Development of a Galactic Magnetic Field Model and its application in identifying sources of Ultra-High-Energy Cosmic Rays in Northern Sky.

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Abstract. New physical conditions were applied to our previous Galactic Magnetic Field model. The relative motion of a Galactic source were also considered. We simulated the propagation of Ultra-High-Energy particles under the influence of Galactic Magnetic Field. In this research the particles were originated from millisecond pulsars located in the northern sky. Considering the relative motion of Galactic sources for a proper time interval, sample test images of millisecond pulsars were produced using cosmic rays of energies ranged in $10^{18}-10^{19}$, $10^{19}-10^{20}$, and $10^{20}-10^{21}$ eV. The results were compared with our previous ones. For each part of the sky considering the structure of Galactic Magnetic Field, the source location and its relative motion to the observer, one may use these images as a guide to find possible sources of the Ultra-High-Energy Cosmic Ray' events. Consequently, a possible method of identifying the sources of these particles were introduced. Some physical limits were discussed.

1. Introduction
The deflection of Cosmic Ray (CR) charged particles in the Galactic and Extragalactic (G & EG) Magnetic Fields (MFs) has been the subject of many researches. At the highest energies, calculating these deflections plays a crucial role to find the origin of Ultra High Energy (UHE) CRs because in this case the deflection from straight-line paths is within few degrees [1]. As one of the most powerful G and EG sources, it is shown that pulsars are capable to accelerate particles up to $10^{19}$eV for proton and up to $10^{20}$eV for Iron nuclei [2, 3, 4, 5, 6]. So considering the deflections of these particles, one may construct hypothetical pulsar images in a CR sky.

Through studies based of physical processes such as Synchrotron Radiation, Polarization of electromagnetic waves in different wavelengths, Zeeman Effect and Zeeman splitting and Faraday Rotation Measure (FRM) [13, 14, 15, 16], G and EG MFs were mapped. These strength and correlation lengths of GMFs, may fitted to the putative models of GMF.

2. The specifications of the model
Essentially, three models were considered for GMF in the disk, included: Concentring Rings (CCR), Axisymmetric Spiral (ASS) and Bisymmetric Spiral (BSS) models of GMF [15]. Following our previous works [1, 7, 8], now an ASS GMF model is adopted for the Galactic disk in which 2 radial reversals [17] occurs. Such a model is in consistence with the turbulent dynamo theory [14].
In our previous model, we have been considered a constant magnetic field strength \( B_0 = 10 \, nG \) \( \text{Stanev et al., [18]} \) with a regular magnetic field \( B = B_0 e^{-L/3000} \) along the \( z \) axis \([1, 7, 8]\).

Here, the model were developed using an ASS model of GMF in Galactic disk \([9, 10, 11, 12]\), which is considered to have a cylindrical form with an average thickness of 0.3 kpc \([19]\). The regular component considered in the direction of spiral arms. In the halo, the vertical distribution of total magnetic field is taken from Cox \([20]\). Here the only physical bond was the distribution of matter in the Galaxy, which is exerted through two essential parameters, i.e. \( B \) (strength of GMF) and \( L_c \) (MF coherence length). No other interactions were considered for UHECR’ propagation in the Galaxy and the deflections from the straight line pathes were considered to be only due to different gyro-radiuses of particles. To consider a randomly oriented field we have used a coherence length, \( L_c \), of order of \( \sim 100 \text{pc} \) and less in the vicinity of the source (i.e. pulsar). The total magnetic field were considered to have a regular component and a randomly oriented one. Far from the source, the coherence length were considered to have a value of around 2 kpc. A Random Walk Method (RWM) were used to calculate the actual path of the particle.

We also added a few other parameters, included the rigidity of the projected particle from proton to iron nuclei and also the relative motion of source during an observation epoch. GZK processes were off, as the propagation is just considered in the Galaxy. Now The time delay of observed particles is just due to their deflected paths in varying GMF:

\[
\tau = \gamma \alpha (D - d) \, \text{years}
\]

where \( D \) and \( d \) are in parsecs and \( \alpha \) is \( \sim 3.26 \) and \( \gamma \) is 1 for particles with rigidity of 1.

2.1. Deflection Angles and the Picture of Source in a CR Sky

As what we followed in the previous works \([1, 7, 8]\), for each possible source the time delay distributions for different energy ranges (\(10^{18}, 10^{19}, 10^{20}\) and \(10^{21} \, \text{eV}\)) were calculated. Using the relation of the average time delay, \( \tau \), and deflection angle \([21, 22, 23, 24]\):

\[
\tau(E, d) \approx \frac{\theta^2(E, d) d}{4}
\]

the values of \( \theta \) were calculated for each energy interval.

In this research we constricted the picture of sources using particles of different energy intervals (figure 1).

3. The Results

As an example, our results were shown for two objects studied before: 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 \([25, 26]\). For J0621+25, we have tracked the deflected protons and calculated the resulted \((l, b)\) pairs around the source. These results are shown in figure 1.

It is obvious that considering more details for GMF cause higher degrees of deflection up to 5 degrees for protons ejected from a Galactic source. Here it is also shown that adding a parameter of relative motion of an object may cause an elongation in the picture as seen here. But such an oblateness is observable in large epochs. For example to reach the above picture, we considered this source was ejecting particles for more than \(10^3 \text{years}\).

Our results shows that considering the structure are GMF arms and disk, may cause large deflection angles in the directions of detected particles. But still more studies are needed to verify a Galactic origin of UHECRs. In fact the correlation lengths and magnetic field strengths between Galactic Arms and the direction of \( B_{\text{regular}} \) are much more complicated than our simple models and the effect of adding more details is not clear.

An interesting case may occurs for a young pulsar, when the correlation length of random component of magnetic field around the pulsar and behind the shock is \( \sim 100 \text{pc} \) and less. In
such a case our model predicts the highest degrees of deflection, i.e. $\sim 12\text{degrees}$ and more for protons up to a few $10\text{EeV}$, with a correlation length of $\sim 100\text{pc}$ and $\sim 15\text{degrees}$ and more for a correlation length of $\sim 50\text{pc}$. This result may shift the G to EG region to a few $10\text{EeV}$.

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