

# Enigmas of Cosmic Ray Anisotropy

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**Abstract**—Three familiar enigmas of cosmic ray anisotropy in the PeV- and sub-PeV-ranges of energy are considered: so-called inverse anisotropy, the irregular nature of the energy dependence of the amplitude and phase of the first harmonic, and the contribution from a single source.

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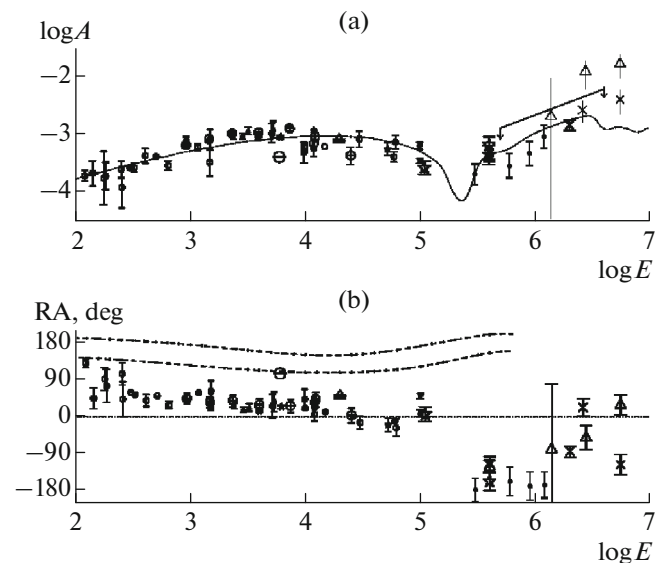
## INTRODUCTION

One of the most interesting regions of the cosmic ray (CR) energy spectrum lies within the PeV-energy bands. It is that region in which a bend in the spectrum (a so-called knee) is observed. Its origin is still a subject of studies and debate. This region can be approached from low energies in the TeV range when investigating the shape of the spectrum, mass compositions, and anisotropy of CRs. However, these experiments are difficult to conduct, due to the low intensity of CRs. In this work, we describe three of the many problems of investigating anisotropy in the range of PeV energies and lower.

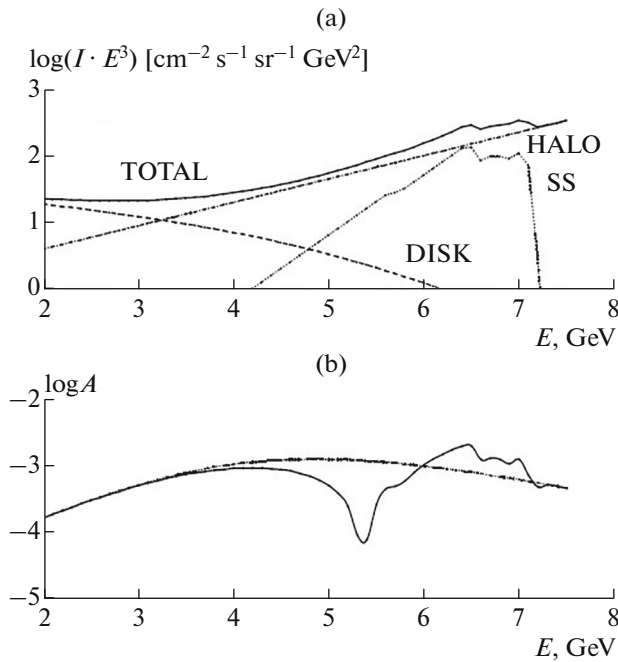
## ENIGMA 1: INVERSE ANISOTROPY

The Solar System is located on the periphery of our Galaxy. Most CR sources such as supernova remnants and pulsars are located in the so-called Inner Galaxy, toward its center. The density gradient of the sources is directed from the Outer to the Inner Galaxy. The same could be also expected for the CR density: it should fall from the galactic center to the periphery. The so-called large-scale CR anisotropy should have the phase of the first harmonic or the maximum of the expected intensity in the direction from the Outer Galaxy to the Inner Galaxy, i.e., in the region of galactic longitudes  $l = -90^\circ \dots +90^\circ$ . In Fig. 1 (bottom panel), the measured anisotropy phases are shown in equatorial coordinates. The experimental data were taken from [1]. When converted to the galactic coordinate system, these data occupy the region between the two dotted lines. It can be seen that while the expected phases are within the range of galactic longitudes  $l$  from  $-90^\circ$  to  $+90^\circ$  (i.e., in the Inner Galaxy), the observed phases lie within the range of  $+90^\circ$  to  $+270^\circ$ . This phenomenon is called *inverse anisotropy*.

This phenomenon can be explained by assuming that inverse anisotropy is a local effect associated with the spatial orientation of the magnetic field or fluctuations of the density of the interstellar medium in the vicinity of the Solar System. The Sun is located in the Local Bubble in the inner part of the Orion Arm. The density of the magnetic field and interstellar medium in the Arm is higher, and the diffusion of the particles is slower than between the arms. The particles that move from the Inner Galaxy to the arm run into a sort of wall; some of them rebound in the opposite direction, are accumulated, and create an inverse CR density gradient.



**Fig. 1.** Observed amplitude (top panel) and phase (bottom panel) of the first harmonic of CR anisotropy, presented in equatorial coordinates.



**Fig. 2.** (a) Schematic of the formation of the CR energy spectrum with contributions from the Galactic Disk, Halo, and a single source. (b) Amplitude of the first harmonic of anisotropy with the contributions from the Disk + Halo + single source (solid line) and the same with the contributions from only Disk + Halo without a single source (dotted line).

Another explanation could be connected with the obvious inhomogeneity of the spatial and temporal distribution of the CR sources. One source or more must be sufficiently close to the Earth, both spatially and temporally. To be responsible for the formation of the inverse anisotropy, however, these sources must be concentrated predominantly in the Outer Galaxy.

## ENIGMA 2: SPECIFIC BEHAVIOR OF ANISOTROPY AMPLITUDE AND PHASE

We can see from Fig. 1 that the amplitude and phase of the first harmonic of CR anisotropy behave in a very bizarre way as the energy rises. The experimental data were taken from [1]. The solid line in the top panel corresponds to calculations according to the model described by the authors in Section 2. The region between the dotted lines in the bottom panel shows the anisotropy phase expected if the experimental data are converted into galactic coordinates, since they were obtained in the 30°–60° range of inclination.

The smooth and slow growth of the amplitude up to an energy of around 10 TeV is followed by a drastic drop at higher energies, reaches its minimum at 200–300 TeV, and then continues to grow. The phase slowly falls from ~40° to ~0° as the energy rises from 0.1 to 100 TeV. It changes drastically to the opposite phase at the same energy of around 200–300 TeV, where the

minimum amplitude is observed, and then begins to recover slowly at PeV-scale energies. Below, we try to construct a model that explains the observed behavior of the anisotropy based on only three components of the total CR flux: the Galactic Disk, the Halo, and a single source.

Let us denote the intensity of the CR fluxes for the above components as  $I_d$ ,  $I_h$ , and  $I_{ss}$ , respectively. Their energy spectra are shown in Fig. 2a.

We denote the amplitudes of the first harmonic for these three components as  $A_d$ ,  $A_h$ , and  $A_{ss}$ , respectively. If the CRs consist of only two components, the Disk and Halo, their total amplitude is determined as

$$A = \frac{A_d I_d}{I_d + I_h}.$$

The slowdown in the rise of anisotropy is associated with the growing portion of the Halo, the amplitude of which is assumed to be equal to zero:  $A_h = 0$ . With such behavior of the total anisotropy, however, there is no minimum observed at energies of 200–300 TeV. Assuming a growing contribution by a single source could in this case be helpful. The hard energy spectrum of the single source and its localization in the Outer Galaxy result in the observed minimum of the amplitude of anisotropy, calculated in this case as

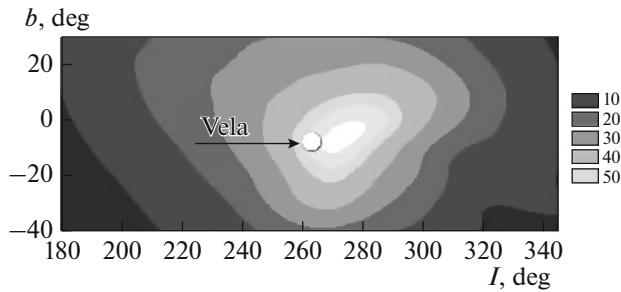
$$A = \frac{A_d I_d - A_{ss} I_{ss}}{I_d + I_h + I_{ss}}.$$

Its behavior is shown in Figs. 1a and 2b by the solid line. The minus sign in the numerator of the above expression results from the single source being assumed to exist in the Outer Galaxy, which partially compensates for the CR flux from the Inner Galaxy.

## ENIGMA 3: CONTRIBUTION FROM A SINGLE SOURCE

The assumption about the existence and important role of a single source was used to explain a remarkably sharp bend in the spectrum of extensive air showers (EASs) [2]. The assumption is based on the obvious inhomogeneity of the spatial and temporal distribution of the CR sources and the density of the interstellar medium. Due to this inhomogeneity, one source would seem to have exploded comparatively recently, and near the Solar System. Its contribution to the total CR intensity is considerable and forms a small peak (knee) above the background of the rest of the sources.

To search for a single source, we used the so-called difference approach in [3]. It differs from the traditional way of searching for sources according to the direction of the maximum CR intensity. A condition of this approach is that the difference between the characteristics of EASes that arrive from the direction toward the source and from the opposite direction must be maximal. It is resistant to random experimental errors and allows us to investigate the entire celes-



**Fig. 3.** 2D profile of normalized quantity  $\chi^2$  that indicates the galactic coordinates of the direction in which the maximum difference between the EAS age distribution is observed. The white dot near the center indicates the direction toward the Vela source.

tial sphere, including regions outside the line of sight of the experimental setup.

To search for anisotropy, we used experimental data obtained with the experimental GAMMA facility installed on Mount Aragats in Armenia [4]. The age of a shower, determined by the steepness of the function of the spatial distribution of the charged particle density, was taken as the parameter for comparing EAS characteristics. The distributions of the EASes according to this parameter were compared for the forward and inverse directions, and their difference was characterized by normalized quantity  $\chi^2$ . A two-dimensional profile of this quantity is shown in Fig. 3. The maximum difference between the distributions in galactic coordinates was found in the direction of lon-

gitude  $l = 277 \pm 3^\circ$  and latitude  $b = -5 \pm 3^\circ$ . The nearest source in this direction is the Vela system (Vela X + Vela J), a good candidate for the single source responsible for the formation of the knee in the CR energy spectrum at PeV-range energies.

An alternative explanation of the observed maximum could be the influence of a regular magnetic field in the vicinity of the Solar System, caused by the proximity of the spiral arm of the Galaxy. However, we should note that this influence should be weak enough not to disturb the diffusive nature of the CR propagation at energies in the PeV- and sub-PeV-ranges.

## CONCLUSIONS

In this work, we considered only three enigmas of CR anisotropy at energies in the PeV range and below. However, there are many more. Like Prince Hamlet, we can say “There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy.”

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