An update on cosmic-ray anisotropy studies with IceCube

The ICECUBE Collaboration

Abstract: The IceCube neutrino observatory detects energetic muons from the interaction of TeV cosmic rays with the Earth’s atmosphere at a rate of about 2 kHz. The integration of this high rate over the course of several years of operation has provided us with a data set of several billion events with cosmic-ray energies between 20 and 400 TeV. A data set of this size, combined with the degree-scale angular resolution of IceCube for cosmic-ray muons, can be used to search for anisotropy in the arrival direction of cosmic rays at the per-mille level or lower. Previous studies based on data taken with partial configurations of IceCube show significant anisotropy over a wide range of angular scales in two energy bands of about 20 TeV and 400 TeV. We present an update on studies using all currently available cosmic-ray data from IceCube, which consist of 150 billion events collected between 2007 and 2012.

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1 Introduction

Several years of observations from tens of GeV to PeV energies have shown that cosmic rays arrive at the Earth with a small anisotropy of order $10^{-4}$ – $10^{-3}$. The most prominent feature in the anisotropy is a large angular scale structure of per-mille amplitude that is usually described as a dipole. Significant structure is also present with a smaller amplitude and characteristic angular sizes between 15° and 30°. In addition, the topological structure of the anisotropy changes at energies in excess of approximately 100 TeV, often interpreted as a change in phase of the dipole component of the global anisotropy [1].

IceCube collects a large number of cosmic-ray induced muon bundles (see section 2). The high degree of alignment of the muons with the parent cosmic-ray particles enables the study of the distribution of cosmic-ray arrival directions at a level of about $10^{-5}$. The median energy of cosmic rays producing the muons collected by IceCube is about 20 TeV. Higher energies can be reached by selecting for larger events. IceCube provided the first sky map of the cosmic-ray arrival direction up to 400 TeV median energy range from the southern hemisphere [2][3], confirming the topological change in the observed anisotropy. With the IceTop air-shower array it was possible to determine the anisotropy up to about 2 PeV [4]. The sky map obtained by subtracting the large angular scale components (a dipole and a quadrupole in spherical harmonics) from the data [5], shows significant small angular scale structures in cosmic-ray anisotropy, similarly to observations in the northern hemisphere [6][7].

In this paper we present an update on previous cosmic-ray anisotropy studies using data collected by IceCube from June 2007 to May 2012. First, we calculate the angular power spectrum of the cosmic-ray map to search for anisotropy over a wide angular range. We then concentrate on the study of the anisotropy at very small angular scales by fitting and subtracting the large scale structure from the map. Finally, we present the resulting sky maps of cosmic ray arrival distributions.

A separate analysis of the stability of the large scale anisotropy with time is also presented in these proceedings [8].

2 The IceCube Observatory

The IceCube neutrino telescope [9] consists of a cubic-kilometer array of 5160 Digital Optical Modules (DOMs) deployed on 86 vertical cables, or strings, between depths of 1450 m and 2450 m in the glacial ice sheet at the geographic South Pole. In this work, IceCube is used as a cosmic-ray detector by exploiting its sensitivity to energetic muons produced in the interaction of cosmic rays with the Earth’s atmosphere. The Cherenkov light emitted by energetic muons as they propagate through the ice is recorded by DOMs. The amplitude and timing of the light signals can be used to reconstruct the arrival direction of the muons and therefore of their parent cosmic-ray particle.

IceCube was operated in partial configurations from the beginning of detector construction in 2005 until the completion of the detector in 2010. Partial configurations were labeled according to the number of active strings of DOMs that were deployed in the ice at the time. For instance, the final configuration of IceCube (called IC86) consists of 86 detector strings. A list of the detector configurations used in this work is given in Table [1].

3 Data selection

Events in IceCube are recorded using a simple multiplicity trigger that requires coincident hits in eight DOMs within a 5 µs window. All locally-coincident hits within a ±10 µs window are recorded for each trigger, and overlapping windows are merged. The trigger rate shows a seasonal modulation of ±10% over the year due to changes in
atmospheric conditions that affect muon production in air showers. The average trigger rate for the IC86 configuration is about 2.7 kHz. The integration of this high rate of cosmic-ray muons over a period of about five years results in a combined data set of about 150 billion events that is used in this work to search for cosmic ray anisotropy.

The anisotropy search relies on a precise estimate of the arrival direction of each cosmic-ray event. A first estimate of the event arrival direction is obtained using a $\chi^2$ linear-track fit to the DOM hits pattern. This coarse estimate is used as a seed for a more complex likelihood-based algorithm that implements some aspects of the light generation and propagation in the ice. Simulation studies indicate that the median angular resolution of this algorithm is about 3°. In this analysis, we only consider muon events with a reconstructed zenith angle of less than 70°, which limits our sky exposure to the declination range $-90° < \delta < -20°$. The angular resolution degrades very quickly for events with a larger zenith angle.

Due to the high trigger rate, only a very limited amount of data is stored and transmitted for each cosmic-ray event. A compact Data Storage and Transfer (DST) format is used to store the results of the online likelihood reconstruction together with a selected list of event variables. This data is transmitted from the South Pole via the South Pole Archival and Data Exchange (SPADE) satellite communication system. Given its high statistics and reasonable angular resolution, we use the DST data set for cosmic-ray anisotropy studies.

The median energy of the DST set is about 20 TeV and the average trigger rate for the IC86 configuration is about 2.7 kHz. The integration of this high rate of cosmic-ray muons over a period of about five years results in a combined data set of about 150 billion events that is used in this work to search for cosmic ray anisotropy.

The sky maps are constructed using the HEALPix pixelisation of the celestial sphere, which provides bins of equal solid angle. The selected HEALPix resolution ($N_{\text{side}} = 64$) divides the sphere into 49152 pixels with an average size of about 1°.

A relative intensity map of deviations of the data counts from the reference level is constructed using the expression $\delta I_i = (N_i - \langle N_i \rangle)/\langle N_i \rangle$, where $N_i$ and $\langle N_i \rangle$ are the number of observed events and the number of reference events in the $i$th pixel, respectively. A smoothing procedure is applied to the data to increase the sensitivity of the search to structures with angular scales larger than the map pixel size. The smoothing process sums all events in each pixel to the events in all pixels contained within a certain angular distance (or “smoothing radius”). The statistical significance of any observed deviation with respect to the reference level is calculated according to [13].

### 5 Results

Similarly to what was presented in Ref. [5], an angular power spectrum of the relative intensity map was used to estimate the strength of the anisotropy over a wide range of angular scales. The power spectrum was calculated using the PolSpice software package [12] that corrects systematic effects introduced by the partial sky coverage of our data.

The spectrum, shown in Fig. 1, exhibits significant power at low-$\ell$ multipoles (i.e., large angular scales). This dominant large scale feature has been previously reported by IceCube [2] and is usually described as the combination of the dipole ($\ell = 1$) and quadrupole ($\ell = 2$) modes of the spherical harmonic functions. In agreement with the results of the previous study, a significant departure from the isotropic level is also observed at angular scales roughly between 15° and 30° (i.e., for multipole between $\ell \sim 5$ and $\ell \sim 12$).

The improvement in statistics from the combination of all available IceCube data reveals a departure from isotropy at higher multipole modes than previously observed. The spectrum indicates that the relative intensity sky map should exhibit anisotropy up to angular scales below 10° ($\ell \sim 20$).

The presence of small scale anisotropy is also evident in the one-dimensional projection of relative intensity as a function of right ascension shown in Fig. 3 for the declination range $-75° < \delta < -35°$.

In order to reveal the smaller scale anisotropy, the dipole and quadrupole terms of the spherical harmonic

### Table 1: Detector configurations that were used to collect the data analyzed in this work. The final configuration of IceCube consists of 86 strings of DOMs deployed in the ice (IC86), each partial configuration is indicated as “IC” followed by the number of deployed strings that participated in the data acquisition during each period.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Start</th>
<th>End</th>
<th>Live-time (days)</th>
<th>No. of events ($\times 10^9$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC22</td>
<td>06/2007</td>
<td>04/2008</td>
<td>269.4</td>
<td>5.3</td>
</tr>
<tr>
<td>IC40</td>
<td>05/2008</td>
<td>05/2009</td>
<td>335.6</td>
<td>18.9</td>
</tr>
<tr>
<td>IC59</td>
<td>06/2009</td>
<td>06/2010</td>
<td>335.0</td>
<td>33.8</td>
</tr>
<tr>
<td>IC79</td>
<td>06/2010</td>
<td>05/2011</td>
<td>299.7</td>
<td>39.1</td>
</tr>
<tr>
<td>IC86</td>
<td>05/2011</td>
<td>05/2012</td>
<td>332.9</td>
<td>52.9</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td>150</td>
</tr>
</tbody>
</table>

2. http://www2.iap.fr/users/hivon/software/PolSpice/
functions were fit and subtracted from the relative intensity map. The best fit coefficients are given in Table 2 for the spherical harmonic fit functions in Ref. [5]. The residual maps were smoothed to search for small-scale anisotropy. A map of relative intensity after the dipole- and quadrupole-subtraction is shown in Fig. 3 for a smoothing radius of 20°. The map shows excellent agreement with previous results. Smaller scale structure is revealed in this analysis by fitting and subtracting the dipole and quadrupole terms of the spherical harmonic functions. In addition to the anisotropy observed in the IC59 analysis with typical sizes between 15° and 30°, new structure with an angular scale of about 5° degrees is revealed in the cosmic ray flux. This observation represents the first detection of TeV anisotropy at such a small angular scale, close to the angular resolution of IceCube for cosmic rays.

Maps of relative intensity and pre-trial statistical significance are shown in Fig. 4 before (Figs. 4a and 4b) and after (Figs. 4c and 4d) the dipole and quadrupole subtraction procedure for a 5° smoothing radius. The high significance of the small-scale structure shown in the dipole- and quadrupole-subtracted maps indicates for the first time the presence of anisotropy in the flux of TeV cosmic rays at angular scales of about 5°, close to the angular resolution of IceCube for cosmic rays.

Table 2: Dipole and quadrupole coefficients for the best fit to the relative intensity map. The indicated uncertainties are statistical only. A good agreement is found between these values and those reported in [5].

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Value ($ \times 10^{-4}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_0$</td>
<td>$-0.05 \pm 0.82$</td>
</tr>
<tr>
<td>$p_1$</td>
<td>$3.01 \pm 0.28$</td>
</tr>
<tr>
<td>$p_2$</td>
<td>$-2.84 \pm 0.28$</td>
</tr>
<tr>
<td>$p_3$</td>
<td>$-0.08 \pm 1.42$</td>
</tr>
<tr>
<td>$Q_1$</td>
<td>$-0.03 \pm 0.64$</td>
</tr>
<tr>
<td>$Q_2$</td>
<td>$-2.69 \pm 0.20$</td>
</tr>
<tr>
<td>$Q_3$</td>
<td>$-8.14 \pm 0.20$</td>
</tr>
<tr>
<td>$Q_4$</td>
<td>$-2.01 \pm 0.09$</td>
</tr>
<tr>
<td>$Q_5$</td>
<td>$-4.77 \pm 0.09$</td>
</tr>
</tbody>
</table>

Figure 3: Dipole- and quadrupole-subtracted relative intensity map for a smoothing radius of 20°. The structure observed in this map shows good agreement with IC59 results [5].

6 Discussion

An update is presented on the study of cosmic ray anisotropy at TeV energies with the IceCube detector. In this work, we use a sample of about 150 billion events collected with IceCube in several detector configurations over a period of five years.

The analysis of this sample reveals the presence of significant anisotropy with amplitudes at per-mille level and lower over a wide range of angular scales. The observed large-scale component of the anisotropy shows good agreement with previous results. Smaller scale structure is revealed in this analysis by fitting and subtracting the dipole and quadrupole terms of the spherical harmonic functions.

In addition to the anisotropy observed in the IC59 analysis with typical sizes between 15° and 30°, new structure with an angular scale of about 5° degrees is revealed in the cosmic ray flux. This observation represents the first detection of TeV anisotropy at such a small angular scale, close to the angular resolution of IceCube for cosmic rays.

The origin of the observed cosmic ray anisotropy is not known, and further full sky observations as a function of energy, primary mass and possible correlations with spectral anomalies are necessary to probe deeper into the origin of the observations. It is possible that the anisotropy is a signature of the discreet random distribution of nearby galactic sources of cosmic rays. The energy dependence of the anisotropy structure could arise from the dominance of one or another source at different energies mainly due to differences in ages of the cosmic ray accelerators [16, 17].
Figure 4: Relative intensity and pre-trial statistical significance maps in equatorial coordinates for the combined IceCube data set. The maps are shown before (top) and after (bottom) the dipole- and quadrupole subtraction procedure. A 5° smoothing radius was used for all maps. The maps show an anisotropic structure that is statistically significant at an angular scale of about 5°.

Although current models of cosmic ray propagation in the interstellar medium predict a dipole anisotropy, some astrophysical interpretations of the small scale anisotropy were provided as well [19, 20]. On the other hand, the small scale structure of the anisotropy might simply be an effect of the turbulent interstellar magnetic field in our vicinity [21]. The local interstellar magnetic field is thought to be associated to the Loop I shell expanding from the Scorpion-Centaurus Association and to be relatively regular up to several tens of parsec [22], i.e. the order of magnitude of the estimated proton mean free path in the interstellar medium [23]. Cosmic-ray protons with energy 1-10 TeV happen to have a gyro-radius of the order of the heliospheric size, therefore it is possible that the interstellar magnetic field perturbed by the heliosphere provides significant pitch angle scattering to influence and re-distribute the arrival directions [24, 25, 26].

References

[8] IceCube Coll., paper 0411, these proceedings.