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Correlation of Ultra High Energy Cosmic Rays with Compact Radio Loud Quasars

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Abstract

Angular correlations of ultra-high energy cosmic rays with cosmologically distant sources may provide clues to these mysterious events. We compare cosmic ray tracks with energies above $10^{20}eV$ to a compilation of radio-loud compact QSO positions. The statistical method emphasizes invariant quantities and a test of *statistical independence* of track and source distributions. Statistical independence is ruled out by several independent statistics at confidence levels of less that 10^{-3} (99.9%.), indicating that track directions and QSO source positions are correlated at a highly significant level.

1 Introduction

The origin and propagation of the highest energy cosmic rays [1, 2, 3, 4, 5] present a major challenge to current understanding of astrophysics. The problem has developed over many decades. In 1966 Greissen, Kuzmin and Zatsepin (GZK)[6] discovered a theoretical upper limit on cosmic ray energies of about $4 \times 10^{19}eV$. The limit is due to laboratory-established pair and photo-nuclear production processes occuring on the cosmic background radiation. Due to these processes, protons of such energies are unable to

propagate distance greater than about 50 Mpc. Other nuclei are even more severely restricted [7]. It is commonly believed [8, 9, 10] that the only possible astrophysical sources of particles with such high energies are the active galactic nuclei (AGN). The vast majority of AGN are cosmologically distant. There are insufficient alternative sources within 50 Mpc of Earth to produce the observed events. Hence the origin of numerous events above $4 \times 10^{19} eV$ is very puzzling.

The angular distribution of so-called "GZK-violating" events may contain important clues. In searching for a possible source for the Fly's Eye event FE320 ($320 EeV$), Elbert and Sommers [11] noticed that its arrival direction was very close to the remarkable quasar 3C147. Farrar and Biermann (FB)[12] pointed out that 3C147 is a compact quasar with jets about one-tenth the size of a full-sized quasar with radio lobes. The spectrum of 3C147 is cut off at low radio frequencies, providing another characteristic of its compactness.

Here we re-examine possible correlation of compact radio-loud quasars and cosmic-ray track directions. FB claimed a correlation between track directions and compact quasars, defined by the following three criteria:

1 The quasar should be listed in the NASA/IPAC extragalactic database (NED).

2 The object should be radio loud. In practice FB required that the object appear in the Kühr catalog [13]. This catalog contains a total 1835 radio sources including all those whose flux density at 5 GHz is ≥ 1 Jy.

3 The object should have flat or falling spectrum at low radio frequencies.

We organize our study somewhat differently from previous work. First, we pay extra attention to the baseline of the statistic, namely the definition of "no signal", employing several independent methods. This makes the study more reliable and more conservative than previous ones. Second, we employ invariant quantitites, both for the purposes of conceptual correctness and also to correct substantial relative systematic errors. Third and most importantly, we make no attempt to validate any proposed correlation. In fact, correlations can exist in such myriad forms that any statistical procedure accepting one form over another *a posteriori* can be suspect.

Of pivotal importance is that any proposed relation of GZK-violating cosmic rays and cosmological sources should test a crisp hypothesis. The default for cosmologically-distant sources is a relation of *statistical independence* of the arrival directions relative to the direction of the sources. Besides the GZK attenuation, scrambling of directions by intergalactic fields also tends to wash out any correlation of source-track directions. Independence is a well-defined hypothesis which can be tested without introducing model-dependence or extraneous postulates for these puzzling events.

2 More on the Data, and Analysis

There is a total of 285 quasars in the Kühr catalog which have a flat or falling spectrum at low radio frequencies. The catalog contains no quasars within ± 10 degrees of the galactic plane. Furthermore the density of quasars in the catalog is much smaller in the southern hemisphere than the northern hemisphere.

Candidates displaying spectra similar to quasars but not classified as quasars were ignored. If all sources with flat or falling spectrum at low radio frequencies were included, then the total number of sources would be about 500, close to the number cited by Farrar and Biermann. We will find that the remaining sources, not classified as quasars, do not show any correlation with track directions in our data set.

There are 25 track events available with energies exceeding $10^{20} eV$, a value chosen to be well beyond the GZK-violating regime. The events are listed in Table 1. We exclude those events which have galactic latitude ≤ 10 degrees since the catalog also imposes this cut. The cut removes 7 of the 25 events, leaving 18 tracks to be compared to the catalog QSO sample.

Rather than attempting to explain correlation, our strategy is to test independence. Independence of tracks and sources is expressed by the joint distribution

$$f(tracks, sources) = f(tracks) f(sources),$$

where we follow the usual practice of labeling a distribution by its argument. The coordinates of tracks and sources has previously been taken to be the right ascsension and declination. Using coordinates as statistics can introduce a human bias, namely the coordinate system of RA, DEC. To

make an invariant statistic, we map each track and source into unit vectors $\hat{x}_{track}, \hat{x}_{source}$ on the surface of the celestial sphere. We then look at the distribution of $\hat{x}_{track} \cdot \hat{x}_{source}$, which being invariant does not depend on the coordinate system. The angle γ between each track (i) and source $(j)$is defined by

$$\gamma_{ij} = cos^{-1}(\hat{x}_{track} \cdot \hat{x}_{source}).$$

One can also interpret γ as the minimum geodesic distance along the unit sphere between the two objects, removing all reference to the astronomical coordinates.

To incorporate the experimental errors, we examine γ^2 in units of the reported errors. The Akeno Giant Air Shower Array (AGASA) group reports an error cone containing 68% of the events. An error cone is ideal because it is also an invariant concept. In Ref. [14] the authors use an angular error of 1.8^o for the AGASA and 3^o for the rest of the detectors. We also adopt these error values for our analysis and later examine how our results change if we allow the errors to change slightly. The only exception to this is the Fly's Eye event where the error in DEC and RA are reported as given in Table 1. Letting the particular error for each event be denoted $\delta\gamma$, we create a statistic

$$\delta\chi_i^2 = min_j(\gamma_{ij}^2/\delta\gamma_i^2).$$

Our $\delta\chi_i^2$ is the analogue of FB's statistic $\delta\chi_{FB}^2 = min_j((RA_i - RA_j)^2 + (DEC_i - DEC_j)^2)/\delta\gamma_i^2$, which is not invariant due to the curvature of the sphere. While one might not expect problems when angles are small, the RMS *relative* deviation of the two measures (in equatorial coordinates) is about 1.46 in the data set.

The distribution of $\delta\chi^2$ in the regions of very large $\delta\chi^2$, which come from distantly mismatched points, is of minor concern for testing independence. We are primarily concerned with testing the null distribution in the region of small $\delta\chi^2 \sim 1$. The region of $\delta\chi^2 \sim 1$ is the region of a "good fit" between the track and the source as determined by the relative error. This is the region where proposals of correlation might make a difference. We chose to examine the integral probability in the bin of $\delta\chi^2 \leq 1$ as our main statistic, similar to the choice of FB. For reference our figures also show the distribution of $\delta\chi^2$ over the entire range spanned by the data, and we examine this distribution separately.

We examined the null distribution of $\delta\chi^2$ using two separate methods to generate uncorrelated tracks and sources. In one procedure, we distributed 285 fake source points randomly on the sky, excluding the galaxy cut, and calculated $\delta\chi^2$ using the track data set. In generating the random sample we kept the density of sources in the northern and southern hemispheres equal to that of the catalog. The distribution of $\delta\chi^2$ was determinined by repeating this 10,000 times. We call this the "isotropic null" (although by excluding the galaxy and using different northern/southern densities it is not isotropic). In the other method we were concerned that correlations or anisotropy of the source catalogue might skew the isotropic null. Consequently we took the 285 sources, and generated a new set of 285 sources by 10,000 random 3-parameter orthogonal transformations. A small fraction of sources landing inside the galaxy-cut region were re-distributed randomly. Similarly, any sources landing in the northern or sourthern hemisphere and causing a density larger than the catalog were randomly re-distributed into the other hemisphere. (As a consistency check, we also generated 10,000 distributions from orthogonal tranformations without re-distribution, without finding any differences.) We calculated the $\delta\chi^2$ distribution using the track data set, and repeated for 10,000 trials. The "orthogonal null" so determined retains any correlations of the sources among themselves, while scrambling any relation to the tracks. Of course both procedures use the actual track data, so that any bias or correlation from that is taken into account. The distribution of $\delta\chi^2$ in the null procedure is shown in Fig. 1. Only one of the null distribution is shown since the difference between the two nulls was found to be small.

A crude summary of the two null distributions finds an expected average of about 2.5 events, on the average, in the $\delta\chi^2 \leq 1$ bin. From the null distribution we can also evaluate the probability of fluctuations in the independent distribution to give any number of events above any determined particular value, the "P-value" or "confidence level" of the data.

3 Results

The data and actual quasar positions yielded 8 events with $\delta\chi^2 \leq 1$. These events can be read off from the Table. The quasar 3C147 happened to be very close to the boundary of the galaxy cut region and was excluded from

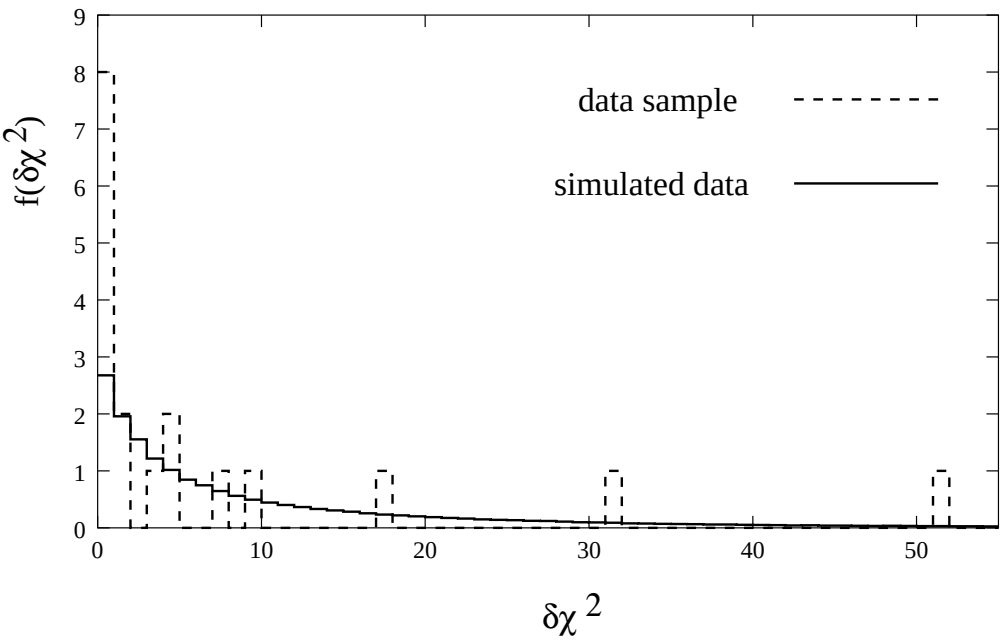

Figure 1: The distribution of residual $\delta\chi^2$ for individual events for the data set (solid line) and the simulated data (dashed line). Both distributions are normalized to the total number of 18 events cited in the text.

our analysis. Including 3C147 would exaggerate our conclusions, and the precise choice of the cut does not change our results qualitatively.

The null distribution is convincingly ruled out on the basis of 8 events. From the null distribution, the probability for independent source and track distributions to fluctuate to give 8 events is 0.06%. If one were to assume Gaussian statistics (we do not) the same result would be expressed as a roughly 3.5σ effect. Or, the null hypothesis of an uncorrelated data sample is ruled out with 99.94 % confidence level.

The data's distribution of $\delta\chi^2$ (Fig. 1) shows a peak at small $\delta\chi^2$ values which is inconsistent with the distribution of $\delta\chi^2$ seen in the Monte Carlo. Of the 18 events, 8 have arrival directions within one standard deviation from one of the compact quasars and 11 have arrival directions within two standard deviations from one of the compact quasars. The closest quasar and its angular separation from the cosmic ray is also shown in the Table.

As we completed this work, a paper by Sigl *et al* appeared [15] studying

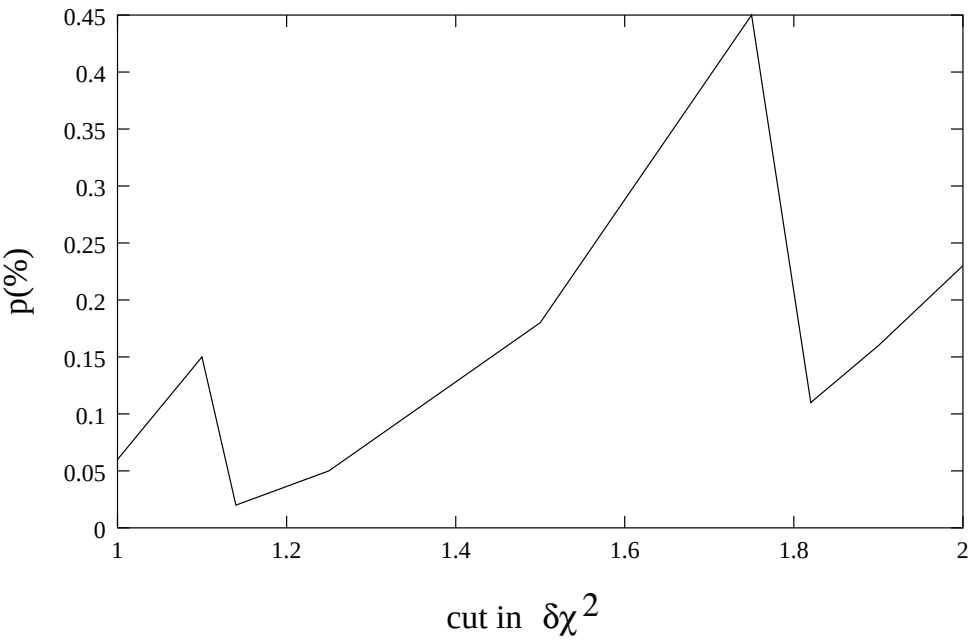

Figure 2: The probability (P-value) $p\%$ in percent that the correlation between the arrival directions of cosmic rays and compact quasars is due to a chance coincidence, as a function of the cutoff on the residual $\delta\chi^2$.

correlations of tracks and selected sources. Gamma-ray blazars, and a selection of QSO's different from ours leads to few coincidences in a statistical test described in the references. There is no contradiction to having a different data set or a different statistical test lead to no detected correlations, when there are correlations in our data. The P-values we report are not affected by the existence of another study involving different assumptions.

For example, we also studied the Kühr catalogue entries *not* classified as quasars. This sample of sources with flat or falling spectrum at low radio frequencies consists of 212 sources. Among these we found one coincidence with $\delta\chi^2 < 1$ and three coincidences with $\delta\chi^2 < 2$. Applying the same methods as described above, we found the probability of independence in this case to be 91%.

There appears, then, to be something special about the compact, radio loud QSO sources.

There is a third, independent way to estimate the probabilities of the

data observed. It seems reasonable to consider a Poisson distribution for the (integer) number of galaxies inside a given error cone. Taking the larger 3^o error for simplicity, each track has been given 0.00382 steradians of solid angle in which to search for a random QSO coincidence. There were 285 galaxies spread over $0.74(4\pi)$ steradians, on the average. This gives a mean of $285 \times 0.00382/(0.74(4\pi)) = .12$ random QSO coincidences per track. When we sum these naively over 18 tracks, and ignore the finite area of the sky, the estimate gives a mean of about 2.1 events with $\delta\chi^2 \sim 1$ in the data set. This number is reasonably close to the expectation from the Monte Carlo of 2.5 events.

In a Poisson distribution, the P-value to get 8 events from a distribution with a mean of 2.1 is about 1.5×10^{-3} This is an independent estimate of the P-value of the data, which we find quite consistent with the Monte Carlo. Meanwhile the Monte Carlo results take into account more details. Indeed, there are reasons not to trust the Poisson argument: unlike the case of points dropping on a plane, the sphere has finite area, and is periodic in its variables, a constraint that complicates the counting of identical combinations. When we pursued this in more detail by Monte Carlo, examining the probabilities of getting N tracks in regions of fixed angular size, small deviations from Poisson behavior were observed, which were difficult to quantify or separate from fluctuations in the absence of an alternative model. For the reader who arbitrarily assumes a Poisson distribution, the confidence level against the null is about 99.9%.

The procedure so far is sensitive to the precise choice of angular errors used in the analysis. We made the choice that was also used in Ref. [14] for cluster analysis. To explore this sensitivity, we examined the dependence of chance probabilities (P-values) in the null as a function of the cutoff on the residual $\delta\chi^2$. The result is shown in Fig. 2 where P-values given in percent $p\%$ are shown. As typical of a small data set, the plot shows substantial variations in $p\%$ as a function of the cut. This occurs due to an integer number of track-QSO coincidences changing as the cut is varied. Objectively this constitutes a search with a free parameter favoring the null. If we found a case agreeing with the null, we could propose changing the angular errors as a free parameter, and create support for the null. The region $0 < \delta\chi^2 < 2$ was searched. However the maximum $p\%$ found was 0.43%, so no such arguments are possible.

Finally, in a study to make use of all the $\delta\chi^2$ values in the data's dis-

tribution, we evaluated the formal *likelihood* of data values of $\delta\chi^2$ given the null distribution. We first fit the numerically evaluated, normalized orthogonal null distribution $f_{null}(\delta\chi^2)$ with a smooth interpolating function over the region $0 < \delta\chi^2 < 60$ units, which is the data's range. The smooth fit used several parameters and introduced negligible error. The log-likelihood of the data $\mathcal{L}_{data}$ was calculated by

$$\mathcal{L}_{data} = \sum_i log(f_{null}(\chi_i^2).$$

An advantage of likelihood is that no binning is involved, and sensitivity to particular integer counts in each bin is totally eliminated. We then calculated the likelihood of a generic competing model, consisting of a normalized one-sided Gaussian distribution of $\delta\chi^2$ centered at zero and with *fixed* width k of one unit normalized by an arbitrary parameter a, plus the null distribution normalized by $1 - a$. It is important that as a model of correlation the generic model keeps the width of the Gaussian fixed at one unit as part of its hypothesis. Since we have no prior information about the relative populations of correlated and uncorrelated components, parameter a was left free. Twice the difference of maximum log-likelihoods $2T$ is a very robust statistic distributed by the χ_1^2 distribution, including the effects of a free-parameter. The results were $2T = 8.8$, $a = 0.41$, which yields a P-value rejecting the null at the 99.97% confidence level. Dependence on the Gaussian width was also consistent with $k \sim 1$: the maximum likelihood and 1/2-unit variation occured at $k = 1.24 \pm 0.45$.

4 Conclusion

For the data set of cosmic rays with energies above $10^{20}eV$, the hypothesis of statistical independence of track directions and radio-loud QSO's from the *Kühr* catlogue is not consistent with the data. Several independent statistics yield results that are consistent with one another and not consistent with independence. There exists highly significant correlations between the track and source directions.

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Cosmic ray event	RA (degrees)	Dec. (degrees)	Compact QSO RA,Dec. (B1950)	$\delta\chi^2$
HP101	201	71	13 39 29.90, 69 38 30.4	0.5
HP115	322	47		
HP116	353	19	23 37 58.3, 26 25 17	7.0
HP126	179	27	12 04 54.8, 28 11 34	0.8
HP158	128	67	08 59 23.02, 68 09 15.7	1.1
HP159	199	44	13 25 10.53, 43 42 00.3	0.5
YU122	74.6	45.4		
AG101	124.25	16.8	07 59 55.6, 18 18 35	4.1
AG213	18.75	21.1	01 09 23.7, 22 28 43.0	0.97
AG106	281.25	48.3	18 51 08.9, 48 52 06.0	0.6
AG144	241.5	23.0	15 38 30.18, 14 57 22.1	31.7
AG105	298.5	18.7		
AG150	294.5	-5.8	20 08 25.90, −15 55 37.6	51.3
AG120	349.0	12.3	23 28 08.6, 10 43 46	4.5
AG104	345.75	33.9	23 27 45.8, 33 31 58	9.9
VR135	306.7	46.8		
SU197	187.1	32	12 19 01.1, 28 30 57	1.8
SU155	333.1	-56	22 04 26.2, −54 01 14	0.6
SU147	354.6	-74	23 53 24.6, −68 37 42	3.8
SU132	117.4	-2	07 43 20.8, −00 37 00	0.3
SU126	231.3	-30	15 19 37.6, −27 19 29.6	0.7
SU116	356.4	-56	23 53 24.6, −68 37 42	17.1
SU106	146.6	-43		
SU106	129.9	-26		
FE320	85.2 ± 0.5	$48.0^{+5.2}_{-6.3}$		

Table 1: Cosmic ray events with energy $E > 10^{20}$ eV. For the AGASA events the error is given by the angular cone radius $\sigma_r = 1.8^o$. The corresponding σ_r for the rest of the events excluding the Fly's Eye event is 3^o [14]. The blank spaces under the compact QSO column correspond to cases for which the event was within $\pm 10^o$ of the galactic plane.

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