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# ULTRA-HIGH-ENERGY COSMIC RAY ACCELERATION BY MAGNETIC RECONNECTION IN NEWBORN PULSARS

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RESUMEN

Investigamos la posibilidad de que los rayos cósmicos ultra energéticos (UHECR) observados arriba del límite GZK sean protones acelerados en zonas de reconección localizadas sobre la magnetósfera de pulsares de milisegundos recién formados por un colapso inducido por acreción (AIC).

ABSTRACT

We investigate the possibility that the ultra-high energy cosmic ray (UHECR) events observed above the GZK limit are mostly protons accelerated in reconnection sites just above the magnetosphere of newborn millisecond pulsars that are originated by accretion induced collapse (AIC).

*Key Words:* **COSMIC RAYS — MHD — PULSARS: GENERAL**

## 1. INTRODUCTION

The detection of cosmic ray events with energies beyond $10^{20}$ eV (UHECRs) poses a challenge for the understanding of their nature and sources. If UHECRs are mostly protons, then they should be affected by the expected Greisen-Zatsepin-Kuzmin (GZK) energy cutoff ($\sim 5 \times 10^{19}$ eV), which is due to photomeson 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, if the UHECRs are mostly protons from nearby sources (located within $\sim 50$ Mpc), then the arrival directions of the events should point toward their sources since they are expected to be little deflected by the intergalactic and Galactic magnetic fields (e.g., Medina Tanco, de Gouveia Dal Pino, & Horvath 1998). The present data shows no significant large-scale anisotropy in the distribution related to the Galactic disk or the local distribution of galaxies, although some clusters of events seem to point to the supergalactic plane (Takeda et al. 1999).

We here discuss a model in which UHECRs are mostly protons accelerated in magnetic reconnection sites outside the magnetosphere of very young millisecond pulsars being produced by accretion induced collapse (AIC) of a white dwarf (de Gouveia Dal Pino & Lazarian 2000; hereafter GL2000). When a white dwarf reaches the critical Chandrasekhar mass $\sim 1.4 M_{\odot}$ through mass accretion, in some cases it collapses directly to a neutron star instead of exploding into a supernova. The accretion flow spins up the star and confines the magnetosphere to a radius $R_X$ where plasma stress in the accretion disk and magnetic stress balance (Arons 1993). At this radius the equatorial flow will divert into a funnel inflow along the closed field-lines toward the star, and a centrifugally driven wind outflow (see Fig. 1 of GL2000). To mediate the field lines of the star with those opened by the wind and those trapped by the funnel inflow emanating from the $R_X$ region a surface of null poloidal field forms (e.g., Shu et al. 1994). This reconnection region dominated "*helmet streamer*", will release magnetic energy that will accelerate particles to the UHEs.

A primary condition on the reconnection region for it to be able to accelerate particles of charge $Ze$ to energies $E$ is that its width $\Delta R_X \geq 2\, r_L$, where $r_L$ is the particle Larmor radius $r_L = E/Ze\, B_X$ , and $B_X$ is the magnetic field (normal to particle velocity) at the $R_X$ region. This condition and the field geometry imply

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(GL2000):

$$B_{13} \gtrsim Z^{-1}\, E_{20}\, \Omega_{2.5k}^{-4/3} \left(\frac{\Delta R_X/R_X}{0.1}\right)^{-1/2} \quad , \tag{1}$$

where $B_{13}$ is the stellar magnetic field in units of $10^{13}$ G, $\Omega_{2.5k}$ is the stellar angular speed in units of 2500 s$^{-1}$, and $E_{20}$ is the particle energy in units of $10^{20}$ eV. We find that stellar magnetic fields $10^{12}$ G $< B_\star \lesssim 10^{15}$ G and angular speeds $4\times10^3$ s$^{-1}$ $\gtrsim \Omega_\star > 10^2$ s$^{-1}$ (or 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 $\tau_\star \equiv \Omega_\star/\dot{\Omega}_\star \simeq 4.3\times10^7$ s $B_{13}^{-2}\,\Omega_{2.5k}^{-2}$. We can show that the condition that the magnetosphere and disk stresses are in equilibrium at the inner disk edge results in a disk mass accretion rate that is super-Eddington. This supercritical accretion will last for $\sim \tau_\star$. As it approaches the end, the newborn pulsar decreases its rotation speed due to electromagnetic radiation at a rate $\tau_\star^{-1}$. The spectrum evolution of the accelerated UHECRs is thus determined by $\tau_\star^{-1}$. The particle spectrum $N(E)$ is obtained from $\dot{N} = N(E)\,\frac{dE}{dt} = N(E)\,\frac{dE}{d\Omega_\star}\,\dot{\Omega}_\star$ (GL2000):

$$N(E) \simeq 5.8\times10^{34}\,\mathrm{GeV}^{-1}\,\xi\, Z^{-1/2}\, B_{13}^{-1/2}\, E_{20}^{-3/2} \left(\frac{\Delta R_X/R_X}{0.1}\right)^{-1/4} \quad , \tag{2}$$

where $\xi$ is the reconnection efficiency factor; the derived spectrum above is very flat which is in agreement with the observations.

The total number of objects formed via AICs in our Galaxy is limited by nucleosynthesis constraints to a very small rate $\sim 10^{-5}$ yr$^{-1}$. Hence, the probability of having UHECR events produced in the Galaxy will be only $P \simeq f_b\, \tau_{AIC}{}^{-1}\, t \simeq 2\times10^{-6}$, where $f_b \sim (\Delta R_X/R_X)^2 \simeq 10^{-2}$ is the emission beaming factor caused by the magnetic field geometry, and $t = 20$ yr accounts for the time the UHECR events have been collected in ground-based detectors so far. Since the individual contribution to the observed UHECRs due to AICs in our Galaxy is so small we must evaluate the integrated contribution due to AICs from all the galaxies located within a volume which is not affected by the GZK effect, i.e., within a radius $R_{50} = R_G/50$ Mpc. Assuming that each galaxy has essentially the same rate of AICs as our Galaxy and taking the standard galaxy distribution $n_G \simeq 0.01\, e^{\pm0.4}\, h^3$ Mpc$^{-3}$ (with the Hubble parameter defined as $H_o = h$ 100 km s$^{-1}$ Mpc$^{-1}$), the resulting flux at $E_{20} \geq 1$ is $F(E) \simeq N(E)\, n_G\, \tau_{AIC}{}^{-1}\, R_G$, which gives

$$F(E) \simeq 1.1\times10^{-27}\xi\,\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\, Z^{-1/2}\, B_{13}^{-1/2}\, E_{20}^{-3/2}\, \tau_{AIC,5}{}^{-1}\, n_{0.01}\, R_{50} \left(\frac{\Delta R_X/R_X}{0.1}\right)^{-1/4} \tag{3}$$

where $\tau_{AIC,5}{}^{-1} = \tau_{AIC}{}^{-1}/10^{-5}$ yr$^{-1}$, and $n_{0.01} = n_G/0.01$ h$^3$ Mpc$^{-3}$. Observed data by the AGASA experiment (Takeda et al. 1999) gives a flux at $E = 10^{20}$ eV of $F(E) \simeq 4\times10^{-30}$ Gev$^{-1}$ cm$^{-2}$ s$^{-1}$, so that the reconnection efficiency factor needs to be only $\xi \gtrsim 3.6\times10^{-3}$ in order to reproduce the observed signal.

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