The spectrum of Galactic Cosmic Rays of the highest energies

Tadeusz Wibig* **and Arnold W. Wolfendale**†

*University of Lodz, Department of Physics ;
Soltan Institute for Nuclear Studies, Uniwersytecka 5, 90-950 Lodz, Poland

†Physics Department, Durham University, Durham, UK

***Abstract*. With measurements of cosmic rays of energy above 1 EeV being made with ever increasing accuracy it is necessary to realise that the residual Galactic spectrum has considerable interest as well as the Extragalactic component. An assessment will be made as to what information accrues about the sources of the Galactic particles and their mode of propagation in the Galaxy.**

***Keywords*: high-energy cosmic rays, Galaxy, Galactic magnetic field,**

I. Introduction

The question about the nature of the particles of the energies around the spectrum feature called the 'ankle', the sharp change of slope around 3 EeV, is one of the most important and still open questions in the Ultra High-Energy Cosmic Ray (UHECR) domain. It is believed that the ankle is related to the extragalactic (EG) origin of the cosmic ray particles. Already when the first UHECR event was observed [1] it was known that the Galactic field is to weak to contain it. Because the lower energy cosmic rays are known to be confined within the Galaxy there must be a point on the energy scale where the Galactic (G) particle flux starts to be dominated by the EG one. It is probably related to the ankle structure. [1]

Our analysis [2] of the shape of CR spectra measured for energies above 10^{17} eV by different Extensive Air Shower (EAS) arrays including recent data from PAO [3] and Hi-Res [4] experiments confirmed the universal shape of the ankle which can be read as a sum of the EG power-law component with an index of 2.1-2.4 and Galactic component which is again a power-law with an index of 3, as before the ankle, reduced by the $\exp(-((E - E_a)/\Delta_a)^2)$ factor above $E_a = 10^{17.5}$ eV [5]. We interpreted the reduction of the G component as caused by the escape of high energy cosmic rays from the Galaxy (the whole: Galaxy and possible Galactic halo region) to intergalactic space.

In the present work we examine this in more details.

[1] There is still a possibility that the G component energies are limited by the acceleration mechanism already at the sources. This idea is related to the final KASCADE experiment conclusion that the 'knee' structure of the CR energy spectrum below 10^{16} eV is a result of the fall of the light component (protons) and successive decreases of the heavier (higher Z) fractions of CR flux. The last Galactic component of iron then starts to drop at 26 × the 'knee' energy which is obviously not far but significantly below the beginning of the ankle. Thus all the ankle particles have to be of EG origin which makes the problem with the ankle shape (if produced by e^+e^- energy losses it needs a pure proton EG flux) and with the total CR energy density.

II. Galactic magnetic fields

A. Regular Galactic field

There are four models of the regular Galactic magnetic fields studied in the present paper.

1) Harari et al. [6]: It is bi-symmetric with even symmetry, which is the preferred model for our Galaxy. The local value in the Sun's vicinity is $B \approx 2\mu$G and it points in the direction $l = 90° + p$ where the pitch angle is $p = -10°$.

In the Galactic Plane ($z = 0$) the field, directed along the spiral arms, has strength

$$B_{sp} = B_0(r)\cos(\theta - \beta \ln(r/\xi_0)). \qquad (1)$$

The angle θ is the azimuthal coordinate around the Galactic Center (clockwise as seen from the North Galactic Pole), r is the Galactocentric radial cylindrical coordinate, $\xi_0 = 10.55$ kpc corresponds to the Galactocentric distance of the maximum of the field in our spiral arm and $\beta = 1/\tan p$.

The field strength

$$B_0(r) = \frac{3r_0}{r}\tanh^3(r/r_1)\mu\text{G}, \qquad (2)$$

(with $r_0 = 8.5$ kpc the Sun's distance to the Galactic Center and $r_1 = 2$ kpc) has the $1/r$ behaviour at $r > 4$ kpc and goes smoothly to zero at the Galactic Center.

For the dependence on z, there are contributions coming from the disk and another from the halo. Both are reduced by the factor of $1/(2\cosh^2(z/z_i))$ with $z_{disk} = 0.3$ kpc and $z_{halo} = 4$ kpc.

2) Alvarez-Muñiz and Stanev [7]: The regular Galactic field in the disk is assumed to have a two-arm logarithmic bi-symmetric spiral with radial reversal form. The local regular magnetic field in the vicinity of the Solar System is assumed to be $\sim 1.5\mu$G and the pitch angle is $p = -10°$. The field decreases with Galactocentric distance as $1/r$ and it is zero for $r > 20$ kpc. In the region around the Galactic Center the field is highly uncertain, and it is assumed that it is constant and equal to its value at $r = 4$ kpc. The spiral field strengths above and below the Galactic Plane are taken to decrease exponentially with two scale heights. The additional dipole field is assumed to be toroidal and its strength decreases with Galactocentric distance as $1/r^3$ with 0.3 μG in the vicinity of the Solar system directed toward North Galactic Pole.

3) Prouza and Ŝmida [8]: The third field analysed is the field proposed by Prouza and Ŝmida It is slightly more complicated toroidal and has dipole structures above and below the Galactic plane.

4) Wainscoat et al. [9]: The fourth is the one with the bi-symmetrical spiral structure taken not from the simple analytic formula as previously but the compilation of different observations made by the Authors There is the 'local arm' introduced among the other four. The magnetic field is supposed to be radial reversal similar to that used for other models. The off-plane regular field is the same as been proposed by Prouza and Ŝmida.

B. Random Galactic magnetic field

Concerning the random field two main models were examined. The single size cells with constant magnetic field vector value and its direction chosen randomly is one. The second is the Kolmogorov turbulence model. The random field was normalized to have the assumed field in the vicinity of the Solar System (8.5 kpc from the GC). This field strength is one of the parameters we studied in the present work.

The average value of the random field component could remain constant in the whole Galaxy and the halo, but we have tested also two other possibilities. The one is the smooth decrease (given above in Sec. II-A1: roughly exponential fall in the z direction and inversely proportionality to $r_{\rm xy}$ – $\langle|\vec{B}_{\rm rnd}|\rangle \sim 1/[\sqrt{1+r^2/4^2}\ \sqrt{1+z^2/5^2}]$). We have also tested the model with the average value of the random field changing along with the value of the regular field ($\langle|\vec{B}_{\rm rnd}|\rangle \sim |B_{\rm reg}|$).

The propagation takes place inside a cylinder of radius of 20 kpc and the height which is the subject of the present studies. Two possibilities were tested: -1 kpc$<z<1$ kpc and -10 kpc$<z<10$ kpc.

1) A Kolmogorov turbulent magnetic field: A turbulent picture of the intergalactic (and Galactic) random magnetic fields is defined by the Fourier modes and their power spectrum

$$B(x) = \int \frac{d^3k}{(2\pi)^3} B(k) e^{i(k\cdot x+\phi(k))}, \qquad (3)$$

where $\phi(k)$ are random phases, and $2\pi/L_{\rm min} < k < 2\pi/L_{\rm max}$ and $L_{\rm min}$ are the lower and upper limits of the magnetic field turbulence scales, respectively.

In the present paper, a particular turbulent random field was realized by replacing the integration in Equation 4 by the sum of 5000 independent Fourier components, each with randomly chosen value of k (limited by $L_{\rm min}$ and $L_{\rm max}$) and random phase ϕ (in the plane perpendicular to k to assure $\vec{\nabla}\cdot\vec{B}=0$). The sum was then normalized to yield the assumed $\langle|B(x)|^2\rangle$.

For the present calculations we have used $L_{\rm min} = 1$ pc and $L_{\rm max} = 100$ pc.

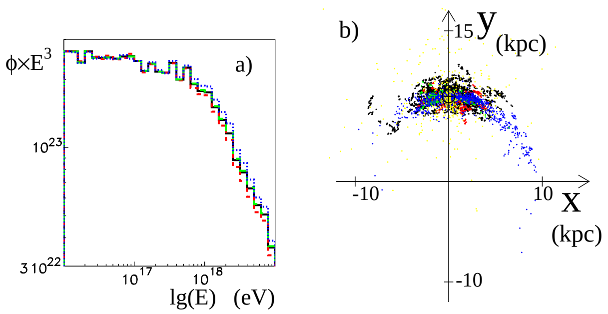

Fig. 1. a) CR Galactic component in the particular magnetic field realization. The different histograms represent uniform (black solid line), [10] (green - dashed almost exactly follow the uniform case), [11] (red - dashed) and the blue (dotted) line for the source density proportional to the magnetic field; b) CR sources contributing to the flux observed at the Earth. Different colors represent different particle energies: black - $10^{16}-10^{17}$eV, red - $10^{17}-10^{18}$eV, green - $10^{18}-10^{19}$eV, blue - $10^{19}-10^{20}$eV, yellow - above 10^{20}eV. For each decade 10000 of events was plotted (except for the $>10^{20}$eV case.

III. RESULTS

The CR are assumed to be produced in a thin disk ($z = 0$, exactly the Galactic plane). In the first approximation the sources can be distributed uniformly, but some radial dependence would be more realistic. We analysed three possibilities: the exponential with characteristic length of 15 kpc as Ref. [10], the broken line approximation from Ref. [11] with maximum density of sources around 7 kpc from the Galactic Centre, and the case of sources distributed along the same spiral structure as the magnetic field. Sources very close to SS (closer than 100 pc) were excluded to help reduce the fluctuations due to the relatively low energy particles trapped by random fields.

First we would like to show that the effect of the source distribution is not very important, when it is not very fast changing function of position close to the Earth.

In Fig.1a we present the CR fluxes calculated according to the different distributions of CR sources. It is clear that the effect is very small. It is understood when one look at the distribution of the sources which contribute to the CR flux *measured* at the Earth. It is shown in Fig. 1b.

The smooth radial change of the source distribution can not make a big difference. The situation in Fig.1 is typical for most of the field representations which give reasonable contributions to the Galactic flux. The particular one used in Fig.1 is the regular field of Alvarez-Muñiz and Stanev with the Kolmogorov random field smoothly decreasing with Galactocentric radius and of strength (near the Sun) of 4 μG. The halo size was set to 10 kpc. This is not the best configuration we found.

For further studies we will apply the uniform source distribution.

In all Figures 2-4, the attenuation by the CMB is not shown.

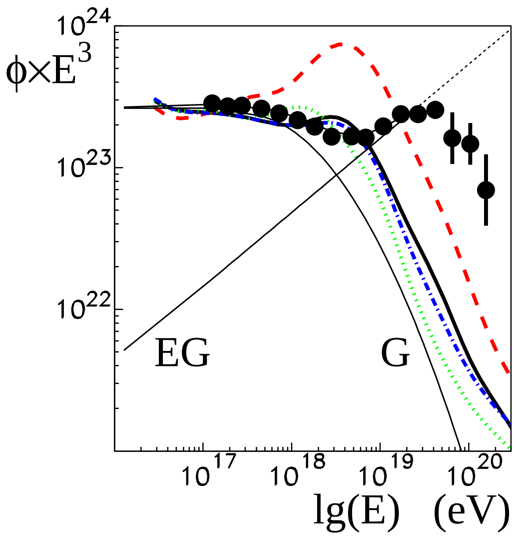

Fig. 2. CR spectra obtained with different Galactic regular magnetic field: [6] - black solid, [7]- red dashed, [8] green dotted, and [9] blue dash-dotted. The points are the 'world summary' from [2] and the thin lines shows the discussed model of G+EG composition of UHECR flux from [5].

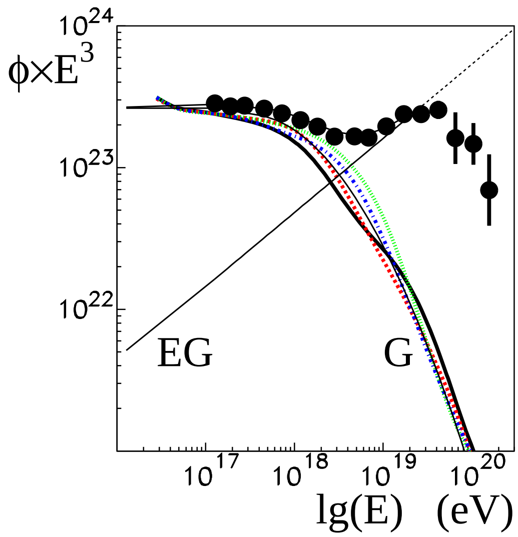

Fig. 3. 'The best' spectra for different regular field configurations: [6] - black solid, [7]- red dashed, [8] green dotted, and [9] blue dash-dotted.

A. *Galactic component spectrum*

We have studied the effect of changing the regular structure of the Galactic magnetic field to check how big the change can be within reasonable limits of uncertainty about the spiral field.

The results are shown in Fig.2. The random field used was in all cases the same - the constant value of 4 μG vector randomly changing its direction each 100 pc traversed by the UHECR particle. The differences are seen but they are not very dramatic. It should be checked then, if these differences are compared with slight modification of the random field component and the halo size.

After extensive simulation searches it is concluded that for each regular field the random field configuration can be roughly adjusted with the same value of magnetic field in a vicinity of the Sun ($\langle|\vec{B}_{\rm rnd}|\rangle = 4\mu$G), the particular results are given in Fig. 3 and the field configurations are:

Harai *et al.*:

$\vec{B}_{\rm rnd}$ - Kolmogorov turbulence;

$\langle|\vec{B}_{\rm rnd}|\rangle \sim 1/(\sqrt{1+r^2/4^2}\ \sqrt{1+z^2/5^2})$

-1 kpc$< z < 1$ kpc.

Alvarez-Muñiz and Stanev:

$\vec{B}_{\rm rnd}$ - Kolmogorov turbulence;

$\langle|\vec{B}_{\rm rnd}|\rangle \sim 1/(\sqrt{1+r^2/4^2}\ \sqrt{1+z^2/5^2})$;

-10 kpc$< z < 10$ kpc;

Prouza & Ŝmida:

$\vec{B}_{\rm rnd}$ - random change each 100 ps;

$\langle|\vec{B}_{\rm rnd}|\rangle \sim |B_{\rm reg}|$; -10 kpc$< z < 10$ kpc;

Wainscoat *et al.*: $\vec{B}_{\rm rnd}$ - random change each 100 ps; $\langle|\vec{B}_{\rm rnd}|\rangle \sim |B_{\rm reg}|$; -10 kpc$< z < 10$ kpc.

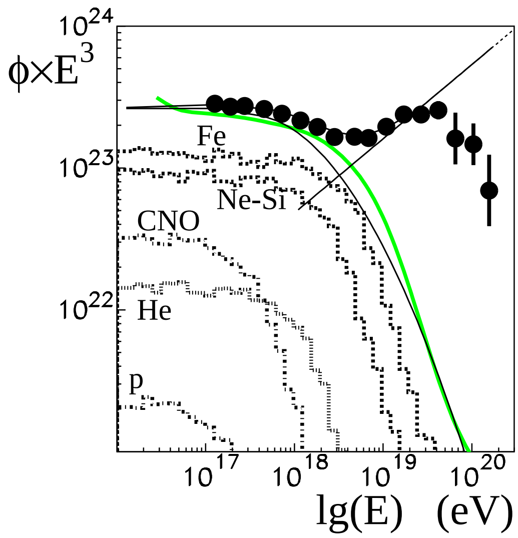

Fig. 4. 'The best' spectra for different regular field configurations shown as in Fig. 3.

B. *Mass composition*

The change of the composition at the end part of the Galactic component spectrum is shown in Fig. 4. The composition at the source is assumed to have p:He:CNO;Si-Ne:Fe= 3:30:7:30:30 according to the KASCADE measurement above the knee (around 3×10^{16}eV).

C. *Anisotropy*

The anisotropy related to the position of the sources within the Galactic disk can be, in principle, a big problem for the Galactic component at very high energies. However, as we have shown, the flux is, up to even very high energies, produced by the particles confined locally,

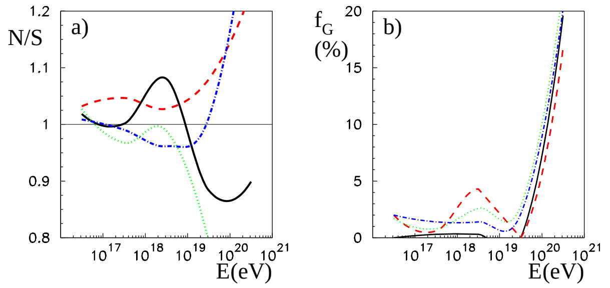

Fig. 5. a) N/S ratio and b) galactic plane enhancement factor for 'the best' adjusted regular field models and iron primaries.

and the role of the random field being here dominant, we do not expect big anisotropies. For the field models listed above we calculated values of two parameters which are of interest here: the North/South asymmetry defined as a ratio of the number of events registered from the Northern to the number of Southern hemisphere events, and the Galactic plane enhancement: the fraction of the number of events forming the particular enhancement over the uniform background in the galactic latitude UHECR distribution plot (details are described in, e.g., [12]). Both parameters are shown in Fig. 5. The N/S ratio is sensitive to the local regular field already around the energy of 10^{18}eV. The undoubtful effect is clearly seen above 10^{19}eV, where the flux of Galactic cosmic rays is about two orders of magnitude overwhelmed by the EG CR flux.

D. *Extragalactic CR deflections*

The small scale anisotropies of UHECR at extremely high energies, where there are no Galactic particles, are, however, disturbed by our Galaxy. The small angular deflection of these particles in the Galactic magnetic field is expected. If the consistent description of the Galactic component flux was found, it is worth estimating the effect on the extragalactic particles coming through it toward the Earth.

We are able to describe the regular component of the Galactic magnetic field, and can calculate the deflection of particles coming from any particular directions. We concentrate our attention on three direction which can be, on one hand, treated as examples showing the average effect and its variation, but, on the other hand, they are not completely 'random'. We choose them according to the analysis in [13] as the directions of three possible close sources of UHECR seen in the PAO anisotropy data. The examples of a few trajectories coming through the Galaxy is shown in Fig. 6.

The summary of deflections for all three sources and the final set of magnetic field models is given in the Table.

The deflection are not big, but they can be significant. For sources as close as CEN-A the Galactic field deflection ougth to be taken into account.

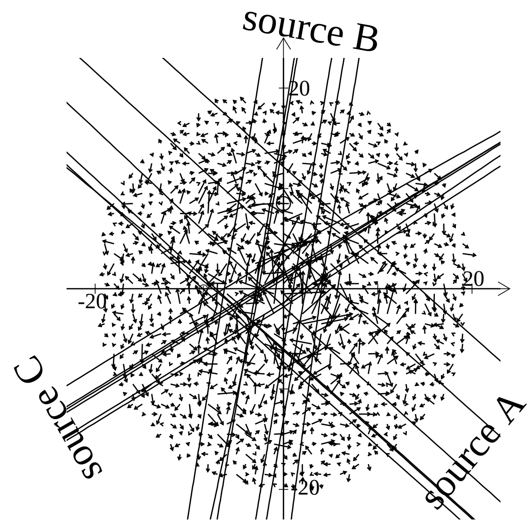

Fig. 6. Deflection of the EG protons of energies above 5.6×10^{19}eV coming from the directions of three sources.The particular magnetic field realization for the model of Harari *et al.* is shown.

TABLE I
MEDIAN DISPLACEMENTS (IN DEGREES) FOR EG PROTONS FROM THE SOURCES INDICATED. COMPARISON WITH OBSERVED DISPLACEMENTS GIVES AN ORDER OF MAGNITUDE ESTIMATE OF THE PARTICLE CHARGE, Z.

field model	source A	source B	source C
Harari *et al.*	0.8	0.4	0.5
Stanev *et al.*	1.0	0.8	1.2
Prouza and Ŝmida	1.2	0.6	0.6
Wainscoat *et al.*	1.7	1.1	1.7

IV. CONCLUSIONS

We have shown that the commonly used models of the Galactic magnetic field, regular as well as random, without substantial changes of the parameters can result in a Galactic component cosmic ray spectrum shape as needed to describe the shape of the ankle, e.g., in Ref. [5].

The deflection of the extragalactic CR particles above 5.6×10^{19}eV (reported to form the famous clusters in the PAO data) was found to be of order of 1° for all the field models used.

REFERENCES

[1] J. Linsley, Phys. Rve. Lett. **10**, 146 (1963)
[2] T. Wibig and A.W. Wolfendale, J. Phys. G **31**, 255 (2005).
[3] Watson, A.A, Proc 30th ICRC (Merida) (2007).
[4] R. Abbasi *et al.*, Phys. Rev. Lett. **100**:101101, (2008); P. Sokolsky and G. B. Thomson, J. Phys. G **34**, R401 (2007).
[5] J. Szabelski, T. Wibig and A.W. Wolfendale, Astropart. Phys. **17**, 125 (2002).
[6] D. Harari, S. Mollerach, and E. Roulet, JHEP 9908:022, (1999).
[7] J. Alvarez-Muñiz J. and T. Stanev, J.Phys.Conf.Ser. **47** 126, (2006).
[8] M. Prouza and R. Ŝmida, arXiv:astro-ph/0307165 (2003).
[9] R.J. Wainscoat *et al.*, ApJ Suppl. **83**, 111 (1992).
[10] M. Hareyama *et al.*, $28^{\rm th}$ ICRC, Tsukuba, Japan, Universal Academy Press, 1941 (2003).
[11] Strong, A&A **422**L, 47 (2004).
[12] T. Wibig and A.W. Wolfendale, J. Phys G **25**,2001 (1999).
[13] T. Wibig and A.W. Wolfendale, arXiv:astro-ph/0712.3403 (2007); "The Origin of Cosmic Rays of the highest energies" this conference.