Frascati Physics Series Vol. 58 (2014)
Frontier Objects in Astrophysics and Particle Physics
May 18-24, 2014

Large Scale Distribution of Arrival Directions of Cosmic Rays Detected at the Pierre Auger Observatory Above 10 PeV

Raffaella Bonino for the Pierre Auger Collaboration*
Osservatorio Astrofisico di Torino (INAF), Università di Torino and Sezione INFN, Torino, Italy

**Av. San Martín Norte 304, 5613 Malargüe, Argentina*
(Full author list: http://www.auger.org/archive/authors_2014_05.html)

Abstract

Searches for large-scale anisotropies in the distribution of arrival directions of cosmic rays with energies above 10 PeV detected at the Pierre Auger Observatory are presented. Although no significant deviation from isotropy is revealed at present, some of the measurements suggest that future data will provide hints for large-scale anisotropies over a wide energy range. Assuming that the cosmic ray anisotropy is dominated by dipole and quadrupole moments in the EeV-energy range, some consequences of the present upper limits on their amplitudes are presented.

1 Introduction

To understand CRs nature and origin large scale anisotropy studies are complementary to measurements of energy spectrum and mass composition. The transition from a galactic to an extragalactic origin should in fact induce a significant change in CRs large scale angular distribution. In particular, if they are still galactic at EeV energies, a %-level modulation is expected (the predicted amplitude varies significantly according to the chosen galactic magnetic field, composition and distribution of sources [1]). On the other hand, if CRs are already extragalactic at 10^{18} eV, no structure except for a CMB-dipole is expected, with an anisotropy amplitude of the order of ~ 0.6 % [2].

A measurable dipole is regarded as a likely possibility in many scenarios of CR origins at EeV energies (e.g. as a signature of their escape from Galaxy or a Compton-Getting effect, in case of extragalactic origin). Otherwise, an excess along a plane would show up as a prominent quadrupole moment, plausible scenario in case of emission of light EeV CRs from sources preferentially located in the galactic disk or in the super galactic plane at higher energies.

Using the large amount of data collected by the Surface Detector array of the Pierre Auger Observatory [3], results of first harmonic analyses of the right ascension distribution performed in different energy ranges above 10 PeV are presented here. A thorough search for large scale anisotropies in terms of dipoles and quadrupoles as a function of both the declination and the right ascension is presented as well.

2 First harmonic analysis in Right Ascension

Thanks to the joint data acquired by both the infill array with 750 m spacing and the regular array with 1.5 km spacing, in this analysis we use the full energy range above 10^{16} eV. The data set analyzed here covers the whole period from 1 January 2004 up to the end of 2012.

2.1 Analysis methods

The statistics accumulated in the EeV energy range allows one to be sensitive to intrinsic anisotropies with amplitudes down to the 1% level. This requires determination of the exposure of the sky and of various acceptance effects at a corresponding accuracy. Possible spurious modulations of experimental or atmospheric origin should thus be taken into account or, alternatively, methods which are not sensitive to these effects should be used.

The first kind of approach could be implemented with a "modified Rayleigh analysis" [4], i.e. the classical Rayleigh formalism slightly modified to account for non-uniform exposure. Each event is weighted with the inverse of the integrated number of unitary cells at the local sidereal time of the event. Energy assignment is then corrected for weather and geomagnetic effects [5, 6], which could represent other sources of systematic effects.

Below 1 EeV weather effects have a significant impact also on the detection efficiency and hence spurious variations of the counting rates are amplified. We adopt in this case the differential "East-West method" [7]. It exploits the differences in the number of counts between the eastward and the westward arrival directions at a given time. Since the instantaneous exposure for events coming from E or W is the same, this difference allows us to remove, at first order, effects of experimental or atmospheric origin without applying any correction, although at the price of a reduced sensitivity. The amplitude and phase can thus be calculated by using the standard first harmonic analysis slightly modified to account for the subtraction of the W sector to the E one.

2.2 Amplitude of the first harmonic

The Rayleigh amplitude measured by any observatory can be used to reveal (or infer) anisotropies projected on the Earth equatorial plane. All the amplitude values are thus divided by the mean value of the cosine of the declination of the observed sky, giving a direct measurement of the component of the dipole in the equatorial plane. The obtained amplitudes are shown in the left panel of Fig. 1, the dashed line in the plot represents the upper values of the amplitude which may arise from fluctuations in an isotropic distribution at 99% C.L..

In the energy ranges 1-2 and 2-4 EeV the measured amplitudes of $(1.0\pm0.2)\%$ and $(1.4\pm0.5)\%$ have a probability to arise by chance from an isotropic distribution of about 0.03% and 0.9%, while above 8 EeV the measured amplitude of $(5.9\pm1.6)\%$ has chance probability of only 0.1%. Since several energy bins were searched, these numbers do not represent absolute probabilities and constitute just interesting hints for large scale anisotropies that will have to be further scrutinized with enlarged statistics.

Upper limits at 99% C.L. on the amplitudes have thus been derived and are shown in the right panel of Fig. 1, together with previous results from other experiments and with some predictions for the anisotropies arising from models of both galactic and extragalactic CR origin (see [8] for more details). The bounds reported here already exclude the particular model with an antisym-

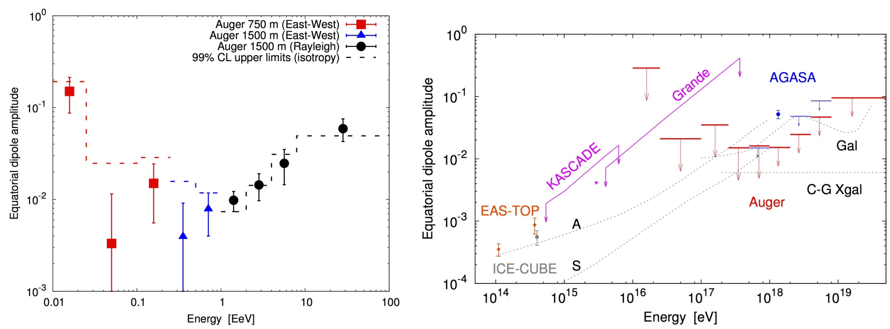

Figure 1: *Left: Equatorial dipole amplitude as a function of energy. Right: Upper limit at 99%C.L. for the equatorial dipole amplitude as a function of energy. Predictions from different models are also displayed (see text).*

metric halo magnetic field (A) above 0.25 EeV and the *Gal* model at few EeV energies, and are starting to become sensitive to the predictions of the model with a symmetric field (S).

2.3 Phase of the first harmonic

The Pierre Auger Collaboration has already reported the intriguing possibility of a smooth transition from a common phase of 270° (compatible with the right ascension of the Galactic Center 268.4°) in the first two bins below 1 EeV to a phase of 100° above 5 EeV [8]. The left panel in Fig. 2 shows this smooth transition in the phase derived with data from 1 January 2004 to 31 December 2010 for the larger array and from 12 September 2007 to 11 April 2011 for the infill. It has been already pointed out that this consistency of phases in adjacent energy intervals is expected with a smaller number of events than the detection of amplitudes standing out significantly above the background noise in the case of a real underlying anisotropy.

This behaviour motivated us to design a prescription with the intention of establishing at 99% C.L. whether this consistency in phases in adjacent energy intervals is real. Once an exposure of 21 000 $\mathrm{km}^2\,\mathrm{sr\,yr}$ is accumulated by the regular array from 25 June 2011 on, and applying the same first harmonic analysis described here, a positive anisotropy signal will be claimed within a global threshold of 1% if a constancy of phase below 1 EeV and/or a transition

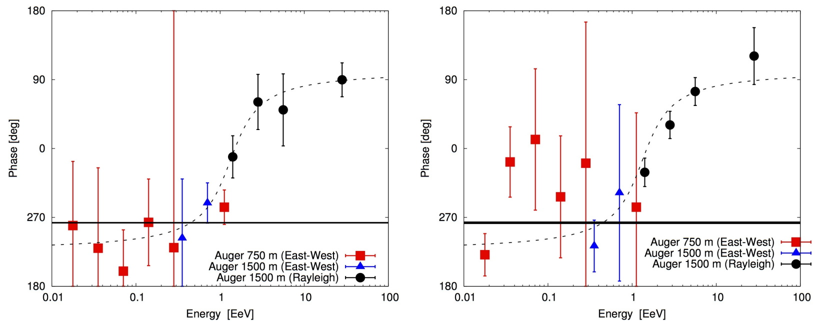

Figure 2: *Phase of the first harmonic as a function of energy with data acquired before (left) and after (right) the beginning of the prescription. The continuous and the dashed lines shown in both plots are the fit defined in* [8].

at ∼1 EeV are observed with the infill and the regular array, respectively.

To report the midterm status of the prescription, the phase of the first harmonic is shown in the right panel of Fig. 2 with data since 25 June 2011 (starting date of the prescription) up to 31 December 2012. At this stage, the values derived from the infill data are still affected by large uncertainties, whereas, the overall behavior of the points derived from the analysis with the regular array shows good agreement with the prescribed curve. The final result of the prescription is expected for 2015, once the required exposure is reached.

3 Spherical harmonic analysis

The analysis presented in the previous section benefits from the almost uniform directional exposure in right ascension of a ground-based observatory operating with high duty cycle, but is not sensitive to a dipole component along the Earth rotation axis. In this section we present a comprehensive search in all directions for any dipole or quadrupole patterns significantly standing out above the background noise [9], whose components are functions of both the right ascension and the declination.

Due to the steepness of the energy spectrum, any mild bias in the estimate of the shower energy with time or zenith angle can lead to significant distortions of the event counting rate above a given energy. The influence of atmospheric conditions and geomagnetic field, the most important effects on shower size, have thus been studied in detail and taken into account [5, 6]. In searching for anisotropies, it is also critical to know accurately the directional exposure of the Observatory, i.e. to accurately determine the operational time of the detector, the geometric aperture and the detection efficiency.

Any angular distribution over the sphere $\Phi(\mathbf{n})$ can be expanded in terms of spherical harmonics, $\Phi(\mathbf{n}) = \sum_{\ell \geq 0} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(n)$, where $\mathbf{n}$ denotes a unit vector taken in equatorial coordinates. Due to the non-uniform and incomplete coverage of the sky at the Pierre Auger Observatory, the estimation of coefficients $a_{\ell m}$ is possible only by assuming a $\ell_{\max}$. The resolution deteriorates by a factor larger than 2 each time $\ell_{\max}$ is incremented by 1. With our present statistics, this prevents the recovery of each coefficient with good accuracy as soon as $\ell_{\max} \geq 3$, which is why we restrict this analysis to dipole and quadrupole searches only.

Assuming that the angular distribution of cosmic rays is modulated by a dipole and a quadrupole, we reconstructed the amplitudes of both moments: the case of a pure dipole is presented in the left panel of Fig. 3. The 99% C.L. upper bounds on the amplitudes that would result from fluctuations of an isotropic distribution are indicated by the dotted line. One can see, similarly to the results presented in the previous section, interesting hints for large scale anisotropies that will have to be further scrutinized with independent data. The corresponding reconstructed directions in orthographic projection with the associated uncertainties are shown in the right panel of Fig. 3 as a function of the energy. All reconstructed declinations are in the equatorial southern hemisphere and the phases in right ascension are smoothly aligned as a function of the energy, as already pointed out in the previous section.

Upper bounds on the dipole and quadrupole amplitudes have been obtained at the 99% C.L. and are shown as a function of energy in Fig. 4, along with generic estimates of the amplitudes expected from stationary galactic sources distributed in the disk considering two extreme cases of primaries: protons and iron nuclei. The expected amplitudes are calculated by considering the Bisymmetric Spiral Structure model with anti-symmetric halo field and a turbulent field generated according to a Kolmogorov power spectrum. Unless the strength of the galactic magnetic field is much higher than in the picture used here, the upper limits on dipole and quadrupole amplitudes challenge

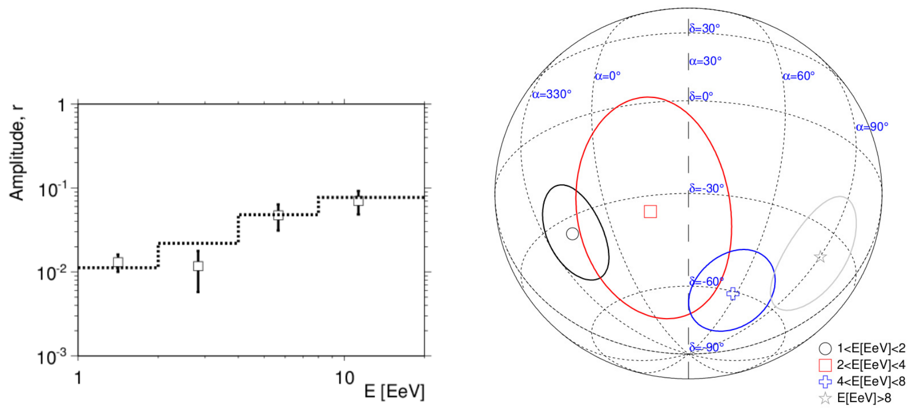

Figure 3: *Left: Amplitude of the dipole as a function of energy. The dotted line stands for the 99% C.L. upper bounds that would result from fluctuations of an isotropic distribution. Right: Directions of the dipole with corresponding uncertainties (circles).*

an origin of CRs from galactic stationary sources distributed in the disk and emitting predominantly light particles in all directions at EeV energy ranges.

4 Auger-TA joint analysis

Full-sky coverage allows the measurement of the spherical harmonic coefficients in an unambiguous way. This can be achieved by combining data from observatories located in both the northern and southern hemispheres. A combined analysis using data recorded at the Telescope Array and the Pierre Auger Observatory has been performed and will be reported in a near future [10].

5 Conclusions

Searches for evidence of large scale anisotropy in the CRs arrival directions have been pursued by the Auger Collaboration. No statistically significant deviation from isotropy is revealed within the systematic uncertainties, even though there are interesting hints for large scale anisotropies that will have to be further scrutinized with independent data. An intriguing phase transition in

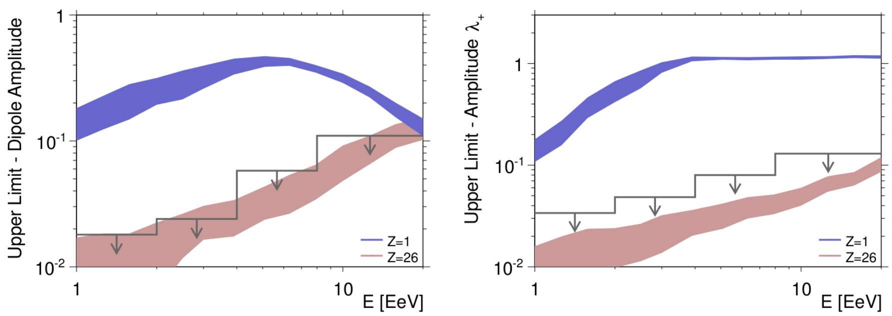

Figure 4: *99% C.L. upper limits on dipole and quadrupole amplitudes as a function of energy. Some generic anisotropy expectations are also shown (see text and* [9] *for more details).*

right ascension has been observed with increasing energy and will be specifically tested through a prescribed test.

Acknowledgements The successful installation, commissioning and operation of the Pierre Auger Observatory would not have been possible without the strong commitment and effort of the technical and administrative staff in Malargüe.

References

1. V. Ptuskin *et al.*, A&A **268**, 726 (1993); J. Candia *et al.*, JCAP **0305**, 003 (2003); G. Giacinti *et al.*., JCAP **07**, 031 (2012).
2. A.M. Hillas, PhLA **24**, 677 (1967); V.S. Berezinsky *et al.*, PhRvD **74** 043005 (2006) and APh **21**, 617625 (2004).
3. A. Castellina, these proceedings, VULCANO Workshop 2014 (2014).
4. S. Mollerach and E. Roulet, JCAP **0508**, 004 (2005).
5. Pierre Auger Collaboration, APh **32**, 89 (2009).
6. Pierre Auger Collaboration, JCAP **11**, 022 (2011).
7. R. Bonino *et al.*, ApJ **738**, 67 (2011).
8. Pierre Auger Collaboration, APh **34**, 628 (2011)
9. Pierre Auger Collaboration, ApJS **203**, 34 (2012); ApJL **762**, L13 (2013).
10. Pierre Auger and Telescope Array Collaborations, paper submitted to ApJ