Correlation between Compact Radio Quasars and Ultrahigh Energy Cosmic Rays

Glennys R. Farrar*
Department of Physics and Astronomy, Rutgers University, Piscataway, New Jersey 08855-0849

Peter L. Biermann
Max Planck Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany

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Some proposals to account for the highest energy cosmic rays predict that they should point to their sources. We study the five highest energy events ($E > 10^{20}$ eV) and find they are all aligned with compact, radio-loud quasars. The probability that these alignments are coincidental is 0.005, given the accuracy of the position measurements and the rarity of such sources. The source quasars have redshifts between 0.3 and 2.2. If the correlation pointed out here is confirmed by further data, the primary must be a new hadron or one produced by a novel mechanism. [S0031-9007(98)07393-1]

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The nature and origin of the highest energy cosmic rays ($E \geq 10^{20}$ eV) is one of the major questions in physics and astronomy. Energies up to 3.2×10^{20} eV [1], corresponding to center-of-mass energies up to $\sqrt{s} \approx$ 800 TeV, have been observed for the primary interaction with an atmospheric nucleon. The showers produced by these cosmic rays indicate that the primary is a hadron such as a proton or light nucleus [1–3], although a photon is not completely excluded. Astrophysical mechanisms to accelerate protons to energies of up to 10^{21-22} eV have been identified [4], but they require exceptional sites. In his pioneering analysis, Hillas [5] observed that the source could be a radio galaxy or quasar, and not much else, based on general considerations.

The conundrum is that nucleons, nuclei, and photons of energy greater than about 5×10^{19} eV have a non-negligible scattering cross section from the cosmic background radiation (CBR), causing their energy to be reduced to this level if they travel far enough through the CBR. This is known as the Greisen-Zatsepin-Kuzmin (GZK) limit [6]. If a proton, nucleus, or photon arrives at Earth with an energy greater than 10^{20} eV, it is exceedingly unlikely to have originated further than 50 Mpc [7–9], whereas suitable astrophysical acceleration sites are located at greater distances [10]. Indeed none are found within the expected scattering cone of the highest energy event at less than the GZK distance [7].

Proposals to resolve the puzzle range from positing superheavy relics—topological defects or heavy particles—whose decay produces nucleons and photons within the GZK distance [11], to positing new particles or mechanisms which evade the GZK bound [8,12,13]. In the GZK-evading mechanisms a proton is accelerated to a higher energy than the observed cosmic ray, presumably by a conventional astrophysical source such as an active galactic nucleus (AGN). It collides with a hadron or photon near the source or in the CBR. Among the high energy secondaries is a "propagator" particle. This could be a new neutral long-lived hadron (uhecron) with mass of a few GeV such as found in light gluino scenarios [8,12] or a neutrino in the Z-burst scenario [13].

The threshold energy for resonant photoproduction is given by $E_{\rm res} \sim \frac{M\Delta}{E_{\rm CBR}}$, where M and Δ are the mass of the primary and the mass splitting to the first excited resonance. The uhecron is neutral and likely to have a smaller radius than a nucleon, so it has a virtually unlimited range for energies below $E_{\rm res} \gg E_{\rm GZK}$. When the uhecron arrives at Earth it interacts and produces a shower like an ordinary nucleon, as long as its mass is lower than about 10 GeV [14]. An important prediction of this scenario is that each ultrahigh-energy cosmic ray (UHECR) should point directly to its source [8].

In the "Z-burst" scenario [13], neutrinos of energy $E_\nu = M_Z^2/2m_\nu = 4 \times 10^{21}(\mathrm{eV}/m_\nu)$ annihilate with dark matter neutrinos in our galactic halo or the halo of the local cluster, producing hadronic jets via $\nu\bar{\nu} \to Z^0 \to q\bar{q}$. The observed UHECR event is initiated by a nucleon or photon from these jets. Because the opening angle between the propagator neutrino and a particle of energy E produced in the Z^0 decay is $\delta\theta \leq M_Z/(2E) \sim 10^{-9}$, the UHECR points to its source in this scenario also.

The purpose of this Letter is to study the prediction of the GZK-evading scenarios that UHECR's point directly to their sources. These can be quasisteller objects (QSO's) at cosmological distances since the propagator particle loses energy only through redshift. By contrast, a proton or nucleus would neither point to an astrophysical source nor be associated with a large z QSO, since its scattering from the CBR excessively dissipates its energy unless $z < 0.01$. The rms deflection of a proton of energy E traversing randomly oriented patches of magnetic field having rms value δB and scale length λ is given by

$$\delta\theta \sim 7.2^\circ \sqrt{d\lambda/200\ (\mathrm{Mpc})^2}\,(\delta B/E) \times (100\ \mathrm{EeV}/10^{-9}\ \mathrm{G})\,, \qquad (1)$$

where d is the distance to the source [2].

We list in Table I all the UHECR events whose energy is at least 1σ above 8×10^{19} eV and whose direction is

TABLE I. Events with $E > 10^{20}$ eV and solid-angled error less than 10 deg^2.

UHECR	Date	Energy	RA (deg)	Dec (deg)	$\Delta\Omega$
FE320	15.10.91	$3.20^{+0.92}_{-0.94}$	85.2 ± 0.5	$48.0^{+5.2}_{-6.3}$	2.6
Ag210	03.12.93	(1.7–2.6)	18.9	21.1	8.0
HP120	18.04.75	1.20 ± 0.10	179 ± 3	27 ± 2.8	6.7
Ag110	06.07.94	1.10	280.7	48.4	8.0
HP105	12.01.80	1.05 ± 0.08	201 ± 8.7	71 ± 2.5	7.1

known with a solid angle resolution of 10 deg^2 or better. The energy cut is imposed in order to exclude contamination from events which may be due to proton primaries. We dare not weaken this cut because the energy determination has a hard-to-quantify systematic uncertainty due to unknown aspects of ultrahigh energy hadron collisions. The angular resolution requirement is necessary to reduce random background. In general the directional determination improves with energy, so both cuts would have to be relaxed in order to enlarge the sample.

A few comments on Table I are in order. The error bars on the energy of the Fly's Eye event include systematic as well as statistical uncertainty. The parameters of the Haverah Park events are taken from [15], with errors on the positions determined by us using the formulas given in Ref. [16]. The angular error in the longitudinal direction, relevant for $\Delta\Omega$, is $\Delta\alpha\Delta\delta\cos\delta$, where $\Delta\alpha$ is the error in right ascension and δ is the declination. Akeno Giant Air Shower Array (AGASA) reports an angular cone radius, denoted σ_r below, defined such that in 68% of the events the true direction is contained within the error cone: 1° from statistical error alone and 1.6° including systematic errors [2,17]. Our information on Ag110 comes from Ref. [2], which does not give an error on the energy measurement, although Ref. [18] quotes a 30% error in general, so we expect this event satisfies our cut. See [2,15] for other high energy events which we cannot use.

A correlation with quasars has already been noted for the two highest energy events. Elbert and Sommers [7] searched within 10° of the highest energy event, the 320^{+92}_{-94} EeV event observed by the Fly's Eye group [1]. They identified the exceptionally radio-loud quasar 3C 147 as an ideal source, aside from its extreme distance. Biermann [19] pointed out that another remarkable quasar, PG0117 + 213, is inside the error cone of the second highest energy event (210 EeV) [17]. At redshifts of 0.545 and 1.293, respectively, their distances (of order 2 and 3.5 Gpc) seemed too great to be seriously considered as sources.

The surface density of QSO's is large enough that these two alignments are not statistically significant and may be accidental. However, acceleration of protons to $\geq 10^{21}$ eV requires a remarkable source, so if the hypothesis is correct it may be possible to identify a more restricted class of sources, with low surface density, for which the correlation is statistically significant.

One of the best-motivated cosmic ray acceleration regions is the jet of an AGN, where relativistic shocks and large magnetic fields are found. Depending on the age of the AGN, the orientation of its jet with respect to Earth, the "clouds" surrounding the inner accretion disk and their relationship to the jets and Earth, and the amount of dust in the host galaxy, the same source can be a blazar, radio galaxy, or a quasar. It can be unusually bright at visible wavelengths and/or optically variable. The shape of its radio spectrum depends on whether it is a full-sized quasar or compact.

One would like to impose the seemingly trivial criterion that the energy flux in cosmic rays implied by the UHECR observation itself not be much larger than the total electromagnetic energy output of the source. However, even this simple condition is not straightforward to implement for AGN's, due to their directional anisotropy. For instance, a blazar pointed away from us has a much higher total energy output than evidenced by its observed luminosity. Moreover the energy output in a given wavelength band can differ by orders of magnitude depending on the intervening material which can "reprocess" the electromagnetic energy.

In examining the properties of 3C 147 we noticed that it is a compact quasar—that is, its jets are only about 1/10 the size of a full-sized quasar with radio lobes. Other indicators of its compact character are its optical variability and the fact that its spectrum is cut off at low radio frequencies [20]. An anomalous spectrum such as this is characteristic of compact radio-loud sources (Compact Steep Spectrum and Gigahertz Peaked Spectrum) [20] and is thought to reflect the presence of material near the central engine (which could provide the target for production of the uhecron or neutrino). We therefore defined the following specific criteria for compact radio loud QSO's (CQSO's):

(i) *QSO in the NASA/IPAC etragalactic database (NED).*

(ii) *Radio-loud.*—In practice, we required that the object appear in the Kühr catalog [21]. This is a compilation containing 1835 radio sources including all those whose flux density is ≥1 Jy at 5 GHz, with the majority above 0.5 Jy. The whole sky, excluding the galactic plane ($|b^{\mathrm{II}}| < 10°$), is covered. The surface density of this class of sources is therefore $1835/(34\,100 \text{ deg}^2) = 0.054 \text{ deg}^{-2}$.

(iii) *Flat or falling radio spectrum at low frequencies.*—One-third of the Kühr catalog entries have a flat or falling spectrum at low frequencies, so the background surface density of the CQSO category is 0.018 deg^{-2}.

We first determine the probability that the UHECR events actually point directly to the candidate sources, given the experimental measurement errors. After that we find the probability that randomly distributed compact QSO's, given their surface density, would have an equally good alignment to that observed.

We employ the method of maximum likelihood, which is a standard tool in high energy physics. For a concise review, see the probability and statistics sections of Ref. [22]. One makes use of the quantity

$$\chi^2 \equiv \Sigma_{i=1}^{N_U}\{|x_i - x_i^0|^2/\sigma_{x,i}^2 + |y_i - y_i^0|^2/\sigma_{y,i}^2\}, \quad (2)$$

where N_U is the total number of UHECR events in the analysis, $(\sigma_x, \sigma_y)_i$ is the error on the ith coordinate, $(x, y)_i$ is the measured value of the coordinate (the UHECR position), and $(x^0, y^0)_i$ is the (hypothetically) true value of the coordinate, namely, the ith source CQSO position. For an error cone σ_r the residual of an event (its contribution to the total χ^2) is $2.28|r - r^0|^2/\sigma_r^2$. The errors on the QSO positions are negligible in comparison with those on the UHECR's. A generalization of Eq. (2) could be used if correlations in the errors on the coordinates of a given UHECR event were non-negligible.

Since there are two degrees of freedom for each event, a residual of about 2 or less corresponds to a good fit. The expected fluctuations in the sum of the residuals is proportionately less than that of any given residual, so that as N_U increases the statistical power of the analysis increases. For a given set of UHECR events and associated hypothetical sources, one determines the confidence level (C.L.) of the fit. The C.L. is the probability, with Gaussian measurement errors, that an ensemble of $N_d = 2N_U$ measurements will produce a χ^2 as large or larger than the observed value. An explicit formula for determining the C.L. corresponding to a given χ^2 and N_d is given in the statistics section of [22]. For orientation, C.L. = 0.44 for $\chi^2 = 10.0$ and $N_d = 10$.

Table II gives the residuals ($\delta\chi^2$) for each of the five events listed in Table I, under the hypothesis the source is the nearest CQSO. As a check of the method, we make the same analysis for a second category of "test" QSO's (TQSO's) chosen to have similar surface density and systematics to the CQSO's, by requiring a QSO in NED with $0.400 \leq z \leq 0.600$. This range of z was intentionally chosen to include 3C147, the QSO associated with the Fly's Eye event, in order to mimic the CQSO search. By using the same portions of the sky, and considering QSO's rather than another type of object, we avoided introducing systematic differences between the TQSO and CQSO classes. There are seven TQSO's in the five cones of radius 5° centered on the five UHECR events, giving a surface density of $0.0178\ \mathrm{deg}^{-2}$. Since there is no physical motivation that having a redshift in the range $0.4 < z < 0.6$ should be related to a QSO's acceleration potential, we should NOT find a positive correlation for the TQSO category.

The first row of Table III gives the probability (C.L.) to find a total χ^2 as good as the one observed for CQSO's. As a check that the results are not skewed by having used the properties of 3C147 to define the CQSO class, we also give the result when the analysis is restricted to the four other events. Evidently, the hypothesis that UHECR primaries travel undeflected from compact QSO's provides an excellent explanation for the observations and is equally good for the restricted analysis. The same is not true for a randomly chosen category of QSO with the same surface density, as evidenced by the very low confidence level ($<2.3 \times 10^{-9}$) for the TQSO fits shown in the second row of Table III.

By a straightforward Monte Carlo calculation, one can determine the probability distribution that *randomly distributed* objects having the same surface density as CQSO's, $0.018\ \mathrm{deg}^{-2}$, produce a given value of χ^2. The large χ^2 of the TQSO's, 61.1, is in fact typical of the random-background case: the probability to find $\chi^2 \geq 61.1$ is 0.59. The most interesting aspect of the χ^2 probability distribution is the area below $\chi^2 = 9.02$, since this is the probability that the CQSO correlation is a statistical fluctuation. The results are given in the bottom line of Table III. The probability that the correlation observed between CQSO's and UHECR's is accidental is 0.005. (Note that the naive procedure of taking the product of the probabilities of finding a random source inside each 1σ error region underestimates this probability by several orders of magnitude due to neglecting configurations in which some small residuals compensate a large one.) Since the correlation hypothesis is *a priori*, there is no reason to restrict to just four events.

Let us summarize the underlying assumptions and limitations of the statistical analysis presented here. First, we have assumed that the position errors are Gaussian and uncorrelated. Therefore our results should be taken

TABLE II. Compact and test QSO's nearest the UHECR's of Table I. Separation (Sep.) is in arcmin.

Compact QSO				Test QSO			
Candidate	z	Sep.	$\delta\chi^2$	Candidate	z	Sep.	$\delta\chi^2$
3C147	0.545	111.6	1.2	3C147	0.545	111.6	1.2
0109 + 224	⋯	119.7	3.5	0133 + 207	0.425	254.4	16.3
1204 + 281	2.177	138.5	0.9	1153 + 317	0.418	286.3	26.4
1851 + 485	1.25	89.0	2.0	1908 + 483	0.513	254.9	16.2
1345 + 73	0.29	183.4	1.4	1300 + 69	0.570	155.1	0.9

TABLE III. Rows 1,2: Probability for compact and test QSO's to produce the observed total χ^2. Row 3: Probability for random sources with surface density of CQSO's (0.018 $\deg^{-2}$) to give χ^2 equal or better than observed. Columns 2,3: all five UHECR events; columns 4,5: excluding Fly's Eye Event.

Source class	χ_5^2	Probability	χ_4^2	Probability
Compact QSO	9.02	0.53	7.82	0.45
Test QSO	61.1	2.3×10^{-9}	59.9	4.9×10^{-10}
Random QSO	≤9.02	0.005	≤7.82	0.03

as qualitative rather than quantitative indicators of the relative probabilities. In the future, cosmic ray experiments should report as detailed information as possible on the positional errors of each high energy event. Second, we have assumed that the density of compact quasars is approximately uniform. This may not be valid due to some physical structure or to nonuniformity in the surveys near the different UHECR's, although there is no obvious reason to suspect this to be the case.

Having an incomplete catalog from which to choose the best source can only reduce, not exaggerate, the quality of the fit if the alignment hypothesis is correct. It cannot lead to an incorrect estimate of the random background probability as long as the surface density is approximately uniform and is computed from the same population as used to find the candidate sources. A dedicated survey near each of the UHECR candidates, and also in several comparable random and nearby patches of sky, would be valuable here. The candidate sources we have identified should be studied in greater detail and with better resolution to learn more about their properties and see if there is a better characterization of the sources.

The hypothesis that compact radio QSO's are responsible for the highest energy cosmic rays gets support from a clustering of events noted by AGASA [2]. Three of the five UHECR events studied here have one or two companions—neighboring events with energy near the GZK bound. The lower energy members of these pairs or triplets either have a low enough energy to be interpreted as a proton consistent with the GZK bound and directions consistent with the angular deflection of protons given in Eq. (1), or small enough angular distance from the CQSO source to be interpreted as having been undeflected.

AGASA has announced the observation of four more events with energy above 10^{20} eV but has not yet released their coordinates, energies, or resolutions [23]. If the correlation pointed out here is real, we predict that each new AGASA event satisfying the cuts will have a compact radio QSO directly behind it, within measurement errors. Near the galactic plane, a radio search may be necessary to check this prediction. Since the random probability to find a CQSO within a 1° cone is 0.05, even a few more events with good directional information can confirm or cast doubt on the correlation we have found.

To summarize, we have found that the highest energy cosmic rays are consistent with traveling undeflected from compact radio quasars. The probablity that this is a statistical fluctuation is 0.005. For the moment these results are only a tantalizing hint that the highest energy cosmic rays may point directly to their sources and travel cosmological distances. However, if this hint is borne out by future data, Nature will have revealed some new particle physics mechanism involving neutral, GZK-evading propagator particles. UHECR's would then complement traditional astronomical tools for studying these extremely distant and powerful sources and their physics.

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*Present address: Department of Physics, New York University, New York, NY 10003.

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