Particle Composition of Ultra-High Energy Cosmic Rays

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Abstract. The origin of ultra-high energy cosmic rays is one of the major unresolved questions in astrophysics. With the progress in construction of experiment AUGER grows also the importance of analysis of the influence of Galactic magnetic field on the propagation of cosmic rays. We present one example of simple application of the direct simulation of cosmic-ray trajectories in the Galaxy. The results are surprisingly rich: the leakage of cosmic rays in the energy range $10^{13} \div 10^{19}$ eV, the origin of the knee in cosmic ray spectrum and the dependence of chemical composition on the characteristics of turbulent magnetic field.

Introduction

The origin of the high-energy cosmic rays and the ultra-high energy cosmic rays (UHECRs[1]) is one of the major unresolved questions in astrophysics, with a degree of uncertainty increasing with an energy of the particles (Fig. 1). The situation is more complicated than in radio, optical or TeV gamma-ray astronomy, where we observe arrival directions of non-charged photons. We can easily locate the positions of their sources from these observations. However, because it is expected that the primary particles with energies above 10^{12} eV or significant part of them are fully ionized and therefore charged atomic nuclei, we must consider the influence of magnetic fields on their propagation from the source to the Earth. This deflection prevents unambiguous identification of possible sources.

It is generally believed that the bulk of CRs with the energy below the knee (around 3×10^{15} eV) has Galactic origin and its main production mechanism is an acceleration by supernovae shocks ([Axford (1994)]). But the origin of the knee remains a mystery. CRs with energies above the knee may be explained either as of extragalactic and or Galactic origin. Since the Larmor radii of the particles with the energy in EeV region become larger than the thickness of the Galactic disk, it is likely that their sources are extragalactic.

We use simple method to model the propagation of cosmic rays in Galactic magnetic field in a wide range of energy (from 10^{13} eV to 10^{19} eV). Although it is the simplest method of modelling the propagation of CRs (purely solution of Lorentz equation) we are showing that it can be successfully used for analysis of observed features of cosmic-ray flux.

Galactic magnetic field

The first evidence of the existence of a Galactic magnetic field (GMF) was derived from the observation of linear polarization of starlight by [Hiltner (1949)]. Many new measurements were done since then using the Zeeman spectral-line splitting (gaseous clouds, central region of the Galaxy), the optical polarization data (large-scale structures of the magnetic field in the local spiral arm) and the Faraday rotation measurements in the radio continuum emission of pulsars and of the extragalactic sources. This is probably the most reliable method for the large scale structure. From these measurements it follows that the Galactic magnetic field has two components — regular and turbulent ([Rand & Kulkarni (1989)]).

[1]For the purposes of this article we define ultra-high energy cosmic rays (UHECRs) as cosmic rays with energy above 10^{19} eV

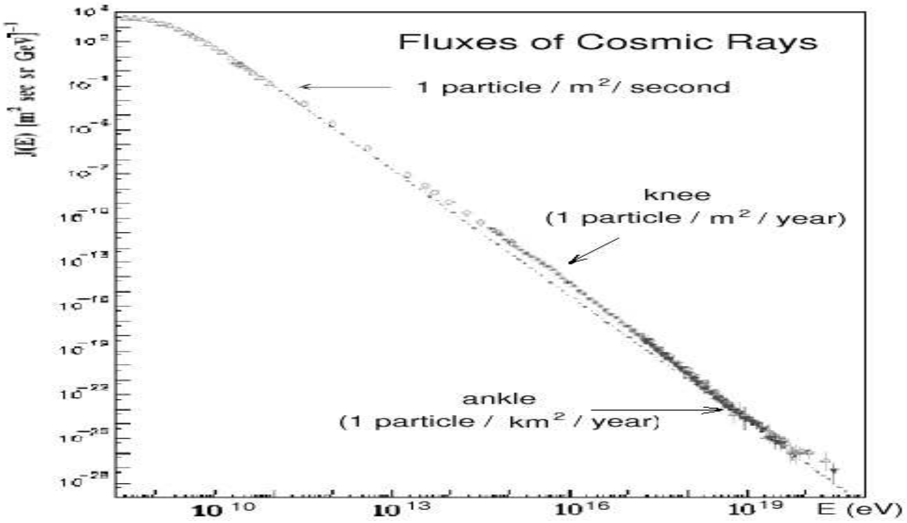

Figure 1. Observed energy spectrum of cosmic rays with energies greater than 10^8 eV. The spectrum should be expressed in the form of a power-law from 10^{11} eV to 10^{20} eV. There are slight changes of slope at 3×10^{15} eV (called knee) and at 6×10^{18} eV (called ankle). The dotted line shows E^{-3} power-law for comparison.

Theoretical global model of GMF

The global models omit the presence of turbulent fields and they are trying to model just the regular component. A basic conservative model of global Galactic plane was established by [Han & Qiao (1994)]. The model assumes a two-arm logarithmic spiral with the constant pitch angle p and shows π-symmetry (Fig. 2).

Discussed model employs cylindrical coordinates — the radial distance r, the position angle Θ and the vertical height z. The radial B_r and azimuthal B_Θ components at the plane position (r,θ) can be given by the following equations:

$$B_\Theta = B_0(r)\cos\left(\Theta - \beta\ln\frac{r}{r_0}\right)\cos p, \tag{1}$$

$$B_r = B_0(r)\cos\left(\Theta - \beta\ln\frac{r}{r_0}\right)\sin p. \tag{2}$$

where p denotes the pitch angle and according to [Stanev (1997)] it is about $-10°$, $\beta = 1/\tan p \doteq -5.67$, r_0 is the Galactocentric distance of the maximum field strength at $l = 0°$ (in the discussed model it has a value $r_0 = 9.0$ kpc) and for $B_0(r)$ it holds:

$$B_0(r) = 3\frac{R}{r}, \tag{3}$$

where R is the Galactocentric distance of the Sun, taken as 8.5 kpc.

Poloidal and toroidal field components

For toroidal field we choose the model with simple geometry (circular discs above and under Galactic plane with Lorentzian profile in z-axis). For cartesian components of toroidal field it holds[2]:

$$B_x = -B_T\sin(\phi) \tag{4}$$

$$B_y = B_T\cos(\phi) \tag{5}$$

[2]The equations above are valid only in the northern Galactic hemisphere, in the southern hemisphere the field has an opposite direction.

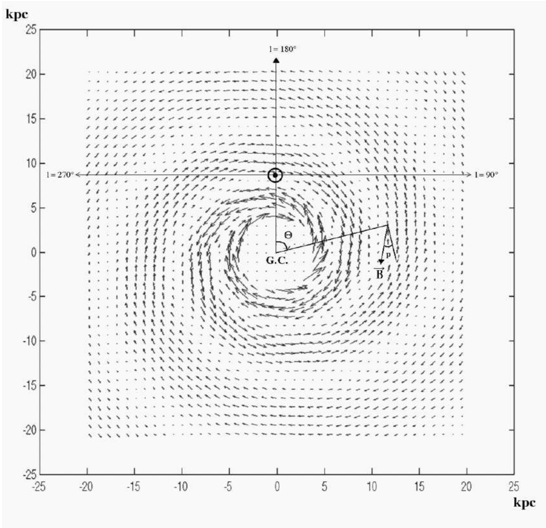

Figure 2. Direction and strength of the regular magnetic field in the Galactic plane is represented by the length and direction of the arrows (from [Han & Qiao (1994)]). The field inside the Galactocentric circle of radius 4 kpc is taken as constant, 6.4 μG.

For the value of B_T we have:

$$B_T = B_{max}\frac{1}{1+(\frac{z-H}{P})^2} \text{ for } x^2+y^2<R^2,$$

$$B_T = B_{max}\frac{1}{1+(\frac{z-H}{P})^2}\exp\left(-\frac{(x^2+y^2)^{1/2}}{R}\right) \text{ for } x^2+y^2>R^2$$

where x and y are positions in Galactic plane. Meaning and values of used constants follow: radius of a circle with toroidal field $R = 15$ kpc, height above Galactic plane $H = 1.5$ kpc, half-width of Lorentzian distribution $P = 0.3$ kpc, and maximal value of toroidal magnetic field $B_{max} = 1\mu$G.

As consequence of existence of the poloidal field (dipole field) we probably observe vertical component of 0.2μG in the Earth vicinity and intensive filaments near Galactic center. Appropriate equations, which we used for description of poloidal field, are the same as the equations for magnetic dipole. The field is symmetrical around Galactic axis. For the total poloidal field strength is then valid (in xz-plane) in polar coordinates (θ ranges from 0 to pi and goes from north to south pole):

$$B = \frac{K}{R^3}\sqrt{3\cos^2(\theta)+1}. \tag{6}$$

Turbulent fields

The model of regular magnetic field described above was enhanced with following configuration of turbulent components: The Galaxy was divided into cubic cells of an assumed size L. Two values of cell length were studied, in particular 10 and 50 pc. The random orientation and strength of the turbulent magnetic field were generated in given fraction of cells and also their position were random. In the accordance with observation the contribution of the turbulent magnetic field was taken equal to $(0 \div 3) \times B(r,\theta,z)$, where $B(r,\theta,z)$ is strength of the regular component.

Propagation of CRs in our model

Our Galaxy model has the following geometrical boundary: the bulge is a symmetric ellipsoid with a major axis in the Galactic midplane 3 kpc long and a minor axis of 2 kpc.

Around the bulge there is a thin cylinder with a radius of 15 kpc and the height of 500 pc. Starting positions of particles reside in the Galactic plane inside an annulus with radii of 3 and 12 kpc. This assumption is in the agreement with the observed positions of supernovae remnants, which are the most probable sources of CRs in our Galaxy below the knee.

We have found that the value $T = 3 \times 10^{12}$ s $\sim 10^5$ yr appears as the most suitable tracking time of particles for the study of nuclei escape rate from the Galaxy. We note that we use only one value of tracking time for whole energy range of particles. The propagation of particle was stopped in a moment when the particle escaped from the Galaxy. From the values of the particle escape one can easily calculate the chemical composition of CRs.

Our starting chemical composition is taken from [Wiebel-Sooth et al. (1998)], who summarized results of several experiments for energy 10^{12} eV. We have divided all nuclei into five groups according to their mass. From each group we choose a nucleus that is the best representative. In this way we have chosen protons and nuclei of helium, oxygen, magnesium and iron as group representatives, with initial abundance equal to 42%, 26%, 13%, 9% and 10%, respectively. As the indicator of the composition, we use mean value of the logarithm of mass number A,

$$\langle \ln(A) \rangle = \frac{\sum n_i (\ln(A_i))}{\sum n_i}, \tag{7}$$

where n_i denotes the number of elements i with mass number A_i. The initial composition at 10^{12} eV is $\langle \ln(A) \rangle = 1.41$ ([Wiebel-Sooth et al. (1998)]).

Results and conclusions

We find following results in our simulation:

- All protons leave the Galaxy as first at energy equal to 4×10^{17} eV closely followed by nuclei of helium and for energies higher than 10^{18} eV no particle will remain in Galactic disk (see Fig. 3).

- We have found that more than 90% of the particles above 10^{16} eV are escaping independently of their charge from the regular magnetic field. We believe that the different nuclei escape rate for the energies above 10^{16} eV is caused mainly by random component of GMF.

- The leakage of nuclei from the Galaxy depends significantly on the characteristics of turbulent magnetic fields (field's strength, their dimensions and locations in the Galaxy and also on the number of cells with turbulent magnetic field). It follows from our simulations that the higher the fraction of the cells with turbulent magnetic fields, the slower is the leakage. The reason is that the magnetic field in cells is equal to the sum of field's strength of regular and turbulent component ($B_{\text{regular}} + B_{\text{turbulent}} \geq B_{\text{regular}}$). Therefore the nuclei are trapped in these cells and their leakage from the Galaxy decreases.

- The behavior of protons and helium nuclei are very similar in the whole studied energy range. They escape more easily than nuclei with higher charge (oxygen, magnesium and iron). Despite of it, they still play important role in CRs, because of their dominant abundance in the initial composition of CRs (comprising together more than two thirds of all particles).

- The result of the different nuclei escape rate is the increase of the abundance of heavier nuclei in the chemical composition of CRs. The comparison of the chemical composition resulting from our modelling with the measurements[3] is shown in Fig. 4. Experimental

[3] We compare our results only with a few experiments, the full review of other can be found in [Wiebel-Sooth et al. (1998)] and references therein.

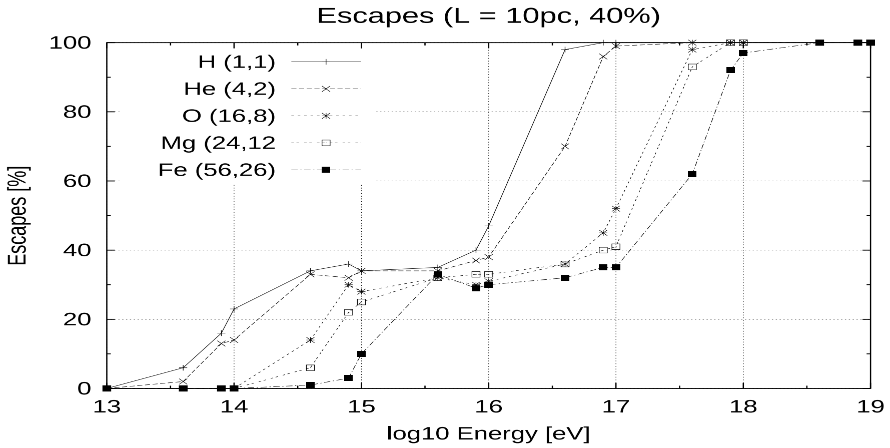

Figure 3. An example of nuclei escape rate from global GMF improved by turbulent MFs located in 40 percents of cubic cells with size equal to 10 pc.

data show unique results only for the energies below 10^{14} eV, where they have measured slight increase of mean $\ln(A)$. Above 10^{14} eV the results of two balloon experiments JACEE ([Takahashi (1998)]) and RUNJOB ([Apanasenko et al. (2001)]) disagree. RUNJOB shows no change in the chemical composition (constant value of mean $\ln(A)$), whereas data from JACEE indicate increase of mean $\ln(A)$. The experimental results from RUNJOB are in agreement with our results, when we modelled the turbulent magnetic fields by the cells with dimension equals to 10 pc. In the case with larger dimension of cells (50 pc) we have found higher leakage of light nuclei (proton and helium) which leads to the same increase of mean $\ln(A)$ as was measured by JACEE.

For energies above 10^{15} eV we have choosen only data from KASCADE ([Hörandel (2002)]). Two methods of data processing show increasing mean $\ln(A)$ from the value equal to the initial composition at 10^{12} eV to the value, when the majority of cosmic rays is composed by heavy elements. Third way (neural net) way gives different results, firstly decrease from the value $\langle \ln(A) \rangle = 2$ to the initial value and above energy equal to 10^{16} eV increase to high value of mean $\ln(A)$.

The results of our modelling have following characteristics above 10^{15} eV: The modelling with only regular GMF does not agree with experimental data, while the cases with turbulent MF show correctly the increase of the abundance of heavy elements at high energies. The discrepancy with the measurements in the cases with turbulent MF makes the value of the energy, where the increase of mean $\ln(A)$ starts. If we take the energy equal to 3×10^{15} eV (knee) as correct, then the differences will be half magnitude and one magnitude for dimensions of cells equal to 10 and 50 pc, respectively. We have found that this discrepancy does not strongly depend on general parameters of our modelling (the tracking time and height of Galactic disk), we believe that this discrepancy can be removed only using more realistic method of modelling motion of atomic nuclei (for review see [Gaisser (1990)]).

- The different leakage of nuclei from GMF produce a breake at energy 10^{16} eV in our modelling, similar to observed characteristic of cosmic ray flux, known as the knee (3×10^{15} eV). Thus our simple model of the propagation of Galactic cosmic rays favour theory about origin of the knee presented by [Ptuskin et al. (1993)].
- We can rule out the model of propagation in GMF without turbulent MF, because there is no agreement with measurements.

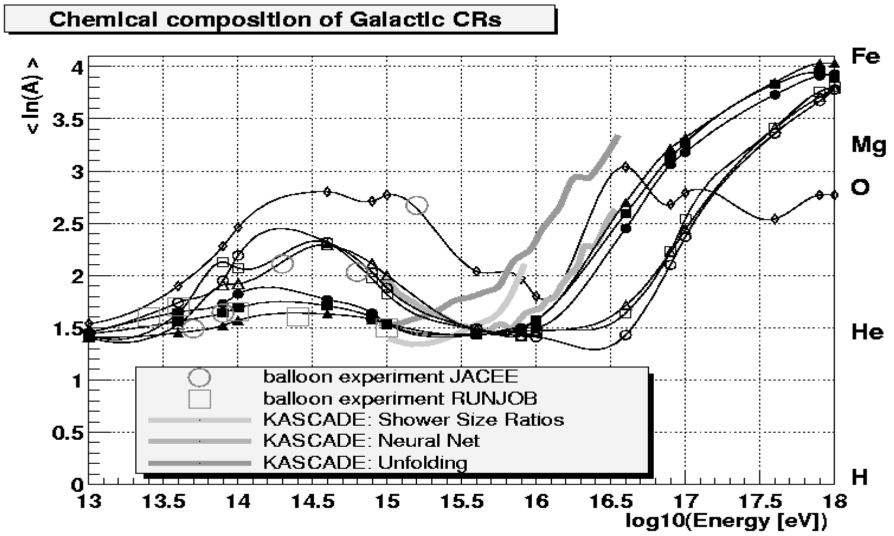

Figure 4. Change of nuclei composition as a result of nuclei escapes from Galactic disk compared with experimental results. The line with diamonds corresponds to modelling without turbulent magnetic field, the lines with circles, squares and triangles indicate number of cells with turbulent magnetic field equal to 10 %, 20 % and 40 % respectively; filled for dimension of cells equal to 50 pc and empty for 10 pc.

The used method is a simple way to simulate the propagation of CR within wide energy range. Despite of good attained results we conclude that the propagation of particles must be solved by more realistic method, especially for particles with energies below 10^{16} eV. We used only one type of the source in the Galactic midplane with constant chemical composition. However, there are indications that we must expect more types of sources in the Galactic and extragalactic space resulting in more complicated cosmic ray flux.

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