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# Ultra-High Energy Cosmic Rays from Young Neutron Star Winds

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## ABSTRACT

The long-held notion that the highest-energy cosmic rays are of distant extragalactic origin is challenged by observations that events above  $\sim 10^{20}$  eV do not exhibit the expected high-energy cutoff from photopion production off the cosmic microwave background. We suggest that these unexpected ultra-high-energy events are due to iron nuclei accelerated from young strongly magnetized neutron stars through relativistic MHD winds. We find that neutron stars whose initial spin periods are shorter than  $\sim 4(B_S/10^{13}\text{G})^{1/2}$  ms, where  $B_S$  is the surface magnetic field, can accelerate iron cosmic rays to greater than  $\sim 10^{20}$  eV. These ions can pass through the remnant of the supernova explosion that produced the neutron star without suffering significant spallation reactions. For plausible models of the Galactic magnetic field, the trajectories of the iron ions curve sufficiently to be consistent with the observed arrival directions of the highest energy events.

The detection of cosmic rays with energies above  $10^{20}$  eV has triggered considerable interest on the origin and nature of these particles. Hundreds of events with energies above  $10^{19}$  eV and a hand full of events above  $10^{20}$  eV have now been observed by a number of experiments such as AGASA (Takeda et al. 1998, 1999; Hayashida 1994), Fly's Eye (Bird et al. 1995, 1993, 1994), and Haverah Park (Lawrence, Reid & Watson 1991). Most unexpected is the large flux of events observed above  $5 \times 10^{19}$  eV (Takeda et al.

1998) with no sign of the Greisen-Zatsepin-Kuzmin (GZK) cutoff (Greisen 1966; Zatsepin & Kuzmin 1966). The cutoff should be present if these ultra-high energy particles are protons produced by sources distributed homogeneously throughout the universe. Cosmic ray protons of energy above  $5 \times 10^{19}$  eV lose their energy to photopion production off the cosmic microwave background and cannot originate further than about 50 Mpc away from us. Alternatively, if ultra-high-energy cosmic rays (UHECRs) are protons from sources closer than 50 Mpc, the arrival direction of the events should point toward their source. The present data shows a mostly isotropic distribution and no sign of the local distribution of galaxies or of the Galactic disk above  $10^{19}$  eV (Takeda et al. 1999). In sum, the origin of these particles with energies tens of millions of times greater than any produced in terrestrial particle accelerators, remains a mystery.

In addition to the difficulties with locating plausible sources of UHECRs in our nearby universe, there are great difficulties with finding plausible accelerators for such extremely energetic particles. Acceleration of cosmic rays in astrophysical plasmas occurs when the energy of large-scale macroscopic motion, such as shocks and turbulent flows, is transferred to individual particles. The maximum possible energy,  $E_{\max}$ , is estimated by requiring that the gyro-radius of the particle be contained in the acceleration region (Hillas 1994) and that the acceleration time be smaller than the time for energy losses. The former condition requires that  $E_{\max}$  is associated with the strength of the magnetic field,  $B$ , and the size of the acceleration region,  $L$ , such that  $E_{\max} \sim ZeBL$ , where  $Ze$  is the charge of the particle. For instance, for  $E_{\max} \sim 10^{20}$  eV and  $Z \sim 1$ , the known astrophysical sources with reasonable  $BL$  products are neutron stars ( $B \sim 10^{12}$  G and  $L \sim 10$  km), active galactic nuclei ( $B \sim 10^4$  G and  $L \sim 10$  AU), radio galaxies ( $B \sim 10^{-5}$  G and  $L \sim 10$  kpc), and clusters of galaxies ( $B \sim 10^{-6}$  G and  $L \sim 100$  kpc) (Hillas 1984; Berezhinsky et al. 1990). However, energy losses usually prevent acceleration to  $E_{\max}$ , and no effective mechanism for UHECR acceleration has been shown to explain the observations for any of these objects (Blandford 1999; Bhattacharjee & Sigl 1998; Venkatesan, Miller & Olinto 1997). Here we show that the early evolution of young magnetized neutron stars in our Galaxy may be responsible for the yet unexplained flux of cosmic rays beyond the GZK cutoff. A preliminary study of this idea can be found in (Olinto, Epstein & Blasi 1999).

Neutron stars, born during the supernova explosion of massive stars, may begin their life rotating rapidly ( $\Omega \sim 3000$  rad s $^{-1}$ ) and with large surface magnetic fields ( $B_S \gtrsim 10^{13}$  G). The dipole component of the field decreases as the cube of the distance from the star's surface  $B(r) = B_S(R_S/r)^3$ , where the radius of the star is  $R_S \simeq 10^6$  cm. As the distance from the star increases, the dipole field structure cannot be causally maintained, and beyond the *light cylinder* radius,  $R_{lc} = c/\Omega$ , the field is mostly azimuthal, with field lines spiraling outwards (Michel 1991). For young, rapidly rotating neutron stars, the light cylinder is just

about ten times the star radius,  $R_{lc} = 10^7 \Omega_{3k}^{-1}$  cm, where  $\Omega_{3k} \equiv \Omega/3000$  rad s<sup>-1</sup>.

The surface of young neutron stars is composed of iron peak elements formed during the supernova event. Iron ions can be stripped off the hot surface of a young neutron star due to strong electric fields and be present throughout much of the magnetosphere (Ruderman & Sutherland 1975, Arons & Scharlemann 1979). Inside the light cylinder, the magnetosphere corotates with the star and the iron density has the Goldreich-Julian (Goldreich & Julian 1969) value:

$$n_{GJ}(r) = \frac{B(r)\Omega}{4\pi Zec}, \quad (1)$$

where  $Z$  is the charge of the nuclei in the magnetosphere,  $e$  the electron's charge, and  $c$  the speed of light. In this estimate, and what follows, we do not include the trigonometric factors related to the relative orientation of the magnetic and rotational axes.

The exact fate of the plasma outside the light cylinder is still a subject of debate (Gallant & Arons, 1994; Begelman & Li, 1994; Chiueh, Li, & Begelman, 1998; Melatos & Melrose, 1996). Observations of the Crab Nebula indicate that most of the rotational energy emitted by the Crab pulsar is converted into the kinetic energy of particles in a relativistic wind (Kennel & Coroniti 1994; Begelman 1998; Emmering & Chevalier 1987). This conversion may be due to properties of the MHD flow, related to magnetic reconnection (Coroniti 1990), or a more gradual end of the MHD limit (Melatos & Melrose, 1996). Some analytical and numerical studies show the development of kinetically dominated relativistic winds (see e.g., Begelman and Li, 1994), but at present the theoretical understanding of the wind dynamics is far from complete.

The basic idea of accelerating plasma by the Poynting flux was proposed by Weber and Davis (1967) (then called *magnetic slingshot*). Later, Michel(1969) showed that for a perfectly spherical flow the complete conversion of the magnetic energy into kinetic energy of the flow could not be achieved due to the cancellation of the toroidal magnetic pressure and the tension force. However, Begelman and Li (1994) reconsidered the problem and showed that even small deviations from a spherical flow could imply an efficient conversion of the magnetic energy into kinetic energy of the wind. They found that the point where the wind becomes supermagnetosonic is not at infinity but at a few times the light cylinder radius. In this case, the conversion of most of the Poynting flux to kinetic energy of the flow could be obtained through the so-called magnetic nozzle effect, provided the magnetic field lines have the right geometry.

In the present study we assume that, at least for some neutron stars most of the magnetic energy in the wind zone is converted into the flow kinetic energy of the particles in the wind and that the rest mass density of the regions of the wind containing iron ions

are not dominated by electron-positron pairs; that is, the electron-positron density is less than  $\sim 10^5$  times that of the iron ions. With these assumptions, the magnetic field in the wind zone decreases as  $B(r) \lesssim B_{lc} R_{lc}/r$ . For surface fields of  $B_S \equiv 10^{13} B_{13}$  G, the field at the light cylinder is  $B_{lc} = 10^{10} B_{13} \Omega_{3k}^3$  G. The maximum energy of particles that can be contained in the wind near the light cylinder is

$$E_{max} = \frac{ZeB_{lc}R_{lc}}{c} \simeq 8 \times 10^{20} Z_{26} B_{13} \Omega_{3k}^2 \text{ eV} , \quad (2)$$

where  $Z_{26} \equiv Z/26$ . In the rest frame of the wind, the plasma is relatively cold while in the star's rest frame the plasma moves with Lorentz factors  $\sim 10^9 - 10^{10}$ .

The typical energy of the accelerated cosmic rays,  $E_{cr}$ , can be estimated by considering the magnetic energy per ion at the light cylinder  $E_{cr} \simeq B_{lc}^2/8\pi n_{GJ}$ . At the light cylinder  $n_{GJ} = 1.7 \times 10^{11} B_{13} \Omega_{3k}^4/Z \text{ cm}^{-3}$  which gives

$$E_{cr} \simeq 4 \times 10^{20} Z_{26} B_{13} \Omega_{3k}^2 \text{ eV} , \quad (3)$$

similar to  $E_{max}$  above (Gallant & Arons 1994; Begelman 1994).

The spectrum of accelerated UHECRs is determined by the evolution of the rotational frequency: As the star spins down, the energy of the cosmic ray particles ejected with the wind decreases. The total fluence of UHECRs between energy  $E$  and  $E + dE$  is

$$N(E)dE = \frac{\dot{\mathcal{N}}}{\dot{\Omega}} \frac{d\Omega}{dE} dE , \quad (4)$$

where the particle luminosity is

$$\dot{\mathcal{N}} = \xi n_{GJ} \pi R_{lc}^2 c = 6 \times 10^{34} \xi \frac{B_{13} \Omega_{3k}^2}{Z_{26}} \text{ s}^{-1} \quad (5)$$

and  $\xi < 1$  is the efficiency for accelerating particles at the light cylinder. The rotation speed decreases due to electromagnetic and gravitational radiation (Lindblom, Owen & Morsink 1998; Andersson, Kokkotas & Schutz 1999). For  $B_S \gtrsim 10^{13}$  G, r-mode gravitational radiation is likely suppressed (Rezzolla, Lamb & Shapiro 1999) and the spin down will be dominated by magnetic dipole radiation given by:

$$I\Omega\dot{\Omega} = -\frac{B_S^2 R_S^6 \Omega^4}{6c^3} . \quad (6)$$

For a moment of inertia  $I = 10^{45} \text{ g cm}^2$ , the time derivative of the spin frequency is,  $\dot{\Omega} = 1.7 \times 10^{-5} B_{13}^2 \Omega_{3k}^3 \text{ s}^{-1}$ , and Eq. (3) gives

$$\frac{dE}{d\Omega} = 1.7 \times 10^{-3} \frac{E}{\Omega_{3k}} . \quad (7)$$

Substituting in Eq. (4), the particle spectrum from each neutron star is

$$N(E) = \xi \frac{5.5 \times 10^{31}}{B_{13} E_{20} Z_{26}} \text{GeV}^{-1} , \quad (8)$$

where  $E = 10^{20} E_{20} \text{ eV}$ .

Neutron stars are produced in our Galaxy at a rate  $1/\tau$ , where  $\tau \equiv 100 \tau_2 \text{ yr}$ , and a fraction  $\epsilon$  of them have the required magnetic fields and initial spin rates to produce UHECRs as well as the right magnetic field geometry to allow efficient conversion of magnetic energy into kinetic energy of the flow. As discussed below, the UHECR ion nuclei scatter or diffuse in the Galactic magnetic field. Taking the confining volume for these particles to be  $V_c$  and the lifetime for confinement to be  $t_c$ , the UHECR density is  $n(E) = \epsilon N(E) t_c / \tau V_c$ , and the flux at the surface of the Earth is  $F(E) = n(E) c / 4$ . For a characteristic confinement dimension of  $R = 10 R_1 \text{ kpc}$  we can write  $V_c = 4\pi R^3 / 3$  and  $t_c = QR/c$ , where  $Q > 1$  is a measure of the how well the UHECR are trapped. The predicted UHECR flux at the Earth is

$$F(E) = 10^{-24} \frac{\xi \epsilon Q}{\tau_2 R_1^2 B_{13} E_{20} Z_{26}} \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} . \quad (9)$$

By comparing with observations, we can estimate the required efficiency factor,  $\xi \epsilon$ . The AGASA experiment finds that the flux at  $10^{20} \text{ eV}$  at Earth is  $F(E) = 4 \times 10^{-30} \text{ GeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$ . Equating this flux with the estimate of Eq. (9), we find that the efficiency factor only needs to be  $\xi \epsilon \gtrsim 4 \times 10^{-6} Q^{-1}$ . The smallness of the required efficiency suggests that young, Galactic neutron stars can be the source of UHECRs even if only a small fraction of stars are born with very rapid spin frequencies and high magnetic fields.

The energy spectrum of cosmic rays below the expected GZK cutoff (i.e., between  $\sim 10^8 \text{ eV}$  and  $\lesssim 10^{19} \text{ eV}$ ) has a steep energy dependence  $N(E) \propto E^{-\gamma}$ , with  $\gamma \approx 2.7$  for  $E \lesssim 10^{15} \text{ eV}$  and  $\gamma \approx 3.1$  for  $10^{15} \lesssim E(\text{eV}) \lesssim 10^{19}$  (Gaisser 1990). The events with energy above  $10^{19.5} \text{ eV}$ , however, show a much flatter spectrum with  $1 \lesssim \gamma \lesssim 2$ ; the drastic change in slope suggests the emergence of a new component of cosmic rays at ultra-high energies which we suggest originates in relativistic winds from young neutron stars. The predicted spectrum of Eq. (9) is very flat,  $\gamma = 1$ , which agrees with the the lower end of the plausible range of  $\gamma$  observed at ultra-high energies. Propagation effects can produce an energy dependence of the confinement parameter  $Q$  and, correspondingly, a steepening of the spectrum toward the middle of the observed range  $1 \lesssim \gamma \lesssim 2$ .

Even though a young neutron star is usually surrounded by the remnant of the presupernova star, the accelerated particles can escape the supernova remnant without

significant degradation for a wide range of initial magnetic fields and spinning rates. The supernova event that formed the young neutron star ejects the envelope of the original star, making it possible for cosmic rays to escape. However, as the envelope expands, the young neutron star spins down and may become unable to emit particles of the necessary energy. A requirement for relativistic winds to supply UHECRs is that the column density of the envelope becomes transparent to UHECR iron nuclei before the spinning rate of the neutron star decreases significantly.

To estimate the evolution of the column density of the envelope, consider a supernova that imparts  $E_{SN} = 10^{51} \mathcal{E}_{51}$  erg to the stellar envelope of mass  $M_{env} = 10 M_1 M_\odot$ . The envelope then disperses with a velocity  $v_e \simeq (2E_{SN}/M_{env})^{1/2} = 3 \times 10^8 (\mathcal{E}_{51}/M_1)^{1/2}$  cm s<sup>-1</sup>. The column density of the envelope surrounding the neutron star is  $\Sigma \simeq M_{env}/4\pi R_{eff}^2$  where  $R_{eff} = R_0 + v_e t$ , where  $R_0$  is the characteristic radius of the presupernova star,  $R_0 \lesssim 10^{14}$  cm. We now have

$$\Sigma \simeq \frac{M_{env}}{4\pi [R_0 + v_e t]^2} = 1.6 \times 10^{16} \frac{M_1^2 \mathcal{E}_{51}^{-1}}{t^2 (1 + t_e/t)^2} \text{ g cm}^{-2}, \quad (10)$$

where  $t$  is in seconds, and  $t_e = R_0/v_e \lesssim 3 \times 10^5 (M_1/\mathcal{E}_{51})^{1/2}$  s. The condition for iron nuclei to traverse the supernova envelope without significant losses is that  $\Sigma \lesssim 100$  g cm<sup>-2</sup>. This “transparency” occurs at times  $t > t_{tr} = 1.3 \times 10^7 M_1 \mathcal{E}_{51}^{-1/2}$  s  $\gg t_e$ .

As the envelope is being ejected, the neutron star spin is slowing due to the magnetic dipole radiation, Eq. (6), so that

$$\Omega_{3k}^2(t) = \frac{\Omega_{i3k}^2}{[1 + t_8 B_{13}^2 \Omega_{i3k}^2]}, \quad (11)$$

where  $3000 \Omega_{i3k}$  rad s<sup>-1</sup> is initial spin rate and  $t_8 = t/10^8$  s. The cosmic ray energy thus evolves according to

$$E_{cr}(t) = 4 \times 10^{20} \text{ eV} \frac{Z_{26} B_{13} \Omega_{i3k}^2}{[1 + t_8 B_{13}^2 \Omega_{i3k}^2]}. \quad (12)$$

The condition that a young neutron star could produce the UHECRs is that  $E_{cr}$  exceeds the needed energy when the envelope becomes transparent; i.e.,  $E_{cr}(t_{tr}) > 10^{20} E_{20}$  eV. This translates into the following condition:

$$\Omega_i > \frac{3000 \text{ s}^{-1}}{B_{13}^{1/2} [4Z_{26} E_{20}^{-1} - 0.13 M_1 B_{13} \mathcal{E}_{51}^{-1/2}]^{1/2}}. \quad (13)$$

From this equation we obtain upper bounds on the surface magnetic field strength and the star’s initial spin period,  $P_i = 2\pi/\Omega_i$ ; i.e.,  $B_{13} < 31 Z_{26} \mathcal{E}_{51}^{1/2}/M_1 E_{20}$  and



$P_i < 8\pi B_{13}^{1/2} Z_{26} E_{20}^{-1} / 3000$  s. For  $M_1 = 2$  and  $E_{20} = \mathcal{E}_{51} = Z_{26} = 1$ , this is just  $B_{13} < 15.4$  and  $P_i \lesssim 10$ ms, not very restrictive values for a young neutron star. The allowed regions in the  $B_S$ - $\Omega_i$  plane are shown in Figure 1 for  $E_{20} = 1$  and 3 and  $M_{env} = 5$  and  $50 M_\odot$ .

For the parameters within the allowed region, the acceleration and survival of UHECR iron nuclei is not significantly affected by the ambient photon radiation. The most important source of radiation in the wind region is the thermal emission from the star’s surface. In the time needed for the envelope to become transparent, the surface cools to  $\sim 3 \times 10^6$  K (Tsuruta 1998). For these temperatures, photodissociation (see, e.g., Protheroe, Bednarek & Luo 1998) and Compton drag have minor effects on the energy and composition of the accelerating iron nuclei. Furthermore, synchrotron losses are unimportant because the plasma is essentially cold in the rest frame of the accelerating plasma.

The relativistic MHD wind from a rapidly spinning neutron star may impart more energy to the supernova remnant than the initial explosion. For initial spin rates  $\gtrsim 1000$  rad  $s^{-1}$ , the rotational energy is  $\gtrsim 10^{51}$  erg, comparable to the kinetic energy of most supernova remnants. Some of the more rapidly spinning neutron stars discussed here may generate highly-energetic supernova events, possibly similar to SN 1998bw (Kulkarni 1998). In this case, the right boundary of the allowed region in Figure 1 should be enlarged because the remnant expands more rapidly than assumed above.

The iron ejected with energies  $\sim 10^{20}$  eV will reach Earth after some diffusion through the Galactic and halo magnetic fields (Zirakashvili, Pochevkin, Ptuskin & Rogovaya 1998). The gyroradius of these UHECRs in the Galactic field of strength  $B_{gal}$  is

$$r_B = \frac{E_{cr}}{ZeB} = \frac{1.4}{Z_{26}} \left( \frac{3\mu\text{G}}{B_{gal}} \right) E_{20} \text{ kpc} \quad (14)$$

which is considerably less than the typical distance to a young neutron star ( $\sim 8$  kpc). Therefore, ultra-high energy iron arriving at the Earth would not point at the source. A Galactic iron source is consistent with an approximately isotropic arrival direction distribution as observed by AGASA for UHECRs (Zirakashvili et al. 1998). In support of this interpretation, we note that the cosmic ray component at  $10^{18}$  eV is nearly isotropic and only after more than  $10^5$  events were observed the distribution shows a slight correlation with the Galactic disk and spiral arms (Hayashida et al. 1999). If these cosmic rays are protons of Galactic origin, the isotropic distribution observed at these energies is indicative of the diffusive effect of the Galactic and halo magnetic fields. The iron arrival distribution at  $10^{20}$  eV probes similar trajectories to protons at a few times  $10^{18}$  eV and should show a similar arrival direction distribution. Therefore, we expect the iron at  $10^{20}$  eV to show a nearly isotropic distribution with a slight correlation with the Galactic center and disk. This correlation should become apparent if the number of observed events grow by orders

of magnitude or if events with energies higher than the present highest energies events are detected. Although some indication of a correlation with the Galactic center for events above  $10^{20}$  eV has been recently reported (Stanev & Hillas 1999), the small number of observed events limits the significance of this finding.

In conclusion, we propose that ultra-high-energy cosmic ray events originate from iron nuclei accelerated by young, strongly magnetic, Galactic neutron stars. Iron from the surface of newborn neutron stars are accelerated to ultra-high energies by a relativistic MHD wind. Neutron stars whose initial spin periods are shorter than  $\sim 4(B_S/10^{13}\text{G})^{1/2}$  ms can accelerate iron ions to greater than  $10^{20}eV$ . These ions can pass through the radiation field near the neutron star and the remnant of the supernova explosion that produced the neutron star without suffering significant deceleration or spallation reactions.

The best test of this proposal is a unambiguous composition determination and a correlation of arrival directions for events with energies above  $10^{20}$  eV with the Galactic center and disk. Both aspects will be well tested by future experiments such as the Auger Project (Cronin 1999) and OWL-Airwatch (Ormes et al., 1997).

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**Figure caption**

Fig. 1

Parameter space for which acceleration and escape of the accelerated particles through the ejecta are allowed. The solid lines refer to particle energy  $E_{cr} = 10^{20}$  eV and dashed lines to  $E_{cr} = 3 \times 10^{20}$  eV. The curves are plotted for two values of the envelope mass,  $M_{env} = 50 M_{solar}$  and  $M_{env} = 5 M_{solar}$ , as indicated. The horizontal line at spin period  $\sim 0.3$  ms indicates the minimum period (maximum angular speed) allowed for neutron stars (Haensel, Lasota & Zdunik 1999) .

