STUDY OF THE ULTRA HIGH ENERGY COSMIC RAYS ARRIVAL DIRECTIONS WITH THE PIERRE AUGER OBSERVATORY

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We present the first results about the studies of Ultra High Energy Cosmic Rays arrival directions using the early data collected at the Pierre Auger Observatory [1] (corresponding to $\sim$ 1 year of data taking of the complete southern array). We discuss in particular:

- the analysis of large-scale patterns in the arrival directions of cosmic rays;
- a search for an excess of events from the direction of the Galactic Center region and from some extragalactic objects;
- the observed correlation between cosmic rays with energies above 60 EeV (1 EeV = 10^{18} eV) and the directions of nearby active galactic nuclei (AGN).

1 Introduction

The identification of the sources of ultra-high energy cosmic rays and the comprehension of the mechanisms by which they acquire their energies have been great challenges since the detection of the first 10^{20} eV event in 1962 at Volcano Ranch [2].

The maximum energy attainable in an accelerator with characteristic magnetic field B and size L is of order $E_{max} \sim ZeBL$. Only a few types of astronomical objects appear able to accelerate protons to 10^{20} eV; these include Active Galactic Nuclei, galaxy clusters, and objects with large radio lobes.

Furthermore, particles with energies above about $6 \cdot 10^{19}$ eV are expected to interact inelastically with cosmic microwave background photons, losing energy at each interaction. As a consequence the cosmic ray flux may be significantly reduced above 100 EeV. Particles exceeding the interaction energy threshold and originating at distances greater than 100 Mpc should never be observed on Earth. This effect, known as the "GZK effect" [3,4], requires the sources of the cosmic rays observed at Earth to be relatively nearby, within about 100 Mpc at most, further reducing the number of possible candidates.

Among the observables that might help to solve the puzzle of the sources, one of the most effective is the study of anisotropy in the UHECR arrival directions. In air-shower experiments the incoming directions of the highest energy cosmic rays are determined well and hence it is possible to estimate whether or not they are isotropically distributed on the sky. At the highest energies ($> 5 \cdot 10^{19}$ eV) the arrival directions point back to the sources because these particles should be only slightly deflected by magnetic fields.

In anisotropy studies, especially on small angular scales, it is fundamental to determine the arrival direction of cosmic rays with great precision. Consequently, an accurate knowledge of the angular resolution of the Auger Surface Detector (SD) is required. We discuss this in section 2, followed by a presentation of results on large- and small-scale anisotropy. The first specific targets chosen by the Auger Collaboration have been the Galactic Center at EeV energies and BL-Lacs and AGN at higher energies.

2 Angular resolution of the Surface Detector

The arrival direction of a SD event is determined by fitting the arrival time of the first particle in each station to a shower front model (see fig.1). The precision achieved in the arrival direction reconstruction depends therefore on the uncertainty in the time measurement and on the effectiveness of the shower front model adopted [5].

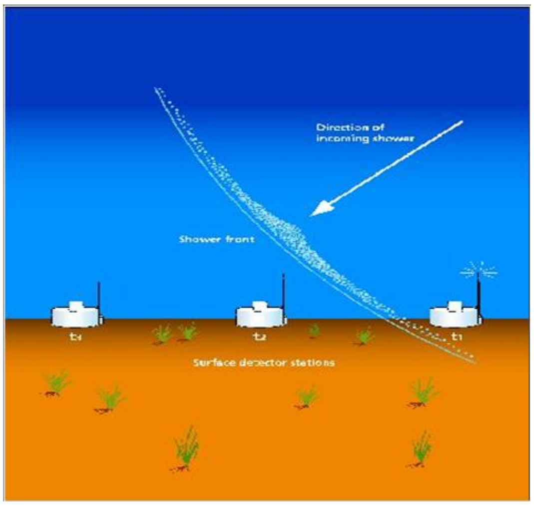

Figure 1: Sketch of the shower front arrival.

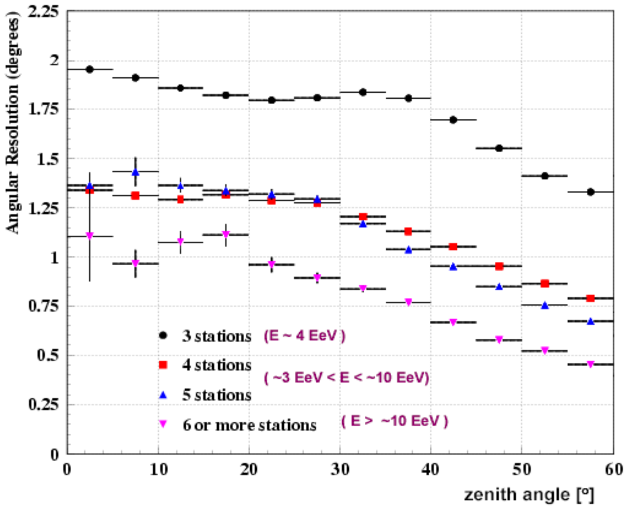

Figure 2: SD angular resolution as a function of zenith angle for different station multiplicities.

The angular resolution is calculated on an event by event basis, from the zenith (θ) and azimuth (ϕ) uncertainties of the geometrical reconstruction. It is defined as the angular radius that would contain 68% of showers coming from a point source.

In fig.2 the angular resolution is shown as a function of the zenith angles for various station multiplicities [6]. It is better than 2° in the worst case of vertical showers with only 3 stations hit and improves significantly with the number of stations. For events with 6 or more stations, corresponding to events with energies above 10 EeV, it is always better than 1°.

3 Large scale anisotropy studies

Lower energy cosmic rays likely originate within our Galaxy, while higher energy particles are believed to be extragalactic. At the transition the large scale angular distribution might change significantly. Large scale anisotropy, especially its evolution with primary energy, represents one of the main tools for discerning between the galactic and extragalactic origin of cosmic rays and for understanding their mechanisms of propagation.

If the transition to extra-galactic sources occurs at the ankle of the spectrum [7], then at 10^{18} eV cosmic rays are still mainly galactic and their diffusive escape from the Galaxy may be efficient enough so that the sky distribution of their arrival directions is not isotropic. The predictions for the shape and amplitude of the corresponding anisotropy are very model-dependent, but a %-level modulation is plausible [8].

On the other hand, if the transition occurs at lower energy [9], i.e. around $5\cdot10^{17}$ eV, then 10^{18} eV cosmic rays are already extragalactic and their sources may be cosmologically distributed. If so then no large-scale pattern would be detectable except for the CMB-like dipole anisotropy[10]. In this case anisotropy amplitudes of the order of $\sim 0.6\%$ are expected.

3.1 Auger results

The statistics accumulated so far by the Auger Observatory permits the study of %-level large-scale patterns, but this is challenging due to the difficulty of controlling the sky exposure of the detector and various acceptance effects, such as detector instabilities and weather modulations.

In order to avoid such problems three complementary analyses have been performed. All show that at EeV energies the Right Ascension (RA) distribution is remarkably compatible with an isotropic sky; an upper limit on the first harmonic modulation of 1.4% in the energy range $1 < E < 3$ EeV has been set [11] (see fig.3 for more details). This result does not confirm the 4% RA modulation found by the AGASA experiment [12] (although the sky regions covered by the two experiments are different) and already sets some constraints on the galactic hypothesis (further statistics and analysis are in any case necessary).

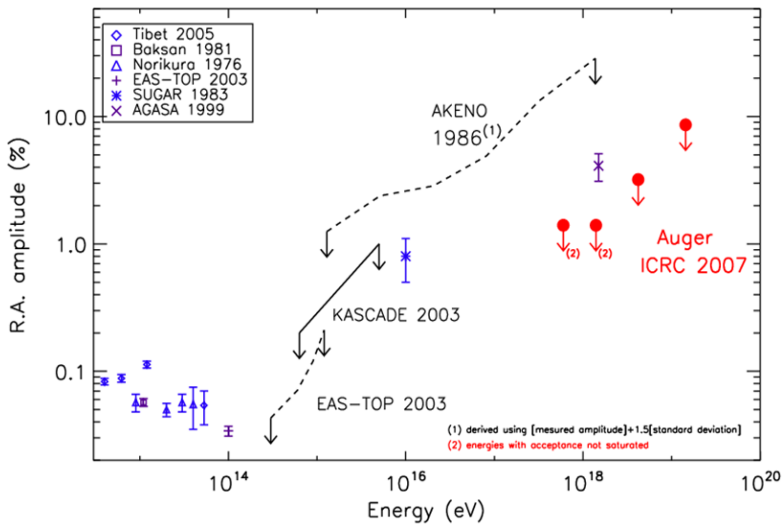

Figure 3: Overview on the results of large scale anisotropy studies; Auger upper limits are drawn *in red.*

4 The Galactic Center region

The Galactic Center is one of the most interesting targets in the study of small scale anisotropies at EeV energies because it contains a super massive black hole, a good candidate accelerator of high-energy cosmic rays. This black hole is believed to be associated with the radio emissions from Sagittarius A*. The H.E.S.S. collaboration has recently observed TeV γ-ray emissions close to this radio source [13]. A further reason of interest for this region is the privileged position of the Pierre Auger Observatory: the GC passes only 6° away from the observatory zenith.

In the past there have been claims of excesses of cosmic rays from the GC region from the AGASA [12] and SUGAR [14] experiments. Both the excesses are located in regions near the GC but not coincident with it (in the case of AGASA the GC is not in its field of view).

4.1 Auger results

Besides the privileged position, another advantage for Auger comes from the exposure of the array: the number of EeV cosmic rays accumulated so far from this part of the sky greatly exceeds that from previous experiments.

The claims of the forerunner experiments are periodically tested by the Auger experiment in different energy ranges and window sizes. In the most recent analysis two different energy ranges have been considered, 0.1-1 EeV and 1-10 EeV, but no significant flux excess has been found in the region around the GC (see tab.1: the numbers of observed events are always compatible with the expected ones) [15]. The distribution of Li-Ma significances for overdensities in this region is consistent with an isotropic sky for both energy ranges.

Table 1: Summary of excesses searches for $0.1 < E < 1$ EeV (*top*)) and $1 < E < 10$ EeV (*bottom*) around the GC in the form of both extended and point-like source.

search	window size	n_{obs}/n_{exp}
extended	10° (TH)	5663 / 5657 = 1.00 ± 0.02(stat) ± 0.01(syst)
	20° (TH)	22274 / 22440 = 0.99 ± 0.01(stat) ± 0.01(syst)
point-like	1.3° (G)	192.1 / 191.2 = 1.00 ± 0.07(stat) ± 0.01(syst)

search	window size	n_{obs}/n_{exp}
extended	10° (TH)	1463 / 1365 = 1.07 ± 0.04(stat) ± 0.01(syst)
	20° (TH)	5559 / 5407 = 1.03 ± 0.02(stat) ± 0.01(syst)
point-like	0.8° (G)	16.9 / 17.0 = 0.99 ± 0.17(stat) ± 0.01(syst)

5 Correlation of UHECR with nearby extra-galactic objects

At the highest energies, above a few $\times 10^{19}$ eV, cosmic rays should be only slightly deflected by magnetic fields. A direct way to search for sources of UHECR is to analyze the distribution of their arrival directions for small-scale clustering and specifically to search for correlations with known astronomical objects that are candidate sources.

5.1 Active Galactic Nuclei

AGN have long been considered to be sites where energetic particle production might take place, and where protons and heavier nuclei could be accelerated up to the highest energies measured so far.

The Auger collaboration searched for a correlation of its highest energy events with these astronomical objects (the selected AGN come from the 12th edition of Véron-Cetty/Véron catalogue [16]). The data set analyzed has been acquired by the surface array during the first 3.5 years of data taking and corresponds to an integrated exposure of about 9000 km^2 sr yr.

Under the assumption of isotropy, it's possible to calculate the probability that any given cosmic ray falls within a fixed distance from any AGN, i.e. the probability P for a set of N events from an isotropic flux to contain k or more events at a maximum angular distance ψ from any member of a collection of candidate point sources. P is given by the cumulative binomial distribution $\sum_{j=k}^{N} C_j^N p^j (1-p)^{N-j}$, where p is the fraction of the sky (weighted by the exposure) defined by the regions at angular separation less than ψ from the selected sources. The degree of correlation has been computed as a function of three parameters: the maximum angular separations ψ_{max}, the maximum AGN distance D_{max} and energy thresholds E_{th}.

The strategy adopted in this analysis requires as a first step an exploratory scan for the minimum of P, aimed to identify the configuration of parameters that maximizes the correlation. The absolute minimum of P was found for $\psi_{max} = 3.1°$, $z_{max} = 0.018$ ($D_{max} = 75$ Mpc) and $E_{th} = 56$ EeV. In this optimized configuration 12 events among 15 correlated with the selected AGN, while only 3.2 were expected by chance if the flux were isotropic.

To avoid the negative impact of trial factors in *a posteriori* search, the Auger collaboration decided to test this hint of anisotropy on an independent data set with parameters specified *a priori*. A prescription was written down, fixing the set of parameters and sources; new data would be analyzed sequentially until the probability to incorrectly reject isotropy was 1% and the probability to incorrectly reject correlation was 5%.

This prescription was tested on an independent data set collected after 27 May 2006 (when the prescription started), with exactly the same reconstruction and calibration algorithms as in the exploratory scan. On 25 May 2007, 6 out of 8 events were found to fulfill the prescription.

After the successful result of this test, a re-scan of the full data set (from 1 January 2004 to 31 August 2007) was performed, adopting newer and somewhat more accurate reconstruction and calibration algorithms. A similar result is obtained, with the correlation maximized for the 27 events with energies above 57 EeV: 20 of these events correlate with at least one AGN for a maximum angular separation $\psi_{max} = 3.2°$ and a maximum distance to AGN $D_{max} \sim 71$ Mpc. The results of this analysis are shown in fig.4.

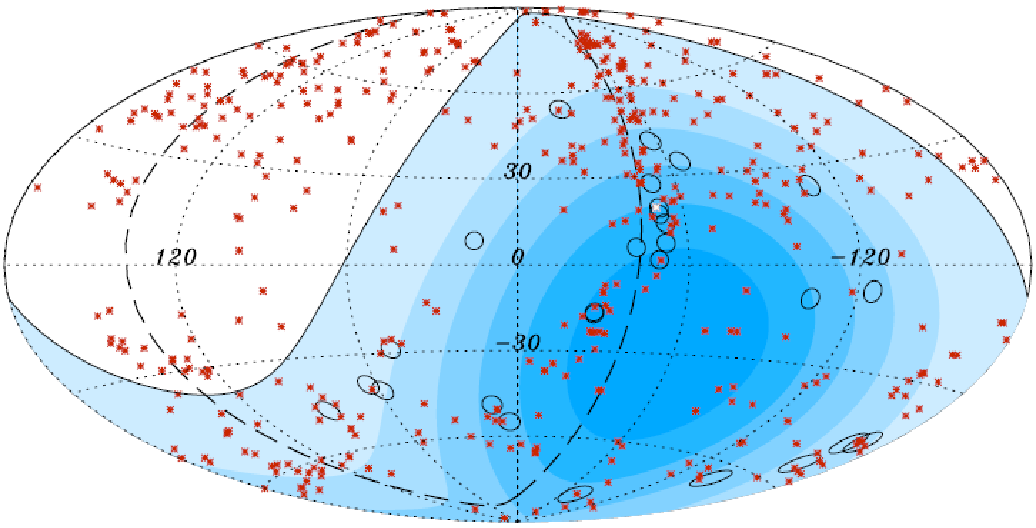

Figure 4: Projection on the celestial sphere in galactic coordinates with circles of radius 3.2° centered at the arrival directions of the 27 cosmic rays with highest energy detected by Auger. The positions of the selected 472 AGN are indicated by red asterisks.

Summarizing, the most important results of this analysis are:

- The anisotropy of UHECR (above 57 EeV) has been confirmed at 99% CL with an a priori test on an independent data set (in [17] a detailed report is given). This is the first time that a so strong signal of correlation is revealed and the hypothesis of an isotropic distribution of these cosmic rays is rejected at such a confidence level.

- The observed correlation is compatible with the hypothesis that UHECR originate from extra-galactic sources within the GZK horizon (i.e. compatible with the flux suppression observed in the spectrum starting at ~ 60 EeV [18]).

- The angular scale of the correlation is a few degrees, suggesting a predominantly light composition.

- AGN are the tracers but cannot be identified unambiguously as the sources: objects with a similar spatial distribution (GRB, quasar remnants, ...) are not excluded. It is also plausible that only a subclass of AGN are the sources.

- Several events lie close to the super-galactic plane (particularly close to Cen A) whereas a paucity of events has been recorded from Virgo.

The Véron-Cetty/Véron catalogue chosen for the correlation search is one of the largest collection of such objects but it is not an unbiased statistical sample. It is incomplete around the Galactic plane and for objects distances greater than 100 Mpc. It is important to note that these flaws are not an obstacle to the limited aim of demonstrating anisotropy.

A significant increase in ultra-high energy cosmic-ray statistics, combined with the future northern site of Auger, should lead to an unambiguous identification of the sources and their characteristics.

5.2 BL-Lacs

Active Galactic Nuclei include different sub-classes of astronomical objects. One of the more attractive candidate classes for UHECR sources is that of BL-Lacs. These are blazars in which the relativistic jet axis of the active galaxy is aligned with our line of sight.

Significant correlations of arrival directions of UHECR with positions of BL-Lacs were found by forerunner experiments with different subsets of BL Lacs and setting different energy thresholds.

A test on all these correlations has been performed with the present Auger data set which is already 6 times larger than those used in preceding cross-correlation searches for energies above 10 EeV. The results of this test [19] do not support previously reported excesses of correlation since the number of correlations found is compatible with that expected for an isotropic flux.

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