{\left[1 + (a/R)^2\right]^{1/2}} \qquad a = J/M$$

There could be a difference $\approx 10^6$ °K.

REFERENCES

Goldreich P.& Julian W. 1969 Ap.J. 157, 869

Gunn J.& Ostriker J. 1969 Phys.Rev.Lett.22, 728

Lindley D. 1989 Nature 337, 595

Sivaram C. 1987 Proceed.19 ICRC Moscow 2 (OG) 183

Sivaram C.& de Sabbata V. 1989 preprint

Taylor F.et al. 1976 Phys.Rev.D14, 1217