Small scale anisotropy predictions for the Auger Observatory

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Abstract. We study the small scale anisotropy signal expected at the Pierre Auger Observatory after 1, 5, 10, and 15 years of operation, from sources of ultra-high energy (UHE) protons. We numerically propagate UHE protons over cosmological distances using an injection spectrum and normalization that fits current data up to $\sim 10^{20}$ eV. We characterize possible sources of ultra-high energy cosmic rays (UHECRs) by their mean density in the local universe, $\bar{\rho} = 10^{-r}$ Mpc$^{-3}$, with $r$ between 3 and 6. These densities span a wide range of extragalactic sites for UHECR sources, from common to rare galaxies or even clusters of galaxies. We simulate 100 realizations for each model and calculate the two point correlation function for events with energies above $4 \times 10^{19}$ eV and above $10^{20}$ eV with the exposure of the Auger South Observatory. We find that for $r \gtrsim 4$, Auger should be able to detect small scale anisotropies in the near future. Distinguishing between different source densities based on cosmic ray data alone will be more challenging than detecting a departure from isotropy and is likely to require larger statistics of events. Combining the angular distribution studies with the spectral shape around the GZK feature will also help distinguish between different source scenarios.

Keywords: cosmic rays detectors, ultra high energy cosmic rays, cosmic rays
1. Introduction

The origin of ultra-high energy cosmic rays (UHECRs) is still a mystery. The extreme energy requirements for astrophysical sources to accelerate cosmic rays above $10^{19}$ eV challenge most models. Given the extreme energies and the lack of anisotropies in the arrival directions, UHECRs are expected to come from extragalactic sources, which increases the energetic requirements. The extragalactic origin of UHECRs should become apparent if a clear Greisen–Zatsepin–Kuzmin (GZK) feature is detected in the UHECR spectrum above $\sim 10^{19.5}$ eV. This feature is evidence of the inelastic interaction of UHECRs with photons of the cosmic microwave background (CMB). In addition, anisotropies in the distribution of arrival directions are expected to unveil the sites of UHECR acceleration once enough data is accumulated above $10^{19}$ eV. (A recent review of the UHECR mystery can be found in [2].)

In the next few years the Pierre Auger Observatory [3] will provide enough statistics to clearly determine the existence and shape of the GZK feature. Auger should also help determine the composition of UHECRs at the highest energies and begin to observe anisotropies in the sky distribution of events. The degree of predicted anisotropies depends on the source distribution and is the main topic of the present work.

Over the past three decades, large UHECR observatories have tried to determine if the GZK feature is present in the UHECR spectrum. The AGASA observatory operated from 1983 to 2003 and claimed an interesting departure from the predicted feature [4]. The more recent High Resolution Fly’s Eye (HiRes) observatory reports a spectrum consistent with the GZK feature [5]. The two observatories use different techniques: AGASA is a ground array of scintillators, while HiRes is a fluorescence telescope observatory. The two techniques have different systematic errors in their energy calibration and their exposures are too small for a clear determination of the GZK feature. The statistical significance of the contradictory conclusions is very low, at the level of $\sim 2$–$3$ standard deviations, and the systematic errors lower the significance even further [6, 7]. The role of systematic uncertainties was recently amplified by the revised analysis of the energy calibration of the AGASA collaboration. According to their new analysis the number of events with energies above $10^{20}$ eV is 5 (instead of 11) [8]. Our numerical simulations in [6] showed that large statistics experiments, such as the Pierre Auger Observatory, are necessary to...
clarify whether the GZK feature is in fact present in the diffuse spectrum of UHECRs. The added ability to observe UHECR events with both a ground array and a fluorescence detector gives the Auger Observatory the best chance to discover the origin of UHECRs.

As the southern site of the Auger Observatory nears completion, an increase by one order of magnitude of the worldwide exposure to the highest energy particles is within reach and with it the possibility of doing astronomy with charged particles. The ability to point back to the sources depends on the UHECR energy, their composition, and the magnitude and structure of cosmic magnetic fields. The energy range between $10^{19}$ and $10^{20}$ eV is of particular importance as it provides a window for charged particle astronomy. Cosmic rays in this energy range suffer smaller deflections by cosmic magnetic fields than their lower energy counterparts. Below $\sim 10^{19}$ eV, the effect of the Galactic magnetic field on the trajectory of cosmic rays can in principle be used to infer the topology of the magnetic field of the Galaxy and/or the primary composition [9].

A key element in determining the origin of UHECRs is the detection of large [10] and small scale anisotropies in their arrival directions [11]. Cosmic rays of energies larger than $\sim 4 \times 10^{19}$ eV may point back to their sources as predicted by some numerical simulations [12]. As large numbers of cosmic rays above $4 \times 10^{19}$ eV are observed, small angle clustering in the arrival directions should become apparent depending on the mean density of sources in the universe.

Clustering on large scales should also become apparent at the highest energies. Interactions of cosmic rays with the cosmic background radiation limit the distance from which cosmic rays with energies above $\sim 10^{20}$ eV can reach the Earth to $\sim 50$ Mpc. The matter distribution within a 50 Mpc radius from the Earth is rather anisotropic, thus large scale anisotropies in the UHECR arrival direction distribution should be observable (see [10,13,14] for anisotropies expected from large scale structures around the Galaxy, and [15] for the effects of the local overdensity due to large scale structure on the spectrum of UHECRs.)

Another important observable that will help infer the origin of UHECRs is their chemical composition as a function of energy. Present data on the composition at the highest energies is rather limited, with no firm conclusions. A proton-dominated or a mixed composition injected spectrum have different implications for the energy of the transition from a Galactic to an extragalactic origin. While a mixed composition favours a transition at the ankle [16,17], a pure proton composition (or very light pollution from heavier nuclei) favours a transition at lower energies (called the dip scenario) [18].

Here we assume a pure proton composition at energies between $4 \times 10^{19}$ and $10^{20}$ eV. An appreciable contamination of heavier nuclei in the observed spectrum is not expected at these high energies even for a mixed composition injection, but the different scenarios imply different injection spectra that best fit the current data. We assume the best fit injection spectrum for a pure proton source, which is softer than the mixed composition case [17] (see [19] for the effect of magnetic fields in the source region and [20] for the effect of maximum energies depending on the source). Given that the relevant energy range is limited (between $4 \times 10^{19}$ and $10^{20}$ eV), the differences in the injection should not have a significant effect and our conclusions regarding small scale anisotropies should apply more generally.

The unknown magnitude and structure of magnetic fields in the Milky Way and the extragalactic medium limit our ability to predict the precise energy threshold for
charged particle astronomy. Observations indicate that magnetic fields strengths in the Milky Way are around a few microgauss, implying a Larmor radius for UHECRs above $4 \times 10^{19}$ eV larger than the size of the Galaxy. The effect of the Galactic magnetic field in the energy range considered here is small except in the direction of the plane and of the Galactic centre, where magnetic distortions may modify the effective celestial exposure of the observatory and the chance probability of clustering in the data [9]. The role of extragalactic magnetic fields in changing the spectrum and clustering of UHECRs is also badly constrained as different simulations give different estimates for the magnitude and spatial structure of these fields (see, e.g., [12,21]). The combined effect of a mixed composition and significant extragalactic fields may move the threshold for detecting anisotropies to larger energies (see, e.g., [22]).

Here, we assume that extragalactic magnetic fields can be neglected for particles with energies above $4 \times 10^{19}$ eV. This assumption holds if magnetic fields in the extragalactic medium are less than $\sim 0.1$ nG with a reversal scale of $\sim 1$ Mpc and the small scale anisotropies are evaluated on angles of $\sim 1^\circ$ [11,7]. This magnitude field is compatible with observational bounds [23] and detailed numerical simulations such as [12] (however, see [21] for different numerical estimates). UHECR observations may eventually measure the strength of the extragalactic magnetic field and its structure (see, e.g., [24,25]). In the meantime, searches for small scale anisotropies should focus on energy thresholds from $4 \times 10^{19}$ to $10^{20}$ eV.

The mean density of UHECR sources can be determined once small scale anisotropies (SSAs) in the arrival directions are observed. Thus far the only experiment to report departures from isotropy is AGASA [26]. The statistical significance of the clustering has been challenged [27] as it depends on the energy threshold and the angular scale chosen for binning the data. Assuming the AGASA data, the number density of sources was estimated to range from $\sim 10^{-6}$ Mpc$^{-3}$ to $\sim 10^{-4}$ Mpc$^{-3}$ with large uncertainties [11,7,28,29]. In [11,7], full numerical simulations of the propagation were performed which account for the statistical errors in the energy determination and the AGASA acceptance. The first study concluded that the AGASA small scale anisotropies indicated a density of sources $\sim 10^{-5}$ Mpc$^{-3}$ [11]. However, when taken together with the observed AGASA spectrum, the SSAs and the GZK feature become inconsistent [7].

Here we study the small scale anisotropy signal expected at the Pierre Auger Observatory after 1, 5, 10, and 15 years of full operations. We numerically propagate ultra-high energy protons over cosmological distances and characterize possible sources by their mean density in the local universe, $\bar{\rho} = 10^{-r}$ Mpc$^{-3}$, with $r$ between 3 and 6, which span the relevant range of extragalactic sites for UHECR sources, from galaxies to clusters of galaxies as recently measured by [30]. In section 2 we review our numerical approach and present the SSA results of 100 realizations of each model. We show the two point correlation functions for events of energies above $4 \times 10^{19}$ eV and above $10^{20}$ eV, list the expected number of doublets, and discuss the expected spectrum for different models. In section 3, we discuss the implications of our results and conclude.

2. Small scale anisotropies and spectra at Auger

The propagation of UHECRs is simulated using the Monte Carlo code described in [6]. We assume that UHECRs are protons injected with a power-law spectrum by extragalactic
sources. The injection spectrum in taken to be of the form
\[ F(E) \propto E^{-\gamma} \exp(-E/E_{\text{max}}), \]  
where \( \gamma \) is the spectral index and \( E_{\text{max}} \) is the maximum injection energy at the source. We fix \( \gamma = 2.6 \) and \( E_{\text{max}} = 10^{21.5} \text{ eV} \) since these values reproduce well the experimental results in the lower energy high statistics region around \( \sim 10^{18.5} \) up to \( \sim 10^{20} \text{ eV} \) (see, e.g. [6]). We focus on events above \( 4 \times 10^{19} \text{ eV} \), which are generated at \( z \ll 1 \); therefore, source evolution is only marginally relevant [11]. We simulate the propagation of protons from the source to the observer by including the photo-pion production, pair production, and adiabatic energy losses due to the expansion of the universe. We assume the universe has matter and dark energy densities as fractions of the critical density given by \( \Omega_{m} = 0.3 \) and \( \Omega_{\Lambda} = 0.7 \), respectively.

Our source distribution in space is generated by a random placement of sources for a given spatial density and particles are emitted from randomly chosen source positions. The source redshifts are generated with a probability distribution proportional to
\[ \frac{\mathrm{d}n}{\mathrm{d}z} \propto r(z)^{2} \frac{\mathrm{d}t}{\mathrm{d}z}, \]  
where \( \frac{\mathrm{d}t}{\mathrm{d}z} \) gives the relation between time and redshift (see, e.g., the expression given in [31]) and \( r(z) \) is defined as
\[ r = c \int_{t_{g}}^{t_{0}} \frac{\mathrm{d}t}{R(t)}, \]  
where \( t_{g} \) is the age of the universe when the event was generated, \( t_{0} \) is the present age of the universe, and \( R(t) \) is the scale factor of the universe. Once a particle has been generated, the code propagates it to the detector calculating energy losses and taking into account the detector energy and angular resolution. The source angular coordinates on the celestial sphere are chosen randomly from a uniform distribution in right ascension and with a declination distribution proportional to \( \cos \delta \).

Since we neglect the effects of the magnetic fields on the propagation, we ignore sources outside the experimental field of view and assign to visible sources a probability proportional to
\[ \frac{r(z)^{-2}\omega(\delta)}{\Delta \theta \Delta \delta}, \]  
where \( r(z)^{-2} \) takes into account the distance dependence of the solid angle and \( \omega(\delta) \) is the relative exposure of the experiment in the given direction.

For a given simulated set of events, we calculate the angular two point correlation function as defined in [28, 32] to study the expected departure from an isotropic distribution in the sky. For each event, the number of events within a circle at an angular distance \( \theta \) and a bin width \( \Delta \theta \) is summed,
\[ N(\theta) = \frac{1}{S(\theta)} \sum_{i>j} R_{ij}(\theta), \]  
and divided by the area \( S(\theta) = 2\pi |\cos(\theta) - \cos(\theta + \Delta \theta)| \) of the angular bin between \( \theta \) and \( \theta + \Delta \theta \), and \( R_{ij}(\theta) = 0, 1 \) counts the events in the same bin.

4 The declination \( \delta \) is defined as being 0° on the equatorial plane and ±90° at the poles, so \( \mathrm{d}\Omega = \cos \delta \mathrm{d}\delta \mathrm{d}\alpha \).
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Table 1. Number of events expected with $E > 10^{20}$ eV (normalized at $4 \times 10^{19}$ eV).

| $\rho$ (Mpc$^{-3}$) | $n_{20}/1$ yr | $n_{20}/5$ yr | $n_{20}/10$ yr | $n_{20}/15$ yr |
|---------------------|----------------|---------------|----------------|---------------|
| Cont.               | 2.9 ± 1.7      | 14 ± 4        | 29 ± 5         | 43 ± 6        |
| $10^{-3}$           | 2.5 ± 1.3      | 13 ± 3        | 26 ± 6         | 39 ± 8        |
| $10^{-4}$           | 2.0 ± 1.4      | 10 ± 4        | 22 ± 6         | 34 ± 7        |
| $10^{-5}$           | 1.6 ± 1.5      | 7.3 ± 3.3     | 14 ± 5         | 20 ± 7        |
| $10^{-6}$           | 0.4 ± 0.7      | 2.1 ± 1.7     | 4.2 ± 2.9      | 7.2 ± 4.3     |

For the Auger observatory in the southern hemisphere, we assume a total acceptance of 7000 km$^2$ sr independent of energy above $10^{19}$ eV. For the angular resolution we used 1, for the energy resolution 20%, and for the exposure dependence on the arrival direction we used the analytical estimate given in [10]. By comparison, AGASA had an acceptance of 160 km$^2$ sr and reported 886 events above $10^{19}$ eV over a decade with an accumulated exposure of 1645 km$^2$ sr yr. If the two experiments had the same energy calibration, Auger would accumulate over $\sim 10^4$ events above $10^{19}$ eV in five years of operation. However, the first released Auger spectrum [33] suggests that the energy calibration of AGASA [4] is systematically high and, consequently, a lower flux is observed for a fixed energy at Auger.

We normalize our simulations to the Auger flux above $4 \times 10^{19}$ eV [33] (indicated in table 1 as $n_{19.6}$, i.e., the number of events above $4 \times 10^{19}$ eV) and determine the number of events with energy above $10^{20}$ eV as a result of our simulations. These numbers are summarized in table 1, for a continuous distribution of sources and for different values of the source density.

The numbers in table 1 require some further comments. The spectrum of cosmic rays reported by Auger as it accumulates data during construction appears to have a dip instead of a bump at energies around $4 \times 10^{19}$ eV. This feature may lead to an incorrect estimate of the number of events expected at higher energies. In figure 1, we show the Auger data
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Table 2. Number of events expected with $E > 10^{20}$ eV using the normalization of the spectrum at $10^{19}$ eV.

| $ar{\rho}$ (Mpc$^{-3}$) | $n_{20}/1$ yr | $n_{20}/5$ yr | $n_{20}/10$ yr | $n_{20}/15$ yr |
|--------------------------|---------------|---------------|----------------|---------------|
| Cont.                    | 5.0 ± 2.2     | 25 ± 5        | 50 ± 7         | 75 ± 8        |
| $10^{-3}$                | 4.2 ± 1.8     | 22 ± 5        | 44 ± 9         | 67 ± 11       |
| $10^{-4}$                | 3.6 ± 2.0     | 18 ± 5        | 38 ± 9         | 58 ± 12       |
| $10^{-5}$                | 2.5 ± 1.8     | 13 ± 5        | 24 ± 8         | 35 ± 10       |
| $10^{-6}$                | 0.8 ± 1.0     | 3.5 ± 2.3     | 7.4 ± 4.2      | 13 ± 7        |

and the predicted spectrum as normalized at $10^{19}$ eV (dashed line) and at $4 \times 10^{19}$ eV (solid line). Systematic uncertainties on the flux and on the energy determination are indicated by double arrows at two different energies [33]. The figure clearly illustrates the fact that the normalization at $4 \times 10^{19}$ eV may cause an underestimate of the number of events expected at higher energies, since most likely the feature observed at that energy is the result of a statistical fluctuation. In order to keep memory of this problem we carry out our analyses for both choices of normalization. The number of events obtained with the normalization at $10^{19}$ eV are reported in table 2, and are systematically higher by a factor $\sim 2$.

We parameterize the mean density for the distribution of sources by $\bar{\rho} = 10^{-r}$ Mpc$^{-3}$, and choose $r$ between 3 and 6. The mean densities of extragalactic astrophysical accelerators of UHECRs should be well represented by this range which covers galaxies, groups, and clusters of galaxies. For example, black holes in centres of normal galaxies should have $r \simeq 3$ while those in active galaxies should have $r \gtrsim 6$. Similar densities are expected for rich clusters of galaxies. The most common extragalactic objects that may house UHECR sources are galaxies, which have $\bar{\rho}$ depending on their type and luminosity ranging from $r = 2$ to 3. For example, the Sloan Digital Sky survey recently reported a comprehensive study [30] of galaxy clustering in a large volume limited sample at relatively low redshifts ($z$ between 0.015 and 0.1). In their samples, galaxy number densities vary between $2 \times 10^{-2} h^3$ Mpc$^{-3}$ (in their sample with limiting $r$-magnitude $-18$) and $6 \times 10^{-5} h^3$ Mpc$^{-3}$ (for the brighter sample). The number density in groups of galaxies range from $6 \times 10^{-4} h^3$ Mpc$^{-3}$ (starting with groups of three galaxies) to richer clusters with $10^{-7} h^3$ Mpc$^{-3}$. Choosing the Hubble parameter, $h = H_0/100$ km/s/Mpc = 0.75, the observed $\bar{\rho}$ range is from $8 \times 10^{-3}$ Mpc$^{-3}$ to $4 \times 10^{-8}$ Mpc$^{-3}$. As we discuss below, detecting SSAs for $\bar{\rho} \gtrsim 10^{-3}$ Mpc$^{-3}$ will require many years of observations, while $\bar{\rho} \ll 10^{-6}$ Mpc$^{-3}$ generate higher UHECR clustering than reported so far, unless magnetic fields move the threshold for charged particle astronomy to energies around $10^{20}$ eV. Such low densities of sources also imply a sharp GZK cutoff in the diffuse spectrum, starting at energies below $10^{20}$ eV. This scenario appears to be disfavoured by current data.

2.1. Two point correlation function above $4 \times 10^{19}$ eV

Figure 2 shows the two point correlation function of simulated events with energies above $4 \times 10^{19}$ eV for the full Auger South aperture and exposures after 1, 5, 10, and 15 years of operation. The number of events is normalized at the Auger data at energy $4 \times 10^{19}$ eV.
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Figure 2. Two point correlation function expected for Auger events above $4 \times 10^{19} \text{ eV}$ (normalized at $4 \times 10^{19} \text{ eV}$) after 1, 5, 10, and 15 years, for continuous distribution of sources (black circles), and number densities of $10^{-3} \text{ Mpc}^{-3}$ (cyan stars), $10^{-4} \text{ Mpc}^{-3}$ (green downward triangles), $10^{-5} \text{ Mpc}^{-3}$ (blue squares), and $10^{-6} \text{ Mpc}^{-3}$ (red upward triangles). No limitation on the minimum distance for sources was imposed. Error bars are asymmetric $1\sigma$. The data points in this and in all subsequent figures have been slightly offset (horizontally) for clarity of presentation.

The black circles show a continuous distribution of sources, while sources with number densities of $10^{-3} \text{ Mpc}^{-3}$ are represented by cyan stars, $10^{-4} \text{ Mpc}^{-3}$ by green downward triangles, $10^{-5} \text{ Mpc}^{-3}$ by blue squares, and $10^{-6} \text{ Mpc}^{-3}$ by red upward triangles. The error bars are asymmetric $1\sigma$ standard deviations calculated in each energy bin for events above and below the mean. It is clear from this figure that after one year with the full Auger South aperture a discrete distribution with $\bar{\rho} \lesssim 10^{-4} \text{ Mpc}^{-3}$ should be distinguishable from a continuous source distribution. After five years, even a $\bar{\rho} \sim 10^{-3} \text{ Mpc}^{-3}$ can be detected at the few $\sigma$ level. After a decade, departure from continuous should be detected at many tens of $\sigma$, while distinguishing between different specific source densities in figure 2 will be more difficult.

In the 100 realizations in figure 2, there are often configurations with sources within 10 Mpc. These randomly placed nearby sources produce a significant dispersion in the two point correlation function at small opening angles and generate an overlap between different choices of $\bar{\rho}$. The presence of sources this close to us is not consistent with current observations by AGASA and HiRes, so we impose a lower limit on the distance to the nearest source. In figure 3, the nearest source is at distances larger than $d_{\text{min}}(\bar{\rho})$, where

$$d_{\text{min}}(\bar{\rho}) = \frac{1}{2} \bar{\rho}^{-1/3}. \quad (6)$$

As can be seen in figure 3, imposing a minimum distance alleviates the degeneracies between different source densities after five years of full Auger South operations. After the first full year exposure, number densities above $10^{-4} \text{ Mpc}^{-3}$ give clear departure from continuous distributions, while for $\lesssim 10^{-3} \text{ Mpc}^{-3}$, five years are necessary.
Figure 3. Same as figure 2 but the minimum distance for nearby sources is $d_{\text{min}}(\bar{\rho})$.

Table 3. Number of doublets for $E > 4 \times 10^{19}$ eV, using the normalization of the number of simulated events to the number of events observed by Auger above $4 \times 10^{19}$ eV.

| $\bar{\rho}$ (Mpc$^{-3}$) | $N_d/1\text{ yr}$ | $N_d/5\text{ yr}$ | $N_d/10\text{ yr}$ | $N_d/15\text{ yr}$ |
|---------------------------|-------------------|-------------------|-------------------|-------------------|
| Cont.                     | $0.33^{+0.77}_{-0.33}$ | $7.13^{+2.77}_{-2.33}$ | $29.7^{+5.3}_{-5.3}$ | $67.5^{+8.1}_{-8.3}$ |
| $10^{-3}$                 | $1.07^{+2.75}_{-0.80}$ | $29.7^{+24.3}_{-12.0}$ | $125^{+94}_{-49}$ | $279^{+204}_{-104}$ |
| $10^{-4}$                 | $3.63^{+5.84}_{-2.21}$ | $96.7^{+139.1}_{-42.3}$ | $355^{+318}_{-129}$ | $844^{+647}_{-313}$ |
| $10^{-5}$                 | $10.6^{+12.0}_{-5.0}$ | $259^{+217}_{-75}$ | $953^{+619}_{-257}$ | $2181^{+1763}_{-530}$ |
| $10^{-6}$                 | $39.6^{+24.6}_{-12.8}$ | $987^{+408}_{-173}$ | $4078^{+3702}_{-658}$ | $9940^{+4681}_{-2010}$ |

In table 3, we list the mean number of doublets ($\bar{N}_d$) expected after 1, 5, 10, and 15 years of Auger South operations for $E > 4 \times 10^{19}$ eV and for $r$ between 3 and 6. In the same table we report, along with $\bar{N}_d$, the asymmetric 1$\sigma$ error bars for realizations with a number of doublets above or below the mean. The opening angle used to count doublets is 1$^\circ$ and the realizations have minimum source distance $d_{\text{min}}(\bar{\rho})$ as in figure 3. It is worth stressing that $\bar{N}_d$ in the table is the total number of doublets, including doublets inside possible higher multiplicity clusters.

If the number of events used in the simulation is normalized to the low energy spectrum as measured by Auger South, then the number of doublets expected in the future Auger operation are those reported in table 4.

2.2. Two point correlation function above $10^{20}$ eV

UHECR clustering and source positions should become easier to identify with events of energies $\gtrsim 10^{20}$ eV, given that at these energies UHECRs are most likely protons and their
trajectories are less likely to be affected by extragalactic and galactic magnetic fields than lower energy events. The difficulty is clearly in the limited statistics of events that can be accumulated in this energy range by Auger South, since the flux is a steeply decreasing power of energy and energy losses that give rise to the GZK feature are also at play in this energy range. A larger array as currently being discussed for the Auger North Observatory should help significantly the ability to do charged particle astronomy at this energy scale.

We simulated the expected angular correlation function in Auger South for events with energies above $10^{20}$ eV for different source densities. In figure 4, the correlation function is shown for sources located at minimum distances $d_{\text{min}}(\bar{\rho})$ as in figure 3. We fixed the number of events above $10^{20}$ eV to the mean number given in table 1 for the

![Figure 4. Two point correlation function for events above $10^{20}$ eV (normalized at $4 \times 10^{19}$ eV) after 5, 10, and 15 years at Auger South for a continuous distribution of sources (black circles), and number densities of $10^{-3}$ Mpc$^{-3}$ (cyan stars), $10^{-4}$ Mpc$^{-3}$ (green downward triangles), $10^{-5}$ Mpc$^{-3}$ (blue squares), and $10^{-6}$ Mpc$^{-3}$ (red upward triangles). The minimum distance for the nearest source is $d_{\text{min}}(\bar{\rho})$.](image)

![Table 4. Number of doublets for $E > 4 \times 10^{19}$ eV, using the normalization of the number of simulated events to the number of events observed by Auger at $10^{19}$ eV.](image)
continuous case. If we let the number of events fluctuate between realizations or change between different source densities the error bars are enhanced. Once Auger has run for five years, the actual number of events above $10^{20}$ eV will be known and the ability of Auger to distinguish between different source densities can be evaluated by comparing the two-point correlation function for the same number of events above $10^{20}$ eV for different source densities. Combining a study of the GZK feature with the small scale anisotropies as shown in figure 1, a possible spectrum appears to be at odds with the observed low energy spectrum. If the solid line in figure 1 is used for the normalization of the number of events above $10^{20}$ eV, then the situation improves somewhat (the number of events above $10^{20}$ eV is roughly doubled in this case). In figure 5 we plot the two point correlation function for the new number of events above $10^{20}$ eV after 5, 10, and 15 years. The number of doublets obtained for this second choice of normalization to the data is shown in table 6.

Table 5. Number of doublets for $E > 10^{20}$ eV with normalization to the Auger data above $4 \times 10^{19}$ eV.

| $\rho$ (Mpc$^{-3}$) | $N_d/5 \text{ yr}$ | $N_d/10 \text{ yr}$ | $N_d/15 \text{ yr}$ |
|---------------------|---------------------|---------------------|---------------------|
| Cont.               | $0.02^{+1.40}_{-0.02}$ | $0.04^{+1.38}_{-0.04}$ | $0.12^{+1.15}_{-0.12}$ |
| $10^{-3}$           | $0.73^{+1.76}_{-0.73}$ | $3.05^{+4.84}_{-1.90}$ | $7.09^{+10.11}_{-3.91}$ |
| $10^{-4}$           | $2.32^{+3.28}_{-1.50}$ | $11.1^{+13.7}_{-6.1}$  | $24.8^{+23.9}_{-12.6}$ |
| $10^{-5}$           | $5.71^{+9.77}_{-3.48}$ | $19.0^{+21.6}_{-9.1}$  | $44.4^{+54.6}_{-19.4}$ |
| $10^{-6}$           | $14.3^{+11.0}_{-5.6}$  | $56.8^{+41.4}_{-14.2}$ | $125^{+94}_{-27}$     |

Table 6. Number of doublets for $E > 10^{20}$ eV normalized at $10^{19}$ eV Auger data.

| $\rho$ (Mpc$^{-3}$) | $N_d/5 \text{ yr}$ | $N_d/10 \text{ yr}$ | $N_d/15 \text{ yr}$ |
|---------------------|---------------------|---------------------|---------------------|
| Cont.               | $0.02^{+0.98}_{-0.02}$ | $0.19^{+0.98}_{-0.19}$ | $0.39^{+1.05}_{-0.39}$ |
| $10^{-3}$           | $3.29^{+5.08}_{-2.08}$ | $13.9^{+15.4}_{-7.1}$ | $30.0^{+32.6}_{-13.8}$ |
| $10^{-4}$           | $10.5^{+9.5}_{-5.3}$  | $46.8^{+50.2}_{-22.8}$ | $102^{+104}_{-46}$   |
| $10^{-5}$           | $23.9^{+33.4}_{-12.5}$ | $76.8^{+94.3}_{-29.4}$ | $187^{+220}_{-78}$   |
| $10^{-6}$           | $59.6^{+33.9}_{-17.9}$ | $228^{+168}_{-46}$   | $503^{+413}_{-93}$   |
2.3. Spectra for different number densities

As shown in [7], the combination of small angle clustering and spectral information is a powerful tool to investigate the nature of UHECR sources. Rarer sources imply stronger small angle clustering of the arrival directions and a sharper decrease in flux at the GZK feature, i.e., a lower number of events at the highest energies. Sources with larger densities have the opposite effect: the GZK feature is shallower (more events at the highest energies) but the clustering is milder. As pointed out in [7], the AGASA data on the small scale anisotropies appear to be at odds with the spectrum, as measured by the same experiment. Here we investigate the potential to use a similar technique with future data from the Pierre Auger Observatory.

In figure 6, we show the energy spectrum around the GZK feature that may be detected by Auger South after 15 years of full aperture operations, assuming a normalization at $10^{19}$ eV. The spectrum is shown for different source densities ranging from a continuous source distribution (black circles) to source densities between $10^{-3}$ Mpc$^{-3}$ (cyan stars) and $10^{-6}$ Mpc$^{-3}$ (red upward triangles). Also shown is the first release of the Auger spectrum (open magenta squares) [33] and an analytical prediction (continuous line).

The number of events at energies above $10^{20}$ eV is a rather sensitive function of the source density, as can be seen in tables 1 and 2. For a spectrum normalized at $10^{19}$ eV, $\sim 75$ events above $10^{20}$ eV should be observed in 15 years of operation of Auger South, for a continuous (and unlikely) distribution of sources, while only $\sim 13$ events in the same energy region should be observed if the sources have a mean local density of $10^{-6}$ Mpc$^{-3}$. The statistical uncertainties in the flux at the highest energies become large if the source...
density is low, and it becomes correspondingly harder to have a precise measurement of the shape of the GZK feature in these cases. For source densities between $10^{-6} \text{ Mpc}^{-3}$ and $10^{-5} \text{ Mpc}^{-3}$ Auger is expected to become statistics dominated at energies $\sim 10^{20.2} \text{ eV}$. However, at this energy the different predicted spectra already differ from that generated by a continuous source distribution by about a factor $\sim 10$. The combination of spectra measurements and anisotropy measurements can play an instrumental role in inferring hints to the nature of the sources of UHECRs, but in some cases Auger North will be needed to detect anisotropies within a decade.

3. Conclusions

The imminent completion of the Auger Observatory in Argentina will mark the beginning of a new era in cosmic ray astrophysics. The combination of a very large ground array and fluorescence telescopes will provide a detailed measurement of the spectrum at the highest energies.

One of the main open questions in Cosmic Ray Physics is the presence of a GZK feature in the spectrum. If this feature is in fact there, it becomes very important to measure its shape, which can provide information on the number of sources and their spatial distribution. Independent of the presence or absence of the GZK feature, the problem of finding an acceleration mechanism and a class of sources that may harbour the accelerator remains of paramount importance. Auger will most likely determine whether the spectrum of UHECRs has the GZK suppression or not. In order to study the acceleration sites, higher statistics data on the arrival direction and composition of UHECRs will be necessary. The first hints of such a new era of charged particle astronomy are likely to come from small deviations from isotropic distributions in the first several years of Auger South operations.

In this paper we made quantitative predictions of the amount of small scale anisotropies expected in Auger in the next decade for a range of plausible source densities.
Small scale anisotropy predictions for the Auger Observatory

We investigated two choices for the normalization of the number of events expected at the highest energies, depending on whether the procedure is applied to the data measured by Auger at $4 \times 10^{19}$ eV or rather at $10^{19}$ eV where statistical errors should be less important. The amount of small angle clustering was quantified through the two point correlation function, both for events above $4 \times 10^{19}$ eV and above $10^{20}$ eV. We conclude that after a few years of running Auger South should detect a departure of the two point correlation function from that expected from a continuous distribution of sources. On the other hand, to measure the mean source density accurately will require larger statistics due to the low flux and statistical fluctuations. The combination of small angle clustering and spectrum of diffuse cosmic rays can provide more stringent constraints on the source density [7], although the statistical error bars on the spectrum for the case of discrete sources, as shown in figure 6, are expected to become relatively large at energies around $10^{20.2}$ eV. The challenge of reaching the required statistics is stronger than discussed in [6] because previous results were obtained adopting the normalization (not the shape) of the AGASA spectrum, which has now been found to lead to cosmic ray fluxes about three times larger than those actually measured by Auger at the present time.

Despite these problems, it is fair to conclude that once the departures from isotropy will be detected, the estimate of the mean density of sources, $\bar{\rho}$, will be within reach. The even more challenging possibility of measuring the spectrum of a single source [11] will require a significant increase in statistics at the highest energies as currently being discussed in the context of the Auger North Observatory or future generation cosmic ray observatories in space.

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