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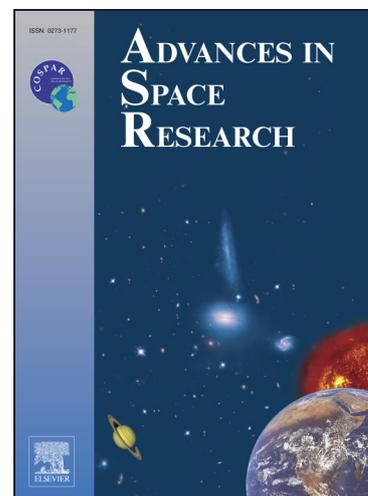
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Puzzles of the Cosmic Ray Anisotropy

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Abstract

We discuss three of the known puzzles of the cosmic ray anisotropy in the PeV and sub-PeV energy region. They are 1) the so called inverse anisotropy, 2) the irregularity in the energy dependence of the amplitude and phase of the first harmonic and 3) the contribution of the single source.

Keywords: inverse anisotropy, amplitude and phase, single source

1 Introduction

One of the most important and simultaneously most difficult studies of the origin of cosmic rays (CR) is the study of their anisotropy. The difficulty is due to the extremely low level of the anisotropy and the steeply falling energy spectrum of CR. In their seminal book 'Origin of Cosmic Rays' issued in 1964 V.L.Ginzburg and S.I.Syrovatskii could only give an upper limit of the anisotropy as $< 1\%$ [1]. More than 20 years later V.L.Ginzburg and his co-authors on the basis of data obtained by Linsley J. could show that the amplitude and phase of the anisotropy are not constant, but vary with the energy [2]. This variability is the consequence of the non-uniformity of the spatial distribution of CR sources and properties of the interstellar medium (ISM). Sources of different locations and ages contribute in different energy regions and magnetic fields of different strength and orientations tend to isotropise the arrival directions of CR particles.

One of the most interesting regions of the CR energy spectrum is sub-PeV and PeV region where the well-known 'knee' is observed. The study of this region is difficult because of the very small intensity of particles and low anisotropy level. That is why there are many unsolved problems and puzzles here which still wait for their solution. Below we describe only three of them.

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2 Puzzle 1: an inverse anisotropy

Due to CR scattering on the chaotic magnetic fields their motion in the Galaxy is like a diffusion from regions of higher to lower CR density. Since the solar system is located at about 8 kpc from the galactic center then the main source of CR - supernova remnants (SNR) and pulsars are concentrated in the Inner Galaxy. The CR density is higher towards the Galactic Center and their gradient is directed from the Inner to Outer Galaxy. Hence we have to expect some anisotropy with the maximum flux from the Inner Galaxy.

The expected and observed situation with the first harmonic of the anisotropy in the sub-TeV region is shown in Figure 1. The upper panel shows the amplitudes and it is seen that they do not exceed the value of 10^{-3} . The lower panel presents measurements of the phase in equatorial coordinates. If transferred to galactic coordinates they occupy the region delimited by two dashed lines. It is seen that when the expected phase of the maximum CR flux is from the Inner Galaxy with $\ell \approx 0^\circ$ [8], the observed phase occupies the longitude ℓ -region between 90° and -90° , i.e. CR come preferentially from the Outer Galaxy. We call this phenomenon an 'inverse anisotropy'.

One of the possible explanations of an inverse anisotropy is to assume that it is a local phenomenon caused by a spatial orientation of the magnetic field or the ISM density fluctuation. The Sun is located in the Local Bubble at the inner edge of the Orion spiral arm. The strength of the magnetic field and of the ISM density in the arm is higher than in the interarm region where the Local Bubble is located. The diffusion in the nearby Outer side of the Galaxy is slower than locally. CR moving from the Inner Galaxy meet like a wall, a part of them reflect from it, accumulate in a number and create an inverse gradient [9].

There might be an alternative explanation [10]. Recent measurements of CR at sub-TeV - sub-PeV energies demonstrated the irregular non-power law shape of the energy spectrum. As an example the spectral hardening at 200-300 GeV noticed in CREAM, PAMELA, AMS-2 experiments can be mentioned, the steepening at the magnetic rigidity of 10TV in the NUCLEON experiment and others. The observed irregularities point to the possible role of local sources. However, to be responsible for an observed inverse anisotropy these local sources should be located mostly in the Outer Galaxy.

We should underline that these explanations are only a possible assumption with many internal uncertainties. However, we should emphasize that the inverse anisotropy is most likely a local phenomenon, which is caused by the reflection of CR from a nearby region of higher ISM density or the dominance of some local sources in the Outer Galaxy.

3 Puzzle 2: peculiarity of the amplitude and phase

In general there are several features noticeable in Figure 1:

- (i) a good consistency of the results at energies up to a few PeV;

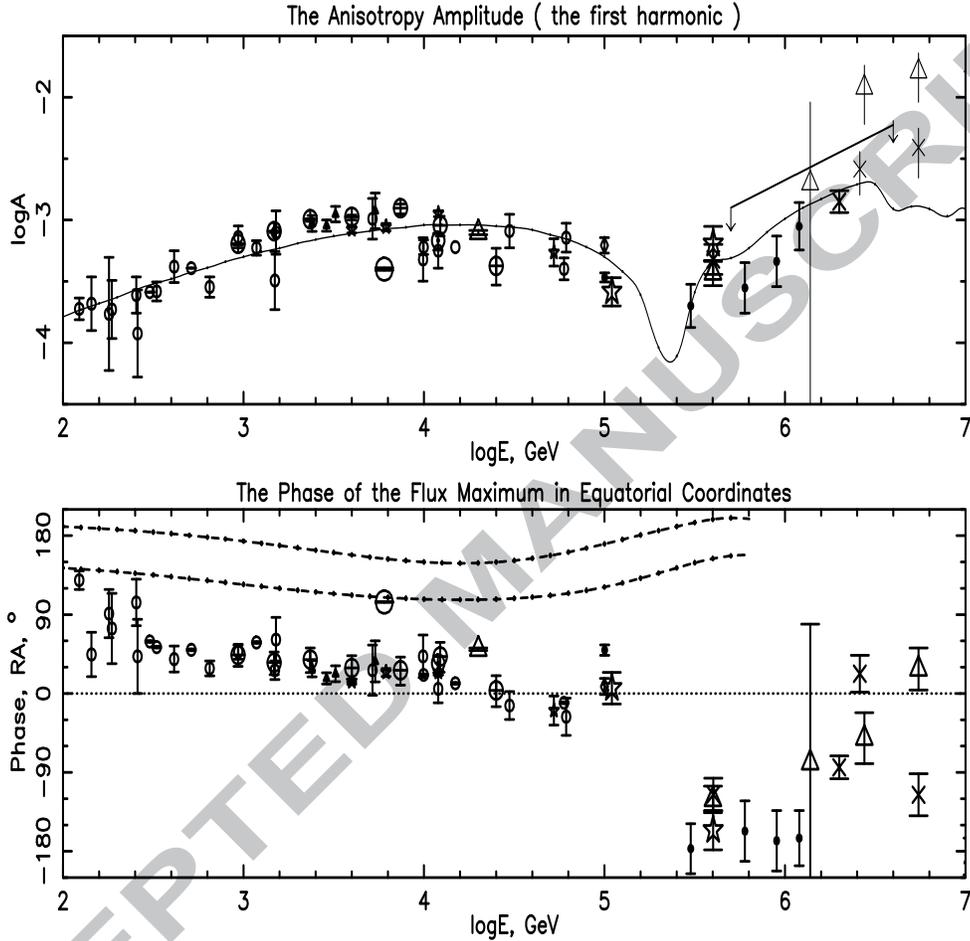


Figure 1: The observed amplitude (upper panel) and equatorial phase (lower panel) of the first harmonic of the CR anisotropy. Data denoted as \circ are taken from the survey presented in [3], \odot - Super-Kamiokande-I [3], \star - Tibet III [4], \triangle - Baksan [5], \diamond - Andyrchi [5], \bullet - EAS-TOP [6]. Thick line above $\log E = 5.7$ with an arrow - upper limits of the amplitude, given by KASCADE [7]. Here and in the text below the energy E is in GeV. The full line in the upper panel relates to calculations with our model described in Section 3 [8]. The area between thin dashed lines in the lower panel denotes the region in *galactic* coordinates corresponding to the RA region occupied by experimental points in equatorial coordinates assuming that the observations were made at declinations about 30° - 60° .

- (ii) the extremely small $\sim 10^{-4} \div 10^{-3}$ amplitude of the anisotropy;
- (iii) the visible rise of the amplitude A with energy E up to $\log E \approx 4$;
- (iv) a moderate fall of the amplitude above $\log E \approx 4$ up to a minimum at $\log E \approx 5.3 \div 5.5$;
- (v) the rise of the amplitude beyond this minimum up to a few PeV;
- (vi) the approximately constant phase at low energies which suddenly changes its direction at about the same energy of $\log E \approx 5.3 \div 5.5$ where the amplitude has a minimum;
- (vii) in the PeV region, where the rise of the amplitude is observed, the phase has an apparent trend to recover up to its previous direction close to $RA \sim 0$.

In what follows we shall endeavour to build a model which can reproduce these features with the minimum number of assumptions. This model contains three basic ingredients: the Galactic Disk, the Halo and the Single Source (SS). Although we separate here the role of the Single Source, we understand that, in fact, it is just part of CR in the Disk.

The details of the model suggested to explain all these peculiar features are given in [8]. Here we give just its main features and they are illustrated in Figure 2. We assume that the anisotropy appears only in the vicinity of the sources, i.e. in the Disk. The amplitude of the anisotropy A is connected with the CR intensity I , its gradient, $gradI$, and the diffusion coefficient D as $A = \frac{3DgradI}{cI}$. If the relative gradient $\frac{gradI}{I} \neq 0$ and $D \propto E^{\delta_d}$ then A in the Disk rises with energy as $A_d \propto E^{\delta_d}$. The anisotropy of CR in the Halo is postulated as being $A_h = 0$ and the isotropy of CR re-entrant from the Halo back into the Disk dilutes the anisotropy of CR produced and trapped in the Disk.

In this treatment we just consider the first harmonic. Later work will deal with higher multipoles. We calculate the amplitude of the first harmonic for the case where only Disk and Halo contribute to CR as

$$A = \frac{A_d I_d}{I_d + I_h} \quad (1)$$

The result is shown in Figure 2b by the dotted line. The rise of the amplitude at energies above 100 GeV is due to the rise of the diffusion coefficient in the expression for A_d mentioned above. The slow decrease of A above ~ 10 TeV is explained by the rising fraction of isotropic CR from the Halo, which overcomes the rise of A_d . However, this scenario does not reproduce the remarkable dip in the amplitude visible in the experimental data at $\log E = 5.3 - 5.5$ and the subsequent rise of the amplitude above this dip (Figure 1a).

We think that these features, if they are real, are connected with the existence of the Single Source, from which the CR energy spectrum is schematically shown by the dotted line in Figure 2a and denoted as 'SS'. However, this idea alone is not enough to reproduce the experimental data and here the examination of the phase of the first harmonic could help. In Figure 2b it is seen that after the moderate decrease in the energy interval 0.1 - 100 TeV the phase suddenly changes to its opposite. We consider this change seriously and propose that CR from the Single Source have a phase opposite to that of the background at lower energies. This is a necessary complementary requirement in our model. The rising part of CR coming from the opposite direction would reduce the

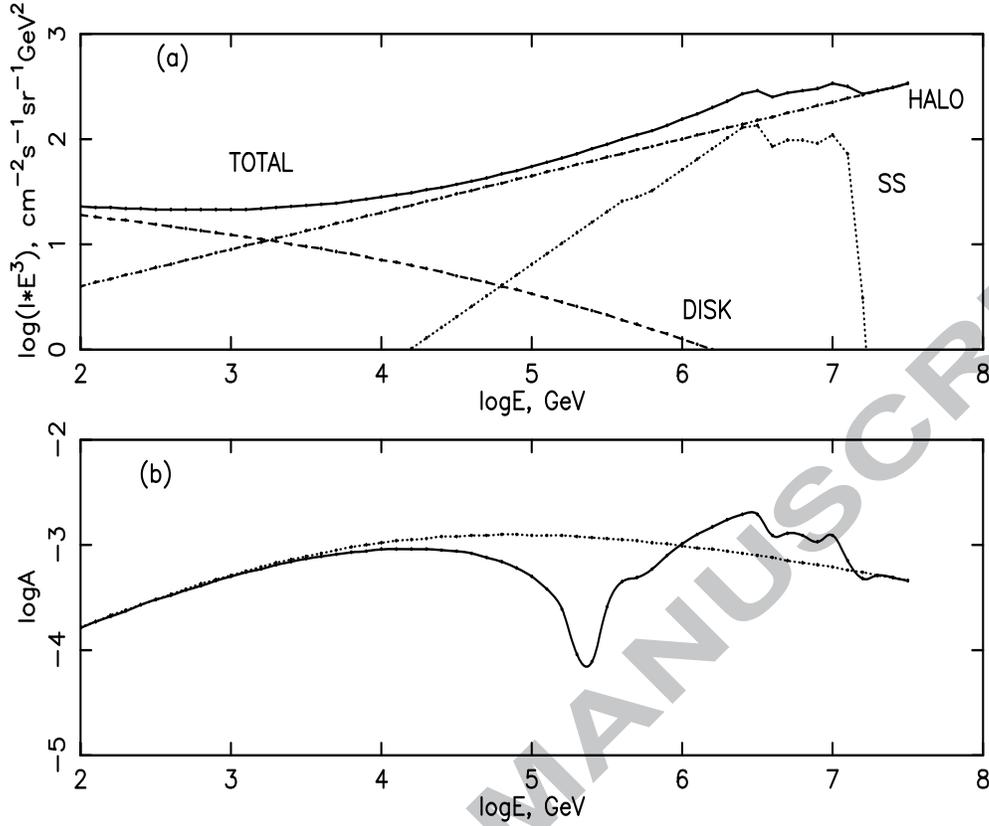


Figure 2: (a) Schematic formation of the CR energy spectrum from the Disk, the Halo and the Single Source. (b) The amplitude of the first harmonic of the CR anisotropy obtained with contributions from Disk + Halo + Single Source (full line) and the same with contributions only from Disk + Halo without Single Source (dotted line).

anisotropy of the background from the Disk and Halo as

$$A = \left| \frac{A_d I_d - A_{ss} I_{ss}}{I_d + I_h + I_{ss}} \right| \quad (2)$$

The result of the calculations with the contribution of the Single Source is shown in Figure 2b by the full line. A comparison with the experimental data is shown also in Figure 1a by the full line. It is seen that after minimum in the dip the amplitude of the anisotropy starts rising again and it is caused by the rising contribution of the Single Source, which has the opposite phase.

We think that the described model with three basic ingredients: Disk, Halo and Single Source is reasonable and is worthy of discussion. The new features advocated here are:

(a) The dominance of the Halo component in the sub-PeV region. It means that the CR which we observe and study in spite of being ourselves inside the Disk come mostly from the Halo. It is disputable but helps to understand the low anisotropy, small radial

gradient of CR intensity and small level of irregularities in the regular power law energy spectrum.

(b) The idea about the Single Source, which has to be nearby and young and creates the knee, usually raises questions: 'if it is nearby why do'nt we see it in the anisotropy?'. It is a very reasonable question and this work gives the answer. The Single Source causes the stronger decrease and the dip in the amplitude of the dipole anisotropy at sub-PeV energies. It is also seen in the change of the phase of the anisotropy at the same energies. It means that the Single Source should deliver CR from the direction opposite to the direction of CR from the background and it is a new assumption in the Single Source scenario. Above the dip energy the amplitude starts to rise again with the opposite phase, as expected.

The dip in this model appears as the result of subtraction of two bigger values. Its position and shape are extremely sensitive to the choice of parameters participating in expression (2). The relatively good agreement with the experimental data is the result of the fitting procedure, but, nevertheless:

(i) it demonstrates the possibility of achieving agreement within the framework of our simplistic model and
(ii) the high sensitivity of the dip to the input parameters of the expression (2) gives the possibility of investigating these parameters when precise results in this energy region are obtained.

(iii) The phase of the first harmonic in the PeV region, where the contribution of the Single Source is big enough, could help to locate it on the sky. The present experimental data have a too big spread to make a conclusion.

We understand that this scenario raises more questions than gives answers. For instance, the main questions are:

(a) Do the Halo and the Single Source really exist? Arguments for positive answers are given in the §3, but more supportive arguments are needed.

(b) Why numerical estimates for CR intensity in the Disk and the Halo, calculated with the expression (2), are smaller than in the observations?

(c) Why is the energy spectrum of CR in the Disk steeper than the spectrum in the Halo? According to our conception developed in [8] the spectrum in the Disk, with its higher turbulence in the interstellar medium due to SN explosions, should be flatter than in the Halo where there are no such powerful sources of turbulence as SN.

(d) To what extent are the simplified assumptions about the shapes and normalisation of the Disk, Halo and Single Source spectra as well as other parameters: A_d , A_h and A_{ss} , reasonable and what will the more sophisticated approach do for the result?

The answers to these and other puzzling questions are the subject of further work.

4 Puzzle 3: the nature of the Single Source

The existence of the Single Source has been proposed by us to explain the puzzling sharpness of the knee in the size spectrum of extensive air showers (EAS) (see [11] and later publications). The physical basis of this proposal is the evident non-uniformity of the spatial and temporal distributions of SN explosions and subsequent SNR. As

a result one SN could explode not very long ago and close to the solar system.. Its contribution to the CR intensity is rather high and it gives rise to a small peak (knee) above the background from other SNR - it is our Single Source.

To search for the Single Source we used the so called difference method [12]. It is different from the traditional study of the CR intensity. Its main idea is that the difference between properties of EAS coming from the direction of the Single Source and from the opposite direction should be maximum. The method is stable against random experimental errors and allows to separate anomalies connected with the laboratory coordinate system from anomalies in the celestial coordinate system. The method allows to study the whole celestial sphere including regions outside of the line of sight of the experimental installation.

To search for an anisotropy we used experimental data obtained with the GAMMA experimental EAS array and have taken the EAS age parameter as a characteristic of the EAS property. The difference between EAS age distributions in two opposite directions was quantified by the reduced χ^2 value [12]. The result of the search is given in Figure 3. The maximum difference in galactic coordinates has been found

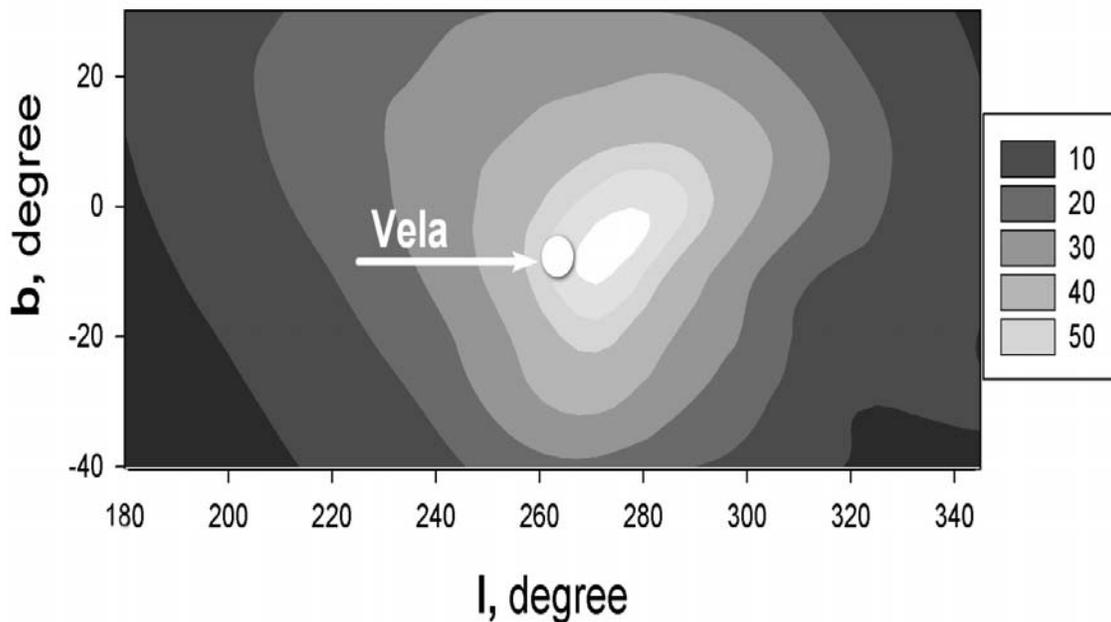


Figure 3: Two-dimensional profile of the reduced χ^2 of the difference between age distributions of EAS coming from opposite directions in galactic coordinates.

at $l = 277 \pm 3^\circ, b = -5 \pm 3^\circ$. The closest source to this location is cluster Vela and therefore it is a good candidate for the role of the Single Source, which is responsible for the knee in the CR spectrum and the minimum in the amplitude of the anisotropy. However, a firm conclusion can be drawn only if it will be confirmed by the analysis of

data from other EAS arrays.

An alternative explanation is the influence of the regular magnetic field in the area surrounding the Earth especially taking into account the nearby spiral arm (see Puzzle 1 of this paper). The only point we should like to stress is that the effect of the regular magnetic field in PeV and sub-PeV energies should be small compared with the effect of the single source in order not to destroy the diffusive character of CR propagation. Additional arguments in favour of the dominance of the single source in the formation of the maximum difference in age distributions of EAS coming from the opposite directions could be the vicinity of Vela source and the 'younger' age of EAS coming from the direction of the maximum since magnetic fields do not change the energy spectrum of EAS and their ages.

In the section 6 of our paper [12] we speculated that a minor shift of the maximum difference from Vela source seen in Figure 3 could be due to the influence of this small regular magnetic field.

5 Conclusion

We mentioned only 3 puzzles existing in the PeV and sub-PeV energy region. However, there are many other there and after Prince Hamlet we can conclude that 'there are many things in heaven and earth, Horatio, than are dreamt of in your philosophy'.

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