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The role of the Galactic Halo and the Single Source in the formation of the cosmic ray anisotropy

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ABSTRACT

The existence of the cosmic ray Halo in our Galaxy has been discussed for more than half a century. If it is real it could help to explain some puzzling features of the cosmic ray flux: its small radial gradient, nearly perfect isotropy and the low level of the fine structure in the energy spectra of the various particles. All these features could be understood if: (a) the Halo has a big size (b) cosmic rays in the Halo have a uniform spatial or radial distribution and (c) the cosmic ray density in the Halo is comparable or even higher than that in the Galactic Disk. The main topic of the paper concerns the present status of the anisotropy and a model for its formation. In our model the extremely small amplitude of the dipole anisotropy is due to the dilution of the anisotropy in the Disk by the dominating isotropic cosmic rays from the Halo. Some minor deviations from complete isotropy in the sub-PeV and PeV energy regions point out to the possible contribution of the Single Source with the phase of its first harmonic opposite to the phase produced by the Disk.

1. Introduction

The observed cosmic rays (CR) have several puzzling features which need to be explained and these are now listed:

(a) Firstly, there is only a small radial gradient in the Galactic Disk (GD) in contrast with expectation, the reason is as follows. The most viable theory of the CR origin is that they are generated in the supernova (SN) explosions and accelerated by the shock waves in the supernova remnants (SNR) [1]. According to recent studies [2,3] the Galactocentric radial distribution of SNR is such that they are mostly concentrated in the Inner Galaxy with the maximum GD surface density at a Galactocentric radius of about $R \approx 3{-}4$ kpc followed by a rapid decrease at larger R. According to the model calculations [4] the radial CR gradient coincides with that of SNR and at the Sun, of radial distance of 8.3 kpc, it should be equal to $S = d(lnI)/dR = (-0.17 \pm 0.05)\ \mathrm{kpc}^{-1}$. Here I is the CR intensity or the SNR density. However, the experimental values for the Outer Galaxy derived by us from the gamma-ray emissivity profile are $(-0.05 \pm 0.03)\ \mathrm{kpc}^{-1}$ for both the second and third quadrants [5,6], so that the observed CR radial distribution is significantly flatter than that expected from the distribution of their proposed sources.

(b) Secondly, there is the surprising near-isotropy of the CR arrival directions. In the sub-PeV region the CR intensity is relatively high and allows the collection of good statistics with detectors of a reasonable size during an acceptable time. Theoretical calculations predict a the slow rise for the amplitude A of the first harmonic with energy E as $A \sim E^{0.3-0.5}$. On the opposite side the experimental measurements indicate a decreasing amplitude above a few TeV with a minimum of about $A \sim 2 \cdot 10^{-4}$ for $E \sim (0.1 - 0.3)$PeV [7,8]. The attempt to explain this decrease by an accidental spatial configuration of the sources is difficult because it shows that the probability of such a favorable configuration is definitely lower than a few percent [9].

(c) The third puzzle is connected with the observed shape of the CR energy spectrum. Due to the stochastic distribution of the SNR in space and time there should be fine structure in the spectrum at some level. All realistic simulations confirm the possible existence of such structures [4]. However, so far, only two structures are firmly established: the so called ‘knee’ at 3–4 PeV and the ‘ankle’ at 3–4 EeV. Below the knee, and between the knee and the ankle, measurements show quite a regular power law shape of the spectrum with only minor structure.

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In the last decade due to improvements in the energy resolution and increased statistics several works find hints of fine structure both below [10–12] and above the knee [13–17]. In the region below the knee the experiments indicate a possible flattening of the proton and nuclei spectra above a rigidity of 200 GV. A similar flattening was also found in the primary electron plus positron spectrum [18–20]. However, the latest precise data from AMS-02 experiment do not show such features, except for positrons, in the same energy region below the knee [21]. The clarification of the situation is the duty of the experimental groups, but in any case the discussed irregularities, if they exist, are relatively small and do not disprove the basic feature of the CR energy spectrum, viz its nearly perfect regular power law shape.

The present paper is an attempt to find a reasonable explanation of this puzzle, with special attention given to the large-scale anisotropy.

2. The present status of the cosmic-ray large-scale anisotropy

The large-scale anisotropy of CR is usually described by the amplitude and phase of the first and second harmonics. The phase, expressed in terms of the right ascension (*RA*), is the direction of the maximum CR intensity. Due to the extremely small deviations from isotropy the measurement of these deviations requires large statistics. Until recently they were concentrated mostly in the TeV and sub-PeV energy regions. Only in the last decade have arrays with the necessary large aperture: Pierre Auger Observatory, Telescope Array, IceCube and IceTop, Yakutsk and KASCADE-Grande accumulated the good statistics necessary to probe PeV and even EeV energies. Also, large EAS arrays such as ARGO-YBJ and Tibet III have produced precise results in the sub-PeV region. Fig. 1 shows the present situation with the measurements of the dipole anisotropy.

In general there are several features noticeable in this survey:

(i) a good consistency of the results at energies up to a few PeV;
(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 $logE, GeV \approx 4$;
(iv) a moderate fall of the amplitude above $logE \approx 4$ up to a minimum at $logE, GeV \approx 5.3 \div 5.5$;
(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 $logE \approx 5.3 \div 5.5$ 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.

3. Interrelation between the Galactic Disk and the Halo

Stars in our Milky Way Galaxy are concentrated in the Disk and likewise are SNR. For simplicity we consider SNR as the only source of CR, their acceleration and the energy. As was already mentioned, the Galactocentric radial distribution of SNR is non-uniform.

It is clear that to fit the observations (see puzzle (a) in the Introduction) we have either to abandon the model with SNR as the

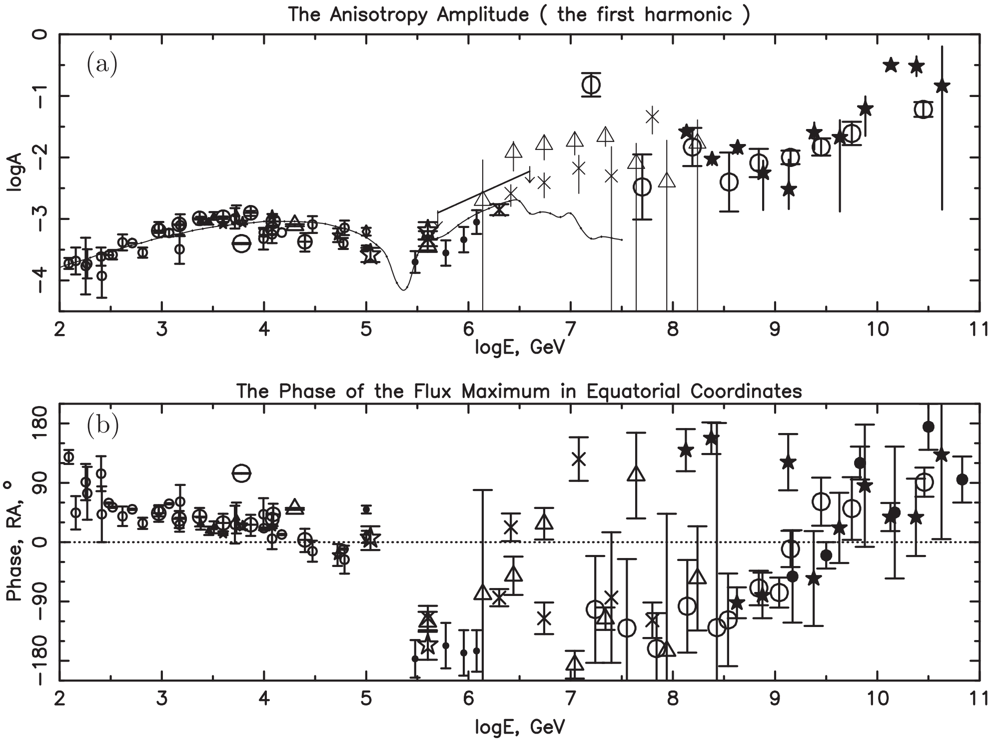

Fig. 1. Amplitude (a) and Phase (b) of the first harmonic of the CR anisotropy. The data at sub-PeV energies have been reproduced from [8]. At higher energies they were taken from the Pierre Auger Observatory [22]: (◯), Telescope Array (only phases were published) [23] (•), Yakutsk [23,24] (☆), KASCADE-Grande [25] (×), Akeno [26] (△). The full line in (a) relates to our model and is reproduced here from Fig. 2b (see Section 5).