Searching for sources of the highest energy cosmic rays: low statistics, pitfalls, and possible clues

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The clustering properties of the highest energy cosmic rays and their correlations with candidate sources are re-examined using the most recently available AGASA data and a rigorous correlation analysis. The statistical methodology incorporates some important points not considered in previous studies. Results include small angle clustering significances consistent with, but somewhat less than, earlier findings, a possible large scale anisotropy for events with energies $E \approx 5 - 8 \times 10^{19}$ eV, and no statistically significant cross correlations with BL Lacertae or blazars. A marginally significant cross correlation exists for events with energies $E > 8 \times 10^{19}$ eV with a set of Abell clusters, but no definitive conclusion can yet be drawn from this result.

1. INTRODUCTION

Investigating cosmic ray airshowers induced by extremely high energy cosmic rays (EHECRs, $E \gtrsim 4 \times 10^{19}$ eV) remains an area of intense interest because of an apparent paradox posed by the onset of the Greisen-Zatsepin-Kuzmin (GZK) effect [1]. As is well known, the paradox is that $\sim 15 - 20$ events have been detected apparently having $E > 10^{20}$ eV but with no currently obvious astrophysical source within the local GZK sphere defined by the 50 – 100 Mpc distance over which cosmic ray protons lose a substantial fraction of their initial energy through interactions with CMB photons [2]. Due to this small number of events, open questions include the existence of statistically significant clustering/anisotropy, correlations with known astrophysical source distributions (e.g., QSOs), the composition/charge of the primaries, and whether the production mechanism is top-down or bottom-up.

This presentation summarizes the analytical approach and results contained in two papers [3]. Because of the three page limit imposed for the TAUP03 conference proceedings, this paper is necessarily abbreviated, informal, and contains only a few references. However, further details concerning methodology, additional figures and tables, and more complete bibliographies can be found in our two papers mentioned above.

2. ANALYTICAL APPROACH

For this study, we use the AGASA data for airshowers with estimated energies $E \geq 4 \times 10^{19}$ eV and zenith angles $\leq 45^\circ$ contained in reference [4]. The results we obtain are based on applying statistical estimators to Monte Carlo simulations of isotropically-distributed arrival directions convolved with the observed AGASA detector acceptance. The distribution of angular pair separations is analyzed with the Landy-Szalay (LS) two point angular correlation function,

$$w(\theta) = \frac{DD}{RR} - 2\frac{DR}{RR} + 1,$$

where the “D” and “R” refer to a single angular position of an event in the data or random catalogs, respectively, so that “DD” represents a pair separation between two events in the data, etc. [5]. Values of $w(\theta) > 0$ then indicate pair correlations beyond those expected in uncorrelated distributions (with

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Figure 1. The two point angular correlation function for 60 AGASA events and 2.5° bin widths.

a MC-derived significance). Figure 1 shows the results for bin widths of 2.5° where the existence of an excess number of pairs in the first bin over that expected from random projection is at greater than the 4σ level.

Clustering probabilities are estimated directly from the simulations by utilizing a counting scheme that identifies distinct multiplet configurations (e.g., doublets, triplets, etc.) instead of counting just pairs within a specified opening (or correlation) angle. The reason for this is that higher order multiplets, such as a triplet, generally have a lower probability for random occurrence than does the presence of the same number of distinct pairs. This can be seen from Figure 2 that shows the joint inclusive probability contours for various doublet-triplet configurations.

The associated LS cross correlation function is

$$\chi(\theta) = \frac{D_1 D_2 / R_1 R_2 - (D_1 R_2 + D_2 R_1) / R_1 R_2 + 1}{R_1 R_2 + 1},$$

(2)

where the subscripts refer to the two samples being cross correlated, and values of $\chi(\theta) > 0$ indicate the two samples are correlated (with a MC-derived significance). Equation (2) is used to investigate whether the AGASA sample can be separated into statistically uncorrelated distributions partitioned by energy, and to search for correlations between the AGASA sample and BL Lacertae, blazars, and Abell clusters of galaxies.

Avoiding the pitfalls in cross correlating cosmic ray arrival directions with catalogs of astrophysical objects requires accounting for
1. Selection effects such as absorption at low galactic latitudes,
2. Catalog completeness and source densities,
3. Intrinsic clustering/correlations between the candidate sources,

Many of the previously published studies finding correlations with various types of objects have not fully considered these points. In our study, we have attempted to be as rigorous as possible.

3. SUMMARY OF RESULTS

Our results can be summarized as follows:
1. Angular correlations exist on $\sim 2.5° - 3°$ scales at the $\geq 4\sigma$ level (MC prob. $\sim 0.1\%$) with no
Figure 2. Joint inclusive probability contours for 60 and 72 AGASA event sample sizes.

Figure 3. The supergalactic latitude distribution of the $5 \leq E < 8 \times 10^{19}$ eV partition.

departures from homogeneity on scales $\gtrsim 4^\circ$,
2. Partitioning the AGASA sample by energy yields three apparently uncorrelated groups with energies $E < 5 \times 10^{19}$ eV, $5 \leq E < 8 \times 10^{19}$ eV, and $E \geq 8 \times 10^{19}$ eV,
3. From Figure 3 the partition with $5 \leq E < 8 \times 10^{19}$ eV appears to be preferentially aligned with the Supergalactic equatorial plane (i.e., in a plane containing a large fraction of galaxies within our Local Supercluster) at the $0.1 - 0.6\%$ MC prob. level; the other two energy partitions are consistent with isotropic distributions,
4. None of the partitions exhibits a statistically significant correlation with BL Lacertae or blazar sky
Figure 4. X-correlation between the highest energy AGASA EHECRS and Abell clusters with $z \leq 0.04$; positive correlations exist to $z \leq 0.06$.

4. DISCUSSION

We have no pretensions of having achieved definitive results. With the small data sample and low statistics, the results could change considerably or disappear with only a few additional events. However, the methodology is robust, and the internal consistency of the implied scenario is somewhat remarkable: the mid-energy distribution ends at approximately the GZK “cutoff” energy, and is apparently correlated with the luminous matter distribution in the Local Supercluster but not that beyond. The high-energy partition may be isotropically distributed, appears uncorrelated with the matter distribution of the Local Supercluster, but may be correlated with the matter distribution outside the Local Supercluster to distances as great as $250 h_{70}^{-1}$ Mpc. Note that testing for energy partitions is independent of the subsequent cross correlation with other distributions. Finally, penalty factors have been considered and will be discussed in the forthcoming paper.

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REFERENCES

1. K. Greisen, PRL 16, 748 (1966); G.T. Zatsepin and V.A. Kuzmin, JETP Lett. 4, 78 (1966).
2. F.W. Stecker, PRL 21, 1016 (1968); C.T. Hill and D.N. Schramm, PRD 31, 564 (1985); V. Berezinsky and S.I. Grigor’ev, A&A 199, 1 (1988); S. Yoshida and M. Teshima, Prog. Theor. Phys. 89, 933 (1993).
3. W.S. Burgett and M.R. O’Malley, PRD 67, 092002 (2003); W.S. Burgett and M.R. O’Malley, “Cross correlating AGASA EHECR arrival directions with candidate sources and sites”, in preparation.
4. M. Takeda et al., ApJ 522, 225 (1999); N. Hayashida et al., e-print arXiv:astro-ph/0008102 (2000); AGASA website.
5. S. Landy and A. Szalay, ApJ 412, 64 (1993).