Mem. S.A.It. Vol. 80, 225

Memorie della

Study of the Ultra High Energy Cosmic Rays arrival directions with the Pierre Auger Observatory

R. Bonino for the Pierre Auger Collaboration

Istituto di Fisica dello Spazio Interplanetario (INAF), Università di Torino and Sezione INFN Torino, Italy, e-mail: `r.bonino@ifsi-torino.inaf.it`

Abstract. 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 (Abraham et al. 2004), 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 regions.

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 (Linsley 1963).

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" (Greisen 1966; Zatsepin & Kuz'min 1966), 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

Send offprint requests to: R. Bonino

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. Here we present the results concerning the Galactic Center region.

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 (Bonifazi et al. 2008).

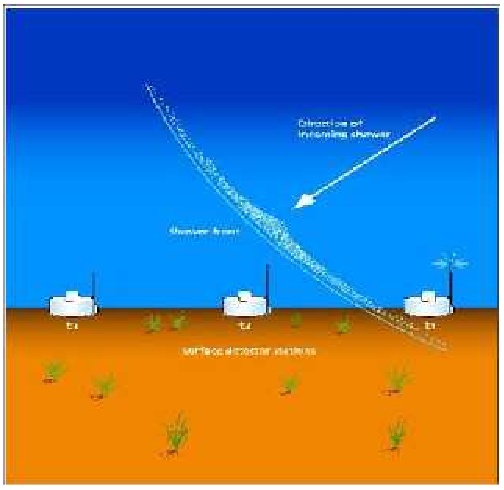

Fig. 1. Sketch of the shower front arrival.

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.

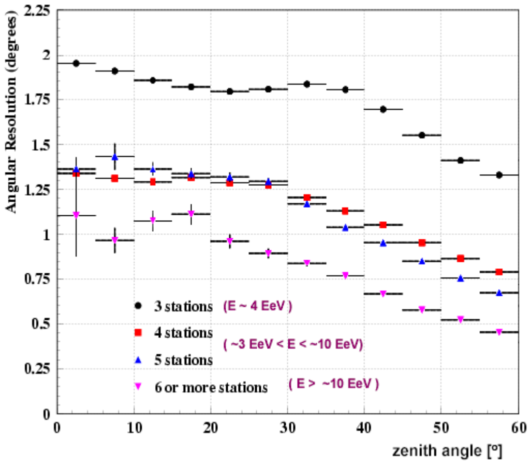

Fig. 2. SD angular resolution as a function of zenith angle for different station multiplicities.

In fig.2 the angular resolution is shown as a function of the zenith angles for various station multiplicities (Ave for the Pierre Auger Collaboration 2007). 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 (Hillas 2005), 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 (Candia et al. 2003).

On the other hand, if the transition occurs at lower energy, i.e. around $5 \cdot 10^{17}$ eV (Berezinsky et al. 2006), 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 (Schwarz et al. 2004). In this case anisotropy amplitudes of the order of $\sim$ 0.6% are expected.

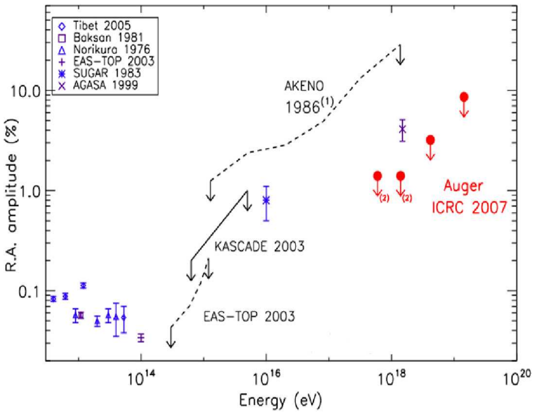

Fig. 3. Overview on the results of large scale anisotropy studies; Auger upper limits are drawn *in red*.

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 (Armengaud for the Pierre Auger Collaboration 2007) (see fig.3 for more details). This result does not confirm the 4% RA modulation found by the AGASA experiment (Hayashida et al. 1999) (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).

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 (Aharonian et al. 2004). 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 (Hayashida et al. 1999) and SUGAR (Bellido et al. 2001) 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 number of observed events is always compatible with the expected one) (Santos for the Auger Collaboration 2007).

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)

The distribution of Li-Ma significances for overdensities in this region is consistent with an isotropic sky for both energy ranges.

References

Abraham, J., et al. 2004, Nuclear Instruments and Methods in Physics Research A, 523, 50

Aharonian, F., et al. 2004, A&A, 425, L13

Armengaud, E., for the Pierre Auger Collaboration 2007, ArXiv e-prints, 706, arXiv:0706.2640

Ave, M., for the Pierre Auger Collaboration 2007, ArXiv e-prints, 709, arXiv:0709.2125.

Bellido, J. A., Clay, R. W., Dawson, B. R., & Johnston-Hollitt, M. 2001, Astroparticle Physics, 15, 167

Berezinsky, V., Gazizov, A., & Grigorieva, S. 2006, Phys. Rev. D, 74, 043005

Bonifazi, C., et al. 2008, Astroparticle Physics, 28, 523

Candia, J., Mollerach, S., & Roulet, E. 2003, Journal of Cosmology and Astro-Particle Physics, 5, 3

Greisen, K. 1966, Physical Review Letters, 16, 748

Hayashida, N., et al. 1999, Astroparticle Physics, 10, 303

Hillas, A. M. 2005, Journal of Physics G Nuclear Physics, 31, 95

Linsley, J. 1963, Physical Review Letters, 10, 146

Santos, E. M., for the Auger Collaboration 2007, ArXiv e-prints, 706, arXiv:0706.2669

Schwarz, D. J., Starkman, G. D., Huterer, D., & Copi, C. J. 2004, Physical Review Letters, 93, 221301

Zatsepin, G. T., & Kuz'min, V. A. 1966, Soviet Journal of Experimental and Theoretical Physics Letters, 4, 78