

Modeling the Galactic Magnetic Field and its Application in verifying a Pulsar Origin of Very High Energy Cosmic Rays

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Abstract. Deflection of Cosmic Ray charged particles under the influence of magnetic fields (Galactic and Extragalactic) causes a nearly isotropic distribution of their observed fluxes especially in lower energy ranges. Anyhow, as very high energy cosmic rays experience less deflections in their paths, they may point out the direction of their sources within a few degrees. We used a Galactic magnetic field model to study the possible Galactic sources of these cosmic rays. The propagation of cosmic rays in this Galactic magnetic field is simulated to estimate average deflection angles into their straight-line paths from their sources. Pulsars with suitable characteristics are selected and deflection regions around them are defined. Compared with the observational data (i.e. detected directions of observed CRs), the possibility of a Galactic origin of ultra high energy cosmic rays is examined. We defined deflection angles in terms of energies for sources in a distance d into center and anti-center directions. The probability of observing cosmic rays of different energies from the direction of a source in a distance d is studied and the possibility of a pulsar origin of very high energy cosmic rays due to some recent models, is discussed.

1. Introduction

The observation of a *knee* (1958) in Cosmic Ray(CR)'s flux, together with supper *GZK* (*Greisen-Zatsepin-Kuzmin*) particles gave rise to models in which acceleration mechanisms and the power of astronomical accelerators (i.e. supernovas, pulsars, Galactic shocks, etc [1, 2, 3]) were discussed. As supernovae models at the prior researches were not able to produce the observed energies [4, 5, 6], the models developed to situations in which particles were originated from a very young pulsar and accelerated up to Very High Energies (VHE) in the pulsar wind [7, 8, 9, 10, 11]. Pulsar origin of CR particles has studied in many researches [6, 7, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20] in which a variety of models were considered to explain both the mechanisms of particle acceleration in the Interstellar Medium (ISM) and the origin of the observed CR's flux [6, 7, 8, 9, 19, 20, 21].

Continuing the theory first started by *Faraday* and observing the Faraday Rotation Measures (FRM) of polarized electromagnetic waves from different sources, estimations of weak Magnetic Fields (MF) of the Galaxy [22, 23, 24] was made possible. These MFs were estimated to have values up to $6\mu G$ around the Sun and up to $10\mu G$ in the inner Galaxy [23, 25, 26, 27, 28, 29, 30].

Particles in the Galaxy have gyroradiuses as: $r_g = \frac{E_{cr}}{ZeB}$. Simple calculations has showed



that the gyroradius of VHE CRs (i.e. $\sim 10^{18} - 10^{19}$ and higher) in the Galactic MF is much less than the typical distance to a young neutron star ($8kpc$) [21] which has the capability of accelerating CR protons up to around $10^{21}eV$ [5, 12]. On the other hand, due to GZK cutoff [31, 32], it is usually accepted that the possible EG sources of VHE CRs should lie within about $100 Mpc$. In a previous work [33, 34] it was showed that assumed EG particles can deflect up to 10 degrees into the direction of their sources. Anyhow, Sigl et al.[35] has showed that there is an inconsistency between the arrival directions of Fly's Eye and Yakutsk events and the possible EG sources within this distance. If there is a pulsar origin for VHE CRs, the galactic directions of these CRs should point out the direction of their Galactic sources within a few degrees.

2. The candidate pulsars

Possible large MFs of a young pulsars ($10^{12} \sim 10^{13}$ G [11] of young pulsars, $10^{14} \sim 10^{15}$ G of magnetars [10]) with low barycentric periods gives less cooling times as [10, 19]:

$$T = \frac{P_{ms}^2}{2B_{12}} \times 10^{15} \quad (1)$$

where B_{12} is the strength of MF in 10^{12} G. Using data from ATNF Pulsar Catalogue [36, 37]; 255 objects out of 2210 objects with a specified distance were selected for which the barycentric period of the pulsar, p_0 , was about $10ms$ and less. A second category was selected with 69 pulsars with surface magnetic flux density in the range $10^{13} - 10^{16}G$. Nevertheless for these Galactic pulsars the cooling times are not in the range specified by Wibig and Wolfendale [10]. Within first category, 234 objects are from inner Galaxy and 21 from outer Galaxy with mean distances: $d=4.6kpc$ (inner Galaxy) and $d=2.5kpc$ (outer Galaxy).

3. The specifications of this simulation

We assumed the arrival directions of particles in GMF to be the Galactic directions of selected pulsars. The particles considered to be protons as above the *ankle*, the composition of observed CRs seems to tend to lower mass particles. Anyhow it is a sophistical assumption, because it is possible that the observed high energy CRs are light nuclei produced in the ISM through interactions of even heavier primary CRs, here obviously we have omitted this case in our first step.

To compare the results, a collection of high energy observed events in the energy ranges $10^{18} - 10^{19}$, $10^{19} - 10^{20}$ and $10^{20} - 10^{21}eV$ from data catalogues of Haverah Park and Volcano Ranch [38], SUGAR [39], Auger [40], Fly's Eye [41], Yakutsk [42, 43, 44] and AGASA [45, 46] have selected. For the propose of this simulation, protons of energies 10^{18} , 10^{19} , 10^{20} and 10^{21} been ejected into GMF with the initial Galactic direction of the object (i.e. pulsar (l, b)). The light path of a particle, $d(b)$, from the pulsar catalogue then is simply its distance [36, 37].

For a proton the gyroradius R is equal to: $R(pc) = \frac{1.08E(PeV)}{B(\mu G)}$ considering particles traveling \mathcal{D} parsecs by deflection in the varying MF of the Galaxy in the form of [47]: $B = B_0 e^{\frac{-\mathcal{L}}{3000}}$, where the regular magnetic field component is along the z axis, \mathcal{L} is the disk height in kpc and regular MF decays exponentially with a decay length of $3000kpc$.

To calculate the actual deflected paths of the particles, we considered a Random Walk Method (RWM) with a varying Length Factor (LF) [48] and calculated the actual deflected path, \mathcal{D} , for each event. To reach the average values of \mathcal{D} , 100 simulations been made for each energy.

The GMF been considered to have a *Kolmogorov* type with a turbulent energy spectrum of :

$$S(k) \sim k^{-\delta} \begin{cases} \text{for one dimension } \delta = \frac{5}{3} \\ k = \frac{2\pi}{\lambda}, \text{ wave number, (or } \frac{2\pi}{L}, L \text{ is Eddy Size)} \end{cases}$$

with varying scales between $L_{min}=20 \text{ pc}$ and $L_{max}=200 \text{ pc}$ [49]. In a previous work [33, 34] it was shown that for *Auger* events the value of k is about $0.006 \text{ Mpc}^2 \text{ yr}^{-1}$, consistence with a *Kolmogorov* type spectrum.

The time delay of observed particles is just due to their deflected paths in varying GMF:

$$\tau = \alpha(\mathcal{D} - d)\text{years} \quad (2)$$

where \mathcal{D} and d are in parsecs and α is ~ 3.26 in an assumption in which all particles are traveling at the speed of light.

3.1. Deflection Angles

For each selected object, the time delay distributions for different energies (10^{18} , 10^{19} , 10^{20} and 10^{21} eV) is calculated. In Galactic condition, the spread in deflection angles is always comparable to the average deflection angles and the average time delay is given as follow [50, 51, 52, 53]:

$$\tau(E, d) \approx \frac{\theta^2(E, d)d}{4} \quad (3)$$

These results are sensitive to LFs and the strength of MF. For LFs of orders of 10 pc and $B_0=10$ and $5 \mu G$, with varying *Kolmogorov* scales between $L_{min}=1 \text{ pc}$ and $L_{max}=100 \text{ pc}$, our results are showed for two typical pulsar located at \sim center direction: J1751-2857 ($l=0.65$, $b=-1.12$), $d=1.44 \text{ kpc}$, $p_0 = 3.9 \text{ ms}$ and J0621+25 ($l=187.31$, $b=4.93$), $d=4.25 \text{ kpc}$, $p_0 = 2.7 \text{ ms}$ in \sim anti-center direction [36, 37]. The result of this simulation for time delays and deflection angles are listed in table 1.

Table 1. The result of this simulation for J1751-2857 and J0621+25 for different energies in EeV

Object Name	$\mathcal{D}(\text{kpc})$				$\tau(\text{yr})$			
	1	10	10^2	$10^3(\text{EeV})$	1	10	10^2	$10^3(\text{EeV})$
J0621 + 25	16.6	4.26	4.25	4.25	4.01×10^4	35.7	0.37	3.50×10^{-3}
J1751 - 2857	1.73	1.44	1.44	1.44	9.30×10^2	7.80	0.08	7.02×10^{-4}
	$\theta(\text{degree})$				$d(\text{kpc})$			
	1	10	10^2	$10^3(\text{EeV})$	1	10	10^2	$10^3(\text{EeV})$
J0621 + 25	6.2	0.18	0.02	less than 0.01	4.25			
J1751 - 2857	1.6	0.15	0.02	less than 0.01	1.44			

For these two objects (as an example) the diagrams of deflection regions were also drawn (Figure 1).

4. The result

We have completed the results of this simulation for 80 objects with the barycentric periods, p_0 , about 10 ms and less with $0 < l, b < 90$. This results are shown in figure 2. For a constant energy of protons, deviation angle has a power law relation with d (the distance of object) as $\theta(d) = a + b \times d^c$ in which c for the objects of figure 2 calculated to be 0.7 ± 0.1 . As a result, it is showed that for a variety of distances the deflection angles are related to both energy and distance as expected (Figure 2), but the structure of Galactic MF is also of special importance. In fact a more precise evaluation of Galactic structure and considering turbulent MFs in some cases cause larger values of deflection angles.

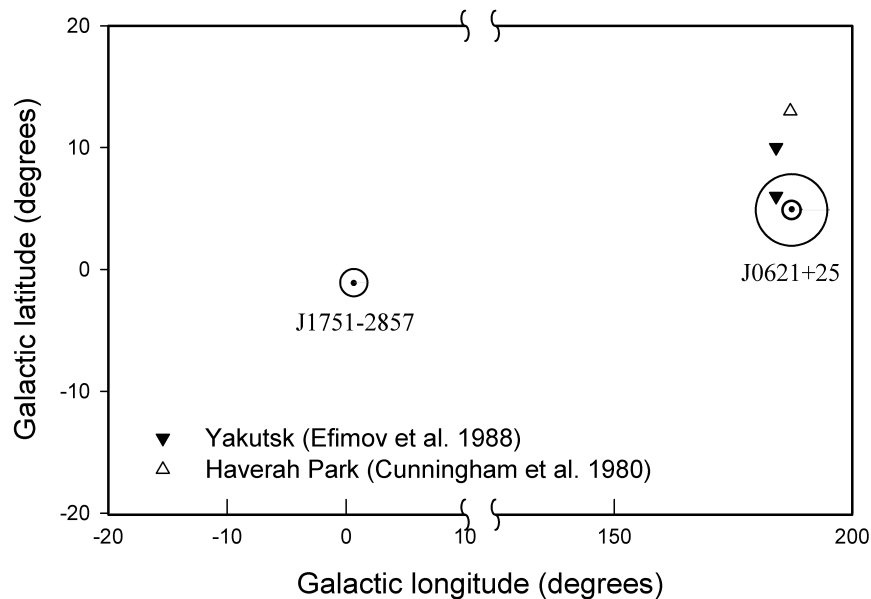


Figure 1. Deflection angles around two sample pulsars. Inner circles represent deflection of protons of 10^{20} eV and outer circles represent deflection of protons of 10^{19} eV .

With the selected parameters of this simulation it is showed that for protons with energies $\sim 10^{20} \text{ eV}$ and above, the average deflection angles are less than 1 degrees. This result means that for these particles having a Galactic pulsar origin, their arrival directions should exactly point to a pulsar or pulsars in the Galaxy. For lower energies, in the range $10^{19} - 10^{20}$, the results are shown in figures 3 with the assumption that all of them were protons.

Our preliminary results shows that for a nearly homogeneous distribution of Yakutsk [42, 43, 44], Volcano Ranch, Haverah Park [38], Auger [40] and AGASA [45, 46] there is a consistency between Galactic directions of 8 objects (out of 80) located at higher distances. This result did not verify for energies above 10^{20} eV . For fast pulsars with distances lower than $\sim 4 \text{ kpc}$ no correlation been observed.

If higher mass particles being considered, higher energies and higher values of deflection angles will resulted, so for the PSNR model [10] another possibility is that the particles are not protons and have higher mass numbers. For a fortiori conclusion, a whole sky survey should be completed.

Acknowledgments

This work has been supported financially by Research Institute for Astronomy and Astrophysics of Maragha (RIAAM) under research project No. 1/2352.

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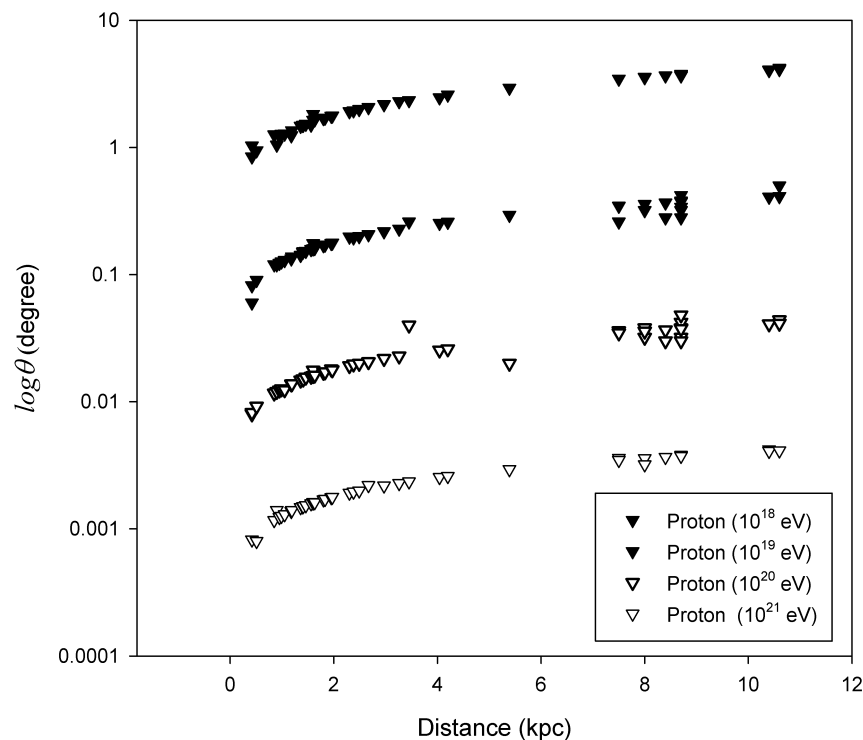


Figure 2. Average values of deflection angles versus distance for objects with $0 < l, b < 90$ (Simulated for protons).

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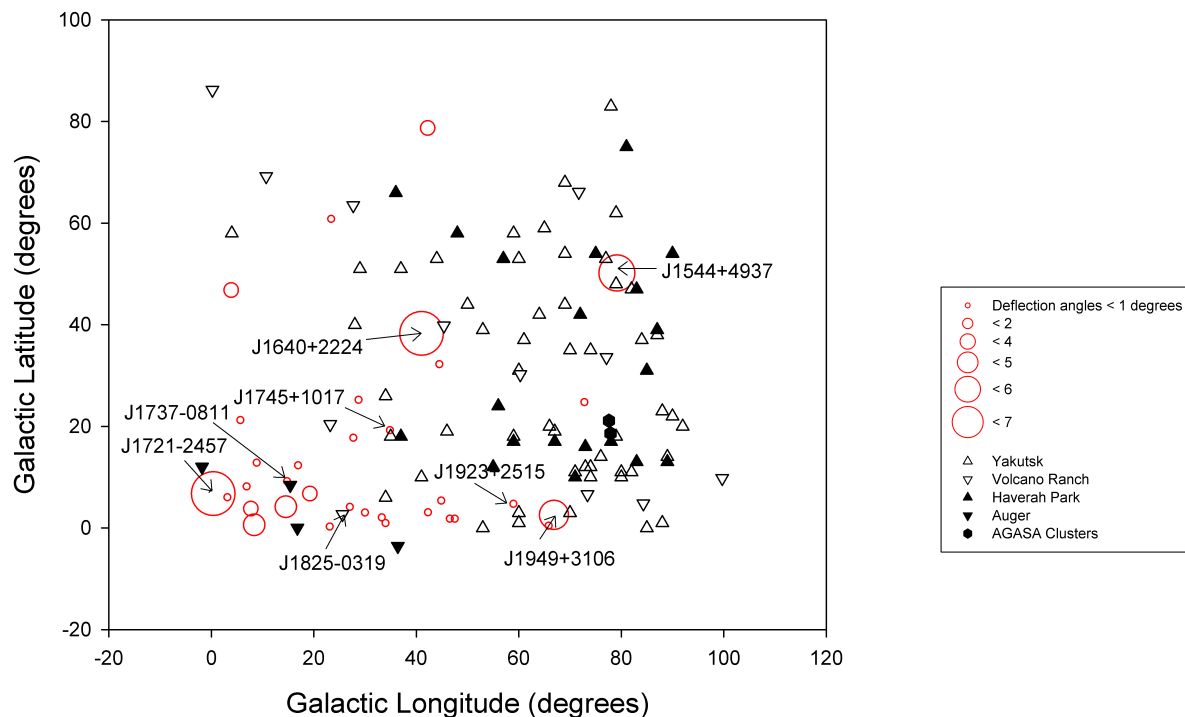


Figure 3. Galactic arrival direction of VHE CRs [38, 39, 40, 41, 42, 43, 44, 45, 46] and Galactic pulsar positions [36, 37] for $0 < l < 90$ and $0 < b < 90$ degrees. The deflection regions also are considered (present simulation).

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