The Galactic Magnetic Field and Propagation of Ultra-High Energy Cosmic Rays

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Abstract. The puzzle of ultra-high energy cosmic rays (UHECRs) still remains unresolved. With the progress in preparation of next generation experiments (AUGER, EUSO, OWL) grows also the importance of directional analysis of existing and future events. The Galactic magnetic field (GMF) plays the key role in source identification even in this energy range. We first analyze current status of our experimental and theoretical knowledge about GMF. Then we present two examples of simple applications of influence of GMF on UHECR propagation. Both examples are based on Lorentz equation solution. The first one is basic directional analysis of the incident directions of UHECRs and the second one is a simulation of a change of chemical composition of CRs in the energy range $10^{13} \div 10^{19}$ eV. The results of these simple analyses are surprisingly rich — e.g. the rates of particle escape from the Galaxy, the amplification of particle flux or a possible Galactic origin of ultra-high energy cosmic rays.

Key words. Cosmic rays – Magnetic fields – Galaxy: general

1. 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. 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. The interesting aspect of the extragalactic CRs with energies exceeding 50 EeV are the energy losses due to the interactions with cosmic microwave background. These energy losses[2] constrain detected UHECRs to have been produced either in the Galaxy or in the sources within 100 Mpc. This distance restriction is known as Greisen-Zatsepin-Kuzmin (GZK) cutoff (Greisen, 1966, Zatsepin & Kuzmin, 1966).

Earth's atmosphere absorbs high energy cosmic rays and so they reveal their existence on the ground only by indirect effects such as ionization and showers of secondary charged particles covering areas up to many km². The energy flux of CRs is rapidly decreasing with their increasing energy. We observe one particle per m² per year at energies of 10^{15} eV but only one particle per km² per year at energies of 10^{18} eV. Thus, we need a large detector to find and measure these rare events. In the next decade the Pierre Auger Observatory should be able to collect several hundreds of events above the GZK cutoff, at least ten times more than all events detected up to now.

We use simple method to model the propagation of cosmic rays in a wide range of energy (from 10^{13} eV to the highest value ever detected 3.2×10^{20} eV). Although it is

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[1] For the purposes of this article we define ultra-high energy cosmic rays (UHECRs) as cosmic rays with energy above 10^{19} eV and extremely high energetic cosmic rays (EHECRs) as cosmic rays with energy above 10^{20} eV.

[2] Mean interaction length is about 6 Mpc, energy loss is about 20 % of actual particle energy per collision.

the simplest method of modelling the propagation of CRs (purely solution of Lorentz equation) we are showing that it can be successfully used for different applications. The results of modelling the directional analysis of UHECR and the chemical composition of Galactic CRs are presented in this work for one model of GMF. In addition, we notice that there are other models of GMF and we also investigate the influence of turbulent magnetic fields.

2. Galactic magnetic field

2.1. Experimental evidence

The first evidence of the existence of a Galactic magnetic field 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. This method is also used for the determination of the global structure of the magnetic fields in the external galaxies. From these measurements it follows that the Galactic magnetic field has two components — regular and turbulent (Rand & Kulkarni (1989)).

Random fields appear to have a length scale $50 \div 150$ pc and they are about two or three times stronger than the regular field. These random field cells have such a small scale (in comparison with kiloparsec scale of Larmor radii of UHECRs) that they are not modelled within global GMF models. However, it follows from recent work of Harari et al. (2002) or Alvarez-Muñiz et al. (2002) that turbulent field plays key role in the clustering, magnification or multiplying of the source images.

We are able to summarize our direct experimental knowledge about the Galactic magnetic field in several statements (according to Beck (2001) and Widrow (2002)):

– The strength of the total magnetic field in the Galaxy is (6 ± 2) μG in the disk and about (10 ± 3) μG within 3 kpc from the Galactic center.
– The strength of the local regular field is (4 ± 1) μG. This value is based on optical and synchrotron polarization measurements. Pulsar rotation measures give more conservative and approximately twice lower value. These rotation measures are probably underestimated due to anticorrelated fluctuations of regular field strength and of thermal electron intensity. On the other hand, optical and synchrotron polarization observations could be overestimated due to presence of anisotropic fields.
– The local regular field may be a part of a Galactic magnetic spiral arm, which lies between the optical arms.

– The global structure of the Galactic field remains unknown.
– Existence of two reversals in the direction towards Galactic center was confirmed recently. The first reversal is lying between the Local and Sagittarius arm, at ~ 0.6 kpc from the Sun, the second one is lying at ~ 3 kpc from the Sun. Some of the Galactic reversals may be due to large-scale anisotropic field loops.
– As expected from the beginning of the 1990s and also recently confirmed, the Galactic center region contains highly regular magnetic fields with strengths up to 1 mG. This extremely intensive field is concentrated in thin filaments oriented perpendicularly to the Galactic plane. The characteristic length of these filaments is about 0.5 kpc.
– The local Galactic field is oriented mainly parallel to the plane, with a vertical component of only $B_z \simeq (0.2 \div 0.3)$ μG, which agrees well with the results obtained for other galaxies.
– The Galaxy is surrounded by a thick radio disk with a scale height of about 1.5 kpc, similar to that of the edge-on spiral galaxies. The field strength in this thick disk is not known, but the global dipole field in the thick disk is also possible.
– The local Galactic field in the standard thin disk has an even symmetry with respect to the plane (it is a quadrupole). This is in the agreement with the galactic dynamo model, which is briefly discussed in the next paragraph.

Other facts used in modelling of GMF have indirect character — they are usually derived from the observations of the other spiral galaxies and of the structure of their magnetic fields or from existing proposals of the mechanisms of magnetic field generation. In general, it is expected, that the Galactic magnetic field encompasses the entire Galactic disk and shows some spiral structure. Further research and measurements in this field have vital importance not only for the observations of UHECRs, but also for the whole cosmic-ray physics and for other astronomical applications, e.g. for Galactic dynamics.

2.2. Theoretical global models 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), based on the Faraday-rotation measurements of 134 pulsars. The model assumes a two-arm logarithmic spiral with the constant pitch angle[3] p and shows π-symmetry, so it is bisymmetric (BSS) magnetic field model. More exactly, it has also a dipole character (it has field reversals and odd parity with respect to the Galactic plane), so it is called BSS-A model.

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[3] The pitch angle determines the orientation of local regular magnetic field. Its sense is clear from Fig. 1. Precise definition of pitch angle is not unique, in this work we used the definition proposed by Han et al. (1999): The galactic azimuthal angle Θ
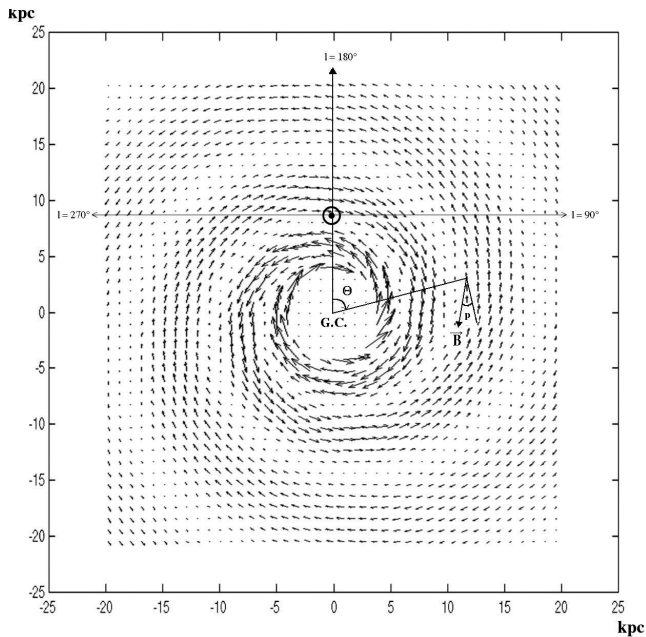
Fig. 1. Direction and strength of the regular magnetic field in the Galactic plane is represented by the length and direction of the arrows. The field inside the Galactocentric circle of radius 4 kpc is taken as constant, 6.4 μG. The model was constructed using parameters from Stanev (1997) and Han et al. (1999), which are in detail described in the text. The sense and orientation of the field and of the angles Θ and p follows from the figure. G.C. denotes the Galactic centre (at $l = 0°$).

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:

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

$$B_r = B_0(r) \cos \left(\Theta - \beta \ln \frac{r}{r_0} \right) \sin p. \tag{3}$$

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

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is defined to be increasing in the direction of galactic rotation. Logarithmic spirals are then defined by:

$$R = R_0 e^{k\Theta}, \tag{1}$$

where R is the radial distance and R_0 is the scale radius. The pitch angle is then $p = \arctan(k)$. This angle is negative for trailing spirals such as in our Galaxy, where R increases with decreasing azimuthal angle Θ. For our Galaxy, the galactic angular momentum vector points toward the south Galactic pole, and Θ increases in a clockwise direction when viewed from the north Galactic pole.

strength at $l = 0°$ (in the discussed model it has a value $r_0 = 10.55$ kpc) and for $B_0(r)$ it holds:

$$B_0(r) = 3\frac{R}{r}, \tag{4}$$

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

The vertical (z) component of the field is taken as zero in approximate agreement with observations. Results of this model are depicted on Fig. 1 and the orientation of the whole system is also clear from this Figure.

The size and field strength in the Galactic halo is extremely important for the cosmic-ray trajectories, but it is very poorly known, as we stated above. Obvious approach to this problem is represented by the work of Stanev (1997), where the field above and under the Galactic plane is taken as exponentially decreasing:

$$|B(r, \Theta, z)| = |B(r, \Theta)|e^{(-|z|/z_0)}, \tag{5}$$

where $|B(r, \Theta)|$ is the vector sum of magnitudes of B_r and B_Θ, with the $z_0 = 1$ kpc for $|z| < 0.5$ kpc and $z_0 = 4$ kpc for $|z| > 0.5$ kpc.

This model was further used also in the described configuration in our computer simulations of the propagation of UHECRs in the GMF.

Alternative models with another field configurations were also proposed. The another possible but according to recent observations a bit less probable configuration is the so-called ASS-S configuration, axisymmetric configuration without reversals and with even parity (Stanev (1997)). However, this configuration has one advantage. It could be much easier modeled using of the very popular dynamo model of magnetic field generation (Elstner et al. (1992)). The bisymmetric mode can also be obtained from dynamo model, but in such case the use of strong non-axisymmetric perturbations is necessary. The other two possibilities of magnetic field configurations — bisymmetric dipole type (BSS-S) and axisymmetric quadrupole type (ASS-A) are also not completely observationally excluded yet (Beck et al. (1996)). Furthermore, some models (Rand & Kulkarni (1989)) employ third basically different type — magnetic field arranged in concentric rings, hence with the pitch angle $p = 0°$. This model seems not to be corroborated by recent observations (Beck (2001)).

The dynamo model has one very interesting consequence for the propagation of CRs — namely that except of relatively flat field in the galactic disc it contains also quite strong toroidal fields above and under the galactic plane. Motions of these fields and their superpositions generates the net field in the Galaxy. The existence of such field is indirectly supported by the existence of radio thick disc mentioned above in the review of observation results. Such field would change the CR trajectories quite essentially, but this type of models was not yet used for UHECR propagation simulation.

3. Propagation of UHECRs in GMF

Within the next sections we describe two simple analyses of cosmic ray propagation in GMF. These analyses are done in different energy ranges and are serving for derivation of different conclusions, but they are involving the very same principles of particle motion in magnetic fields:

The propagation of the main part of UHECR (or more generally of cosmic rays) candidates (charged particles like nucleons, nuclei, electrons, ...) is of course influenced by the magnetic fields. This influence is given simply by the well-known Lorentz equation. The member with electric field in this equation could be neglected, because there is no evidence for large-scale electric fields in the Galaxy. For the acceleration $\boldsymbol{a}$ we get then:

$$\boldsymbol{a} = \frac{q}{m}(\boldsymbol{v} \times \boldsymbol{B}), \tag{6}$$

where q is the charge of particle, m is its relativistic mass, v its velocity[4] and B is the magnetic field strength.

Taking $\boldsymbol{B}$ as constant in suitable small volumes the trajectory of a particle is followed and the resulting deflection is examined.

4. Application No.1: Directional analysis of UHECR

4.1. "Antiparticle tracing" method and recent works

Some computer simulations in the UHECR range were treated for this purposes recently and the effects especially on the changes in spatial distribution were studied.

The method of "antiparticle tracing" is used in all these models. The particle carrying the opposite charge starts its propagation on the position of the Earth in the Galaxy. Its initial velocity vector has spherical coordinates $\sim c, b, l$, where c is the velocity of the light and b and l are the galactic coordinates of the detected particle arrival. Because of the opposite charge such particle traces backwards the trajectory of original detected particle. When the particle leaves from the sphere of influence of the Galactic magnetic field, we are able to evaluate its new galactic coordinates and thus its initial direction before the entrance into GMF.

The first work was published by Stanev (1997). It analyzes the motion of UHECRs in conservative models of BSS-A and ASS-S GMF with similar parameters as were given above. Stanev (1997) examines the shifts for protons with energies ranging from $(2 \div 10) \times 10^{19}$ eV. The second article is by Medina Tanco et al. (1998). The particles with energy equal to 4×10^{19} eV are analyzed in this paper. The changes in regular distributions are followed for the ASS-S model of GMF and for the particles supoosed to be either protons or Fe nuclei. The basic results of both models (magnitudes of deflections) are in good agreement with our model discussed below.

Two other papers appeared recently. In these papers the GMF model of Stanev (1997) was employed to support of specific arguments. Firstly, O'Neill et al. (2001) assumed iron nuclei as the only component of UHECRs and the authors were trying to identify the sources as very young pulsars. Secondly, Tinyakov & Tkachev (2001) investigated correlation between the positions of UHECRs propagated outside from Galaxy and of positions of specific type of blazars. They focused on possible identification of these blazars as UHECR sources and significant attention was payed also to analysis of clustered UHECR events.

Two other works propose the large Galactic magnetic halo with very intensive fields. The first article was published by Ahn et al. (1999), they speculate about large and intensive purely azimuthal magnetic field in the Galactic halo. This field should exist as an analogy to a solar wind and should extend to about 1.5 Mpc. In spherical coordinates r, θ, ϕ it holds then

$$B_\phi = B_S R \frac{\sin\theta}{r}, \tag{7}$$

where $B_S R$ is the normalization factor derived from the values in the solar surroundings, which is equal to 70 μG.kpc. If such field is introduced, the positions of 11 out of 13 EHECRs from Haverah Park, Volcano Ranch, Fly's Eye and AGASA should fall within 20° spherical cap around M87 position. This hypothesis was challenged shortly after its publication by Billoir & Letessier-Selvon (2000). They proved that this at the face-value exciting fact, that M87 could be a single source of UHECRs, is simply based on the fundamental property of the used magnetic field model in halo. The used model of an azimuthal field is simply focusing all positions into the direction of Galactic north pole and M87 is lying near to this pole, and so the small angular distance between computed EHECR positions and between M87 is probably just an interesting coincidence without fundamental physical importance.

The second work was published by Harari et al. (2000) and it proposes the Galactic magnetic wind extending to 1.5 Mpc. The model examines focusing abilities of magnetic wind. Model of the magnetic wind used in this work is purely azimuthal:

$$B = B_7 \frac{r_0}{r} \sin\theta \tanh\left(\frac{r}{r_s}\right), \tag{8}$$

It describes B as a function of the radial spherical coordinate r and the angle to the north galactic pole θ. The term r_0 in this equation is the distance from the Earth to the Galactic center (equal to 8.5 kpc), factor r/r_s was introduced to smooth out the field at small radii (r_s was taken as 5 kpc). B_7 is the normalization factor (the strength of the field in [7 μG] units) and so in conservative models of GMF B_7 should be $\sim 0.3 \div 0.4$. As it is shown in our combined Fig. 2, such magnetic field has to sweep out some fraction of the southern Galactic hemisphere. However, using the data from SUGAR which are also plotted into this

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[4] Almost equal to velocity of light c; UHECRs are reaching the highest known relativistic γ-factors, about 10^{11}.
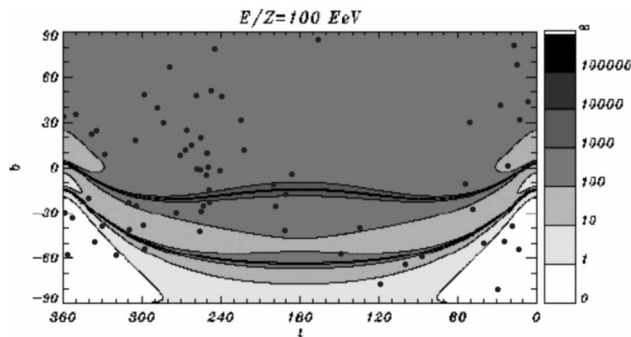
Fig. 2. Contour plots of the amplification of cosmic-ray flux by the Galactic wind (according to Harari et al. (2000)). The plotted dependance of the flux on arrival directions to the Earth was computed for initial isotropic distribution of point sources (outside of the Galaxy) and for $\bar{E} = 10^{20}$ eV. Figure was superposed with coordinates of SUGAR events (black dots) of the arrivals of most energetic particles ($\geq 4 \times 10^{19}$ eV according to Hillas E model of energy estimation of SUGAR events). There are some SUGAR events inside of the white triangle-shaped areas (bottom corners), where the zero cosmic-ray flux is expected.

figure, we are able to show that a such model could not be completely correct. This is due to the fact that these regions with proposed zero particle flux — in contrary to the theoretical expectations — contain several SUGAR events.

Finally, two interesting works treating the turbulent fields appeared recently. Alvarez-Muñiz et al. (2002) carefully analyzed the influence of turbulent fields on possible clustering of UHECRs and Harari et al. (2002) made large study of properties of typical turbulent fields with respect to amplification and multiplication of source images.

4.2. Computer Model

In our simulation we have supposed the conservative Galactic magnetic field model by Han et al. (1999), which was discussed in detail above.

Despite using various types of initial data, we present here only the results for real data. Namely, even such constrained set of data can sufficiently demonstrate all important changes of features of particle flux. These real data[5] were taken from our catalogue of UHECRs[6]. We propagate these particles through Galactic magnetic field assuming various charges — starting as protons (proton number $Z = 1$), continuing as oxygen nuclei ($Z = 8$) and ending with iron nuclei ($Z = 26$). All particles were traced back off the influence of Galactic field. The final distance

[5] The arrival direction (b, l) and energy E was used for each detected particle.

[6] This catalogue was created using available data from several various experiments: Data for from all UHECR experiments with energies above 10^{20} eV, data from AGASA experiment and data from SUGAR experiment for particles with energies above 4×10^{19} eV were used. The catalogue is available on-line (http://www-hep2.fzu.cz/Auger/catalogue.html).
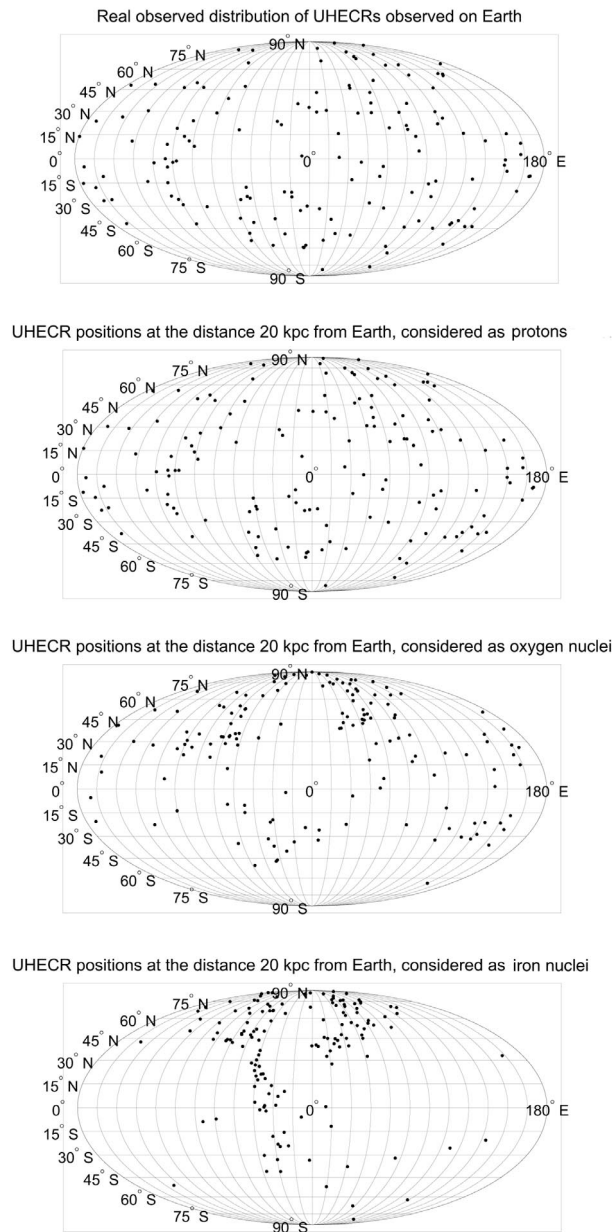

Fig. 3. The original arrival directions (in galactic coordinates) of 145 UHECRs are shown in the uppermost part of the Figure. The other three sky-maps (all in galactic coordinates) are showing the final positions of cosmic ray particles which were propagated to the distance 20 kpc from the Earth. The second map from the top shows final positions of protons (the average angle between the initial and final position of individual particle is $4.3° \pm 2.4°$ [s.e.]). The third map shows final positions of oxygen nuclei (average angle $35° \pm 26°$ [s.e.]) and finally the fourth map shows positions of iron nuclei (average angle $60° \pm 37°$ [s.e.]).

of each particle was assumed to be 20 kpc from Earth. We present here (Figure 3) the results of simulations corresponding the real UHECR data (145 UHECR positions and energies) taken successively as protons, oxygen and iron nuclei.

4.3. Results of particle tracking

We can state that the given deflection ranges (Fig. 3) are in good agreement with previous models (Stanev (1997), Medina Tanco et al. (1998) or O'Neill et al. (2001)) of propagation of UHECRs through the Galactic magnetic field. Hence we can formulate the following conclusions:

- The detail of global structure of GMF is still unknown, but despite that we can claim that its influence is non-negligible for protons and essential for Fe nuclei.
- The simulations of particles with higher charges (e.g. oxygen or iron nuclei) are transforming the isotropic distribution to structures, which show some regularities. The actual forms of these regular structures are rather uncertain, because of rough model of GMF, but their existence could be taken for granted and it is independent on the specific parameters of given model[7]. In accordance with Harari et al. (2002) we observe especially for oxygen and iron nuclei (Fig. 3) that at some places the initial flux is amplified, in other areas it is strongly suppressed.
- GMF is very important also for protons, because it is able to affect the small-angle clustering (as one can see on the second upper part of Fig. 3, where some initial small clusters were transformed into other ones). Small-angle clustering is today lively discussed and it is one of the key features in discrimination between some models of sources (Alvarez-Muñiz et al. (2002)).
- The possibility that the UHECRs originate in the Galaxy (e.g. near the young neutron stars in the form of iron nuclei) is not excluded (see the bottom part of Fig. 3). Furthermore, such UHECRs should originate only in several point sources in our Galaxy, what is again in accordance with the existence of pseudo-regular structures after propagation through the GMF (see also O'Neill et al. (2001) or Harari et al. (2002)).

The theory of Galactic origin of UHECRs could be also combined with the above mentioned fact that also relatively strong (~ 1 mG) fields exist in the form of filaments near Galactic center. In such field the Larmor radius of 10^{19} eV UHECR proton is only about 4 pc.

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[7] Of course, our simulation does not completely exclude the possibility that also the initial directions of particles before they enter into the Galaxy are isotropic. Our conclusions were derived only in one direction of implication — the observed isotropic distribution doesn't necessarily require the initial isotropic distribution for oxygen and iron nuclei. For test of opposite direction of implication we have to make another type of simulations — we have to inject huge numbers of particles isotropically distributed on spherical surface around Galaxy and then detect them on some tiny sphere (or other shape) around Earth's position. This problem was partially treated by O'Neill et al. (2001).

5. Application No.2: Chemical composition of CRs

5.1. Propagation of CRs in our model

We used very simple method to model the propagation of cosmic ray particles in a rather wide range of energy ($10^{13} \div 10^{19}$ eV). The model of regular magnetic field from Stanev (1997) was improved by the introduction 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 an 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. We neglected all possible interactions of particles with matter and kept the energy of particles constant.

Our Galaxy model has the following geometrical boundary: the bulge is a symmetric ellipsoid with a semi-major axis in the Galactic midplane 3 kpc long and a semi-minor axis of 2 kpc. Around the bulge there is a thin cylinder with a radius of 15 kpc and the half-height of 300 pc. Starting positions of particles reside in the Galactic plane inside a circle with a radius of 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 (Green (2001)). We injected all particles together at the starting time, rather than generating particles during the simulation.

As Gaisser (2001) and Brunetti & Codino (2000) have shown, the average time spent by cosmic ray in Galaxy of energy within the range $(1 \div 100) \times 10^9$ eV is $\tau \sim 10^{14}$ s. The energy dependence of τ can be measured by comparing the spectrum of the secondary nuclei to that of the parent primary nuclei. From observation one can deduce that at least in the range $10^{10} \div 10^{12}$ eV, the mean residence time varies approximately as $R^{-0.6}$ (Garcia-Munoz et al. (1987), Swordy et al.(1990) and Engelmann et al. (1990)), where $R = \frac{pc}{Ze}$ is the rigidity of particle with momentum p and atomic number Z. This extrapolation breaks down around 3×10^{15} eV (Gaisser (2001)) because the value of an effective escape length is equal to $c\tau \sim 300$ pc which corresponds to just one crossing of the Galactic disk and the probability of nuclei escape significantly rises. The situation within the highest energy range is not clear, but we expect that the nuclei are not trapped in GMF. The task we have to solve is to find the value of tracking time for the simulation of particles with energies in range $10^{13} \div 10^{19}$ eV. We have found that the value $T = 10^{12}$ s $\sim 3.2 \times 10^4$ yr appears as the most suitable tracking time of particles for the study of nuclei escape rate from the Galaxy. From the equation $\tau \sim R^{-0.6}$ we obtain the value 10^{11} s for proton with the energy in the middle of our range (which is equal to 10^{16}

eV).[8] Despite of it, we use tracking time longer by one order of magnitude. The reason for such choice is that: (1) The value obtained from the observations is valid only for the Galactic disk, where particles stay shorter time than in the Galactic bulge. (2) The mean residence time for nuclei with higher Z will be longer than for proton. (3) The nuclei escape rates are too high (too low) for longer (shorter) tracking times and as such they are not suitable for discrimination between the different nuclei. (We note that we use only one value of tracking time for whole energy range of particles.)

On the other hand the propagation of particle was stopped in a moment when the particle escaped from the Galaxy. The escape occurred when the particle crossed the Galaxy geometrical boundary. 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 the average value of the logarithm of mass number A,

$$< lnA > = \frac{\sum n_i (\ln A_i)}{\sum n_i}, \tag{9}$$

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

5.2. Results and conclusions

We have used only one model of regular GMF in our simulation, although it was improved by random components of the turbulent magnetic field. We have confirmed the influence of such turbulent magnetic fields on the propagation of CRs for all studied nuclei energies. On the other hand the magnetic field of Galactic halo was ignored.

We find following results in our simulation:

– The dependence of nuclei escape rate on the energy is similar for all configurations of magnetic fields. Above the energy of 10^{15} eV the dominant part of escaping particles come from the disk, to the contrary for the particles in the bulge. This is caused, as expected, mainly by the differences in the dimension of the Galactic disk and the bulge. It is worth of noting that the magnetic field in the bulge region is also stronger
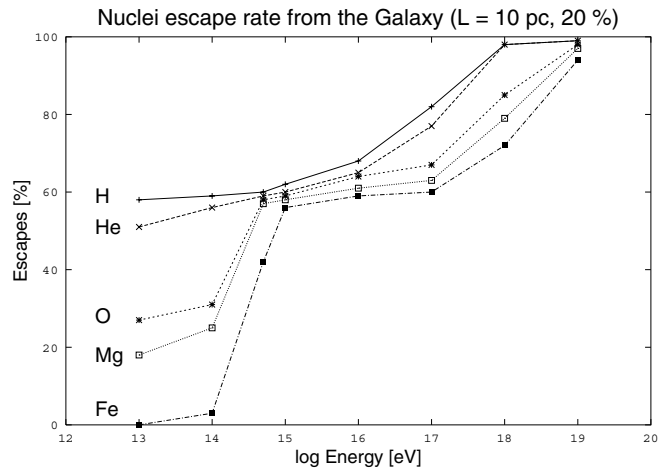

Fig. 4. An example of nuclei escape rate from regular GMF improved by turbulent MFs located in 20 percents of cubic cells with size equal to 10 pc. Because a majority of nuclei escaped from the disk with energy above 10^{15} eV, the rates of escapes are very similar as long as nuclei start to escape from the bulge. Then we can see again distinct differences in escapes in dependence on their charge.
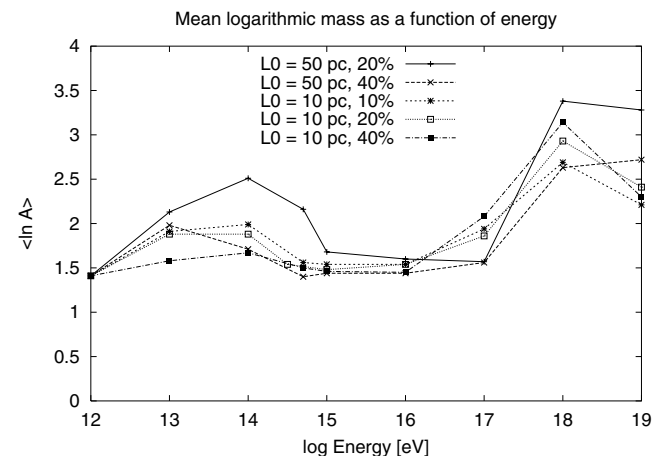

Fig. 5. Change of nuclei composition as a result of nuclei escapes from the whole Galaxy. We can see an increase of mean logarithmic function $< \ln(A) >$ for five different configurations of turbulent magnetic fields. (The decrease in energy range $10^{15} \div 10^{17}$ eV is caused mainly by differences in dimension of the Galactic disc and the bulge. See Fig. 4.)

than inside the disk. Particles are not escaping from the bulge untill they attain energies above 10^{16} eV. Then the leakage will behave in the same way as at the energy below 10^{15} eV inside the disk (Fig. 4). It is again a function of particle charge and we can observe an increase of the abundance of heavy elements (Fig. 5).

– We have found that only 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.

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[8] In fact, the average time spent by cosmic ray in Galactic disc will be shorter than the value obtained from the equation $\tau \sim R^{-0.6}$, because this approximation is not valid for energies above 3×10^{15} eV.

- 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 ($B_{regular} + B_{turbulent} \geq B_{regular}$). Therefore the nuclei are trapped in these cells and their leakage from the Galaxy decreases. Unfortunately all properties of turbulent magnetic fields, which are very important for the propagation of CRs, are not known enough.
- As mentioned above small part of particles above 10^{16} eV remains in the disk, but they do not escape and they even do not start to escape from the bulge. Hence we can infer that the change in chemical composition (see Fig. 5) for energy equal or below 10^{16} eV can be taken as the result of the particle propagation only in the Galactic disk.
- The behaviour 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 used method is a simple way to simulate the propagation of CR within wide energy range, but it is not capable to describe all observed characteristics of CRs. It is necessary to change our approximations and assumptions used in our modelling. The propagation of particles must be solved by more realistic method, for example by diffusion models (Gaisser (1990)), especially for particles with energies below 10^{16} eV (Ptuskin et al. (1993)). 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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