Propagation of Ultra High Energy Cosmic Rays from Galactic Sources in a Fractal Interstellar Medium and Origin Studies

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Abstract. Cosmic rays propagation within the Galaxy is simulated considering a fractal-like distribution of matter and magnetic fields. In such an anomalous diffusion process, the sources of ultra-high energy particles were considered to be galactic pulsars. The coordinate and birth times of sources were chosen from SN and pulsar catalogues. From these sources the primary spectrum of cosmic rays (H, He, CNO, Ne-Si, Fe) in energy range EeV and above were reproduced. The resulted spectrum is used to discuss about the change in cosmic ray sources form Galactic to Extragalactic.

1. Introduction
Different astronomical sources and sites are considered to be responsible of particle acceleration in the Galaxy. In a usual picture, acceleration mechanism are considered to be second and first order Fermi and diffusive shock acceleration mechanisms, all of which are resulting in power law spectrums. Another fact about source fluxes comes from analyzing abundance ratios of secondary to primary particles. For example, analyzing boron-to-carbon abundance ratio, suggests a soft power law energy spectrum at source, \( E^{-\gamma} \), with \( \gamma \sim 2.4 \) and \( \delta \sim 0.5 \) for the propagation path length, \( \Lambda(E) \) (i.e. \( \Lambda(E) = E^\delta \)) [1] (Considering other studies, \( \delta \sim 0.6 \)). Thus in a diffusive propagation with negligible energy loss processes (i.e. Leaky Box Model), the energy spectrum of Cosmic Rays (CR) at source is predicted to be \( \propto E^{-2.1} \). This flux index it produced in different acceleration models, for example the first order fermi mechanism is very efficient in regions with small scale turbulences [2] and in this situation the spectral indexes are nearly \( \sim 2 \).

Diffusive shock acceleration mechanisms were first studied using simple first order Fermi mechanisms by different groups [3, 4, 5, 6], later more complicated situation were analyzed; for example it is showed that ultra-relativistic shocks result power law spectrums with index values of \( \approx 2.2 - 2.3 \) [7]. Today acceleration mechanism are studied in more complicated situation
[8, 9, 10]. At the highest energies the striking problem is that the first order Fermi mechanism and diffusive shock acceleration does not work at highly relativistic shocks, unless in the presence of very weak magnetic fields [11].

When studying the propagation of CR in media with sharp density variations the diffusion approach is inappropriate and an alternative case is propagation in a fractal medium. The anisotropy studies also gives different results as the matter is not uniformly distributed.

2. Fractal Mediums

Diffusion in fractal mediums is governed by different formalisms. In fact, in the frame of diffusion approach where the inhomogeneities of matter and field within the Galaxy are small scale, the evolution of particle number density is formulated by [12]:

\[
\frac{\partial N}{\partial t} = D(E) \Delta N(r, t, E) + S(r, t, E)
\]

in which, D is diffusivity.

But the super-diffusion without energy losses and nuclear interactions has the form of [13]:

\[
\frac{\partial N}{\partial t} = -D(R, \alpha, \beta)D_{0+}^{1-\beta}(\Delta)^{\frac{\alpha}{2}}N(r, t, R) + S(r, t, R)
\]

with \(D(R, \alpha, \beta) = D_0(\alpha, \beta)R^\delta\), anomalous diffusivity; and \(D_{0+}^{\mu}\), Riemann-Liouville fractional derivative and \((-\Delta)^{\frac{\alpha}{2}}\) Riss’ operator [14]. In steady state case \(\frac{\partial N}{\partial t} = 0\) and the equation is possible to be solved using Green’s functions [15].

2.1. Estimations

To numerically produce the expected values of fluxes and compare it with the observed particle fluxes at different energies, some estimated values were used. The key difference of this work is considering the millisecond pulsars as the point source.

More experimental data on proton fluxes makes it a good subject in case studies. One should consider that in the study of Galactic sources for high energy protons, we can not consider a galactic origin for protons with energies higher than \(\sim 10^{19} eV\). Because theoretically, the most attainable energy reported for a proton primary in a pulsar wind is around \(\sim 10^{19} eV\) [16, 17, 18] and just in the case of a young pulsar. Anyhow, we considered the millisecond pulsars of ATNF catalogue [22], and considered their observed positions to estimate their spatial distribution in a cylindrical volume. We used [23]:

\[
F(r, z) = \left(\frac{r}{r_0}\right)^a \exp\left(-b\left(\frac{r}{r_0} - 1\right) - \frac{z}{H_z}\right)
\]

The parameters were calculated using millisecond pulsars of ATNF catalogue, for which \(a = 1.2\), \(b = 2.8\), \(r_0 = 8.5Kpc\), and \(H_z = 0.2\). This function were used later to calculate radial gradient of galactic CR intensity (as described in [24]).

At this assumption it is possible to also produce the flux of other nuclei (figure 2 and 3).

3. Results

At this stage, we used our previous studies [19, 20, 21] in which the propagation of CR is turbulent magnetic fields were studied. We considered the same pulsar distribution function as in equation (3) and compared our results for propagation of only protons in our Galactic magnetic field model. for the simple case of \(\beta = 1\) (see equation 2) our Kolmogorov Magnetic Field (MF) produces a flux which is showed in figure 4. Different values of \(\alpha\) also are considered to compare the result.
It is shown that the Kolmogorov MF of our study produces the results comparable with superdiffusion with $\alpha = 1.45$, considering pulsar origin of CR up to $10^6$ GeV. In fact continuing this flux up to higher energies (i.e. above a few EeV) the results of to model are not fitted for $\alpha = 1.45$. It may lead to this conclusion that one source model at higher energies fails. It is a logical result because at the highest energies, one source models cause large anisotropies in directions of detected ultra high energy events. And such anisotropy is not seen yet.

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