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Bounds on the density of sources of ultra high energy cosmic rays from the Pierre Auger Observatory data

MANLIO DE DOMENICO[1,2], FOR THE PIERRE AUGER COLLABORATION[3]
[1] *Laboratorio sui Sistemi Complessi, Scuola Superiore di Catania, Via Valdisavoia 9, 95123 Catania, Italy*
[2] *Istituto Nazionale di Fisica Nucleare, Sez. di Catania, Via S. Sofia 64, 95123 Catania, Italy*
[3] *Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina*
(Full author list: http://www.auger.org/archive/authors_2011_05.html)
auger_spokespersons@fnal.gov

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Abstract: We present constraints on the density of sources obtained by analyzing the clustering (or absence of clustering) of the arrival directions of ultra-high energy cosmic rays detected at the Pierre Auger Observatory. We consider bounds for isotropically distributed sources and for sources distributed according to the 2MRS catalog.

Keywords: Pierre Auger Observatory, ultra-high energy cosmic rays, clustering, autocorrelation, large scale structure

1 Introduction

The identification of the sources of ultra-high energy cosmic rays (UHECRs) is a major challenge in astroparticle physics. Only few astrophysical objects in the universe are expected to be able to accelerate particles up to 100 EeV (1 EeV is 10^{18} eV) [1]. It is likely that those sources are extragalactic, and only sources closer than about 200 Mpc from Earth can contribute appreciably to the observed flux above 60 EeV. Interactions with the cosmic microwave background by cosmic ray protons, or nuclei, with larger energies lead to strong attenuation of their flux from more distant sources (the Greisen-Zatsepin-Kuz'min (GZK) effect [2, 3]). Observing in the southern hemisphere, the Pierre Auger Collaboration has reported the measurement of a correlation above the isotropic expectation between the arrival directions of cosmic rays with energies exceeding ~ 60 EeV and the positions of active galactic nuclei (AGN) within 75 Mpc [4, 5, 6], at angular scales of $\sim 3°$. This observation, along with the measurement of a suppression of the flux at the highest energies [7, 8] is consistent with an extragalactic origin of the UHECRs and with the expectation from the GZK effect. Note however that the HiRes Collaboration has reported an absence of a comparable correlation in observations in the northern hemisphere [9].

If the deflections in the trajectories of UHECRs caused by intervening magnetic fields are small, the distribution of their arrival directions in the energy range above the GZK threshold is expected to reflect the clustering properties of those local sources. A large number of multiplets of arrival directions is expected if the local density of sources is sufficiently small, whereas fewer multiplets are expected for larger values of the density. Indeed, the lower the density of sources is, the larger is the probability that more than one of the observed cosmic rays come from the same source. Hence, a statistical analysis of clustering in the observed UHECR arrival directions should shed light on the density of their sources, further reducing the list of candidate astrophysical sources. Conversely, if the deviations in the trajectories of UHECRs are large, as expected if heavy nuclei are the dominant composition or if intervening magnetic fields have a strong effect, this approach may not be suitable for establishing constraints on the density of sources, since the clustering signal could be similar to that expected for smaller deflections and a larger density.

Estimates of the density of sources in our cosmic neighborhood have been obtained in the range $10^{-6} - 10^{-4}$ Mpc^{-3} (with large uncertainties), using data from previous experiments, under various assumptions on the sources and their distribution [10, 11, 12, 13, 14]. More recently, approaches involving the two-point autocorrelation function or its variants have been used to constrain the source density. Representative studies can be found in [15], in which source models that trace the distribution of matter in the nearby universe as well as a model with a continuous, uniform distribution of sources were analysed in an autocorrelation study of the first 27 arrival directions of UHECRs with energies larger than 56 EeV measured by the Pierre Auger Observatory [5]. Results from such analyses suggest a source density ranging from 0.2×10^{-4} Mpc^{-3} to 5×10^{-4} Mpc^{-3} with an upper bound $\approx 10^{-2}$ Mpc^{-3} at 95% CL.

In the present study, we derive bounds on the density of sources through an autocorrelation analysis of the set of 67 arrival directions of UHECRs with energies larger than 60 EeV measured by the Pierre Auger Observatory through 31 December 2010. We compare the autocorrelation properties in the data with the expectation from simulation sets of arrival directions drawn from randomly located sources with varying density. We consider two astrophysical scenarios: one with sources distributed uniformly in the nearby universe, and another in which the source distribution follows the large scale structure of nearby matter according to the 2MASS Redshift Survey (2MRS) catalog of galaxies. The bounds apply if the deflections of CR trajectories by intervening magnetic fields do not erase the clustering properties expected from the models at the angular scales considered.

2 Data set

The surface detector of the Auger Observatory consists of 1660 water-Cherenkov stations that detect photons and charged particles in air showers at ground level. A triangular grid of detectors with 1.5 km spacing spans over 3000 km^2, and operates with a duty cycle of almost 100%. The energy resolution is 15%, with a systematic uncertainty of 22% [16]. The angular resolution, defined as the angular radius that would contain 68% of the reconstructed events, is better than $0.9°$ above 10 EeV. The data set consists of 67 events recorded by the Auger Observatory from 1 January 2004 to 31 December 2010, with reconstructed energies above 60 EeV and zenith angles smaller than $60°$. The event selection implemented in the present analysis requires that at least five active nearest-neighbors surround the station with the highest signal when the event was recorded, and that the reconstructed shower core be inside an active equilateral triangle of detectors. The integrated exposure for this event selection amounts to 2.58×10^4 km^2 sr yr.

3 Statistical method and astrophysical models

As an estimator of the clustering, in this study we make use of the two-point autocorrelation function (ACF), i.e. the cumulative number of pairs within the angular distance θ, defined by

$$n_p(\theta) = \sum_{i=2}^{n} \sum_{j=1}^{i-1} \Theta\left(\theta - \theta_{ij}\right) \qquad (1)$$

where n is the number of UHECRs being considered, Θ is the step function and θ_{ij} is the angular distance between events i and j. In figure 1 (left panel) we show the ACF of the arrival directions of CRs with energy larger than 60 EeV measured by the Auger Observatory and the 90% confidence region for the isotropic expectation. In the right panel of figure 1, the autocorrelation of the same set of arrival directions, but restricted to galactic latitudes $|b| > 10°$, is shown. This cut in galactic latitude is needed for the comparison with the scenario based in the 2MRS catalog of galaxies, due to its incompleteness near the galactic plane.

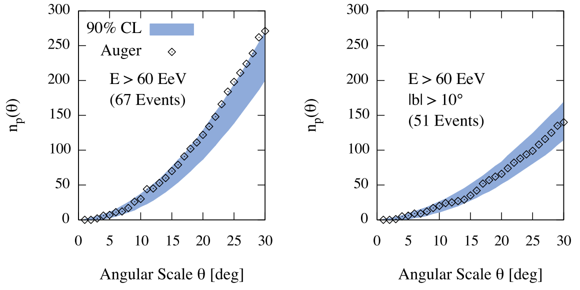

Figure 1: Number of pairs n_p as a function of the angular scale θ for the data (diamonds) and 90% confidence region for the isotropic expectation (shaded area). *Left:* 67 events with energy above 60 EeV. *Right:* 51 events with energy above 60 EeV and galactic latitude $|b| > 10°$.

In our analysis, we only consider angular scales larger than $5°$ to constrain the source density from the ACF. Deflections of this size are likely to affect the trajectories of protons, and they may be larger for heavier nuclei. The effect of magnetic fields, which are not known in enough detail to be taken into account in this analysis, could smooth away the clustering pattern expected from a particular source scenario at scales smaller than the typical deflections. For angular scales ranging from $5°$ to $30°$, we measure the number of pairs $n_p(\theta)$ in the data and we compare it to that in simulated sets of arrival directions with distributions expected in a given astrophysical model, as a function of the source density ρ. This allows us to obtain the range of densities compatible with the observations at a given confidence level. We chose the scenario based on 2RMS galaxies to illustrate the expectations from sources that trace the distribution of matter in the nearby universe, and we investigated the clustering differences with a scenario based on a finite number of random uniformly distributed sources.

The particular choices of the uniform and the 2MRS models is justified by the fact that, for a fixed value of the source density ρ, we are interested in investigating the clustering differences between sets of events following the distribution of matter in the nearby universe and sets of events generated by a finite number of random uniformly distributed sources. In both cases, we assume a power-law injection spectrum at the source with spectral index $s = 2.7$ and an equal intrinsic luminosity of cosmic rays. The simulated particles are successively propagated in a $\Lambda-$Cold Dark Matter universe (Hubble constant at present time $H_0 = 70.0$ km/s/Mpc, density of matter $\Omega_m = 0.27$ and density of energy $\Omega_\Lambda = 0.73$) [17], taking into account non-negligible energy-loss processes in the cosmic microwave background photon field. For a given energy

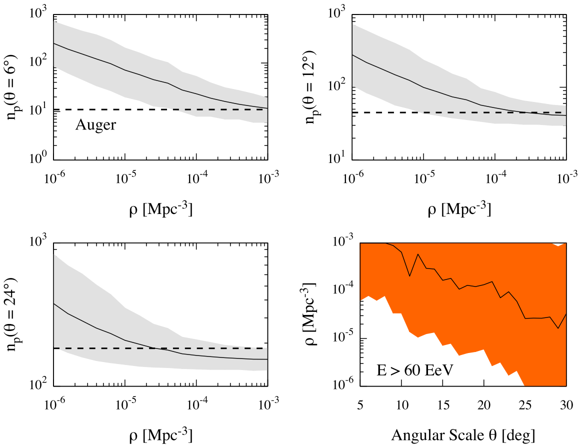

Figure 2: Events with $E > 60$ EeV and a uniform distribution of sources. *Top and bottom-left:* Number of pairs as a function of the source density, for three different values of the angular scale ($\theta = 6°, 12°$ and $24°$). Solid lines indicate the average number of pairs in the case of Monte-Carlo simulations, the shaded area denotes the 90% confidence region and the dashed line indicates the value obtained from the data. *Bottom-right:* source density obtained from the average number of pairs (solid line) and the allowed region for source density with 90% CL (shaded area).

threshold E_{thr} of the events, the probability for a source to generate an event is proportional to the inverse square of its distance D and to a factor accounting for the expected flux attenuation of UHECRs due to the GZK effect. Such a probability is defined by

$$\omega(D, E_{\text{thr}}) \propto \frac{1}{D^2} \frac{s-1}{E_{\text{thr}}^{-s+1}} \int_{E_i(D,E_{\text{thr}})}^{\infty} E^{-s} dE, \qquad (2)$$

where $E_i\,(D, E_{\text{thr}})$ is the initial energy, estimated as in [18], required by the particle to reach the Earth with final energy E_{thr}. Moreover, events are generated by taking into account the non-uniform exposure of the Auger Observatory. The GZK horizon R_{GZK} is defined as the distance within which 90% of the observed flux above the energy threshold is expected to be produced, i.e. $\omega(R_{\text{GZK}}, E_{\text{thr}}) = 0.1$. It is similar for both UHE protons and iron nuclei, but typically much shorter for nuclei with intermediate mass. In what follows we evaluate the predictions from the astrophysical scenarios using the GZK attenuation expected for protons. We tested the density of sources from 10^{-6} Mpc^{-3} to 10^{-3} Mpc^{-3} and present the results for three different values of the energy threshold: 60 EeV, 70 EeV and 80 EeV. For higher values of the energy threshold, the number of events becomes too small to perform a reliable clustering analysis. Conversely, lower energy thresholds imply larger GZK horizons, and the incompleteness of galaxy catalogs limits the discrimination power of the method, as will be discussed at the end of this section. For each value of the density ρ, $N = \frac{4}{3}\pi\rho R_{\text{GZK}}^3$ sources are generated in a sphere with radius $R_{\text{GZK}}(E_{\text{thr}})$ for each energy threshold considered. We make use of the 2MRS catalog because it is the most densely sampled all-sky redshift survey to date. It is a compilation [19] of the redshifts of the $K_{\text{mag}} < 11.25$ brightest galaxies from the 2MASS catalog [20]. It contains approximately 22,000 galaxies within 200 Mpc, providing an unbiased measure of the distribution of galaxies in the local universe, out to a mean redshift of z = 0.02, and to within $10°$ of the Galactic plane. To avoid biases due to its incompleteness in the galactic plane region, we exclude galaxies (as well as event arrival directions) with galactic latitudes $|b| < 10°$ from all analyses. We use galaxies with magnitude $M < -23.1$, which makes the sample complete up to 80 Mpc with density $\approx 10^{-3}$ Mpc^{-3}, the largest values we test. At larger distances, the density of a complete sample is smaller, for instance $\approx 10^{-4}$ Mpc^{-3} for $D = 200$ Mpc. In order to test higher values, we extend the original catalog between 80 Mpc and 200 Mpc with sources isotropically distributed in the sky in number such that the density is also $\approx 10^{-3}$ Mpc^{-3}. Our approach is rather conservative, reducing the clustering signal in the skies obtained in the 2MRS case and providing, as a consequence, smaller values of the lower bounds of the density of sources. The incompleteness of the catalog represents the main impediment for performing our analysis with a lower energy threshold for the events. The GZK horizon increases for decreasing energy thresholds and, as a consequence, a greater isotropic contamination is required to complete the catalog, further reducing the clustering signal due to large scale structure. On the other hand, the number of events decreases by increasing the energy threshold, reducing the discrimination power of clustering detection.

4 Application to the data

The procedure for constraining the source density from the clustering properties of the UHECRs measured with the Auger Observatory is as follows. We evaluate the ACF function of a large number of simulated sets of arrival directions drawn (in number equal to the events in the dataset) from the two astrophysical scenarios under consideration and for different values of the source density. The 95% CL upper (lower) bounds on the source density are the values for which only 5% of the simulated sets show more (less) clustering than the data, at a given angular scale.

We illustrate the procedure in figure 2 (top and bottom-left) for the particular case of the scenario with a uniform distribution of sources, for an energy threshold $E_{\text{thr}} = 60$ EeV, and for three different angular scales, namely $\theta = 6°, 12°$ and $24°$. The solid line is the average number of pairs predicted in this scenario as a function of the source density and the shaded area represents the dispersion in the number of pairs within 90% of the simulations. The dashed line corresponds to the number of pairs in the data. The 95% CL lower and upper limits are the ends of the range in source density for which n_p in the data is within the shaded

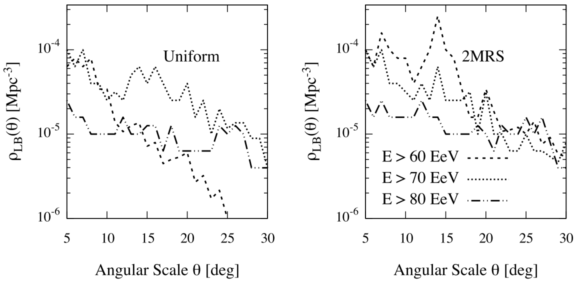

Figure 3: Lower bound (95% CL) on the source density of UHECRs, as a function of the angular scale and for different values of the energy threshold ($E_{\text{thr}} = 60, 70$ and 80 EeV). The number of events corresponding to each energy threshold is 67, 33 and 17, respectively (if the cut $|b| > 10°$ is not applied, otherwise it is 51, 26 and 15, respectively). *Left:* uniform case. *Right:* 2MRS case.

area. In figure 2 (bottom-right) we show the result of this procedure as a function of the angular scale. The solid line is the value of the source density for which the average number of pairs coincides with that in the data at the angular scale considered. The shaded area incorporates the 95% CL limits on the source density. The bounds are (typically) more restrictive at smaller angular scales and their validity depends on the uncertain strength of magnetic deflections. Moreover, such bounds apply if typical magnetic deflections do not significantly modify the clustering properties above the angular scale considered. In practice, the clustering observed in the current data set is insufficient to establish upper bounds on the density of sources at 95%CL for the astrophysical scenarios considered here, and only lower bounds can be derived. In figure 3 we show the lower bound ρ_{LB} (95% CL) for the three energy thresholds considered, for both the uniform (left panel) and the 2MRS (right panel) models. The bounds decrease with increasing angular scales and can also differ by up to one order of magnitude for the same angular scale and different energy thresholds. At relatively small angular scales, the bounds derived from lower energy thresholds are more stringent, being of order of 10^{-4} Mpc^{-3}, regardless of the astrophysical scenario.

5 Conclusions

In this study we have shown that the number of pairs of arrival directions of UHECRs detected with the Pierre Auger Observatory, with energy larger than 60 EeV, can be used to constrain the local density of their sources in particular astrophysical models. We have investigated two scenarios, one with sources uniformly distributed in the nearby universe, and another one with sources distributed following the large scale structure of nearby matter. In both cases, equal intrinsic luminosity of the sources has been assumed. If the effects of intervening magnetic fields do not smooth out the clustering properties of UHECRs on scales of about $5°$ (as can be expected in the case of a proton composition), the measurements imply a 95%CL lower limit on the source density of order 10^{-4} Mpc^{-3}. Conversely, if magnetic deflections are larger, and such that the clustering properties observed reflect the expectation from the source scenario only at larger angular scales, then less stringent lower bounds apply. They are about one order of magnitude smaller for angular scales around $25°$. The bounds apply to specific scenarios, since they depend on the overall distribution of sources.

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