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The birth of Cosmic Ray Astronomy? Results from the Pierre Auger Observatory.

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Abstract. Cosmic Rays have been detected up to energies in excess of 10^{20} eV. At these energies, also the charged nuclear component undergoes relatively small deflection in galactic/extragalactic magnetic fields, of a few degrees. Moreover, if the primaries are nuclei, above ≈ 6'10^{19} eV, they lose energy in the Cosmic Microwave Background Radiation in such a way that at the highest energies they can only reach the Earth from a relatively small region (≈ 100 Mpc). In these conditions it might become possible to trace down the particles to their sources, if they are of astrophysical origin. The Pierre Auger Observatory is performing such a search, with already encouraging results.

Key words. Cosmic Rays – Origin

1. Introduction

Since the second half of last century, cosmic rays experiments are detecting extremely high energy particles, up to energies of the order of $10^{19} - 10^{20}$ eV. These are *macroscopic* energies, the highest energies reached by single particles in the present universe. Only near the inflation era in the early universe similar energies are found.

The Linear Collider will reach TeV energies in an 10 km long accelerator; to reach 10^{20} eV with the same technology, an accelerator of ≈ 10^9 km long, would be needed. It is approximately ten times the radius of Earth orbit; so hopes to produce so much energy in a manmade accelerator are very faint, at the best. Even from the more modest point of view of Center Of Momentum energy, one of these particle interacting with the Earth's atmosphere has a COM energy far larger than that attainable at LHC.

Soon after the discovery of the Cosmic Microwave Background Radiation in 1965, Zatsepin & Kuz'min (1966) and independently Greisen (1966), discovered that the Universe would become opaque to extremely high energy protons, since they would interact with the background photons and photoproduce pions; the threshold for the onset of this process, in the frame in which CMBR appears isotropic, is $E_{GZK} \approx 6 \cdot 10^{19}$ eV. The discovery of this (GZK) "cut-off"[1] would have profound consequences, implying that the sources of the highest energy particles are extragalactic astrophysical objects.

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[1] The term cut-off is not really appropriate: protons from nearby sources within $D \approx 100$ Mpc would propagate with little attenuation, so only a drop in the spectrum due to the lack of more distant sources is expected.

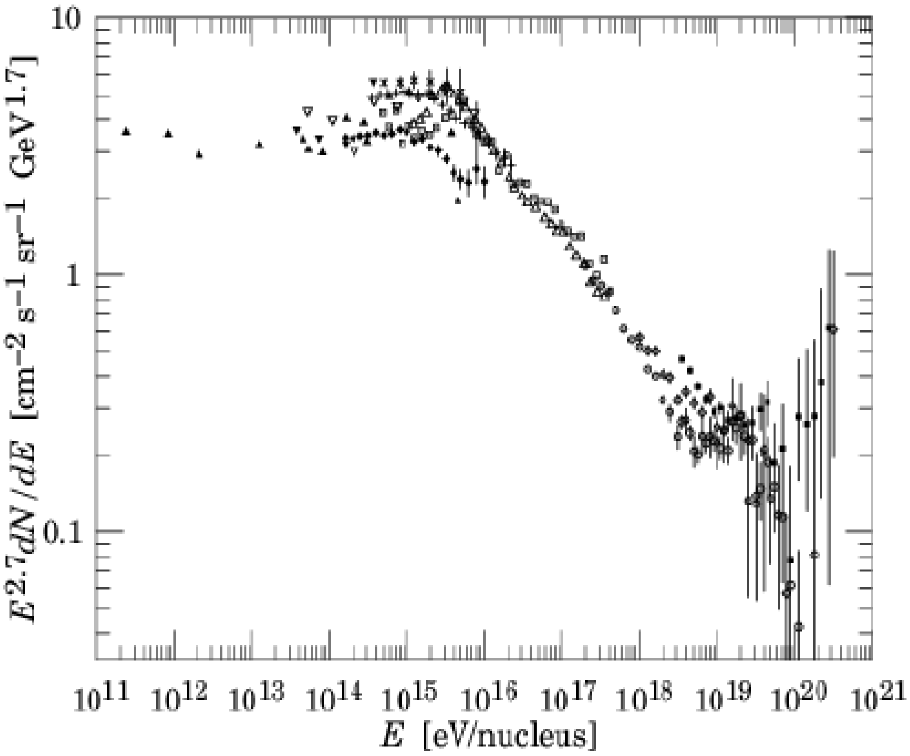

Fig. 1. A compilation of the spectrum of cosmic rays (Particle Data Group et al. 2004).

Moreover, since the reaction responsible is really a low energy photoproduction reaction $\gamma p \to N\pi$ with $E_\gamma \geq 100\ MeV$ on a proton at rest, and it appears at a very high threshold in a frame in which CMBR photons are isotropic, the existence of the threshold would be a direct verification of relativistic frame invariance.

The spectrum of cosmic rays extends from approximately 1 Gev or less to more than $10^{20}\ eV$, with a broken power law spectrum

$$dn/dE \propto E^{-\gamma(E)}$$

with $\gamma \approx 2.7$ ($E < 5 \cdot 10^{15}$), $\gamma \approx 3$ ($5 \cdot 10^{15} < E < 5 \cdot 10^{18}$), $\gamma \approx 2.7$ ($E > 5 \cdot 10^{18}$), although in the last region the errors are very large. A compilation of different experimental results concerning the CR spectrum is reported in Fig. 1, where the flux is multiplied by $E^{2.7}$ to magnify the structures (Particle Data Group et al. 2004). The general trend, as well as some discrepancies at least in the interpretation of different experimental results, are evident. Cosmic Ray experiments are difficult, and relating the results from different sources, even nominally in the same energy range, is almost always difficult. Above $\approx 6 \cdot 10^{19}\ eV$, as stated above, the GZK "cut-off" is expected.

Concerning the sources of Cosmic Rays there is a general consensus that up to $\approx 5\ 10^{15}\ eV$ the production is via shock acceleration in galactic Super Novae remnants (although a direct, clear-cut experimental evidence still lacks), while above some $10^{18}\ eV$ the Galactic Magnetic field is unable to confine protons, so if CRs are protons they are likely of extragalactic origin. There is however very little certainty on the origin of the extreme high energies particles. It is really hard to conceive mechanisms providing (in astrophysical contexts) particles acceleration at these energies, and the number of possible sources is small. So, mechanisms ("top-down") in which the highest energy particles are produced through the decay of some (superheavy) remnant of the Big Bang have been invented. These mechanisms have their own problems however.

As a matter of fact we do not know the origin of CR particles, nor exactly their nature, at these extreme energies. In particular, if particles are accelerated in astrophysical sources, then it is expected that their spectrum is cut at a maximum energy, this because the engine that accelerates could not have been operating for more than the life of the Universe. We do not know where this (real) cut-off is but certainly it is not many orders of magnitude above 10^{20} eV. So, in principle it is not excluded that a decrease of the spectrum is an effect of a cut in the sources.

The situation concerning the highest energy end of the spectrum has been controversial for almost a decade. The former largest experiments, AGASA (Takeda et al. 2003) and HiRes (Bergman 2006) still disagree in their latest reanalysis, although to a statistically unfirm level. On the other hand, due to the small statistics, a clear-cut association of the highest energy particles with astrophysical sources has not yet emerged.

The Pierre Auger Observatory[2] has presented at the last International Cosmic Ray Conference several papers related to the spectrum of Cosmic Rays. Let start from the spectrum itself.

In Fig. 2 is reported the differential spectrum (Roth for the Auger Collaboration 2007) from $\approx$ 2.5 10^{18} eV to the highest energy events, multiplied by $E^{2.6}$. A drop of the spectrum is evident starting around $E \approx 5\ 10^{19}$ eV. A continuation of the spectrum with the same slope at lower energies is excluded at the 6 σ level.

Although this steepening is quite significant, the present statistics does not allow to exclude that it is due to a cut-off at the sources.

2. Search for astrophysical origin

The area of the Auger Observatory ($\approx$ 3000 km^2) with the resulting large statistics of $\approx$ 2000 events above $3 \cdot 10^{19}$ eV, and the good angular resolution, better than $\approx$ 1 degree, makes it possible a search for a correlation of the highest energy events with cosmic sources. There have been several previous attempts, without compelling results.

If the cosmic ray particles are nuclei, then they are deflected by magnetic fields in their travel from the sources to detection. Little is known about intergalactic magnetic fields, but they are probably smaller than a few nG (apart possibly from specific directions). However the Galactic magnetic field ($\approx 3\mu G$) is better known and will influence the propagation of the particles. If they are protons from most of the directions (excluding the galactic plane) the angular deviation would be of few degrees so it will become possible to detect their pointing to sources.

There are different possible strategies for such a search. In the present approach, a test is made for a possible association of cosmic ray directions with the position of known Active Galactic Nuclei. A specific catalogue has been selected (Véron-Cetty & Véron 2006), the Veron compilation of AGN surveys. This catalogue is known to have inadequacies, which however are balanced by the simple approach that it allows. The search has been performed by first finding some evidence of correlation through a scan on a restricted parameter space (energy of events, angular deviation of events from possible sources and redshift of AGNs).

In this preliminary search, a possible correlation has been found, consisting in 13 (out of 15) correlating events with energy $\geq$ 5.7 $10^{19}eV$ within $\approx 3^\circ$ from AGNs (Véron-Cetty & Véron 2006) at $z \leq 0.018$, while 3 were expected. Notice that this energy value corresponds to the inflection of the spectrum it has been found and that $z = 0.018$ cor-

[2] The Observatory has been described in several papers, for instance Dawson for the Pierre Auger Collaboration (2007) and we refer to these papers for its description.

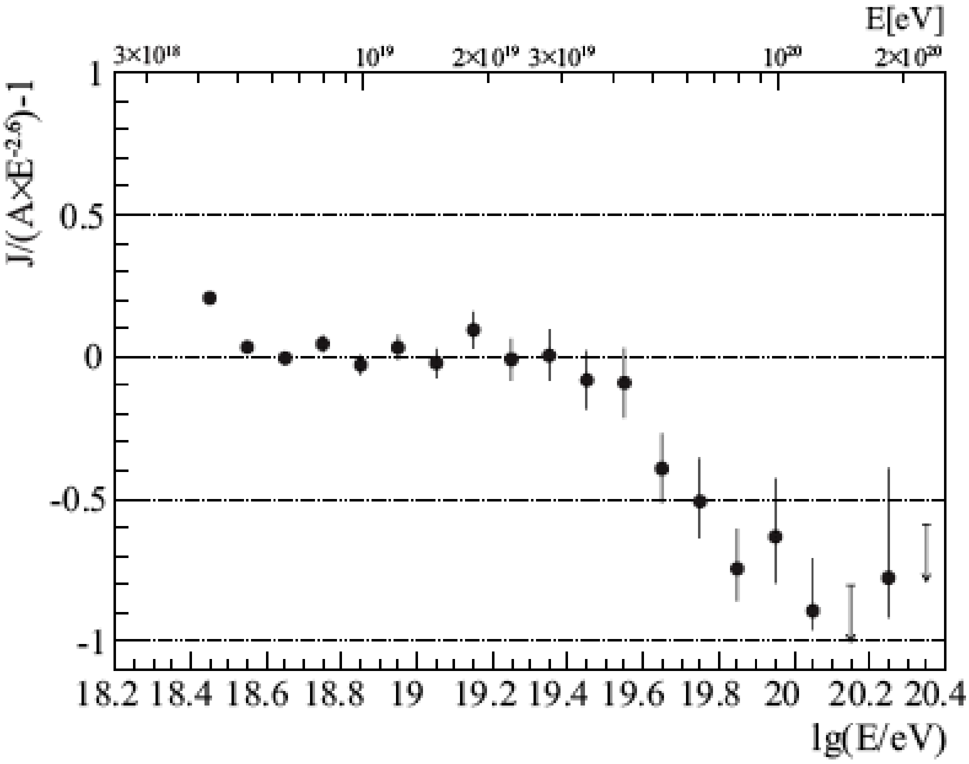

Fig. 2. The spectrum of highest energy cosmic rays from the Pierre Auger Observatory (Roth for the Auger Collaboration 2007; Yamamoto for the Pierre Auger Collaboration 2007).

responds to a distance of ≈ 75 Mpc. Although the probability of a chance coincidence is very low, it has not been used to assess a significance due to its *a posteriori* nature.

Instead, a new search was started by fixing these parameters, and prescribing the end of the search when the probability of incorrectly assessing correlation would have dropped below 1%. This was reached during 2007 (The Pierre Auger Collaboration 2007). In Fig. 3 we present a skymap of the events (27 up to end of August 2007) superimposed to the AGNs positions. The colored areas correspond to equal acceptance of the Observatory.

Some considerations can be made. The events appear to be mainly distributed around the supergalactic plane, where the density of nearby extragalactic sources is enhanced. There are several events around the region of Cen A, and two correlate with this source. On the other hand, no events are detected in the direction of the Virgo super cluster, but in this region the exposure of the Observatory is small.

The fact that the events are anisotropically distributed is confirmed by the autocorrelation analysis: in Fig. 4 the distribution of the relative angular distances within the events is compared to that expected from an isotropic distribution.

The fact that the correlation is strongest for $z < 0.018$ ($D < 75\ Mpc$) and weakens in larger volumes is an indication that the sources visible in high energy cosmic rays are contained in a limited volume, that would confirm the presence of the GZK feature.

3. Conclusions

The Pierre Auger Observatory is now operating with essentially full acceptance. After one

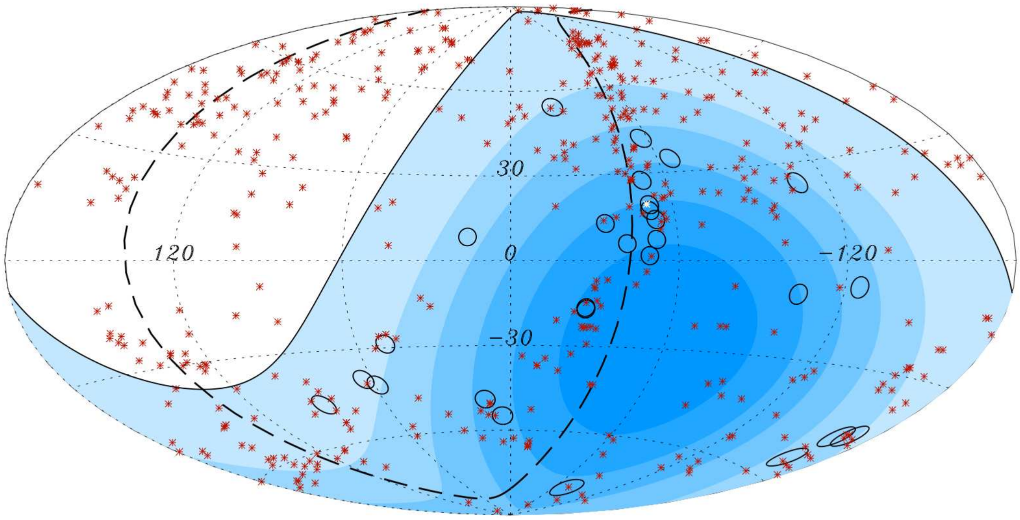

Fig. 3. The sky map of the Auger events with $E > 57$ EeV (Véron-Cetty & Véron 2006). Three degrees circles are drawn around events. The points are AGNs ($z \leq 0.018$) from The Pierre Auger Collaboration (2007).

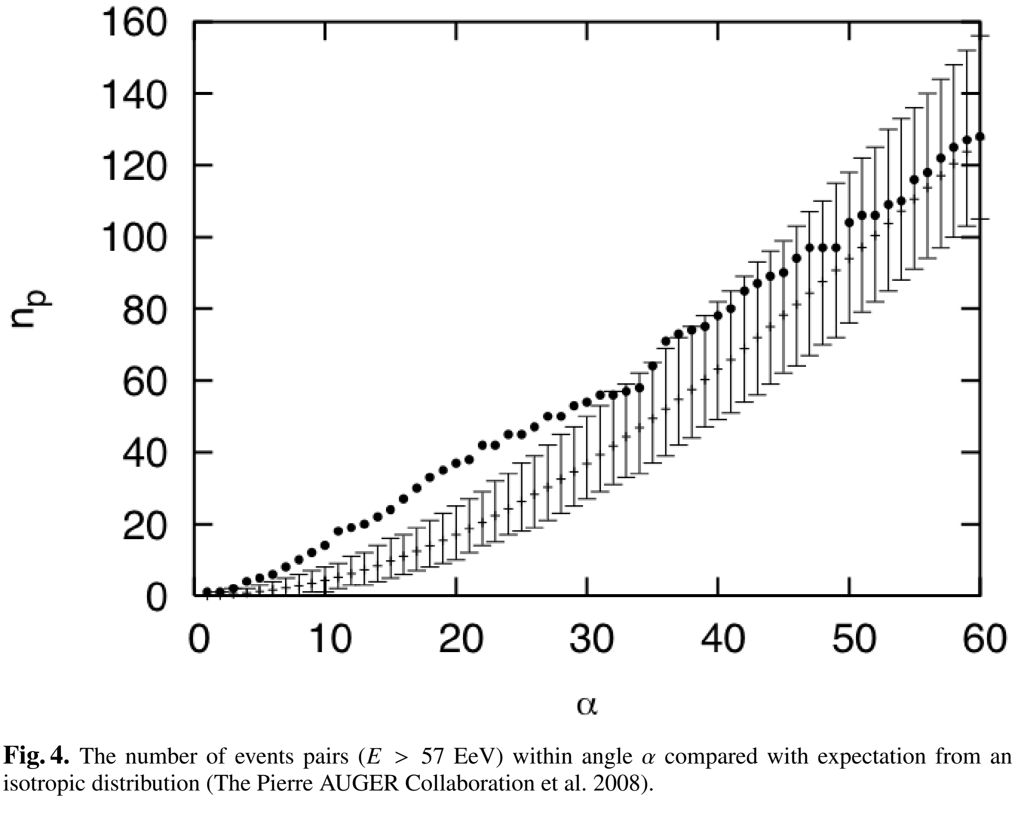

Fig. 4. The number of events pairs ($E > 57$ EeV) within angle α compared with expectation from an isotropic distribution (The Pierre AUGER Collaboration et al. 2008).

equivalent year of data taking, several pieces of information start to converge towards a confirmation of the GZK steepening of the spectrum and a 99% significant correlation of the events with nearby sources.

This result is extremely interesting, and it has to be confirmed by a larger statistics and further analyses. From an astrophysical point of view, the fact that a correlation is found with sources in an AGN catalogue does not exclude that sources are other, since the AGN distribution follows closely that of matter. Also, within the correlating sources no particular preference of types appears, although there have been recently several comments in this sense (Farrar & Gruzinov 2008).

From the Cosmic Rays point of view, the nature of the primary particles has to be better investigated, since there is some indication that they might be heavier nuclei (Unger et al. 2007). Also, the systematics of their energy assignment has to be fully understood. The HIRes experiment, situated in the Northern hemisphere does not confirm the Auger result (Abbasi et al. 2008).

The correlation of Cosmic Rays with astrophysical sources might be the beginning of Ultra High Energy Cosmic Ray Astronomy. Moreover, the results presented show that such a search is indeed possible. In several years of operation we may hope to clarify many of the issues we are facing now, like the type of the sources and the mechanisms of high energy production. We are opening a new window for the study of the violent Universe.

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