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GAMMA RAYS FROM PULSAR WIND SHOCK ACCELERATION

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ABSTRACT

A shock forming in the wind of relativistic electron-positron pairs from a pulsar, as a result of confinement by surrounding material, could convert part of the pulsar spin-down luminosity to high energy particles through first order Fermi acceleration. High energy protons could be produced by this mechanism both in supernova remnants and in binary systems containing pulsars. The pion-decay gamma rays resulting from interaction of accelerated protons with surrounding target material in such sources might be observable above 70 MeV with EGRET and above 100 GeV with ground-based detectors. Acceleration of protons and expected gamma-ray fluxes from SN1987A, Cyg X-3 type sources and binary pulsars will be discussed.

I. INTRODUCTION

Although the Crab and Vela pulsars are among the strongest known gamma-ray point sources, their pulsed radiation represents only a minor fraction of their total spin-down energy loss. The radio pulses contain on average $\approx 10^{-5}$ of the power released and even the pulsed gamma rays from the Vela pulsar represent only .05% of the spin-down luminosity. At least in these cases, acceleration of particles within the magnetosphere is not an efficient means of tapping the spin-down power of a pulsar, the bulk of which is released at or outside the light cylinder as electromagnetic dipole radiation at the pulsar spin frequency. Because the expected plasma frequency just outside the pulsar magnetosphere is above the frequency of the vacuum dipole wave (Arons 1981), the spin-down power will be transported as an MHD wind of relativistic electron-positron pairs (Rees and Gunn 1974, Kennel and Coroniti 1984). If a pulsar wind interacts in some way with a surrounding medium, then a large fraction of the pulsar spin-down power might be channeled into observable radiation through the acceleration of particles.

One possibility is the confinement of a pulsar wind by an expanding supernova remnant. This evidently occurs in the Crab nebula, where 20 - 30% of the $5 \times 10^{38}\,\mathrm{erg\,s^{-1}}$ released by the pulsar appears as synchrotron radiation from relativistic electrons. Rees and Gunn (1974) pointed out that a standing reverse shock must form in the confined pulsar wind, as it decelerates to the subsonic velocity of the shell. Gaisser, Harding and Stanev (1987, 1989) proposed that acceleration of charged particles could take place at the pulsar wind shock through the first order Fermi mechanism. Charged particles travelling back and forth across the shock by scattering from magnetic irregularities, gain energy in each crossing-recrossing cycle. This mechanism is capable of accelerating protons as well as electrons to high energies. Evidence of proton acceleration could appear as high energy γ-rays from decay of neutral pions, produced when the protons undergo nuclear interactions with material of the supernova envelope. Although the density of the Crab supernova shell is now too low to produce observable γ-rays from proton interactions, very young supernova remnants like SN1987A might be good sources to look for signatures of proton acceleration (Berezinsky and Ginzburg 1987, Nakamura *et al.* 1987).

Acceleration of particles in pulsar wind shocks and production of high energy γ-rays may also take place in binary systems (Harding and Gaisser 1990), where the atmosphere, wind or magnetosphere of the companion can confine the pulsar wind. There may in fact be evidence that such an interaction of a pulsar wind with a companion star is occurring in PSR1957+20, the recently discovered eclipsing millisecond pulsar (Fruchter *et al.* 1988). A stationary shock would in this case form between the pulsar and companion near the pressure balance point. Pulsars buried inside molecular clouds may also have confined winds, producing shock-accelerated cosmic rays inside the clouds and such sources may contribute to an enhancement of the diffuse galactic gamma-ray emission.

This paper discusses the acceleration of protons and production of gamma-rays by pulsar wind shocks and the prospects for detection by EGRET of > 70 MeV γ-rays from young supernova remnants and binary pulsars. It appears that EGRET may be more sensitive to detection of these signals than the ground-based air shower arrays currently in operation.

II. PULSAR WIND SHOCK FORMATION

The power in magnetic dipole radiation from a pulsar with rotation frequency Ω and magnetic dipole moment m is

$$L_d = \frac{2m^2\Omega^4 \sin^2\theta}{3c} \approx 4 \times 10^{43}\,\mathrm{erg/s}\, B_{12}^2 P_{\rm ms}^{-4} \tag{1}$$

where $P_{\rm ms}$ is the period in ms, $B_{12} = (B_o/10^{12}\mathrm{Gauss})$ is the surface magnetic field, and θ is the angle between the dipole and rotation axes. Virtually all of this power may appear as a relativistic wind which carries both particles (predominantly electron-positron pairs) and wound-up magnetic field away from the pulsar. Since the magnetic field is dipolar ($\approx r^{-3}$) inside the pulsar light cylinder, $r_{LC} = c/\Omega = 5 \times 10^6\,\mathrm{cm}\,P_{\rm ms}$, and toroidal ($\approx r^{-1}$) in the wind, the field strength at a distance r is

$$B = B_o\,(\frac{r_o}{r_{LC}})^3\,(\frac{r_{LC}}{r}) = 8 \times 10^9\mathrm{Gauss}\,B_{12}P_{\rm ms}^{-3}(\frac{r_{LC}}{r}), \tag{2}$$

where $r_o = 10^6$ cm is the neutron star radius. Winds from pulsars with short periods have higher magnetic fields because the light cylinder, inside which the field falls off most rapidly, is closer to the neutron star.

Confinement of pulsar winds can occur if surrounding material provides enough pressure to balance the wind ram pressure. The confining material then creates a standing reverse shock in the wind. If the pulsar is surrounded by a supernova remnant, then the pulsar wind sweeps out the inner part of the expanding envelope to form a roughly spherical cavity around the pulsar, filled with relativistic particles and magnetic field. A binary companion may also provide pressure in the form of a stellar wind, atmosphere or magnetosphere to shock the pulsar wind.

a) Supernova Remnants

The situation where a pulsar wind is confined by the inner part of an expanding supernova shell is shown schematically in Figure 1. The pulsar wind model of a supernova remnant was first proposed by Rees and Gunn (1974) and by Pacini and Salvati (1973) to explain how the power generated by spin-down of the Crab pulsar is converted to relativistic particles which radiate the observed synchrotron emission. The model assumes that the spin-down power from a young pulsar inside the remnant drives a relativistic MHD wind with luminosity L_d approximated by Eqn (1). The radius of the shock r_s is calculated (Rees and Gunn 1974) by balancing ram pressure in the wind with the accumulated energy density in the shocked wind cavity:

$$r_s = \sqrt{\frac{u_{\rm min}}{3\,c}}\, u_{\rm min}\, t \approx 3.5 \times 10^{13}\,{\rm cm}\; t_{\rm yr}\, u_{500}^{3/2}, \tag{3}$$

where $t_{\rm yr}$ is the age of the supernova in years and $u_{500} = u_{\rm min}/500\,{\rm km\,s^{-1}}$ is the velocity of the inner envelope.

From Eqn (2), the magnetic field in the pulsar wind can be estimated at $r = r_s$ as

$$B_s \approx 10\,{\rm G}\; B_{12}\, P_{10}^{-2}\, t_{\rm yr}^{-1}\, u_{500}^{-3/2} \tag{4}$$

The above expression gives $B \approx 10^{-4}$ G for the Crab pulsar, which is in good agreement with the field inferred from the observed synchrotron emission from the nebula.

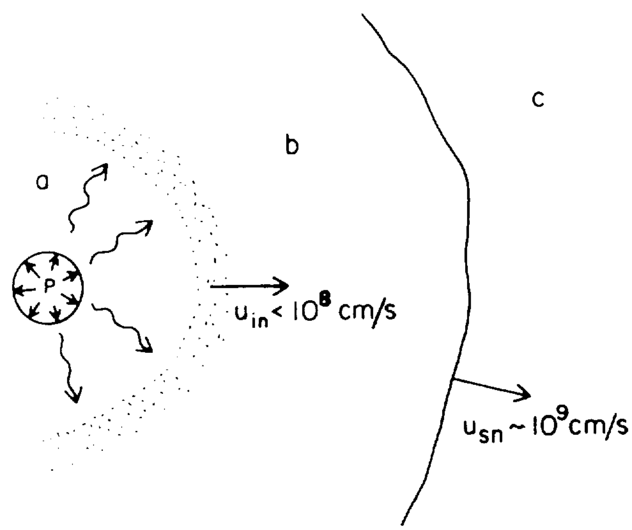

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FIG. 1 - Schematic view of a pulsar wind in a supernova remnant. The inner circle of radius r_s is the reverse shock in the wind generated by the pulsar (P), whose rotation axis is normal to the plane of the figure. Region (a) is the shocked pulsar wind cavity, which is confined by the supernova envelope (b), expanding into the interstellar medium (c).

b) Binary Pulsars

Pulsar wind shocks can also form in binary systems containing rapidly spinning, non-accreting pulsars. Accretion will not take place if the light cylinder of the rotating neutron star, r_{LC}, is inside the Alfven radius, $r_A = 1.5 \times 10^8\, B_{12}^{4/7}\, \dot{M}_{18}^{-2/7}$ cm, where $\dot{M}_{18} = \dot{M}/10^{18}\,{\rm g\,s^{-1}}$ is the accretion rate. In this case, the ram pressure from the pulsar wind outside the light cylinder everywhere exceeds the ram pressure of the accretion flow and cannot maintain a stable force balance condition analogous to the Alfven radius. Any accreting material will be blown away by the pulsar wind. Therefore, systems having short period pulsars with

$$P < 31\,\mathrm{ms}\,\mathrm{B}_{12}^{4/7}\,\dot{\mathrm{M}}_{18}^{-2/7} \tag{5}$$

will be powered by rotation (Ruderman *et al.* 1989, Harding and Gaisser 1990).

There are several possibilities for confining a pulsar wind in a binary system, at least over a limited solid angle. If the companion star generates a wind, possibly induced by the incident pulsar luminosity, a shock forms where ram pressure of the two winds balance (cf. Fig. 2). In the absence of a stellar wind, the pulsar wind can be confined by the static atmosphere or magnetosphere of the companion where the gas or magnetic pressure balances the ram pressure of the pulsar wind.

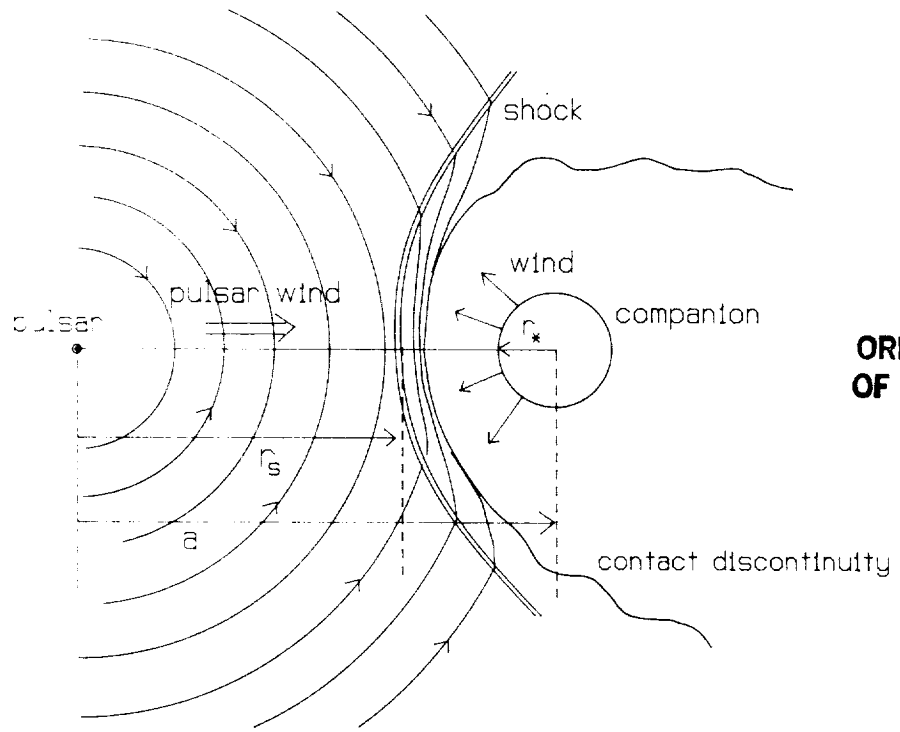

FIG. 2 - Schematic view of pulsar wind shock formation in a binary system for the case of confinement by the companion star wind.

In the case where the pulsar wind is confined by a stellar wind from the companion, the shock location is determined by balancing $L_d/(4\pi r^2 c)$ with $(\rho v^2)_\mathrm{w} = \dot{M}_\mathrm{w} v_\mathrm{w}/(4\pi r^2)$ or

$$\frac{L_d}{4\pi r_s^2 c} = \frac{\dot{M}_\mathrm{w} v_\infty}{4\pi (a - r_s)^2}\left[1 - \frac{r_*}{a - r_s}\right]^{1/2} \tag{6}$$

where $\dot{M}_\mathrm{w}$ and v_∞ are the mass loss rate and terminal velocity of the wind, r_s is the distance of the shock from the neutron star and r_* is the companion star radius. An approximate solution for the shock location r_s in the limit $r_s << a - r_*$, is

$$\frac{r_s}{a} \approx \frac{\sqrt{A_w}}{1 + \sqrt{A_w}} \tag{7}$$

$$A_w = \frac{L_d}{\dot{M}_w\, v_w\, c} = \frac{2\times10^7 B_{12}^2 P_{\rm ms}^{-4}(\frac{r_*}{R_\odot})^{1/2}}{\dot{M}_{18}\,(\frac{v_\infty}{v_{\rm esc}})\,(\frac{M}{M_\odot})^{1/2}} \tag{8}$$

where M is the companion star mass and $v_{\rm esc} = (2GM/r_*)^{1/2}$ is the escape velocity from the companion. The quantity A_w is essentially the ratio of pulsar wind ram pressure to stellar wind ram pressure and is the critical parameter determining solutions for r_s. In order to calculate the location of the shock, one needs a model for the companion star wind which gives values for $\dot{M}$ and v_∞. Harding and Gaisser (1990) discuss two possible models in which the wind from the companion is induced by the pulsar wind luminosity: 1. If the pulsar wind luminosity incident on the companion star exceeds its Eddington luminosity, a wind will be driven by radiation pressure, 2. If the incident luminosity is sub-Eddington, then a thermally-driven wind may result (Cheng 1989). In the latter case, the shock radius turns out to be independent of the pulsar luminosity, with the quantity $A_w = 11.5(v_\infty/v_{\rm esc})^3(a/r_*)^2$ from Eqn (8) dependent only on the system geometry and the wind terminal velocity.

If the companion star has a surface magnetic field, B_*, then magnetic pressure may be sufficient to stand off the pulsar wind. In this case, the shock location can be found by balancing $[B_*(r_s)]^2/8\pi$ with $L_d/(4\pi r_s^2 c)$. Assuming a dipole field, solutions for the shock location are determined by the quantity

$$A_m = \frac{2L_d}{B_*^2 a^2 c}, \tag{9}$$

which scales with the ratio of pulsar wind ram pressure to magnetic pressure. The condition that the shock form above the companion star surface, or $(a - r_s) \geq r_*$, requires that $A_m \leq (1 - r_*/a)^2 \leq 1$, which from Eqn (9) gives a limit on the companion star field capable of standing off the pulsar wind,

$$B_* \geq \left(\frac{2L_d}{c}\right)^{1/2} \frac{1}{(a - r_*)}. \tag{10}$$

If neither a wind or a magnetosphere of the companion provides enough pressure to stand off the pulsar wind above its surface, then the static gas pressure of the atmosphere, $\rho kT/m_H$, will balance the pulsar wind ram pressure. In this case, pressure balance will occur close to the companion star surface, so that the shock distance from the pulsar is $r_s \approx a - r_*$.

III. PARTICLE ACCELERATION

Following the pioneering work of the late seventies (Axford *et al.* 1977, Blandford and Ostriker 1978), shock acceleration has gained considerable attention as a mechanism for generating highly energetic particles in a variety of astrophysical sources ranging from supernovae to the Earth's bow shock. If the shock is formed by collisionless processes, particles can travel back and forth across the shock front by scattering from magnetic irregularities, gaining some energy on each crossing. The theory of diffusive shock acceleration (cf. Drury 1983 for review) has concentrated primarily on strong parallel shocks (where the magnetic field is parallel to the shock normal). The standard treatment also is for non-relativistic shocks for which $u_1,\, u_2 \ll c$. Such a shock produces a power law spectrum of accelerated particles

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escaping downstream with index of the differential energy spectrum $\alpha = (\xi + 2)/(\xi - 1)$, where ξ is the shock compression ratio.

The shock in the pulsar wind differs from the canonical case in two ways. First, because of the toroidal field of the wind, the shock is quasi-perpendicular rather than parallel. Second, the shock is relativistic in that the velocity of the unshocked wind relative to the shock front is $u_1 \approx c$. Treatments of acceleration by relativistic shocks (Peacock 1981; Kirk and Schneider 1987) indicate that they are more efficient at accelerating particles than non-relativistic shocks (the energy gain per crossing is larger). Calculations show that the accelerated particle spectrum is flatter than for a non-relativistic shock with the same compression ratio. However, the resulting spectral index is somewhat uncertain, since the two approximations usually made to treat scatterings in the non-relativistic case, pitch angle scattering or hard-sphere scattering, give different results in the relativistic case (Ellison 1989, private comm.). Thus, the description of particle acceleration by relativistic shocks is still incomplete.

The maximum energy to which (charged) particles can be accelerated in the shock is determined by the balance of the energy gain rate with losses. The energy gains of the particles crossing the shock compete with energy losses through radiation and inelastic collisions and with diffusion away from the shock. In almost all situations, the pulsar wind shock will form well outside the pulsar light cylinder, where the magnetic field in the wind is low and consequently synchrotron radiation from protons will not be important. The maximum energy, $E_p^{\max}$, to which protons can be accelerated by a spherical shock of radius r_s is therefore found by equating the acceleration time to the time, $t_d \approx r^2/D$, for protons to diffuse away from the shock, where D is the diffusion coefficient and r is usually taken to be the shock radius. The minimum value of the diffusion coefficient, $D_{\min} = r_L v/3$, where $r_L = 3.3 \times 10^9 \mathrm{cm}\, E_{\mathrm{TeV}}/B$ is the Larmor radius, v is the particle velocity, and E is the particle energy, gives an upper limit on the acceleration rate and hence an upper limit on the maximum energy that can be achieved. For the pulsar wind, which is highly relativistic (Kennel and Coroniti 1984), $u_1 \approx c$, and the resulting estimate for the maximum proton acceleration energy, using the non-relativistic treatment (Lagage and Cesarsky 1983), is

$$E_p^{\max} \approx \sqrt{\frac{3(\xi - 1)}{\xi(\xi + 1)}}\, e\, B_s r, \tag{11}$$

Because of the inverse dependence on field strength, which from Eq (2) is large, and the relativistic velocity of the wind, the pulsar wind shock is extremely efficient at accelerating particles to high energy.

In cases where the shock radius is the same as the distance of the shock from the pulsar, the magnetic field strength at the shock from Eqn (2) with $B_s = B(r = r_s)$ gives a maximum proton energy of

$$E_p^{\max} \approx 7 \times 10^{18}\,\mathrm{eV}\, B_{12} P_{\mathrm{ms}}^{-2} = 10^{16}\,\mathrm{eV}\, L_{38}^{1/2} \tag{12}$$

for a strong shock with $\xi = 4$. It is interesting that the maximum energy in Eqn (12) depends only on pulsar parameters and is independent of the structure and dynamics of the confining material. This is because $E_p^{\max} \propto r_s B_s$ and the magnetic field at the shock, B_s, is inversely proportional to r_s. This scale invariance of the maximum proton acceleration energy makes this mechanism applicable to models of binary sources of VHE and UHE γ-rays as well as to pulsars in supernova remnants. Furthermore, there is a simple relation between the pulsar spin-down luminosity, $L_{38} = L_d/10^{38}\mathrm{erg\,s^{-1}}$, and the predicted maximum proton energy. Eqn (12) will hold for pulsar wind shocks in supernova remnants, because the confining shell will form a spherical shock around the pulsar at a distance $r = r_s$.

For pulsar wind shocks in binary systems, the geometry is somewhat more complicated and Eqn (12) then represents an upper limit to the maximum proton energy. In the case of confinement by a stellar wind or magnetosphere, the diffusion length scale which determines the maximum proton energy depends on how close the shock is to the companion star. If $r_s << a - r_*$, then the radius of the shock will be approximately r_s and the diffusion timescale, $t_d = r_s^2/D$, but if $r_s \approx a - r_*$ with the shock near the companion star, then the shock radius will be approximately r_* and $t_d = r_*^2/D$. The maximum proton energy in these two cases is (Harding and Gaisser 1990)

$$E_p^{\max} = 7 \times 10^{18}\,\mathrm{eV}\, B_{12} P_{\mathrm{ms}}^{-2} \begin{cases} 1, & r_s << a - r_* \\ \dfrac{r_*}{(a-r_*)}, & r_s \approx a - r_* \end{cases} \tag{13}$$

Note that in the case $r_s << a - r_*$, the r_s dependence drops out of $E_p^{\max}$ as in Eqn (12), so that the maximum proton acceleration energy depends only on pulsar parameters. In the case of wide binaries, where $r_s \approx a - r_*$, the maximum proton energy may be substantially reduced.

IV. GAMMA-RAY PRODUCTION

Protons accelerated at the pulsar wind shock could produce high energy gamma rays and neutrinos through the decay of neutral pions, which would result when the protons interact with surrounding material (or conceivably ambient photons if their density is high enough). The bremsstrahlung emission from electrons produced as secondaries in the nuclear interactions may also make a contribution at low energies, although the magnetic fields in these sources are high enough to make the bremsstrahlung negligible at higher energies. In the case of young supernovae, the target material is the expanding envelope. In binary systems, the target material could be the companion star wind or atmosphere. Since the geometry and proton transport in these situations are so different, we discuss gamma-ray production in these two types of sources separately.

a) Supernova Remnants

Supernovae are considered to be likely sites of cosmic-ray acceleration and it was noted some time ago that evidence for such acceleration might be observed in young supernova remnants in the form of gamma-rays from nuclear interactions of accelerated protons (Berezinsky and Prilutsky 1978; Sato 1977; Shapiro and Silberberg 1979). Following the explosion of SN1987A in the Large Magellanic Cloud, a number of experiments have attempted to detect these γ-rays over a wide range of energies (see Harding 1989 for review) and models of the pion-decay γ-ray production from nuclear interactions have been developed and refined (e.g. Gaisser *et al.* 1987, 1989 [GHS]; Berezinsky and Ginzburg 1987; Yamada *et al.* 1987). These models assume that acceleration of protons results from the presence of a pulsar deep inside the remnant. Their results indicate that details of the confinement of accelerated protons and the mixing of protons with gas in the envelope make a crucial difference in the predicted gamma-ray fluxes and light curves.

Thus far, the models have made highly simplified assumptions about the transport and distribution of protons in the envelope in order to calculate gamma-ray fluxes and light curves. For example, Yamada *et al.* (1987) assume that the accelerated protons are not confined at all and freely propagate through the envelope. The resulting light curve peaks and decays within a year after the explosion. On the other hand, GHS have assumed that the protons are confined by the high magnetic field surrounding the pulsar. The production of γ-rays through nuclear interactions then requires that the cosmic rays mix with the gas in the envelope by diffusion or bulk motion. The mixing of the shocked wind with the gas in the envelope could result, for example, from Rayleigh-Taylor instabilities at the wind-envelope interface. The exact amount of energy going into γ-rays then depends on the degree of mixing of shell material with the shocked wind containing the accelerated protons and magnetic field. In this case the light curves can peak as late as 6 years after the explosion. They also showed that the light curves were very sensitive to the assumed distribution of protons in the envelope and to the degree of mixing of protons with gas.

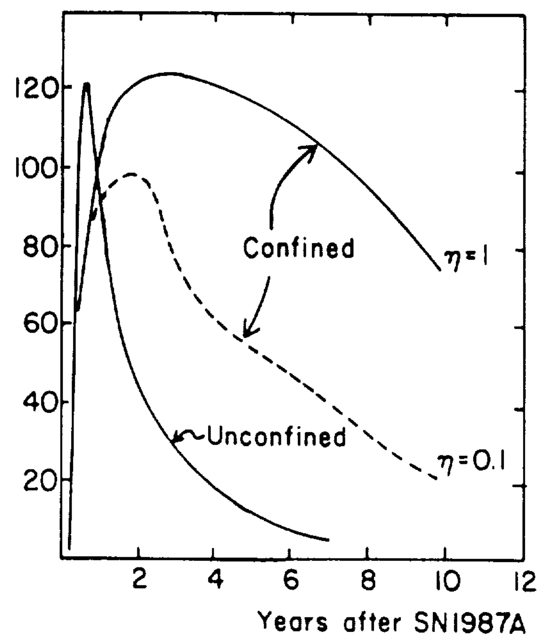

FIG. 3 - Comparison of light curves for models with confinement (from GHS) and free propagation (from Nakamura *et al.* 1987).

Figure 3 shows the calculated gamma-ray light curves in these two cases for SN1987A, showing that if the protons are unconfined the source has already peaked, whereas if the confinement picture is correct the source may last long enough to be detectable with future satellite experiments. In the case of proton confinement, the high energy photon signal will be observable between time t_1 when the shell becomes optically thin to > 100 MeV γ-rays and time t_2 when the shell becomes so diffuse that protons lose their energy from adiabatic expansion before interacting. For a total ejected mass $M \approx 15\, M_{\odot}$, $t_1 \approx 1$ year. The time t_2

occurs when the interaction rate of accelerated ions with the gas falls below the expansion rate. After this time the dominant energy loss will be by adiabatic expansion (Berezinsky and Prilutsky, 1978). If the accelerated particles are not completely mixed with the gas in the expanding envelope, t_2 depends on the amount of the gas mixed into the cosmic ray bubbles and could even be such that $t_2 < t_1$ (i.e. photon production never occurs) if there is not enough mixing.

Cosmic ray mixing and transport in a supernova shell has been considered in greater detail by Harding *et al.* (1990a,b). Assuming that protons are accelerated at a constant rate by the shock deep inside the pulsar wind cavity, they must diffuse to the wind-envelope boundary, suffering adiabatic losses from the expansion. This boundary is Rayleigh-Taylor unstable because the low-density pulsar wind is exerting a pressure on the denser overlying envelope. At the boundary, bubbles containing pulsar wind, tangled magnetic field and cosmic rays will grow and penetrate the inner edge of the envelope through Rayleigh-Taylor instability. Transport of the bubbles outward through the envelope together with leakage of material into the bubbles provides the mixing of cosmic rays and target material necessary for gamma-ray production. From the maximum growth timescale and scale size of the instability, they find that Rayleigh-Taylor perturbations will reach the non-linear phase in less than a year. The estimated rate at which the bubbles move out into the envelope indicate that the cosmic rays will stay confined in the inner part of the shell while interacting. Protons confined to the slowest moving, densest part of the envelope will have a lower energy loss rate from adiabatic expansion and a higher nuclear interaction rate than protons distributed uniformly throughout the envelope (GHS). These factors contribute to a higher gamma-ray productivity. This must be balanced, however, with the larger attenuation of gamma-rays coming from deep inside the envelope.

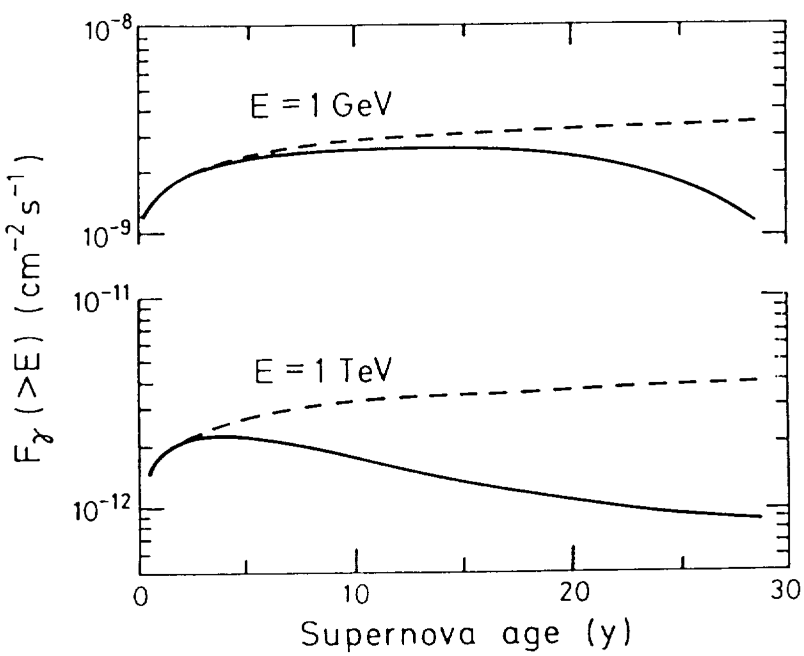

FIG. 4 - GeV and TeV gamma-ray light curves for SN1987A showing result of a full treatment (solid curve) and assuming that all protons entering envelope interact immediately (dashed curve). Fluxes are normalized to a proton luminosity of 10^{39} erg s^{-1}.

The spectrum of cosmic rays convected into the envelope will differ from that produced by shock acceleration due to adiabatic deceleration in the expanding cavity and the finite rate of convection out of the cavity. Harding *et al.* (1990a,b) find that these factors can make a significant difference in the predicted gamma-ray fluxes over previous models, which assumed that the spectrum of interacting protons is the same as the acceleration spectrum. In fact the full diffusion treatment results in a peak gamma-ray flux nearly a factor of ten lower than that predicted by GHS, who did not consider the details of injection into the shell. Also, because the rate of diffusion of the protons in the envelope depends on their energy, the light curves should be energy dependent. Figure 4 shows light curves for SN1987A from a Monte Carlo calculation which models the injection, diffusion and nuclear interactions of protons in the expanding envelope using model 10HMM of Pinto and Woosley (1988). The difference between the TeV and GeV light curves, evident after only a few years, illustrates the necessity of taking account of diffusion and adiabatic deceleration.

Several experiments sensitive in both the TeV (air Cherenkov arrays) and the 100 TeV (air shower arrays) region are operating in the Southern hemisphere and have searched for high energy signals from SN1987A since its discovery. The experiments cover a range of time periods and energies, but none of these experiments has at present reported a continuous signal from the supernova. However, many of the reported flux upper limits (see Harding 1989, for review) are based on measurements taken before the time when the shell is expected to become optically thin. The only signal reported so far is from the JANZOS air shower experiment, which observed a transient flux of photons above 3 TeV on January 14-15, 1988 of $F_\gamma(> 3\mathrm{TeV}) \sim 2 \times 10^{-11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at the 4σ level (Bond *et al.* 1988b).

FIG. 5 - Minimum proton luminosity vs. proton spectral index required for a detectable signal by air shower experiments and by EGRET, using sensitivity limits from Gaisser *et al.* (1989), Ciampa *et al.* (1988), Bond *et al.* (1988a) and Kanbach *et al.* (1988).

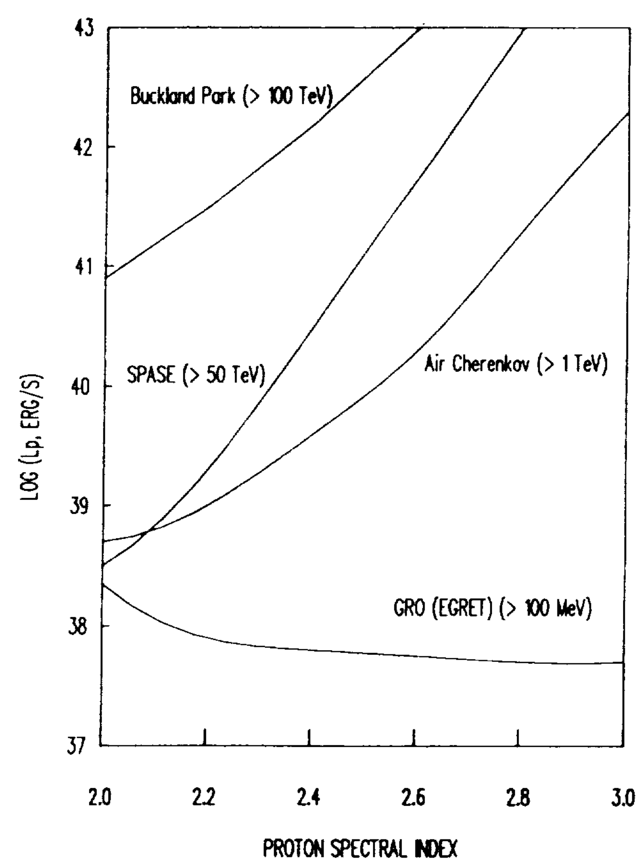

Figure 5 shows the dependence on proton spectral index of the minimum proton luminosity required for detection of a signal by various instruments, using the model of GHS. Because of its high altitude and favorable location (the supernova is always at the same zenith angle of 21^0), the South Pole Air Shower Array (SPASE) has a relatively low threshold, less than 50 TeV. From Figure 5, it is evident that detectors with higher energy thresholds are more sensitive to the proton spectral index. Given the pulsar power limit of 10^{38} erg/s from the bolometric light curve, which may now be levelling off (Bouchet *et al.* 1990), the ground-based air shower detectors will only be able to see a signal from SN1987A if the proton spectral index is near 2. As the proton spectral index increases, more of the power appears at lower γ-ray energies. The EGRET detector is most sensitive around the π^0-decay peak and would detect a γ-ray signal more easily for higher proton spectral indices, but is in fact the most sensitive even for spectral index 2.

If a TeV signal is seen, the accompanying γ-ray flux around 100 MeV should be well above threshold for detection by EGRET, which has a sensitivity level of 5×10^{-8} cm^{-2}s^{-1}. Comparison of the curves in Fig. 5 shows that even if there is no visible TeV signal there could still be a detectable signal around 0.1-1 GeV. This could happen if the proton spectrum cuts off below 10 TeV or if it is too steep to produce an observable signal above 1 TeV. An interesting possibility remains for observing a high luminosity γ-ray signal from SN1987A. Woosley and Chevalier (1989) have suggested that the 0.5 ms observed optical periodicity (Kristian *et al.* 1989) is the rotation period of a central pulsar which has been spun up by accretion of $\approx 0.1 M_\odot$ of the inner envelope that did not reach escape velocity in the explosion. A strong surface magnetic field, temporarily buried by the accreted material, may eventually emerge and the pulsar could turn on with a very high spin-down luminosity.

b) Binary Pulsars

Acceleration of protons at pulsar wind shocks in binary systems may also produce observable VHE and UHE γ-rays through nuclear interactions. If the target material in these systems is provided by the companion star wind or atmosphere, the γ-ray signal would be periodic with the binary orbital period. If the shock is near the companion then the target subtends a relatively large solid angle at the proton source (i.e. the shock). This model therefore can convert accelerated proton luminosity into γ-rays more efficiently than models in which the protons are accelerated at the pulsar. There are a number of known binary sources where acceleration in a pulsar wind shock could be occurring. The binary X-ray source Cygnus X-3 has been reported to be a source of TeV and possibly PeV γ-rays at the 4.8 hr X-ray period. Both accretion and pulsar rotation have been suggested as the power source in this system, but the energy implied by the TeV and PeV γ-rays may favor (and perhaps require) a pulsar. There are also a number of binary systems known to contain spinning-down pulsars. The recent discovery of an eclipsing radio pulsar (Fruchter *et al.* 1988) has generated considerable interest in the interaction of a pulsar wind with a companion star.

The observed parameters of these systems may be used to compute the flux of pion-decay γ-rays expected in the pulsar wind model. The integral photon flux at Earth, averaged over the orbital period of the binary, may be written as

$$\Phi_\gamma(> E_\gamma) = \frac{\Delta\phi_\gamma}{\Delta\Omega\, d^2} \frac{\Delta X}{\lambda} \epsilon_\gamma\, \epsilon_p\, L_d, \tag{14}$$

where $\Delta\Omega$ is the solid angle into which the accelerated protons are emitted, d is the distance to Earth, $\Delta\phi_\gamma$ is the duty cycle which represents the fraction of the orbital period during which photons are emitted toward the observer, ϵ_γ is the gamma-ray production efficiency, ϵ_p is the efficiency for proton acceleration, ΔX is the target thickness and $\lambda \approx 60\,\mathrm{g\,cm^{-2}}$ is the proton interaction length. The factors in this equation have been grouped in this way for comparison with earlier estimates of the relation between the observed signal and luminosity at the source, especially the estimate of Hillas (1984) for Cygnus X-3. In addition, for $E_\gamma > 10^{14}$ eV, absorption of photons in the microwave background due to $\gamma\gamma \rightarrow e^+e^-$ must be accounted for.

TABLE 1
GAMMA-RAY FLUX FROM BINARY PULSARS

PSR	P (ms)	Log(P)	P_b (days)	d (kpc)	L_d (erg/s)	E_p^{max} (TeV)	$\Phi_\gamma(>1\mathrm{TeV})$ ($\mathrm{ph\,cm^{-2}s^{-1}}$)	$\Phi_\gamma(>100\mathrm{MeV})$ ($\mathrm{ph\,cm^{-2}s^{-1}}$)
1913+16	59	-17.1	0.32	4.33	1.6 (33)	50.3	4.5 (-14)	7.3 (-10)
0655+64	195.6	-18.2	1.03	0.27	3.4 (30)	2.35	—	5.9 (-10)
1831–00	520.9	-17	1.81	3.13	2.9 (30)	2.15	—	3.6 (-12)
1855+09	5.4	-19.8	12.33	0.44	4.1 (33)	81.2	1.2 (-11)	1.6 (-7)
2303+46	1066.4	-15.4	12.34	2.0	1.3 (31)	4.64	—	3.7 (-11)
1953+29	6.1	-19.5	117.35	2.92	5.7 (33)	95.6	4.2 (-13)	5.5 (-9)
0820+02	864.9	-16	1232.4	0.79	6.3 (30)	3.18	—	1.2 (-10)
1957+20	1.61	-19.9	0.381	1.0	1.2 (35)	445	8.9 (-11)	8.9 (-7)
1620–26	11.1	-18.1	191.44	2.1	2.4 (34)	195	3.6 (-12)	4.2 (-8)
CYG X–3	12.6	-13.5	0.2	10	6.2 (38)	3 (4)	3.4 (-9)	3.4 (-5)

Table 1 lists the known binary pulsars with some of their observed parameters: pulsar period P, period derivative $\dot{P}$, orbital period P_b and distance d (cf. Dewey *et al.* 1986). Source distances (except for Cyg X-3) were determined from radio pulse dispersion measure, assuming a mean interstellar electron density $\langle n_e \rangle = .03\,\mathrm{cm^{-3}}$. The table also shows the pulsar dipole luminosity from Eqn (1), the maximum energy of protons which could be accelerated at the pulsar wind shock from Eqn (13) and the predicted γ-ray fluxes, Φ_γ, above 1 TeV and 100 MeV. According to Eqn (13), the maximum proton acceleration energy may depend on shock radius in those systems where $r_*/a << 1$. Determination of the shock radius, however, requires knowing what confines the pulsar wind, *i.e.*, companion star wind, atmosphere or magnetosphere. The maximum proton energies listed in the table do not include any geometrical reduction factor, so for some of the sources the actual shock acceleration energy could be much lower. The predicted γ-ray fluxes are calculated from Eqn (14), assuming a thick target ($\Delta X = \lambda$), a proton solid angle $\Delta\Omega = 1$ sr, proton acceleration efficiency $\epsilon_p = 0.5$ and gamma-ray duty cycle $\Delta\phi_\gamma = 1$ (which effectively gives a peak flux). The gamma-ray production efficiency, ϵ_γ, is computed from a convolution of the differential spectrum of accelerated protons, assumed to be a power law with index $\alpha = 2$, with the target density, the production cross section for π^0's and the π^0 decay spectrum (Gaisser 1988, Harding and Gaisser 1990). The bremsstrahlung emission from secondary leptons has been ignored.

The low mass X-ray binary Cygnus X-3 has been observed as a source of TeV and possibly PeV γ-rays at the 4.8 hr X-ray period (see Goodman 1989, for review). The luminosity required in accelerated protons to produce the observed γ-ray flux could be as high as 10^{39} erg/s (Hillas 1984; Nagle, Gaisser and Protheroe 1988), depending on assumptions about the beaming factor and spectrum. Since this power exceeds the Eddington limit for accretion onto a neutron star, it has been suggested that the power source is rotational energy release by a fast pulsar (Bignami *et al.* 1973, Vestrand and Eichler 1982). A period of 12.6 ms in TeV γ-rays has been reported by the Durham group (Chadwick *et al.* 1985). The periodicity, not yet confirmed by other groups (Ramana-Murthy 1989), appears sporadically in the signal and measurements of changes in this period over ≈ 7 years give a period derivative $\dot{P} \approx 3 \times 10^{-14}\,\mathrm{s\,s^{-1}}$ (Turver 1989, priv. comm.). If interpreted as electromagnetic dipole spin-down of a pulsar, these values of P and $\dot{P}$ give a magnetic field strength of 6×10^{11} G and dipole luminosity $6 \times 10^{38}\mathrm{erg\,s^{-1}}$.

Since the shock location and maximum proton acceleration energy depend on the pulsar dipole luminosity, the pulsar period and magnetic field need not be known separately in applying the pulsar wind shock model to the Cyg X-3 system. The maximum proton acceleration energy, $E_p^{\max}$, scales with $L_d^{1/2}$. Assuming the dipole luminosity $L_d = 6 \times 10^{38}\mathrm{erg\,s^{-1}}$ implied by the values of P and $\dot{P}$ observed by Chadwick *et al.* (1985) gives $E_p^{\max} = 3 \times 10^4$ TeV. Because Cygnus X-3 is a close binary, the geometrical factor in Eqn (13) is close to unity. Using the formula in Eqn (14) for two values of proton spectral index α, the predicted flux of $>$ TeV γ-rays from the source is $3.4 \times 10^{-9}\mathrm{ph\,cm^{-2}\,s^{-1}}$ for $\alpha = 2$ and $3.0 \times 10^{-11}\mathrm{ph\,cm^{-2}\,s^{-1}}$ for $\alpha = 2.7$. The predicted flux of > 100 MeV γ-rays is $3.4 \times 10^{-5}\mathrm{ph\,cm^{-2}\,s^{-1}}$ for $\alpha = 2$ and $1.9 \times 10^{-4}\mathrm{ph\,cm^{-2}\,s^{-1}}$ for $\alpha = 2.7$. In order to compare with phase-averaged observed fluxes, the peak flux predictions should be multiplied by the observed 4.8 hr duty cycle, $\Delta\phi_\gamma \approx 0.1$. With the assumptions made, the $\alpha = 2$ TeV flux predicted for Cygnus X-3 is greater than has been observed (Dowthwaite *et al.* 1984). The > 100 MeV fluxes tabulated are consistent with the SAS 2 measurement (SAS 2 is 1.1×10^{-5} above 35 MeV, Lamb *et al.* 1977, Fichtel *et al.* 1987 and earlier references therein), but are somewhat above the upper limit from the COS B observations (Hermsen *et al.*, 1987), which is about 10^{-6} for > 70 MeV photons. The primary reason that the predicted fluxes are high in the pulsar wind acceleration model is because of the much higher efficiency for generating a gamma-ray signal from Cyg X-3 than the Vestrand-Eichler model. Since the accelerator is closer to the target material, a greater fraction of the accelerated protons can interact to produce gamma-rays. Consequently, the fraction of the pulsar spin-down power which is converted to accelerated protons need not be as large. Alternatively, emission from the source may be sporadic at the highest energies.

A number of radio pulsars have been discovered in binary systems and some of these could possibly be observable sources of high energy γ-rays. Since the parameters of the companion star winds are not determined in these systems (in several systems, the companion is probably a neutron star and a wind would not be expected) it was assumed that $r_s << a - r_*$ to calculate E_p^{max}. There are several sources (aside from Cyg X-3) for which the predicted fluxes of > 100 MeV γ-rays are above or near EGRET sensitivity threshold of $5 \times 10^{-8}\,\mathrm{ph\,cm^{-2}s^{-1}}$. Because of the dependence of maximum proton energy on pulsar luminosity, these are also the systems capable of producing γ-rays above 1 TeV. One of these, PSR1957+20, is the eclipsing millisecond pulsar believed to be evaporating its companion by means of an induced wind (Phinney *et al.* 1988, Kluzniak *et al.* 1988, Cheng 1989). If the mass loss from the companion is sufficient to evaporate it in the pulsar's lifetime ($\dot{M} \approx 10^{16}$ g/s), then Eqn (7) gives a shock distance of $r_s/a \approx 0.6$, or a stand-off distance from the companion of $0.4a$, corresponding roughly to the required eclipse radius. Another system, PSR1855+09, contains a 5 ms pulsar and is at a distance of less than 500 pc, giving a predicted flux > 100 MeV which is well above EGRET sensitivity.

Recently, emission at TeV energies has been reported by von Ballmoos *et al.* (1989) and de Jager *et al.* (1989) from these two binary pulsars. Data from PSR1957+20, folded with the 9 hr orbital period, shows a peak in the phase plot at the position of the $L4$ Lagrange point. The reported peak flux above 2 TeV is $1.1 \times 10^{-9}\,\mathrm{photons\,cm^{-2}\,s^{-1}}$, much higher than the predicted flux in Table 1. This difference is due to the small γ-ray solid angle of $\Delta\Omega \approx .009$ derived by von Ballmoos *et al.* (1989) from the width of the phase peak ($\Delta\phi_\gamma = .018$), whereas $\Delta\Omega = 1$ sr was taken to compute the fluxes in Table 1. A peak at the $L4$ position in the orbital phase plot of PSR1957+20 may also have been seen at > 100 MeV in COS-B data (von Ballmoos *et al.* 1989). A TeV signal was also reported by de Jager *et al.* (1989) at the 5.4 ms pulsar period of PSR1855+09 at a marginal significance level. Signals which are observed to be pulsed at the pulsar period, however, must originate from acceleration near or within the pulsar magnetosphere and would not be expected from particles accelerated at the pulsar wind shock.

The currently favored model for the origin of binary systems containing short period pulsars is spin up by an accretion disk (Alpar *et al.* 1982). The accretion spin-up period depends on the neutron star magnetic field, with a spin-up period in the 10 ms range requiring a field around 10^9 Gauss. This evolution model accounts quite well for the observed binary pulsars, which all have low magnetic fields. The high luminosity implied by the observed Cyg X-3 gamma-ray flux requires not only a short period but also a high magnetic field, incompatible with an accretion spin-up evolution. A fast pulsar as the power source in Cyg X-3 would therefore have originated in a relatively recent supernova explosion that occurred within the pulsar spin-down time of 7000 yr. Confined pulsar wind sources of this type would be more rare than the accretion spun-up binary pulsars, which have ages of around 10^8 yr.

V. CONCLUSION

Pulsars are one of the most important sources planned for study by EGRET. Although the primary focus will be the detection of pulsed gamma-ray signals, the possibility of shock acceleration in sources containing pulsars makes the search for steady gamma-rays from young supernovae and gamma-rays pulsed at the orbital period of binary pulsars also worthwhile. Observation of evidence for proton acceleration in supernovae would be very exciting. Although a steady high energy gamma-ray signal has yet to be detected from SN1987A with current ground-based detectors, EGRET may offer the best sensitivity and therefore the best chance for observing a signal from this source. Evidence for proton acceleration in binary systems may already have been observed in the form of > TeV gamma-rays from Cyg X-3 and several other binary X-ray sources.. The current controversy surrounding the existence of a periodic 4.8 hr signal in 100 MeV gamma-rays from Cyg X-3 will hopefully be resolved by EGRET. In addition, several radio pulsars in binary systems appear to be good gamma-ray source candidates. Those with the shortest orbital periods would be the easiest to identify in a limited observing time.

The pulsar wind shock model described here is only one possibility for particle acceleration near pulsars. However, it provides a means for channelling a large fraction of the full rotational energy loss of the pulsar into relativistic particles. If EGRET is able to detect gamma-rays from some of these systems, it may also be possible to identify the peak at 70 MeV which is the signature of pion-decay, indirect evidence for proton acceleration. Furthermore, any indication that efficient particle accelerators exist in binary systems known to contain spinning-down pulsars will help in understanding systems like Cyg X-3, where the source of power is still a mystery.

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DISCUSSION

Volker Schonfelder:

In the gamma-ray spectrum from SN1987, which you showed, there was a gap between the π° - decay component and the electron synchrotron component. Would this gap not be filled by bremsstrahlung of secondary electrons from $\pi^{\pm}$ production?

Alice Harding:

Bremsstrahlung from secondary electrons and positions would be present depending on the strength of the magnetic field and the density in the envelope. In the pulsar wind model, the magnetic field is high enough where the protons interact to make synchrotron radiation dominate the secondary lepton's energy loss.

Mal Ruderman:

Characteristic estimates for e^{-}/e^{+} energies in a pulsar wind suggest TeV (and perhaps more in many cases). Even before reaching a shock boundary these electrons can produce TeV gamma-rays by compton scattering on optical light (or IR) from a nearby companion in close binaries or other sources in SNR's. Has this contribution to TeV gamma-ray emission from pulsar winds been considered?

Alice Harding:

To my knowledge, no one has made a calculation of this contribution.