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Arrival direction distribution of cosmic rays from ≃100 PeV to the highest energies detected at the Pierre Auger Observatory

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At the Pierre Auger Observatory, several searches for anisotropies in the distribution of arrival directions of cosmic rays detected above $\simeq$ 100 PeV are being undertaken. Although no significant deviation from isotropy has been revealed at present, some measurements related to the angular distributions at large scales are suggestive of dipole patterns of small amplitudes over a wide energy range. Upper limits on the dipole and quadrupole moments derived from these analyses are presented. They constrain scenarios in which cosmic rays could originate from stationary Galactic sources emitting in all directions up to the *ankle* energy.

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1. Introduction

Despite important advances undertaken in revealing the nature of Cosmic Rays (CRs), their origins, as well as the details of their propagation from the different candidate sources until their arrival on Earth, are still enshrouded with mystery. Not only are the mechanisms of their production still subject to debate, but even questions about the processes leading to acceleration up to observed energies greater than 10^{20} eV are still unsolved. The present situation in the CR field is of great interest; first, because existing experiments have accumulated a large number of events enabling a panel of conclusive physics analysis. Second, because a path leading to the determination of the origin of CRs is becoming more precise relying at the same time on the energy spectrum, on the primary particle composition, and on the arrival directions anisotropies. The Pierre Auger Observatory [1] is located in Argentina (centered at 69° 20’ W, 35° 20’ S) at 1400 m above sea level, corresponding to 870 g.cm^{-2}. It consists of a Surface Detector array (SD) comprising 1660 autonomously operated water-Cherenkov detectors of 10 m^2 area each. The detectors are filled with 12 tons of purified water and three photomultipliers are used to detect the Cherenkov light produced by charged particles. The surface detectors are spread over a 3000 km^2 area and are placed on a triangular grid of 1.5 km spacing. The SD array is overlooked by 27 fluorescence detector telescopes (FD) distributed at five sites [2]. Stable data-taking started in January 2004 and the Observatory has been running with its full configuration since 2008. By now, an unprecedented number of UHECR events have been detected by the ground array and the fluorescent telescopes. At energies $E \geq 10^{19}$ eV, over 10^4 events have been recorded by the Pierre Auger Observatory. For each event, several observables can be reconstructed, the key ones being the energy of the primary particle, the arrival direction and, for the events detected by the fluorescence telescopes, the atmospheric depth of the air shower maximum. These and other observables allow one to shed some light on the nature of primary particles and the origins of UHECR.

In the first section, the energy spectrum and composition measurements reported by The Pierre Auger Collaboration are presented. The second section reports up-to-date results on searches for anisotropies at large scales.

2. Cosmic ray energy spectrum and composition

The all-particle energy spectrum is perhaps the most prominent observable of CRs being investigated. It carries combined information about UHECR sources and about the Galactic and/or intergalactic media in which CRs propagate. The ankle, a hardening seen in the all-particle spectrum at about 5×10^{18} eV, is generally considered to mark the transition from Galactic to extragalactic CRs. At the highest energies, a flux suppression due to energy losses by photo-pion production and photo-disintegration in the CMB is expected for protons and nuclei, respectively. In fact, this so-called GZK-effect [5, 6] is the only firm prediction ever made concerning the shape of the UHECRs spectrum. First observations of a cut-off were reported by HiRes and Auger [7] [8]. However, at present we cannot be sure whether this flux suppression is an imprint of the aforementioned GZK energy losses or whether it is related to the maximum cosmic ray acceleration energy at the sources. The so-called dip-model of the ankle [3] interprets the ankle as being the imprint of protons suffering e^+e^- pair-production in the CMB. Thus, it requires protons to be dominant

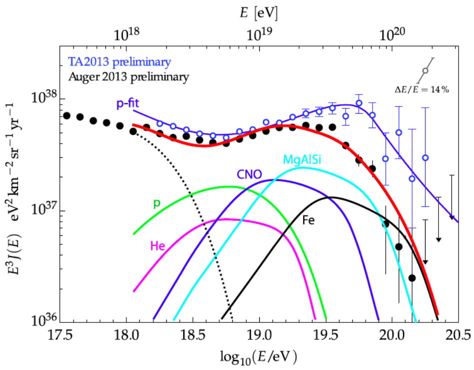

Figure 1: Recent measurements of the flux of CRs by the Auger and TA collaborations [11, 9]. From [12].

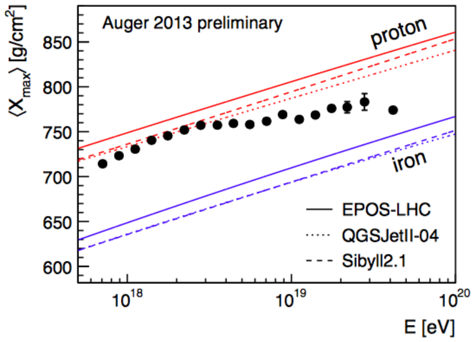

Figure 2: Evolution of $\langle X_{\max} \rangle$. Measurements are from the hybrid data set of Auger [9].

at energies both above and below the ankle, and the transition to occur below the ankle energy. Recent results of energy spectra of the Pierre Auger Observatory as well as Telescope Array are presented in figure 1. Spectra of the two observatories clearly exhibit the ankle at $\simeq 5\times10^{18}$ eV and a flux suppression above $\simeq 4\times10^{19}$ eV, and are compared to simplified astrophysical scenarios. In the case of Telescope Array, the ankle occurs at an energy which is compatible with the dip-model under the assumption of a pure proton composition. Also, the flux suppression at the highest energies is in accordance with the energy loss processes of the GZK-effect. In the case of Auger, however, the suppression starts at lower energies as compared to the propagation calculations unless the maximum energy of sources is set to approximately 10^{20} eV [9]. A good description of the Auger all-particle energy spectrum is obtained for $E_{max,p} \simeq 10^{18.7}$ eV, with a mix of protons and heavier nuclei being accelerated up to the same rigidity, so that their maximum energy scales like $E_{max,Z} \propto Z \times E_{max,p}$ (colored curves in figure 1 [10]), pointing to an increasingly heavier composition towards the suppression region.

It is now clear that any interpretation of the energy spectrum is strongly linked to the composition of the primary CRs. Composition measurements at the Pierre Auger Observatory are illustrated in figure 2. The data clearly indicate a change of behavior at a few EeV, i.e. in the ankle region. Under the hypothesis that no new interaction phenomena in the air shower development come into play in that energy range, the data support that the composition evolves from light to medium light above 4×10^{18} eV when compared to post-LHC interaction models.

3. Anisotropies

Anisotropies in arrival directions are yet another observable that, together with the energy spectrum and the CR chemical composition, appears as a fundamental key to understand CRs. The Pierre Auger Observatory has carried out different analyses in searching for anisotropies in several energy ranges and different angular scales. Large-scale anisotropy studies take advantage of the large accumulated data in the Pierre Auger Observatory to search for dipole or quadrupole patterns in the arrival directions of the detected CRs. The method consists of "fitting" the CR arrival distribution with a sine wave and determining its amplitude and phase. The results on

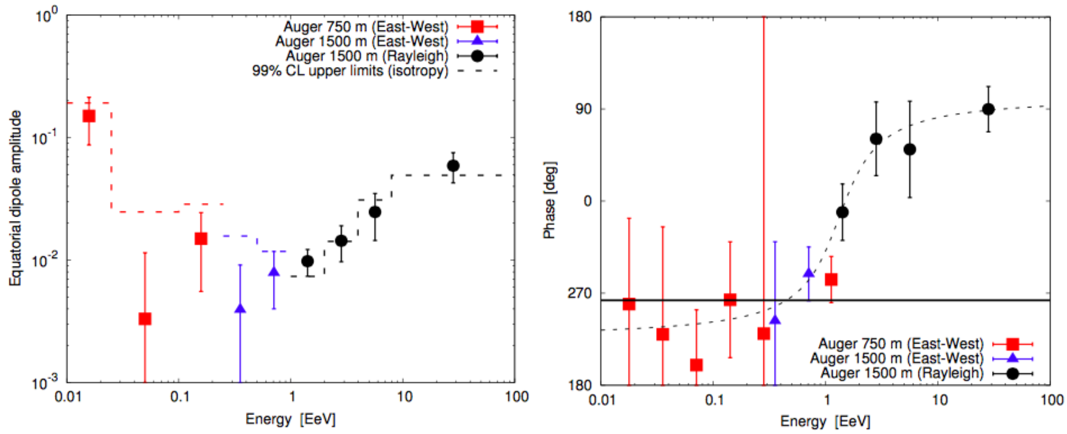

Figure 3: Equatorial dipole amplitude (left) and phase (right) evolution as a function of energy. Black circle : modified Rayleigh analysis, blue triangles : East-West analysis, red squares infill data with East-West analysis. Three point lie above the 99% CL line in the amplitude plot while the phase shows a smooth evolution from the Galactic center towards the galactic anti-center directions [13].

amplitude and phase are represented in each energy bin. Interesting results arose from the search of first harmonic modulations in the right ascension distribution. Figure 3 represents the results on the equatorial dipole amplitudes for four orders of magnitude in energy. Below 1 EeV, data from the denser array (750 m spacing) in Auger are used because of the low detection threshold compared to that of the regular array (1500 m spacing). Two different analysis methods were used; the East-West method consists of subtracting the measured fluxes in E and W directions before using a standard harmonic analysis on the difference. This method is suited at low energy because, below full efficiency of the detector, spurious anisotropies could rise from a non-uniform directional exposure in right ascension. As both E and W sectors are equally affected by detector instabilities and weather conditions, direction-dependent effects can be removed and no correction on the event rates is needed. The other method relies on a classical Rayleigh analysis, which accounts for the non-uniform directional exposure of the detector. Above full efficiency, the directional exposure is accurately estimated by the consideration of the event rate modulations due to weather effects and the quasi-instantaneous monitoring of the effective detection surface. Below 1 EeV, weather effects also affect the detection efficiency, thus the method reliability is guaranteed only above this energy. No strong evidence for anisotropy is found. However, in the energy range above 1 EeV, 3 out of 4 points are above the 99% Confidence Level (CL) line (only 1% of isotropic samples would generate equal or larger amplitudes). Moreover, the phase evolution also shown in figure 3, points to a smooth transition from the Galactic center direction ($\simeq 270^\circ$) to the anti-center one (90°). To confirm the observed phase effect in adjacent energy bins, a prescribed test with an aperture of 21,000 km^2 sr with independent data set is currently being performed.

It is noteworthy that if any such anisotropy is confirmed, it would be remarkably small. By now, stringent limits are thus derived for the equatorial dipole amplitude as shown in figure 4. The predictions labeled A and S stand for two different Galactic magnetic field symmetries (an-

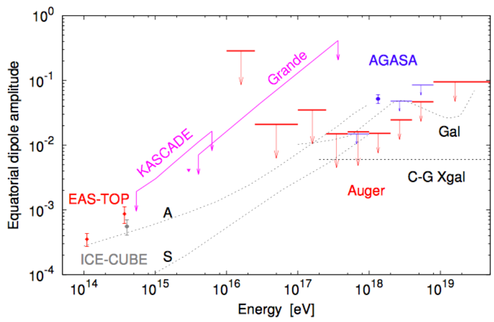

Figure 4: Upper limit at 99% CL for the equatorial dipole amplitude as a function of energy [13].

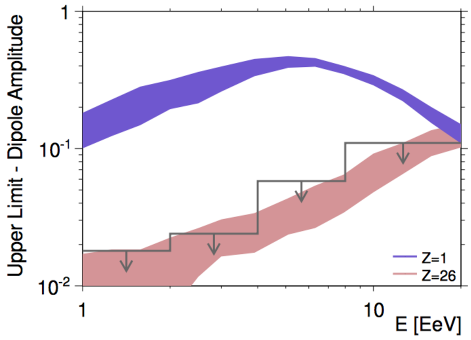

Figure 5: Upper limit at 99% CL for the dipole amplitude as a function of energy, along with anisotropy amplitude expectations from stationary Galactic sources for a proton and an iron CR composition.

tisymmetric and symmetric) corresponding to models in which CRs at 1 EeV are predominantly of Galactic origin. They escape from the Galaxy by diffusion and drift motion and this causes the predicted anisotropies. Current results already exclude magnetic fields with an antisymmetric halo (A) above 0.25 EeV and start to be sensitive to the predictions of a model with a symmetric field (S). In the model labeled Gal [14], a purely Galactic origin is assumed for all CRs up to the highest energies. In this case, the anisotropy is caused by purely diffusive motion due to the turbulent component of the magnetic field. Some of the predicted amplitudes at a few EeV are already excluded by Auger current bounds. The prediction labeled C-G Xgal is the expectation from the Compton-Getting effect for extragalactic CRs due to the motion of our Galaxy with respect to the frame of the CMB dipole ($\simeq$ 0.6%). More events are needed to achieve a sensitivity to such low amplitudes.

Searches for dipole and quadrupoles reconstructed simultaneously in right ascension and declination have also been conducted. The method relies on expanding the flux into spherical harmonics to retrieve the corresponding coefficients. A dipole corresponds to the mode ℓ=1 while a quadrupole corresponds to ℓ=2. Non-zero ℓ modes would appear if the flux varies on angular scales of $\simeq 1/\ell$. Thus, dipole and quadrupole searches look for variations of the order of $\simeq$1 rad. Due to the partial sky coverage, no higher order moments can be determined with good accuracy mainly because the resolution is degraded as $\exp(\ell_{\mathrm{max}})$, where ℓ_{max} is the highest order assumed for the expansion in spherical harmonics. This prevents from the recovery of the coefficients for $\ell_{\mathrm{max}} \geq 3$ in Auger data. Also in this analysis, the estimation of the directional exposure is of prime importance. Because modulations are also looked for in declination, geomagnetic effects are also taken into account in the direction exposure estimation. Upper limits are presented in figure 5 where generic estimates of the dipole amplitudes expected from stationary Galactic sources distributed in the disk are represented considering protons and iron nuclei as CR primaries. The hypothesis that the light component of CRs could originate from stationary sources distributed densely in the Galactic disk and emitting isotropically is excluded.

4. Conclusion

Explanations of the observed features of the energy spectrum are still not supported by conclusive experimental results that could shed light on the transition from Galactic to extragalactic CRs. Around the ankle, while composition measurements indicate a predominantly light composition, a high level of isotropy is found in the arrival directions of CRs excluding any Galactic stationary source in the Galactic disk. The astrophysical interpretation of the data is still delicate; the source distributions, spectral indexes, compositions and maximum energies up to which sources can accelerate UHECRs are all free parameters leading to many acceptable interpretations. The fact that the Galactic and extragalactic magnetic fields are also poorly known certainly adds more complexity to the interpretation of anisotropy results. An anisotropy study based on the separation between a light component and a heavier one would enable one to distinguish between a propagation effect and a source transition scenario in the ankle region.

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