



The cosmic ray anisotropy below 10^{15} eV

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Abstract. The measurement of the anisotropy in the cosmic ray (CR) arrival direction distribution provides important informations on the propagation mechanisms and on the identification of their sources. In the last decade the anisotropy came back to the attention of the scientific community, thanks to several new two-dimensional representations of the CR arrival direction distribution which clearly showed the existence of anisotropies at different angular scales in both hemispheres. The origin of the observed anisotropies is still unknown. So far, no theory of CRs in the Galaxy exists yet to explain the observations leaving the standard model of CRs and that of the local magnetic field unchanged at the same time. In this paper the observations of Galactic CR anisotropy will be briefly summarized, with particular attention to the results obtained by the ARGO-YBJ experiment in the Northern Hemisphere.

1 Introduction

The CR arrival direction distribution and its anisotropy has been a long-standing problem ever since the 1930s. In fact, the measurement of the anisotropy is a powerful tool to investigate the propagation mechanisms and the spatial source distribution determining the CR world as we know it.

As CRs are mostly charged nuclei, their paths throughout the Galaxy are deflected and highly isotropized by the action of galactic magnetic field (GMF) they propagate through before reaching the Earth. The GMF is the superposition of a regular and a chaotic contribution. Although the strength of the non-regular component is still under debate, the local total intensity is supposed to be $B = 2 \div 4 \mu\text{G}$ (Beck, 2001). In such a field, the gyroradius of CRs is given by $r_{\text{a.u.}} = 100 R_{\text{TV}}$, where $r_{\text{a.u.}}$ is in astronomic units and R_{TV} is the particle rigidity in TeraVolt.

The high degree of isotropy observed in the CR arrival direction distribution suggests that the propagation in the Galaxy of CRs trapped by the magnetic field can be described in terms of diffusion, at least up to 10^{16-17} eV (Berezinskii, 1990).

The measurement of the anisotropy is complementary to the study of the CR energy spectrum and elemental composition to understand the origin and propagation of the radiation and to probe the structure of the magnetic fields through

which CRs travel. In fact, while the elemental composition of CRs observed at the Earth is a quantity averaged over all possible propagation trajectories and large time intervals, thus mainly probing the diffusive propagation mechanisms, the anisotropy, on the contrary, can give information on the structure of the magnetic field near the solar system.

In principle any anisotropy reflects a motion. As an example, three different effects may lead to a CR anisotropy. The first effect is related to the motion of the Earth/Solar System with respect to the isotropic CRs rest frame (the so-called Compton-Getting effect, Compton and Getting, 1935). The second is due to nearby and recent CR sources (pulsars or SNRs). For an isotropic propagation, a CR source distribution in the Galaxy is expected to lead to a dipole anisotropy pointing toward the average CR source, with an intensity inversely proportional to the distance to these sources (Erylykin and Wolfendale, 2006; Blasi and Amato, 2012; Pohl and Eichler, 2013; Sveshnikova et al., 2013; Battaner et al., 2015). The third effect is due to the leakage from the Galaxy.

In this paper the observations of Galactic CR anisotropy will be briefly summarized, with particular attention to the results obtained by ARGO-YBJ in the Northern Hemisphere. The ARGO-YBJ experiment has been in stable data taking for more than 5 years at the YangBaJing Cosmic Ray Laboratory (Tibet, P. R. China, 4300 m a.s.l., 606 g cm^{-2}). With a duty-cycle of $\sim 87\%$ the detector collected about 5×10^{11}

events in a wide energy range, from few hundreds GeV up to 10 PeV. A summary of the main physics results obtained by ARGO-YBJ can be found in Di Sciascio (2014).

2 Large-scale anisotropy

Data show that the almost perfect isotropy is broken by a dipole-like feature with an amplitude of $\sim 10^{-4}$ – 10^{-3} evolving with the energy (the so-called “Large-Scale Anisotropy”, LSA). The existence of two distinct broad anisotropy regions in sidereal time, one showing an excess of CRs (called “tail-in”), distributed around 40 to 90° in Right Ascension (R. A.), the other a deficit (the “loss cone”), distributed around 150 to 240° in R. A., has been clearly observed by many experiments with increasing sensitivity and details in both hemispheres (for a review see, for example, Di Sciascio and Iuppa, 2013).

The LSA observed by the ARGO-YBJ experiment at about 1 TeV in 2008 and 2009, during the latest minimum of the solar activity, is shown in Fig. 1 (Di Sciascio, 2013). The center of the “tail-in” component is close to the direction of the heliospheric tail, which is opposite to the proper motion direction of the solar system. The center of the “loss cone” deficit component points to the direction of the north Galactic pole. These observations rule out the hypothesis that a Compton-Getting effect due to the motion of the heliosphere with respect to the local interstellar medium (expected as a dipole with a maximum in the direction of the Galactic Center decl. $\simeq 49^\circ$, R. A. $\simeq 315^\circ$ and a larger amplitude 3.5×10^{-3}) is a major source of the anisotropy.

2.1 Energy dependence

In Fig. 2 the amplitude and phase of the first harmonic (upper and middle plots, respectively) measured by different experiments (muon telescopes or Extensive Air Shower (EAS) arrays) are shown as a function of the primary CR energy. As can be seen from the plots:

- The amplitude of the CR anisotropy is extremely small (10^{-4} – 10^{-3}).
- A slow increase of the amplitude to a maximum at few TeV is observed. After the maximum the anisotropy decreases to a minimum at ~ 100 TeV. Evidence for a new increase for higher energies appears from data.
- The phase of the first harmonic is nearly constant (slowly decreasing) around 0h. A dramatic change of phase is observed around ~ 100 TeV, suggesting a dipole opposite to the initial one. This observation clearly rules out that the Compton-Getting effect is a major source of the anisotropy.

An intriguing result by IceCube (Abbasi et al., 2012) is the confirmation of the EAS-TOP finding (Aglietta et al.,

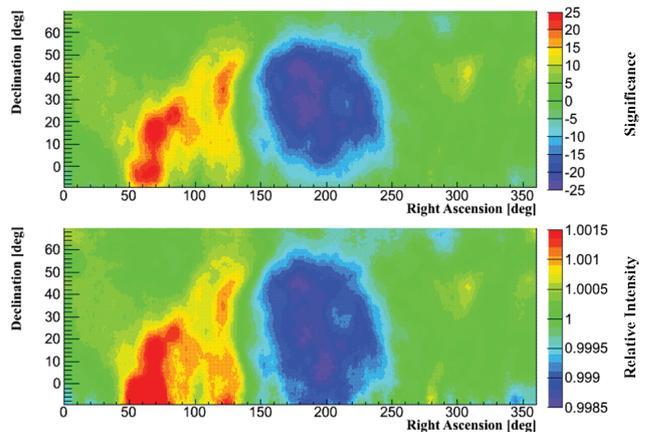


Figure 1. Large scale anisotropy observed by ARGO-YBJ (Di Sciascio, 2013). The upper panel shows the significance map in standard deviations (SD), the lower panel gives the CR relative intensity. The sky maps are in the equatorial coordinate system. The corresponding proton median energy is about 1 TeV.

2009) in the Northern Hemisphere, that the anisotropy “flip” around 100 TeV and its morphology changes. Below about 100 TeV, the global anisotropy is dominated by the dipole and quadrupole components. At higher energies the non-dipolar structure of the anisotropy challenges the current models of CR diffusion. At PeV energies the IceTop experiment showed that anisotropy persists with the same structure as at ~ 400 TeV, but with a deeper deficit (Aartsen et al., 2013).

As discussed by some authors (Desiati, 2013), whether the strengthening of the deficit region at PeV energies is due to propagation effects from a given source or to the contribution of heavier nuclei at the knee is not clear. In the lower panel of Fig. 2 the proton, Helium and light ($p + \text{He}$) component energy spectra measured by Pamela, CREAM and ARGO-YBJ are shown. As can be seen, recent results obtained by ARGO-YBJ show that the knee of the light component spectrum starts at about 650 TeV, well below the PeV, suggesting that heavier nuclei dominate at the knee (for a description of these preliminary analyses see Di Sciascio, 2014).

The measurement of the anisotropy for each of the CR charge groups individually across the knee should be a high priority of the next generation ground-based experiments in order to discriminate between different propagation models of CRs in the Galaxy.

2.2 Time dependence

The study of temporal variation of CR anisotropy is a useful tool to probe the local interstellar space surrounding the heliosphere and to investigate the effects of solar activities on the magnetic structure of the heliosphere. In fact, as suggested by different authors (Desiati and Lazarian, 2013; Drury, 2013; Schwadron et al., 2014; Zhang et al., 2014), the

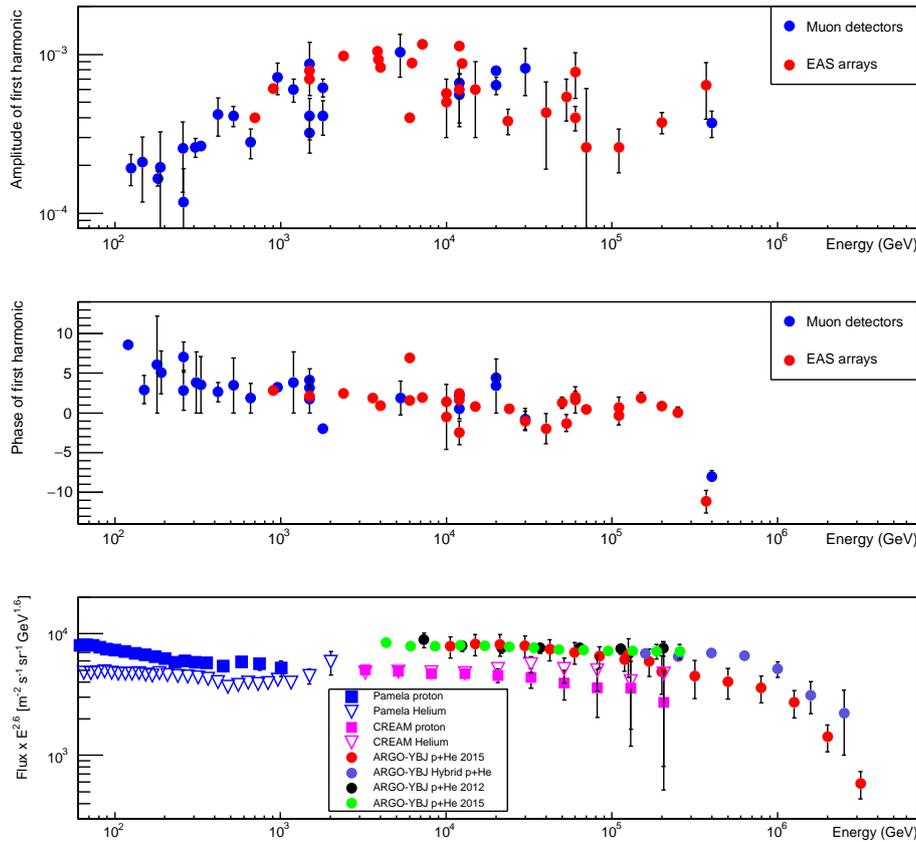


Figure 2. Amplitude and phase of the first harmonic (upper and middle plots, respectively) measured by different experiments (muon telescopes or Extensive Air Shower (EAS) arrays) as a function of the CR primary energy (for details and references see Di Sciascio and Iuppa, 2013). The lower plot shows the p , He and light ($p + \text{He}$) component energy spectra measured by Pamela, CREAM and ARGO-YBJ (Di Sciascio, 2014).

magnetic fields of the heliosphere may have an influence on the CR arrival direction distribution.

The structures of the “tail-in” and “loss-cone” components seem to be almost stable and insensitive to solar activities in the multi-TeV range (Amenomori et al., 2010; Desiati, 2013), in despite of conflicting results obtained by Milagro (Abdo et al., 2009). This indicates that the CR anisotropy in this energy range may not be related to the heliospheric magnetic field, suggesting a large-scale origin due to global streaming of the Galactic CRs (Qu et al., 2012).

3 Medium/small scale anisotropy

In the last few years some experiments collected so large statistics to allow the investigation of anisotropic structures on smaller angular scale than the ones corresponding to the dipole and the quadrupole, showing that the CR intensity has quite a complicated structure unaccountable simply by kinetic models. Along this line, the observation of some regions of excess down to $\sim 10^\circ$ (the so-called “Medium/Small Scale Anisotropy”, MSA) in the rigidity region $\sim 1\text{--}30$ TV stands out (Di Sciascio and Iuppa, 2013).

In 2007, modeling the LSA of 5 TeV CR, the Tibet-AS γ collaboration ran into a “skewed” feature over-imposed to the broad structure of the “tail-in” region (Amenomori et al., 2007, 2009). Afterwards, Milagro claimed the discovery of two localized regions of excess 10 TeV CRs on angular scales of 10° (Abdo et al., 2008), observation confirmed by ARGO-YBJ in 2009 (Vernetto et al., 2009). The observation of similar small scale anisotropies has been reported also by Ice-Cube (Abbasi et al., 2011) in the Southern Hemisphere. The importance of this observation lies in the unexpected confinement of a large flux of low rigidity particles in such narrow beams.

Figure 3 shows the ARGO-YBJ sky map in equatorial coordinates as obtained with about 3.7×10^{11} events reconstructed with a zenith angle $\leq 50^\circ$ (selecting the declination region $\delta \sim -20^\circ \div 80^\circ$) (Bartoli et al., 2013). According to the simulation, the median energy of the isotropic CR proton flux is $E_p^{50} \approx 1.8$ TeV (mode energy ≈ 0.7 TeV). The boxes represent the parametrization of the 4 regions of interest selecting the part of signal more than 3 SD.

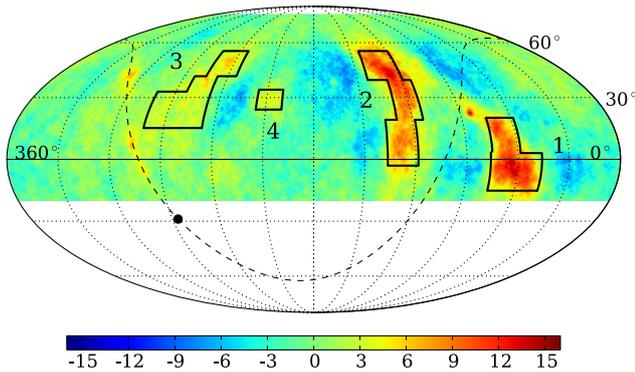


Figure 3. ARGO-YBJ sky-map in equatorial coordinates (Bartoli et al., 2013). The color scale shows the statistical significance of the observation in SD. The dashed line represents the Galactic Plane and the black point the Galactic Center.

The most evident features are observed by ARGO-YBJ around the positions $\alpha \sim 120^\circ$, $\delta \sim 40^\circ$ and $\alpha \sim 60^\circ$, $\delta \sim -5^\circ$, spatially consistent with the regions detected by Milagro (Abdo et al., 2008). These regions are observed with a statistical significance of about 15 SD. On the left side of the sky map, several new extended features are visible, though less intense than the ones aforementioned. The area $195^\circ \leq R. A. \leq 290^\circ$ seems to be full of few-degree excesses not compatible with random fluctuations (the statistical significance is up to 7 SD). We note that the region 4 is located in the “loss cone” of the LSA, near the North Galactic pole. The observation of regions 3 and 4 is reported by ARGO-YBJ for the first time. Recently HAWC confirmed the observation of the region 4 even if with smaller statistics (Abeysekara et al., 2014). We note that the regions over which ARGO-YBJ observes significant MSA have total extension ~ 0.8 sr, i.e. one third of the ARGO-YBJ field of view in celestial coordinates.

3.1 The multiplicity spectrum

The events recorded by the ARGO-YBJ experiment are classified as a function of the particle multiplicity, i.e. the number of fired strips on the central carpet (for details see Di Sciascio, 2014). Figure 4 reports the multiplicity spectra for the 4 MSA regions observed by ARGO-YBJ (top-down). The number of events collected within each region are computed for the event map e as well as for the background one b . The relative excess $(e - b)/b$ is computed for each multiplicity interval. The horizontal axis reports the multiplicity, the vertical one the relative intensity (for details see Bartoli et al., 2013).

The black plot reports the region 1 multiplicity spectrum. It is the hardest one detected by ARGO-YBJ and it shows a flattening around multiplicity 400 at relative intensity $\sim 0.7 \times 10^{-3}$. The region-2 multiplicity spectrum (red plot) is flatter than the one of region 1 and it turns out to be compatible with the constant result obtained by Milagro

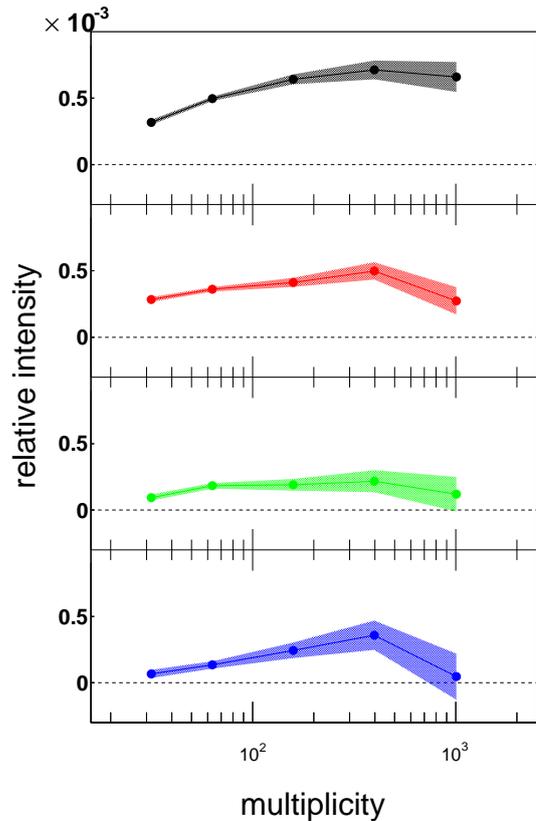


Figure 4. Size spectrum of the four MSA regions observed by ARGO-YBJ (regions 1 to 4 starting from the top) (Bartoli et al., 2013). The vertical axis represents the relative excess $(e - b)/b$. The statistical errors are represented as coloured bands around the experimental points.

(Abdo et al., 2008). The average intensity is $\sim 0.35 \times 10^{-3}$. The excesses in both regions are harder than the spectrum of the isotropic part of CRs. Similar results are obtained for the region 3 (green graph), although the intensity is settled around $\sim 0.2 \times 10^{-3}$. The region 4 (blue graph), the least significant one, has a hard spectrum which rises up at a multiplicity between 300 and 400. The elemental composition and the energy spectrum of these regions are not known. In the hypothesis of a proton point-source having the average declination of region 1 the energy corresponding to a multiplicity 400 is about 15 TeV.

3.2 Time dependence

The stability of the fractional excess in all four MSA regions has been investigated with data recorded by ARGO-YBJ in the 2007–2012 years, when the solar activity gradually increases. As it can be seen in Fig. 5, there is no evidence either of a seasonal variation or of constant increasing or decreasing trend of the emission, as expected from the cancellation of many systematics in measuring relative quantities. The average flux values are $(0.50 \pm 0.04) 10^{-4}$, $(0.37 \pm 0.03) 10^{-4}$,

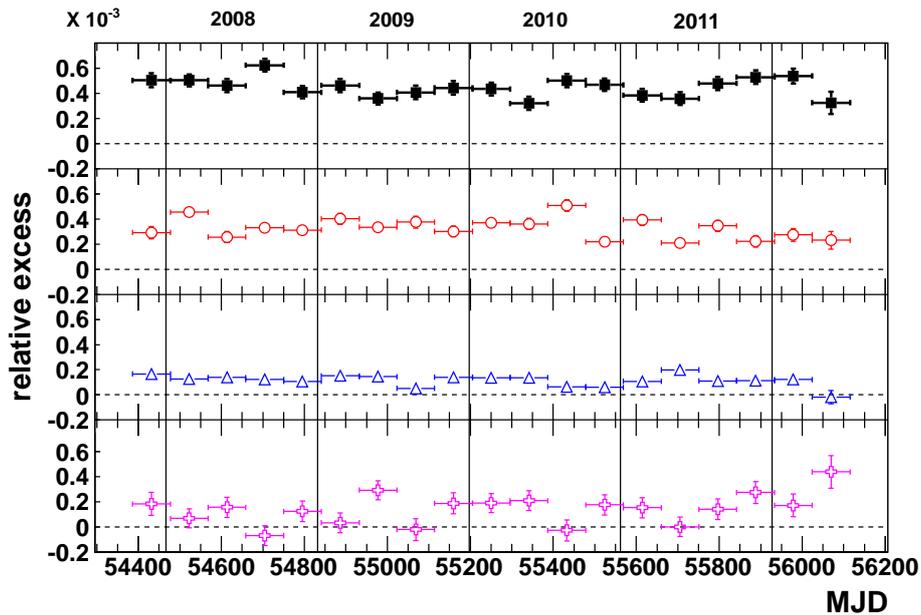


Figure 5. The relative event excess with respect to the background in the regions 1 to 4 as a function of the observation time is shown starting from the top (Bartoli et al., 2013). The time-bin width is approximately 3 months.

$(0.16 \pm 0.03) 10^{-4}$ and $(0.14 \pm 0.03) 10^{-4}$ for regions 1, 2, 3 and 4, respectively ($\chi^2/\text{d.o.f.}$ 23/18, 33/18, 38/18 and 28/18) (Bartoli et al., 2013). This result seems to exclude any effect of the solar activity on the MSA.

4 Origin of the Galactic CR anisotropy

Summarizing, data reveal two characteristics of the CR anisotropy that cannot be described by any standard diffusion model of CR propagation in the interstellar medium, showing that the propagation of CR inside the Galaxy is not well-understood yet.

1. The measured dipole amplitudes (Fig. 1, upper panel) are smaller, even by two orders of magnitude at PeV energies, than predictions by models with a strong dependence of the diffusion coefficient upon rigidity ($\delta \geq 0.5$ favoured by current B/C and antiproton data, Di Bernardo et al., 2010): the so-called “CR anisotropy problem” (Hillas, 2005; Blasi and Amato, 2012).
2. The diffusion approximation, valid only for the isotropic part of the CR distribution function, foresee only a dipole, but the CR arrival direction distribution in sidereal time is not purely dipolar (the observation of structures down to about 10° implies multipoles of order 18). Above 100 TeV the dipole term seems to disappear and the flip of the phase suggests an anisotropy with a direction opposite to that observed at lower energies.

So far, no theory of CRs in the Galaxy exists yet to explain the observations at different angular scales leaving the standard model of CRs and that of the local magnetic field unchanged at the same time.

To explain the “CR anisotropy problem” some authors proposed a reduction of the diffusion coefficient in the solar neighborhood (Zirakashvili, 2005). It has been also suggested that a spatial correlation of the diffusion coefficient with the sources of turbulence in the interstellar medium reduces the CR gradient and the anisotropy (Evoli et al., 2012).

Recently, some authors discussed the possibility of a misalignment between the regular magnetic field and the CR gradient (Mertsch and Funk, 2015). They found that if the field direction and the gradient direction are close to $\sim 90^\circ$, the dipole amplitude is considerably suppressed and can be reconciled with observations. They showed also that it is not possible to determine the direction of the CR gradient (and thus the direction of the closest CR sources) from the dipole direction, thus hampering the search for nearby sources.

A number of models beyond the standard diffusion approximation have been proposed. For example, it was discussed the possible role of magnetic fields of the heliosphere (Lazarian and Desiati, 2010; Desiati and Lazarian, 2013; Drury, 2013; Schwadron et al., 2014; Zhang et al., 2014) and the effect of scattering on the local magnetic field turbulence structures (Giacinti and Sigl, 2012; Ahlers, 2014). In addition, some exotic models suggesting that the small scale anisotropy is the result of decay of quark matter in the pulsars (Perez-Garcia et al., 2014) or in the self-annihilation of dark matter (Harding, 2013) have been also proposed.

5 Conclusions and perspectives

The origin of the observed anisotropy is still unknown. The distribution of sources, the irregularities of the magnetic field, in particular in the Sun neighbourhood, likely contribute to some extent to shape the CR spatial distribution. All these components could be disentangled in the future with next generation ground-based experiments able to measure the anisotropy of Galactic CRs for each of the CR charge groups individually.

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