# Full-Sky Search for Ultra High Energy Cosmic Ray Anisotropies

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## Abstract

Using data from the SUGAR and the AGASA experiments taken during a 10 yr period with nearly uniform exposure to the entire sky, we search for anisotropy patterns in the arrival directions of cosmic rays with energies $> 10^{19.6}$ eV. We determine the angular power spectrum from an expansion in spherical harmonics for modes out to $\ell = 5$. Based on available statistics, we find no significant deviation from isotropy. We compare the rather modest results which can be extracted from existing data samples with the results that should be forthcoming as new full-sky observatories begin operation.

## 1. Introduction

Ultra high energy cosmic rays (UHECRs) are one of the most enigmatic phenomena in the universe. Despite the fact that the existence of particles with energies $> 10^{20}$ eV has been known for over 40 years, their origin continues to be an intriguing puzzle [1,3]. The distribution of arrival directions is perhaps the most helpful observable in yielding clues about cosmic ray origin. Certainly, a positive identification of the sources requires a careful study of such distribution over the full celestial sphere. This is the main inspiration for this note.

## 2. Angular Power Spectrum

The SUGAR array was operated from January 1968 to February 1979 in New South Wales (Australia) at a latitude of $30°30'$ South and longitude $149°38'$ East [11]. The array consisted of 47 independent stations on a rectangular grid covering an area $S \approx 70$ km$^2$. The primary energy was determined from the total number of muons, $N_\mu$, traversing the detector at the measured zenith angle $\theta$. The total aperture for incident zenith angles between $\theta_1$ and $\theta_2$ was found to be

$$A = \int_{\theta_1}^{\theta_2} S \; p(N_\mu, \theta) \; \cos\theta \, d\Omega \,. \tag{1}$$
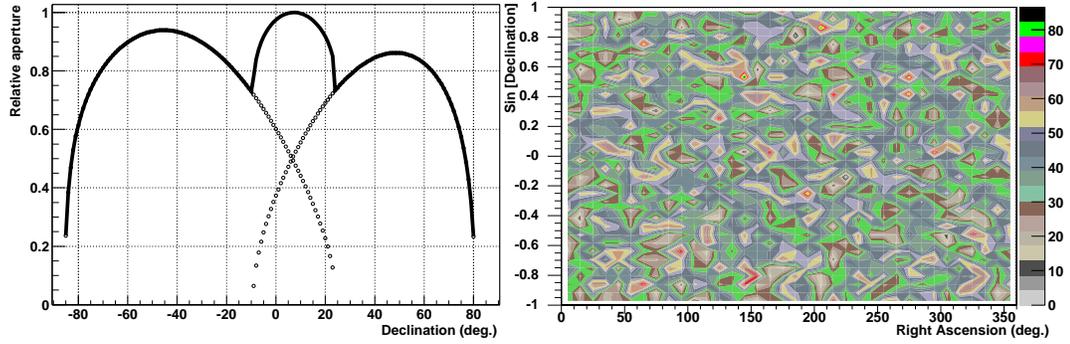
**Fig. 1.** Left: Declination dependence of SUGAR and AGASA relative apertures (dotted) according to the prescription given in Ref. [9]. The solid line indicates the combined relative aperture. Right: Intensity of the cosmic ray sky in equatorial coordinates as seen by the SUGAR and the AGASA experimets.

Here, $p(N_\mu, \theta)$ is the probability that a shower falling within the physical area was detected, $S \cos\theta$ is the projected surface of the array in the shower plane, and $d\Omega$ is the acceptance solid angle. The SUGAR Collaboration reports [11] a reasonable accuracy in assessing the shower parameters up to $\theta = 73°$. The estimated angular uncertainty for showers that triggered 5 or more stations is reported as $3° \sec\theta$ [11]. However, the majority of events were only viewed by 3 or 4 stations, and for these the resolution appears to be as poor as $10°$ [7]. Of particular interest for this analysis, $p(N_\mu > 10^8, \theta < 55°) \approx 0.85$ [2], yielding a total aperture $A \approx 125$ km$^2$ sr. This provides an exposure reasonably matched to that of AGASA, which is described next. The AGASA experiment occupies farm land near the village of Akeno (Japan) at a longitude of $138°30'$ East and latitude $35°30'$ North [4]. The array, which consists of 111 surface detectors deployed over an area of about 100 km$^2$, has been running since 1990. About 95% of the surface detectors were operational from March to December 1991, and the array has been fully operational since then. A prototype detector operated from 1984 to 1990 and has been part of AGASA since 1990 [10]. The aperture for events with primary zenith angle $0° < \theta < 45°$ and energies beyond $10^{19.25}$ eV is found to be $A \approx 125$ km$^2$ sr [4].

Surface arrays in stable operation like SUGAR or AGASA have nearly continuous observation over the entire year, yielding a uniform exposure in right ascension. However, the relative detection efficiency has a small dependence on declination that it is well known and can be easily corrected for [9]. As one can readily see in Fig. 1, the combined aperture of SUGAR and AGASA arrays is

nearly uniform over the entire sky. The expected event rate is found to be

$$\frac{dN}{dt} = A \int_{E_1}^{E_2} E^3 J(E) \frac{dE}{E^3} \approx \frac{A}{2} \langle E^3 J(E) \rangle \left[ \frac{1}{E_1^2} - \frac{1}{E_2^2} \right] , \tag{2}$$

where $\langle E^3 J(E) \rangle \approx 10^{24.6}$ eV$^2$ m$^{-2}$ s$^{-1}$ sr$^{-1}$ stands for the observed UHECR flux, which has a cutoff at $E_2 = 10^{20.5}$ eV [1]. Thus, in approximately 10 yr of running each of these experiments should collect $\approx$ 50 events above $E_1 = 10^{19.6}$ eV, arriving with a zenith angle $< \theta_{\max}$. Here, $\theta_{\max} = 45°$ for AGASA and $\theta_{\max} = 55°$ for SUGAR. Our sub-sample for the full-sky anisotropy search consists of the 50 events detected by AGASA from April 1990 to May 2000 [6], and the 49 events detected by SUGAR with $\theta < 55°$ [11]. The arrival directions of these events are plotted in Fig. 2 (equatorial coordinates B.1950).

In what follows, we use real-valued spherical harmonics [9], and the arrival directions are given in equatorial coordinates, namely, right ascension ($\alpha$) and declination ($\delta$). The intensity distribution of a set of $N$ arrival directions $\Omega_i(\alpha_i, \delta_i)$ can be written as,

$$I(\alpha, \delta) = \frac{1}{\mathcal{N}} \sum_{i=1}^{N} \frac{1}{\omega_i} \delta(\Omega - \Omega_i) , \tag{3}$$

where $\omega_i$ is the relative exposure at arrival direction $\Omega_i$ and $\mathcal{N}$ is the sum of the weights $\omega_i^{-1}$. For any spherical distribution the natural measure of anisotropy patterns is in terms of the spherical harmonics $Y_{\ell m}$. The intensity over the sphere reads,

$$I(\alpha, \delta) = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\alpha, \delta) . \tag{4}$$

The set of spherical harmonics coefficients $a_{\ell m}$ are uniquely defined,

$$a_{\ell m} = \int I(\alpha, \delta) Y_{\ell m} d\Omega \quad \Rightarrow \quad a_{\ell m} = \frac{1}{\mathcal{N}} \sum_{i=1}^{N} \frac{1}{\omega_i} Y_{\ell m}(\Omega_i) . \tag{5}$$

The intensity distribution is shown in Fig. 1. Although full anisotropy information is encoded into the coefficients $a_{\ell m}$ (tied to some specified coordinate system), the (coordinate independent) angular power spectrum,

$$C(\ell) = \frac{1}{(2\ell + 1)} \sum_{m=-\ell}^{\ell} a_{\ell m}^2, \tag{6}$$

provides a gross summary of the features present in the celestial distribution together with the characteristic angular scale(s) [8]. The power in mode $\ell$ is sensitive to variation over angular scales of $\ell^{-1}$ radians. The estimated angular uncertainty for some of the events in the SUGAR sample is possibly as poor as $10°$ [7]. Hence, we only look in this study for large scale patterns such as dipole [5] or quadrupole moments. Our results to this juncture are largely encapsuled in Fig. 2. The angular power spectrum is consistent with that expected from a random distribution for all (analyzed) multipoles.
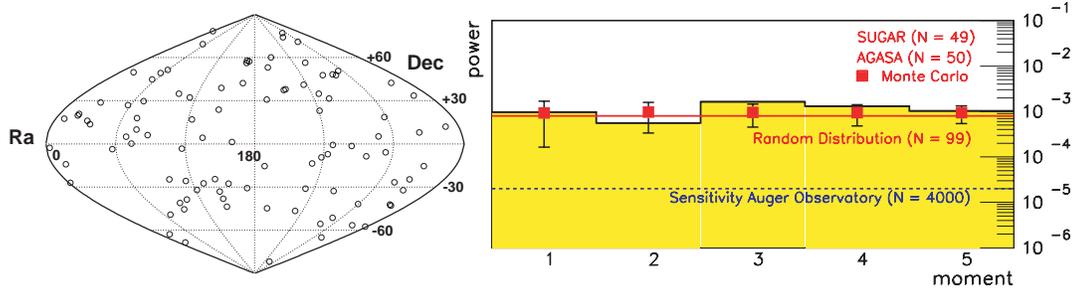
**Fig. 2.** Left: Arrival direction of the 99 events observed above $10^{19.6}$ eV by the SUGAR ($\theta < 55°$) and the AGASA ($\theta < 45°$) experiments. Right: Angular power spectrum (histogram). The horizontal lines indicate the expected mean value, $\overline{C}(\ell) = (4\pi N)^{-1}$, from an isotropic distribution. The squares represent randomly distributed Monte Carlo values of 1000 sets of 99 events each.

## 3.  Sensitivity of the Pierre Auger Observatory (PAO)

The PAO is designed to measure the energy and arrival direction of UHE-CRs with unprecedented precision. It will consist of two sites, one in the Northern hemisphere and one in the Southern, each covering an area $S \approx 3000$ km$^2$. The base-line design of the detector includes a ground array consisting of 1600 water Čerenkov detectors overlooked by 4 fluorescence eyes. The angular and energy resolution of the ground array are typically less than 1.5° (multi-pole expansion $\ell \sim 60$) and less than 20%, respectively. The detectors are designed to be fully efficient ($p \approx 1$) out to $\theta_{max} = 60°$ beyond $10^{19}$ eV, yielding a nearly uniform sky $A \approx 1.4 \times 10^4$ km$^2$ sr [9]. In 10 yr of running the two arrays will collect $\approx 4000$ events above $E_1 = 10^{19.6}$ eV. As can be seen from Fig. 2, such statistics will allow one to discern asymmetries at the level of about 1 in $10^4$.

## 4.  References

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