Multi-scale TeV cosmic-ray anisotropy observed with the ARGO-YBJ experiment

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Multi-scale TeV cosmic-ray anisotropy observed with the ARGO-YBJ experiment

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Abstract. The distribution of the cosmic-ray arrival direction provides essential information about the source distribution, the propagation medium and the diffusive process that primaries undergo. To the current knowledge of the local interstellar medium, cosmic rays in the rigidity range $10^{12} - 10^{13} \, V$ are re-accelerated within few hundreds of astronomic units, what makes the TeV anisotropy an important probe to investigate the outer space until that horizon. We report the observation of anisotropy in the TeV cosmic-ray arrival direction measured with the ARGO-YBJ experiment, at angular scales in the range $10^\circ - 180^\circ$ and with intensity $10^{-4} - 10^{-3}$. Findings of other experiments are confirmed and new details on the cosmic-ray distribution in the declination range $-10^\circ - 70^\circ$ are given.

1. Introduction
Among all the experimental results about cosmic rays (CRs), those on the arrival direction distribution play a special role. In fact, apart from some kinetic effects (which provide dipolar distributions, see [1]), the low energy (i.e. $< 10^{15} \, eV$) CR distribution is expected to be highly isotropic, because of the strength of the galactic magnetic field (GMF).

The GMF can be thought of as the superposition of a regular field, whose lines roughly follow the optical arms, and a non-regular one, describing local deviations due to the intergalactic medium (e.g. the reconnection with the stellar magnetic fields). In the Local Inter-Stellar Medium (LISM), the regular GMF is $\approx 3 \, \mu G$ strong, whereas the intensity of the non-regular component is $\approx 2 - 4 \, \mu G$ [2]. In such a field, the gyroradius of CRs is $r_{pc} \approx 5 \times 10^{-4} \, R_{12}$, where $r_{pc}$ is in parsec and $R_{12}$ is in units of $10^{12} \, V$. As a consequence, CRs below $10^{15} \, eV$ do not carry directional information for distance larger than $\approx 1 \, pc$. As no potential CR sources closer than $\approx 200 - 300 \, pc$ are there, no deviation is traditionally expected from the isotropy. If any, just a weak dipole would be there, tracing out the contribution of the closest and most recent CR sources.

On the other hand, a detailed map of the GMF based on radio synchrotron, optical polarization and Zeeman splitting data is available only down to parsec scales, where the ISM is full of non-regular magnetic structures. Therefore, GMF local structures might be nearby, capable of accelerating CRs and deviating their trajectories, beaming them along certain directions. In this sense, magnetic fields might be responsible for an-isotropy instead of isotropy.

In recent years, the topic of the anisotropy made a comeback in CR physics, because of the improvement of the experimental result accuracy. The traditional result quoted by various
In this work the observation of the CR anisotropy with the ARGO-YBJ detector is reported. Results will be given about the quest for CR structures either for what concerns the “large” scale anisotropy (LSA) and the “medium” scale one (MSA), i.e. down to angular scales as wide as 10°.

2. Analysis of the ARGO-YBJ data

The ARGO-YBJ experiment [10] is a wide field of view air shower array located at the YangBaJing Cosmic Ray Laboratory (Tibet, P.R. China, 4300 m a.s.l., 606 g/cm²). Details about the experimental layout and the event reconstruction can be found in [10, 11].

The results from two different analyses are reported in this work, one for the LSA and one for the MSA.

**LSA-oriented analysis.** The search for LSA was carried out on data collected from January 2008 to December 2009. The reconstructed events were selected to fire more than 40 pads on the central carpet, to have with zenith angle less than 45° and such that the RMS of the residuals of the shower front conical fit is less than 9 ns. The average acquisition rate for these events is ≈ 670 Hz. The statistics under consideration is made of 3.6 × 10¹⁰ EASs. The zenith cut selects the declination region δ ≈ −15° ÷ 75°. Data were arranged in seven different multiplicity range, in order to study the LSA energy dependence. The average isotropic flux of CRs (hereafter “background”) is estimated with the all-distance equizenith method (ADEM [3]), sensitive to the whole harmonic spectrum, implemented via recursive iteration algorithms. 2D maps representing the significance of the observation and the relative intensity of the anisotropy were drawn out and projections along the right ascension (RA) have been analyzed in the Fourier space to get the amplitude and the phase of the former two harmonics.

**MSA-oriented analysis.** The search for MSA was conducted on data collected from November 2007 to May 2011. All events firing 25 pads or more in the central carpet were used. Among them, only those with reconstructed zenith angle less than or equal to 50° were used to fill the maps. The triggering showers that passed the selection were ≈ 3.0 × 10¹¹, for an average acquisition rate as high as ≈ 3140 Hz. Data were arranged in five different multiplicity range. The CR background was estimated with the “Direct Integration” method (DIM). A discussion of this method to detect the MSA can be found in [12]. The time interval used to compute the average spans 3 hours and makes us confident that the results are reliable for structures up to 35° wide.

3. Results

A mollweide representation of the LSA is provided in the figure 1. It can be observed the large deficit in the RA region 140° − 250° surrounded by two excess regions, a weaker one in the RA region 270° − 10° and a brighter one for RA values 45° − 140°. The amplitude of the first harmonics A₁ in the Fourier expansion of the RA projection is reported in the figure 2 as a function of the energy. The result is in fair agreement with findings from other experiments.
is worth noticing that ARGO-YBJ is the first experiment ever observing either the rise of the LSA intensity below $8 \times 10^{-10}$ TeV and the fall-off of the signal around $20 \times 30$ TeV, clearing up the problem of the inter-calibration of different experiments. Also the phase of the first harmonic was found to be in agreement with the literature, smoothly changing from $\approx 3.0$ hrs to $\approx 0.5$ hrs in the $900$ GeV $\sim 24$ TeV region.

The figure 3 represents the ARGO-YBJ sky map as it appears after that structures wider than $35^\circ \sim 45^\circ$ in RA are averaged out (DIM). Two distinct excesses are resolved within the RA $= 45^\circ \sim 140^\circ$ region (compare with the figure 1), labelled as region “1” and “2”. The map is represented in equatorial coordinates and the excesses are symmetrically distributed with respect to the Galactic plane ($b \approx \pm 35^\circ$ and $l \approx 180^\circ$). The region 2 appears to be made of two distinct spots, whereas the brightest zone of the region 1 lays at the boundary of the ARGO-YBJ field of view. Several other features are visible in the left part of the map, whose origin is still under investigation. In the figure 4 the multiplicity spectrum obtained for the region 1 and 2 is pictured. The vertical axis represents the relative excess measured in each region with respect to the estimated isotropic CR flux. It is worth to recall that the background estimation is carried out by filtering out signals wider than $35^\circ \sim 45^\circ$ in RA. The regions were suitably parametrized to compute the excess. The region 1 has a spectrum harder than isotropic CRs, at least up to $10 \sim 20$ TeV. The region 2 is weaker and no significant deviations from the isotropic CR background can be appreciated above 1 TeV. We notice that the relative intensity of the MSA is less than $10^{-3}$. 
4. Conclusions
Recently the CR anisotropy came back to the attention of the scientific community, thanks to several new 2D representations of the CR arrival direction distribution. Models to explain the whole set of observations are missing and deep implications on the Physics of CRs in the LISM are expected. ARGO-YBJ observed anisotropic structures on angular scale as wide as $10^\circ - 90^\circ$, in the rigidity range $10^{12} - 10^{13}$ V. The intensity spans $10^{-4}$ to $10^{-3}$, depending on the rigidity and the region considered. Further studies are on the way to achieve a better separation of the signal in the harmonic space, as well as to investigate the nature of the phenomenon.

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