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Ultra-high energy cosmic ray acceleration by accretion-induced collapse pulsars in the local universe

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Abstract. We discuss the possibility that the ultra-high energy cosmic rays (UHECRs) observed above the GZK limit could be mostly protons accelerated in magnetic reconnection sites just above the magnetosphere of newborn millisecond pulsars originated by accretion-induced-collapse (AIC-pulsars). We find that the observed total flux of UHECRs can be produced by the integrated contribution from all AIC-pulsars of the local distribution of galaxies within a distance which is unaffected by the GZK cutoff (< 50 Mpc) (de Gouveia Dal Pino & Lazarian 2000). We also examine the potential acceleration mechanisms in the reconnection site and find that first-order Fermi acceleration cannot provide either sufficient efficiency (due to synchrotron losses) or the expected spectral index for the UHECR particle spectrum. This leaves the one-shot acceleration via an induced electric field within the reconnection region as the only viable process for UHECR acceleration. We find that AIC-pulsars with surface magnetic fields $10^{12} - 10^{15}$ G, and spin periods $\sim 1 - 60$ ms, are able to accelerate particles to energies $> 10^{20}$ eV, but the magnetic field just above the Alfvén surface must be predominantly toroidal for the particles to be allowed to escape from the acceleration zone without being deflected. Synchrotron losses impose important constraints on the magnetic field topology of any UHECR accelerators involving compact sources with strong magnetic fields.

1 Introduction

The origin and nature of the observed ultra-high energy cosmic rays (UHECR) with energies beyond 10^{20}eV remains a mystery. If they are mostly protons, they should be affected by the expected GZK energy cutoff ($\sim 5 \times 10^{19}$ eV), due to photo-pion production by interactions with the cosmic microwave background radiation, unless they are originated at distances closer than about 50 Mpc (e.g., Medina Tanco, de Gouveia Dal Pino & Horvath 1997). On the other hand, as protons from nearby sources (located within $\sim$ 50 Mpc), they should be little deflected by the intergalactic and Galactic magnetic fields and point toward their sources (e.g., Medina Tanco, de Gouveia Dal Pino & Horvath 1998). The present data although statistically modest, seem to indicate an extragalactic origin for the UHECR events as there is no significant large-scale anisotropy related to the Galactic disk, halo, or the local distribution of galaxies, although some clusters of events seem to point to the supergalactic plane (Takeda et al. 1999).

Several source candidates and acceleration mechanisms have been invoked to explain these UHECR events, but all of them have their limitations (see, e.g., Protheroe 1999, Blandford 2000, and Olinto 2000, 2001, for reviews). Among the potential $Zevatrons$ (or UHECR accelerators), unipolar inductors, like millisecond pulsars with very strong magnetic fields (B $> 10^{12}$ G), appear as an attractive possibility. Particles can, in principle, extract the required energies from an induced e.m.f. across the few open field lines of a rapidly rotating pulsar, but a large electric field parallel to the magnetic field can be easily shorted by electron-positron pairs, or alternatively, the accelerated particles may lose most of their energy gain by curvature radiation while dragged along by the magnetic dipole field. To overcome these difficulties imposed by acceleration in regions located close to the surface of a pulsar, in a recent work (de Gouveia Dal Pino & Lazarian 2000, hereafter Paper I), we have speculated that UHECRs could be mostly protons accelerated in magnetic reconnection sites $outside$ the magnetosphere of newborn millisecond pulsars produced by accretion induced collapse (AIC) of a white dwarf (see Fig. 1). The accretion flow spins up the star and confines the magnetosphere to a radius R_X where both plasma stress in the accretion disk, and magnetic stress balance. At this radius, which also defines the inner radius of the accretion disk, the equatorial flow diverts into a funnel inflow along the closed field-lines toward the star, and a centrifugally driven wind outflow. To mediate the geometry of dipole-like field lines of the star with those opened by

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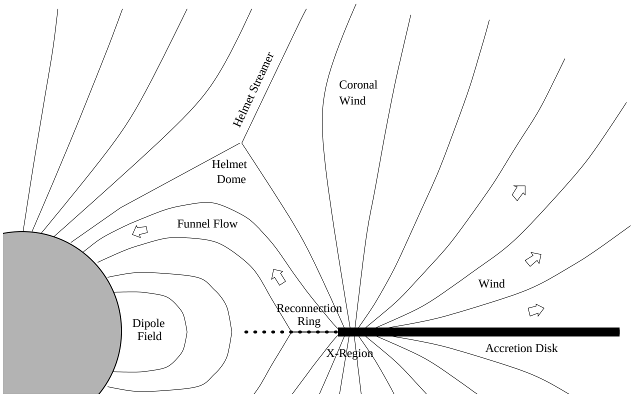

Fig. 1. Schematic representation of the magnetic field geometry and the gas accretion flow in the inner disk edge at R_X. UHECRs are accelerated in the magnetic reconnection site at the helmet streamer (extracted from Paper I).

the wind and those trapped by the funnel inflow emanating from the R_X region, a surface of null poloidal field lines is required, which is is labeled as "$helmet\ streamer$" in Fig. 1. Across the null surface, the poloidal field suffers a sharp reversal of direction. According to the Ampère's law, large electric currents must flow out of the plane shown in Fig. 1, along the null surfaces, and in the presence of finite electric resistivity, dissipation of these currents will lead to reconnection of the oppositely directed field lines (e.g., Lazarian & Vishniac 1999). The magnetic energy released by reconnection in the helmet streamer drives violent outward motions in the surrounding plasma that may accelerate copious amounts of cosmic rays. Let us investigate the potential acceleration mechanisms in the reconnection site.

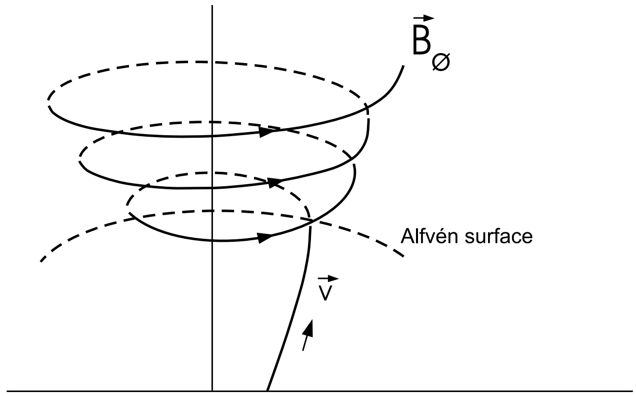

Fig. 2. Development of a toroidal field, B_ϕ, from the winding up of a poloidal line, (B_p), above the Alfvén surface.

2 Acceleration in the Reconnection Region

On regions of strong magnetic fields, like those around pulsars, fast reconnection (with $v_{rec} \sim v_A$, where v_A is the Alfvén velocity) is ensured by the presence of an anomalous resistivity. Following Lazarian & Vishniac (1999), we can estimate the width of the reconnection site for which the resisitivity should be anomalous, $\delta \simeq 10^9\,\mathrm{cm}\,\Omega_{2.5k}^{-1} u_9^{-1}$, where u_9 is the thermal velocity in units of 10^9 cm s^{-1}, and $\Omega_{2.5k} = \Omega_\star / 2.5 \times 10^3$ s^{-1}, with $\Omega_\star$ being the angular speed at the stellar surface. This value of $\delta \simeq 10^9$ cm is more than appropriate to produce fast reconnection through anomalous resistivity over the entire region since $\delta >> R_X$ (see below). Therefore, whatever processes are invoked to accelerate the particles, it is realistic to assume that the reconnection velocity is an appreciable fraction of the local Alfvén velocity which approaches c in the conditions we deal with. Any limitations on the efficiency at which acceleration may occur will then come solely from the way by which particles will manage to escape from the strong magnetic fields around the pulsar.

2.1 First-Order Fermi Acceleration

In this case, the acceleration process is analogous to the first-order Fermi acceleration of cosmic rays in magnetized shocks. At the reconnection region of Fig. 1 (see the helmet streamer), the left and right parts of the magnetic flux move towards each other with the velocity v_{rec}. As a result, charged particles in the left side of the reconnection zone "see" the right part of the magnetic flux to approach them with a velocity $2v_{rec}$, and it is easy to show that for a particle probability distribution $p(\theta) = 2\sin\theta\cos\theta d\theta$ (where θ is the pitch angle between the particle velocity and the magnetic field), the average energy gain per crossing of the reconnection region is $\langle \frac{\Delta E}{E} \rangle = \frac{4}{3}\frac{v_{rec}}{c}$, and the resulting particle spectrum of accelerated cosmic rays is (see de Gouveia Dal Pino & Lazarian 2001, hereafter Paper II)

$$N(E)dE \sim E^{-5/2}dE \quad (1)$$

This equation indicates that the particle spectrum produced by first-order Fermi acceleration in a reconnection site is steeper than that produced in shocks, and also steeper than the observed spectrum of UHECRs (see below).

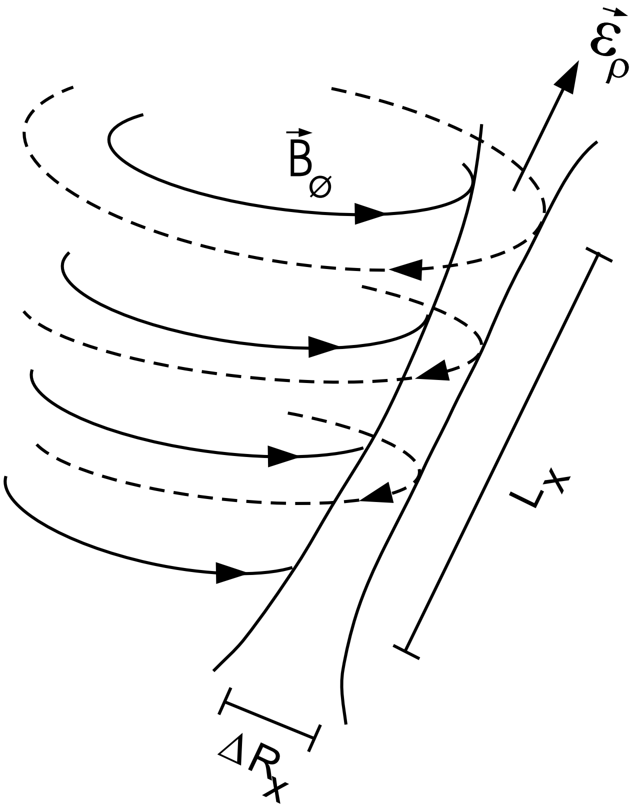

Fig. 3. Schematic representation of the reconnection region just above the Alfvén surface.

2.2 Synchrotron Losses

In the case of UHECR acceleration, the energy losses per revolution around a magnetic field line may be very substantial, and the classical synchrotron loss formulae should be modified. In the presence of very strong magnetic fields, the amount δE of energy lost by a particle of energy $E_{20} = E/10^{20} eV$ when deflected by an angle $\delta\varphi$ in the magnetic field will be given by (Paper II)

$$\frac{\delta E}{E} \approx 1.04 \times 10^{11} \delta\varphi E_{20} \sin\theta, \tag{2}$$

which is independent of the magnetic field intensity. Therefore, in the UHE particle regime, the synchrotron losses in strong magnetic fields are so large, even for very small deflection angles, that they exclude any possibility for particle acceleration via reflecting particles back and forth within the reconnection zone, as required in Fermi acceleration processes. Fermi acceleration would be possible for UHECRs only if the magnetic fields in the system were $\lesssim 1$ G. Since in the AIC-pulsars, very strong magnetic fields are present and actually provide the energy reservoir for particle acceleration, we conclude that Fermi processes are *not* suitable in this case. We show below instead, that direct acceleration by the induced electric field in the reconnection zone is the only viable mechanism.

2.3 One-Shot Acceleration

Protons can be in principle accelerated by a large induced electric field (normal to the plane of Fig. 1) within the reconnection region at the helmet streamer (Paper I). However, in a more realistic three-dimensional geometry, the accelerated particles escaping perpendicularly out of the plane of Fig. 1 will be strongly deflected by poloidal field lines in their way out of the system, thus loosing most of their energy by synchrotron effects. On the other hand, it is well known from magnetized-winds theory (e.g., Spruit 1996) that beyond the Alfvén surface (i.e., the surface at which the wind flow emerging from the disk/star system reaches the Alfvén velocity, v_A), the inertia of the gas causes the poloidal lines ($\boldsymbol{B}_p$) to wind up and the field becomes preferentially toroidal i.e. $B_\phi \gg B_p$ (see Fig. 2). In this case, as the accelerating electric field, which is perpendicular to the annihilating magnetic field lines, is mostly poloidal ($\boldsymbol{\epsilon}_p$) (see Fig. 3), the particles will be accelerated (and allowed to escape) along the poloidal direction without being deflected by the field lines, therefore, without suffering substantial synchrotron losses.

In a reconnection event, the condition that particles of charge Ze can be accelerated to energies E by an electric voltage drop, $V = Ze\epsilon_p$, is given by $E = ZeV = ZeB_\phi \xi L_X$, where $\xi = v_{rec}/v_A \simeq v_{rec}/c$ is the reconnection efficiency factor, and L_x is the length of the reconnection region (see Fig. 3).

For fast reconnection, $\Delta R_X/R_X \lesssim 1$, and $L_X/\Delta R_X \approx v_A/\xi v_A \approx \xi^{-1}$. This results $E \approx Ze\Delta R_X B_\phi$, or (Paper II)

$$B_{13} \gtrsim 0.8 \times E_{20} Z^{-1} \Omega_{2.5k}^{-4/3} \tag{3}$$

where $E_{20} = E/10^{20}$ eV, $\Omega_{2.5k} = \Omega_\star/2.5 \times 10^3$ s^{-1}, and $B_{13} = B_\star/10^{13}$ G.

The relation above indicates that stellar magnetic fields 10^{12} G $< B_\star \lesssim 10^{15}$ G and angular speeds 4×10^3 s^{-1} $\gtrsim \Omega_\star > 10^2$ s^{-1}, which correspond to spin periods 1 ms $\lesssim P_\star <$ 60 ms, are able to accelerate particles to energies $E_{20} \gtrsim 1$.

A newborn millisecond pulsar spins down due to magnetic dipole radiation in a time scale given by $\tau_\star = \Omega_\star/\dot{\Omega}_\star \simeq 4.3 \times 10^7$ s $B_{13}^{-2}\,\Omega_{2.5k}^{-2}$. We have shown in Paper I that the condition that the magnetosphere and the disk stresses are in equilibrium at the inner disk edge results a disk mass accretion rate that is "super-Eddington". Nonetheless, this supercritical accretion will last for a time τ_D, which is only a small fraction ($f_D \simeq 0.03$) of $\tau_\star$. The acceleration of the UHECRs in the reconnection zone will occur during the supercritical accretion event, and their spectrum evolution will be, therefore, determined by $\tau_D = f_D \tau_\star$.

The rate of magnetic energy that can be extracted from the reconnection region is $\dot{W}_B \simeq (B_X^2/8\pi)\,\xi v_A\,(4\pi R_X\, L_X)$, where $v_A \sim c$, and the corresponding UHECR flux emerging from the reconnection site can then be estimated as $\dot{N} \simeq \dot{W}_B/E$. In this case, it is easy to show that the particle spectrum $N(E)$ is obtained from $\dot{N} = N(E)\,\frac{dE}{dt} \simeq N(E)\,\frac{dE}{d\Omega_\star}\,\dot{\Omega}_\star/f_D$, and is given by (Paper II)

$$N(E) \lesssim 1.6 \times 10^{33}\,\mathrm{GeV}^{-1}\,Z^{-1/2}\,B_{13}^{-1/2}\,E_{20}^{-3/2} \quad (4)$$

This equation predicts that $N(E) \propto E^{-3/2} = E^{-1.5}$, which is a flat spectrum in good agreement with the observations (e.g., Olinto 2000).

Since the total number of sources formed via AICs in our Galaxy is limited by nucleosynthesis constraints to a very small rate $\tau_{AIC}{}^{-1} \simeq 10^{-5}$ yr^{-1}, we find that the total UHER flux must be given by the integrated contribution from AIC-pulsars of the whole distribution of galaxies located within a volume which is not affected by the GZK effect, i.e., within a radius $R_{50} = R_G/50$ Mpc. This results (Paper II)

$$F(E) \lesssim 3.1 \times 10^{-29}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,Z^{-1/2}\,B_{13}^{-1/2} E_{20}^{-3/2}\,\tau_{AIC,5}{}^{-1}\,n_{0.01} R_{50} \quad (5)$$

where $\tau_{AIC,5}{}^{-1} = \tau_{AIC}{}^{-1}/10^{-5}$ yr^{-1}, $n_{0.01} = n_G/0.01$ h^3 Mpc^{-3}, and n_G is the standard galaxy distribution.

Observed data by the AGASA experiment (Takeda et al. 1999) gives a flux at E =10^{20} eV of $F(E) \simeq 4 \times 10^{-30}$ Gev^{-1} cm^{-2} s^{-1}, so that the efficiency of converting magnetic energy into UHECR should be $F(E)_{obs}/F(E)/ \simeq \xi' \gtrsim 0.1$ in order to reproduce such a signal.

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