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Observations of the anisotropy of cosmic rays at TeV–PeV

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Abstract. During the past decade, multiple observatories have reported significant observations of the anisotropy of cosmic rays in the TeV energy band. The anisotropy has been observed at large scales and small scales in both the Northern and Southern Hemispheres. The source of the anisotropy is not well-understood, though both a galactic and a heliospheric origin have been suggested. We discuss recent observations of the shape and energy dependence of the anisotropy, with particular attention to measurements by the IceCube Neutrino Observatory in the Southern Hemisphere and the Milagro and High-Altitude Water Cherenkov (HAWC) observatories in the Northern Hemisphere.

1 Introduction

Recent observations of the distribution of arrival directions of TeV cosmic rays at Earth have demonstrated the presence of an anisotropy at an intensity level of 10^{-3}. Measurements in the Northern Hemisphere were performed by the Tibet ASγ array (Amenomori et al., 2005), Super-Kamiokande (Guillian et al., 2007), Milagro (Abdo et al., 2008, 2009), EAS-TOP (Aglietta et al., 2009), MINOS (de Jong, 2011), ARGO-YBJ (Di Sciascio, 2013; Bartoli et al., 2013), and most recently HAWC (BenZvi et al., 2013). In the southern sky observations covering a large energy range have been made with the IceCube (Abbasi et al., 2010, 2011, 2012) and IceTop (Aartsen et al., 2013) detectors.

The anisotropy has been observed on both large angular scales ($> 60°$ in extent) and small scales ($< 20°$) over the full sky. Including all observations performed during the past decade, the intensity of the large-scale anisotropy has been investigated between 1 TeV and 1 PeV, and the time dependence of the large-scale structure has been observed continuously over the most recent solar cycle. We discuss these results in Sects. 2.1 and 2.2. The small-scale anisotropy is described in Sect. 3. Although the source of the anisotropy is not well-understood, we describe several origin scenarios as the data are presented.

2 Large-scale structure

The large-scale anisotropy in the TeV cosmic rays can be described as a linear combination of dipole and quadrupole components. Defining the relative intensity of the distribution of cosmic ray arrival directions as

$$\delta I(\alpha,\delta) = \frac{\Delta N}{\langle N\rangle} = \frac{N(\alpha,\delta) - \langle N(\alpha,\delta)\rangle}{\langle N(\alpha,\delta)\rangle}, \quad (1)$$

where α and δ are right ascension and declination, and N is the number of events at (α, δ), we find that the amplitude of δI is approximately 10^{-3}. The top panel of Fig. 1 shows δI measured at 20 TeV with IceCube (Santander et al., 2013a). While only the southern sky is shown, a similar structure is consistently observed in the Northern Hemisphere by several experiments: a large-scale excess near $\alpha = 110°$, and a corresponding deficit near $\alpha = 220°$.

2.1 Energy dependence

The energy dependence of the large-scale anisotropy has been studied over a large energy range using the IceCube Neutrino Observatory. IceCube is comprised of 5160 optical modules deployed 1.4 km below the South Polar ice sheet, and it is sensitive to the TeV muons produced in cosmic ray air showers between 10 TeV and 10 PeV. On the surface of the ice sheet, the IceTop detector of 86 surface stations is used to observe air showers above 100 TeV.

Figure 1 shows the large-scale structure observed by IceCube and IceTop (Santander et al., 2013a). The complete IceCube cosmic-ray data set, consisting of $> 10^{11}$ individual air showers, has a median energy of 20 TeV, moderately higher in energy than the observations performed by surface arrays in the Northern Hemisphere. At 20 TeV the anisotropy exhibits an excess near $\alpha = 110°$ and a deficit near $\alpha = 220°$.

Using the number of triggered optical modules and the zenith angle of the muons as a proxy estimate of the energy of the primary cosmic ray, the IceCube data can be used to produce a high-energy data set with a median energy of 400 TeV (Abbasi et al., 2012). These data are shown in the middle panel of Fig. 1, and exhibit a “flip” in the orientation of the anisotropy, with a significant deficit present at $\alpha = 110°$. Because of the energy overlap between IceCube and IceTop above 100 TeV, it is possible to produce an independent intensity map of IceTop events with a median energy of 400 TeV (Aartsen et al., 2013). The independent IceTop data set also exhibits a significant deficit at $\alpha = 110°$.

Due to the large dynamic range of IceTop, we may also produce a sky map of the cosmic rays with a median energy of 2 PeV; this map is shown in the bottom panel of Fig. 1. At high energy the deficit at low right ascension persists, but its amplitude is nearly 3×10^{-3}, several times larger than at 400 TeV (Aartsen et al., 2013).

The observation of large-scale structure can be explained as a consequence of the diffusion of cosmic rays from nearby sources in the galaxy. For example Erlykin and Wolfendale (2006), Blasi and Amato (2012), Pohl and Eichler (2013), and Sveshnikova et al. (2013) have conducted numerical experiments indicating that a large-scale anisotropy at the 10^{-3} level can easily arise from cosmic rays diffusing from nearby supernova remnants. Alternatively, Biermann et al. (2013) have proposed a magnetized field flow from old supernova remnants as the origin of the large-scale structures. While the anisotropy we observe is a particular realization of the distribution of sources in the galaxy, an average over many numerical simulations can produce the behavior observed in the data, including growth in the relative intensity as a function of energy and sudden flips in the phase of the anisotropy (Blasi and Amato, 2012; Pohl and Eichler, 2013; Sveshnikova et al., 2013).

2.2 Time dependence

Several authors have suggested that the heliosphere can have a significant influence on the cosmic-ray anisotropy (Desiati and Lazarian, 2013; Drury, 2013; Schwadron et al., 2014). Measurements of the time dependence of the anisotropy over periods comparable to one solar cycle may suggest the presence or absence of a heliospheric effect. In recent years conflicting measurements of time dependence have been reported in the literature. For example, the Milagro collaboration claimed an increase in the amplitude of the dipole component of the anisotropy over seven years of measurements ending in 2007 (Abdo et al., 2009). In contrast, data from the Tibet ASγ detector indicated no significant changes in the anisotropy during nine years of measurements ending in 2008 (Amenomori et al., 2010).

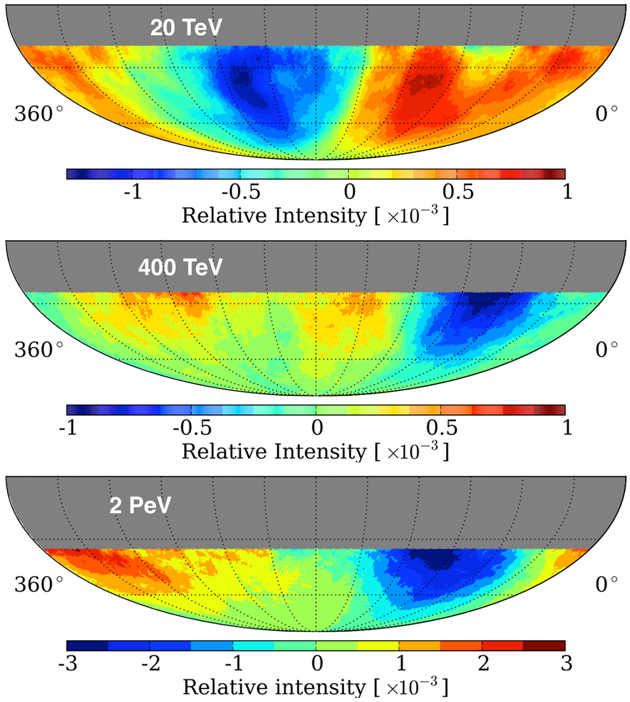

Figure 1. Top: large-scale anisotropy observed with IceCube, 20 TeV median energy, from Santander et al. (2013a). Middle and bottom: IceCube 400 TeV relative intensity map (Abbasi et al., 2012) and IceTop 2 PeV map (Aartsen et al., 2013).

More recently a long-term study of the cosmic-ray anisotropy has been reported by combining data from IceCube with its precursor experiment, the AMANDA detector (Santander et al., 2013a, b). The combined data cover twelve years of observation ending in 2012. No significant time variations in the large-scale anisotropy were observed during this period, with the exception of IceCube data from 2008 (Santander et al., 2013b). However, this was the first year of regular IceCube operations so it is possible that the variation is the result of an instability in the detector.

The AMANDA-IceCube data cover the second half of the 23rd solar cycle and the first half of the 24th solar cycle. IceCube will continue to collect cosmic ray data for the next decade, and the construction of new detectors such as HAWC will allow long-term simultaneous measurements of the anisotropy at complementary energy scales.

3 Small-scale anisotropy

In addition to the large-scale anisotropy observed by many experiments since the year 2000, multiple experiments have also observed regions of excess and deficit on small angular scales of about 10° to 20°. The small-scale structures were observed first by Milagro (Abdo et al., 2008), a water Cherenkov gamma-ray detector located in New Mexico, USA, and as fit residuals of the large-scale structure observed by the Tibet ASγ array (Munakata et al., 2007). The Milagro Collaboration identifed two strong regions of excess at the 10^{-4} level: one located at $\alpha = 60°$, and a second located at $\alpha = 120°$. These two regions are shown in Fig. 2.

Though Milagro was a gamma-ray detector, a careful analysis of the data showed that these regions were comprised of hadronic cosmic rays. Monte Carlo simulations of several flux hypotheses indicated that the first region is described by a cutoff in the energy spectrum above 10 TeV, and the second region is described by a simple power law. The Milagro observations have been followed up and confirmed by the ARGO-YBJ Observatory (Bartoli et al., 2013) and the HAWC Observatory (BenZvi et al., 2013), which both have lower energy thresholds than Milagro. The relative intensity of the cosmic rays observed by HAWC is shown in Fig. 3.

In the southern sky, IceCube data have been used to observe small-scale anisotropies beginning in 2008. The relative intensity observed by IceCube, determined for the complete data set with median energy 20 TeV, is shown in Fig. 2 (Santander et al., 2013a). Like the observations in the Northern Hemisphere, there is a significant excess at $\alpha = 120°$. However, the large excess at $\alpha = 60°$ is not present in the IceCube data. In addition, while the Northern Hemisphere measurements are dominated by excess regions, the southern sky shows regions of excess and deficit of equal amplitude.

The causes of the differences between the IceCube data and the observations in the Northern Hemisphere are not yet understood, but there are several possible explanations. One possibility is that the small-scale structure has a strong energy dependence, and so ARGO-YBJ and HAWC (1 TeV), Milagro (1 TeV), and IceCube (20 TeV) are not observing the same features. Another possibility is a difference in mass composition between the data. Above several TeV the flux of primary cosmic rays is dominated by helium over protons (Ahn et al., 2010). However, since IceCube detects cosmic rays by observing muons, it has a trigger bias against heavier nuclei at its energy threshold (Abbasi et al., 2011). This raises the possibility that IceCube is not observing a population of cosmic rays equivalent to that shown by lower-energy Northern Hemisphere experiments. The effect of mass composition on the anisotropy has not been studied, so this issue must be resolved with future analysis.

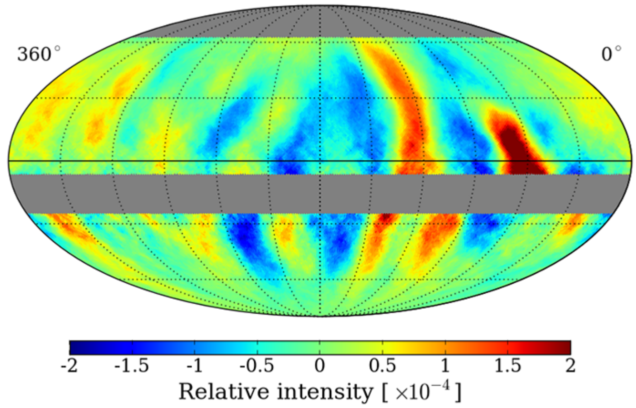

Figure 2. Small-scale anisotropy observed in the Northern Hemisphere by Milagro (Abdo et al., 2008) and in the Southern Hemisphere by IceCube (Santander et al., 2013a).

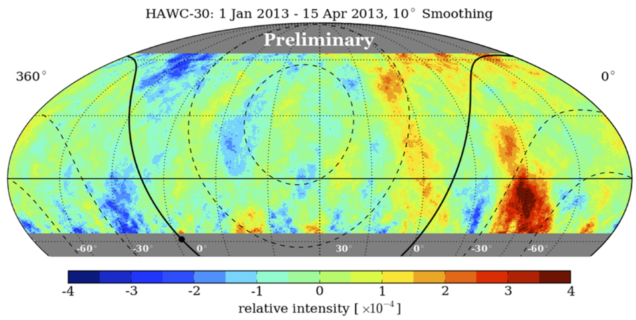

Figure 3. Small-scale anisotropy observed in the Northern Hemisphere by the HAWC Gamma-Ray Observatory (BenZvi et al., 2013).

3.1 Time and energy dependence

The time- and energy-dependence of the small-scale anisotropy has been investigated using IceCube and IceTop data (Abbasi et al., 2012; Aartsen et al., 2013). Unlike the large-scale structure, the small-scale anisotropy does not appear to persist to either the 400 TeV or the 2 PeV energy bands. However, there are no significant variations in the structures over time during the observation periods between 2008 and 2012.

4 Origin of small-scale structure

Following the initial observation of the small-scale anisotropy by Milagro, several authors hypothesized that unusual magnetic field configurations could allow concentrated beams of hadronic particles to propagate to Earth from accelerators hundreds of parsecs away (Drury and Aharonian, 2008; Salvati, 2010).

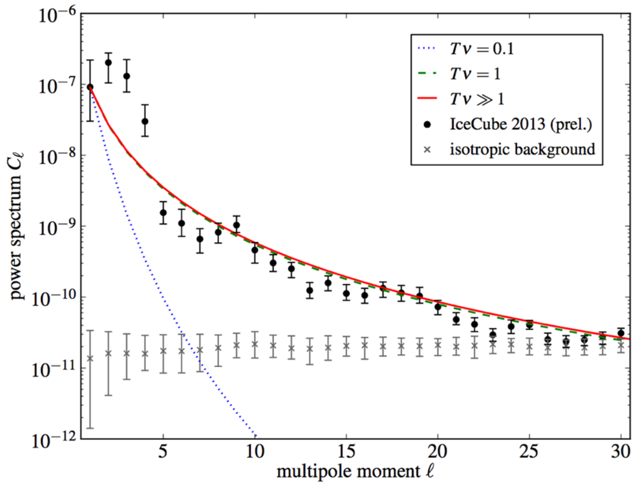

Figure 4. Comparison of the IceCube power spectrum against the angular correlations predicted by distortion of a large-scale anisotropy by a turbulent magnetic field. From Ahlers (2014).

More recent work has focused instead on the possibility that small-scale structure is produced by distortion of dipole anisotropies originating in particle diffusion as cosmic rays propagate through turbulent magnetic fields in the galaxy. For example, Giacinti and Sigl (2012) have carried out numerical simulations of cosmic ray diffusion in the galaxy to demonstrate that magnetic turbulence can give rise to 10° to 20° structures like those in real data. Of course, these studies are not predictive, as the actual structures observed at Earth are produced by the particular realization of the random magnetic field in our galaxy.

Ahlers (2014) has approached this same problem analytically, showing the effect of isotropic turbulence as a function of time on an initially dipolar anisotropy. The advantage of this technique is its quantative description of the distortion of a global dipole anisotropy into higher multipole anisotropies using the angular power spectrum of the data.

Figure 4 shows the angular power spectrum of the combined IceCube cosmic-ray arrival direction distribution recorded between 2008 and 2012 (Santander et al., 2013a; Ahlers, 2014). The data points are helpful to visualize the relatively large amount of power at low multipole moments $\ell < 5$ (see Figs. 1 and 2), as well as the small but still significant power at moments up to $\ell = 20$, which correspond to angular scales of order 10°. The light gray band indicates the expected power spectrum of an isotropic angular distribution of cosmic rays, estimated for many random realizations of the IceCube data.

According to the model developed by Ahlers (2014), the sum of multipoles in the power spectrum is conserved while high-order multipoles grow (in relative terms) as cosmic rays propagate through a turbulent field. As a result, an initially dipolar distribution will leak into higher multipole moments. The asymptotic strength of the high-order multipoles at times much longer than the diffusion relaxation time is shown as a red curve in Fig. 4. This curve appears to be a reasonable description of the IceCube data above $\ell = 5$, supporting the hypothesis that the small-scale anisotropy originates in magnetic scattering.

5 Conclusions

A 10^{-3} anisotropy in the TeV–PeV cosmic rays has been established with a full decade of observations in both the Northern and Southern Hemispheres. The energy dependence of the anisotropy exhibits a change in relative orientation and an increase in amplitude as a function of energy, which are expected features of the diffusion of cosmic rays from nearby galactic accelerators. Simulations of diffusion also indicate that turbulent magnetic fields can explain the origin of the small-scale anisotropy. This hypothesis is further supported by the shape of the angular power spectrum.

At low energies (< 10 TeV), conflicting measurements have been reported on the time dependence of the anisotropy. However, above 10 TeV both the large- and small-scale structures appear to be stable over times comparable to the length of the solar cycle. With IceCube and HAWC expected to record very large numbers of cosmic rays during the next decade, we should soon have significant data to study the influence of the heliosphere on the anisotropy.

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