

Galactic Ultra-High-Energy Cosmic Rays

A.V. Olinto¹, R.I. Epstein², and P. Blasi¹

¹*Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637, USA*

²*NIS-2, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*

Abstract

The absence of the expected GZK cutoff strongly challenges the notion that the highest-energy cosmic rays are of distant extragalactic origin. We discuss the possibility that these ultra-high-energy events originate in our Galaxy and propose that they may be due to iron nuclei accelerated from young, strongly magnetic neutron stars. Newly formed pulsars accelerate ions from their surface through relativistic MHD winds. We find that pulsars whose initial spin periods are shorter than $\sim 4(B_S/10^{13}\text{ G})$ ms, where B_S is the surface magnetic field, can accelerate iron ions to greater than 10^{20} eV . These ions can pass through the remnant of the supernova explosion that produced the pulsar without suffering significant spallation reactions. Depending on the structure of the galactic magnetic field, the trajectories of the iron ions from galactic sources can be consistent with the observed arrival directions of the highest energy events.

1 Introduction:

The detection by AGASA (Hayashida 1994; Takeda et al. 1998, 1999), Fly's Eye (Bird et al. 1995, 1994, 1993), and Haverah Park (Lawrence, Reid & Watson 1971) of cosmic ray events with energies above the expected Greisen-Zatsepin-Kuzmin (GZK) cutoff (Greisen 1966; Zatsepin & Kuzmin 1966) has triggered considerable interest (see e.g. Cronin 1999; Bhattacharjee & Sigl 1999 for recent reviews). The cutoff should be present if the ultra-high energy particles are protons from extragalactic sources. Cosmic ray protons of energies above 5×10^{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 directions 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 (Takeda et al. 1998). In sum, the origin of these ultra-high energy particles remains a mystery. Here we discuss how the early evolution of young pulsars may be responsible for the yet unexplained flux of cosmic rays beyond the GZK cutoff (Blasi, Epstein, & Olinto 1999).

2 UHECRs from Newborn Pulsars:

When neutron stars are born during the collapse of supermassive stars, they begin their life with very fast rotation ($\Omega \sim 3000\text{s}^{-1}$) and very large magnetic fields (on the star's surface $B_S \gtrsim 10^{13}$ G). Inside the light cylinder (i.e. $r \lesssim R_{lc}$ where $R_{lc} = c/\Omega$) a magnetosphere corotates with a dipole magnetic field component that scales as $B(r) = B_S(R_S/r)^3$ where the radius of the star $R_S \simeq 10^6$ cm. The magnetosphere has a density (Goldreich & Julian) $n_{GJ}(r) \simeq B(r)\Omega/4\pi Zec$, where Z is the charge of the magnetospheric nucleus, e the electric charge and c the speed of light. As the distance from the star increases, the dipole field structure cannot be maintained and beyond the *light cylinder* the field is mostly azimuthal. 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 $\Omega_{3k} \equiv \Omega/3000\text{ s}^{-1}$).

Iron nuclei stripped by strong electric fields from the surface of the neutron star, fill much of the magnetosphere. From the light cylinder, a relativistic plasma expands as a magnetohydrodynamic (MHD) wind (Gallant & Arons 1994). The field strength ($B \propto r^{-1}$) and geometry in this region are such that the plasma moves relativistically with Alfvén speed close to the speed of light. In the rest frame of the wind, the plasma is relatively cold while in the star's rest frame the plasma moves with $\gamma \sim 10^9 - 10^{10}$.

The typical energy of the accelerated cosmic rays can be estimated by considering the magnetic energy per ion at the light cylinder $E_{cr} = B_{lc}^2/8\pi n_{GJ}$. At the light cylinder the magnetic field strength is $B_{lc} =$

$10^{10} \text{ G } B_{13} \Omega_{3k}^3$ and $n_{GJ} = 1.7 \times 10^{11} \text{ cm}^{-3} B_{13} \Omega_{3k}^4 / Z$ which gives

$$E_{cr} = 4 \times 10^{20} \text{ eV } Z_{26} B_{13} \Omega_{3k}^2, \quad (1)$$

where $Z \equiv 26 Z_{26}$ and $B_S \equiv 10^{13} \text{ G } B_{13}$. The spectrum of accelerated UHECRs is determined by the evolution of the rotational frequency: As the neutron star ages, the rotation speed decreases due to electromagnetic and gravitational radiation. For initial periods of $\gtrsim 1 \text{ ms}$ and $B_S \gtrsim 10^{13} \text{ G}$, the spin down is dominated by magnetic dipole radiation given by: $I \dot{\Omega} = -B_S^2 R_S^6 \Omega^4 / 6c^3$.

For a moment of inertia $I = 10^{45} \text{ g cm}^2$, the star's spin down time is $t_{sd} \equiv \Omega / \dot{\Omega} \sim 1.8 \times 10^8 \text{ s } B_{13}^{-2} \Omega_{3k}^{-2}$, and the spectrum can be found to be (Blasi, Epstein, & Olinto 1999):

$$N(E) dE = \frac{\dot{Q}}{\dot{\Omega}} \frac{d\Omega}{dE} dE = \frac{\xi 5.5 \cdot 10^{31}}{B_{13} E_{20} Z_{26}} \text{ GeV}^{-1}. \quad (2)$$

The particle flux is thus $\dot{Q} = \xi n_{GJ} \pi R_{lc}^2 c = \xi \frac{B_{13} \Omega_{3k}^2}{Z_{26}} 6 \times 10^{34} \text{ s}^{-1}$ where $\xi < 1$ is the efficiency for accelerating particles at the light cylinder. The energy as a function of spin frequency in Eq.(1) gives $dE/d\Omega = 1.7 \times 10^{-3} E / \Omega_{3k}$.

Young neutron stars are most likely distributed in the Galactic disk at typical distances $\sim 8 \text{ kpc}$. If they are produced at a rate $1/\tau$ where $\tau = 100 \tau_2 \text{ yr}$, the flux of particles on Earth is

$$F(E) = \frac{N(E)}{\pi R^2 \tau} = \frac{\xi 10^{-23}}{\tau_2 B_{13} E_{20} Z_{26}} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}. \quad (3)$$

Assuming an isotropic distribution of the arrival directions, the AGASA experiment finds a flux at 10^{20} eV of $F(10^{20} \text{ eV}) = 4 \times 10^{-30} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$. Therefore, the efficiency need only be $\xi \gtrsim 4 \times 10^{-7}$. Furthermore, the spectrum derived above is very flat, $N(E) \propto E^{-1}$, another property in good agreement with the data.

Even though the young neutron stars are surrounded by the remnants of the presupernova star, the accelerated particles can easily 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 also ejected 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. Thus, an additional requirement for this scenario is that the column density of the envelope becomes transparent 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 $E_{SN} = 10^{51} E_{51} \text{ erg}$ on the stellar envelope of mass $M_{env} = 10 M_1 M_\odot$. The envelope then disperses with a velocity $v_e \simeq (2E_{SN}/M_{env})^{1/2} = 3 \times 10^8 (E_{51}/M_1)^{1/2} \text{ cm s}^{-1}$. The column density of the envelope surrounding the neutron star is $\Sigma \simeq M_{env}/4\pi R_{eff}^2$ where $R_{eff} = R_0 + v_e t$. The initial value R_0 is characteristic of pre-supernova stars and $R_0 \sim 10^{13} \text{ cm } R_{13}$. We now have

$$\Sigma \simeq \frac{M_{env}}{4\pi [R_0 + v_e t]^2} = 1.6 \times 10^{14} \text{ g cm}^{-2} \frac{M_1^2 E_{51}^{-1}}{t^2 (1 + t_e/t)^2},$$

where t is in seconds, and $t_e = R_0/v_e = 3 \times 10^4 R_{13} \sqrt{M_1/E_{51}} \text{ s}$. The condition for iron nuclei to traverse the supernova envelope without significant losses is that $\Sigma < \Sigma_t \simeq 100 \text{ g cm}^{-2}$. At late times compared to t_e , this ‘‘transparency’’ condition gives $t > t_{tr} = 1.3 \times 10^7 M_1 E_{51}^{-1/2} \text{ s}$.

At the same time, the neutron star loses energy at a rate given by dipole radiation whose solution is

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

where Ω_{i3k} is the initial spin period and $t_8 = t/10^8$ s. The evolution of the maximum energy is thus given by

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

Since the maximum energy decreases as the source evolves, the condition that a source 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:

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

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., $B_{13} < 31Z_{26} E_{51}^{1/2}/M_1 E_{20}$ and $P_i < 8\pi B_{13}^{1/2} Z_{26} E_{20}^{-1}$. For $M_1 = 2$ and $E_{20} = E_{51} = Z_{26} = 1$, 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 - Ω_i plane are shown in Figure 1 for $E_{20} = 1$ and 3. The iron ejected with energies $\sim 10^{20}$ eV will reach Earth after some diffusion through the Galactic and halo magnetic fields. The gyroradius of these UHECRs in the Galactic field of strength B_{gal} is

$$r_B = \frac{E_{cr}}{ZeB} = 1.4 \text{ kpc} Z_{26}^{-1} \left(\frac{B_{gal}}{3\mu\text{G}} \right)^{-1} E_{20}$$

which is a few times the typical distance to a young neutron star (~ 8 kpc). Therefore, the ultra-high energy iron arriving at the Earth would not point at the source. According to Zirakashvili et al. (1998), a Galactic iron source is consistent with the arrival direction distribution observed by AGASA for UHECRs.

In support of this interpretation, we note that the cosmic ray component at 10^{18} eV is nearly isotropic. If these cosmic rays are protons of galactic origin, the isotropic distribution observed at these energies may be 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. Depending on the exact strength and structure of the magnetic field in the Galaxy and the halo of the Galaxy, the ultra-high energy iron may retain some memory of the source direction. As the data improves at the highest energies a preference for the galactic plane should become evident. In addition, the relativistic wind may also accelerate some lighter nuclei that can help constrain the scenario and the structure of the Galactic and halo magnetic fields.

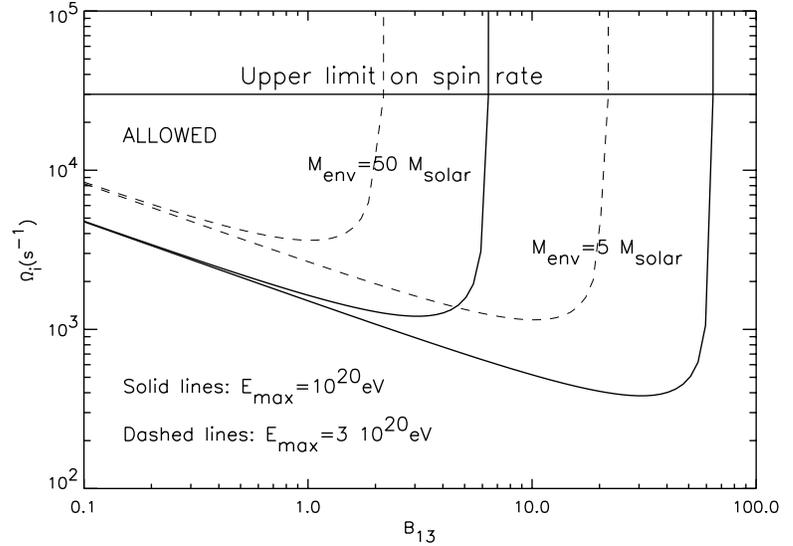


Figure 1: Allowed region of parameters for efficient acceleration.

3 Conclusion

We have discussed the possibility that the ultra-high-energy events observed past the GZK cutoff originate in our Galaxy and are due to iron nuclei accelerated from young, strongly magnetic neutron stars. Iron from

the surface of newborn neutron stars are accelerated to ultra-high energies by a relativistic MHD wind. Pulsars whose initial spin periods are shorter than $\sim 4(B_S/10^{13} \text{ G})$ ms can accelerate iron ions to greater than 10^{20} eV . These ions can pass through the remnant of the supernova explosion that produced the pulsar without suffering significant spallation reactions.

This proposal can be tested by future experiments such as the Auger Project. 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 . Both aspects will be testable with future experiments. Finally, a detailed study of the lighter element components expected to reach us from this process will also help constrain this scenario.

Acknowledgments

The research was partly supported by NSF through grant AST 94-20759 and DOE grant DE-FG0291 ER40606 at the University of Chicago and partly carried out under the auspices of the U.S. Department of Energy with support by IGPP at LANL.

References

- Bird, D.J. et al., Phys. Rev. Lett. 1993, 71 3401; ApJ 1994, 424, 491; ApJ 1995, 441, 144
Bhattacharjee, P., & Sigl, G. 1999, Phys. Repts. submitted, astro-ph/9811011
Blasi, P., Epstein, R.I., & Olinto, A.V., 1999, to be submitted
Cronin, J.W., Rev. Mod. Phys. 1999, 71, S165
Gallant, Y.A., & Arons, J. 1994, ApJ 435, 230
Greisen, K., Phys. Rev. Lett. 1966, 16, 748
Hayashida, N., Phys. Rev. Lett. 1994, 73, 3491
Lawrence, M.A., Reid, R.J.O. & Watson, A.A., J. Phys. G Nucl. Part. Phys. 1991, 17, 733
Takeda, M. et al., Phys. Rev. Lett. 1998, 81, 1163; *ibid*, 1999, astro-ph/9902239, submitted to Astrophys. J.
Zatsepin, G.T., & Kuzmin, V.A., Sov. Phys.-JETP Lett. 1966, 4, 78
Zirakashvili, V.N., Pocheikin, D.N., Ptuskin, V.S., & Rogovaya, S.I., Astron. Lett. 1998, 24, 139