Preprint typeset in JHEP style - HYPER VERSION

FERMILAB-PUB-10-005-A

A Faraway Quasar in the Direction of the Highest Energy Auger Event

Ivone F.M. Albuquerque

Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL, 60510 and Instituto de Física, Universidade de São Paulo, São Paulo, Brazil
ifreire@fnal.gov

Aaron Chou

Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL, 60510
achou@fnal.gov

Abstract: The highest energy cosmic ray event reported by the Auger Observatory has an energy of 148 EeV. It does not correlate with any nearby (z<0.024) object capable of originating such a high energy event. Intrigued by the fact that the highest energy event ever recorded (by the Fly's Eye collaboration) points to a faraway quasar with very high radio luminosity and large Faraday rotation measurement, we have searched for a similar source for the Auger event. We find that the Auger highest energy event points to a quasar with similar characteristics to the one correlated to the Fly's Eye event. We also find the same kind of correlation for one of the highest energy AGASA events. We conclude that so far these types of quasars are the best source candidates for both Auger and Fly's Eye highest energy events. We discuss a few exotic candidates that could reach us from gigaparsec distances.

Keywords: cosmic rays, acceleration of particles, radio galaxies, particle physics .

Contents

1. Introduction

Observatories such as the Pierre Auger and the High Resolution (HiRes) Fly's Eye have recently shed light on some of the open questions regarding the high energy end of the cosmic ray spectrum. However, much is yet to be revealed. Among the open questions are the origin of ultra high energy (above $\sim 6 \times 10^{19}$ eV) cosmic rays (UHECR), the acceleration mechanism involved in their production, and their composition.

As a first step in the search for the astrophysical sources of UHECR, the Auger collaboration has observed an anisotropy of the UHECR arrival direction at 99% CL [1], via a correlation of cosmic ray arrival directions with nearby Active Galactic Nuclei (AGNs). The correlation with this anisotropic pattern in the sky does not imply that the AGN are necessarily the sources of UHECR, but rather that the cosmic rays tend to come from where the large scale structure of matter density is distributed. It suggests that the deflection of cosmic ray trajectories by galactic and extragalactic magnetic fields may be small enough that cosmic ray astronomy becomes possible. To add to the puzzle, a similar correlation with nearby AGN has not been seen in the HiRes data [2].

Both experiments have observed [3, 4] the expected Greisen-Zatsepin-Kuzmin (GZK) suppression [5] in the cosmic ray spectrum due to resonant scattering on the cosmic microwave background photons. Furthermore, the Auger correlation with nearby AGN is compatible with the expectation of the resulting GZK particle horizon.

Here we focus our research on the highest energy events, those with energy above 10^{20} eV. Naively, one would expect that the highest energy UHECRs would be the least deflected by magnetic fields, and hence would be the events most likely to point back to their astrophysical sources. Paradoxically, there are no known plausible sources within the GZK sphere for the highest energy events, leading some to hypothesize that UHECR are produced by nearby, energetic, transient sources such as gamma ray bursts [6, 7] or AGN flares [8, 9]. These sources would not necessarily have large photon fluxes observed concurrently with a UHE hadronic cosmic ray flux.

Another exciting possibility is that new, exotic physics may be responsible for the unimpeded propagation of UHECRs over cosmological distances. Although the presence of the GZK feature is compatible with a standard particle composition of UHECR, it does not rule out the possibility of a small fractional flux of an exotic component. Such an exotic flux may indeed be able to penetrate through the opaque wall of background photons and travel far larger distances without attenuation.

Inspired by a thorough search [10] for the source of the highest energy event so far detected (by the Fly's Eye collaboration [11]), we search for a possible source of the Auger highest energy event. This event does not correlate with any nearby AGN from the Véron-Cetty and Véron catalog [12] used in the Auger correlation studies nor with any nearby source capable of producing such an energetic event. This lack of correlation is particularly puzzling because the event points back to an apparently well-covered region of the sky between the Virgo and Centaurus superclusters, where the VC catalog would be expected to be complete for the highest luminosity, nearby AGN. Instead, we find that the most energetic event so far detected by the Auger collaboration, points to a faraway quasar, well beyond the GZK radius. This quasar has the same characteristics as the one which correlates with the Fly's Eye event.

We also analyze the arrival direction of AGASA's 11 events above 10^{20} eV [13]. It should be noted however that AGASA's energy scale is systematically 30% higher than the HiRes/Fly's Eye energy scale [14] while Auger's energy scale is around 15% lower. Unlike the Auger and HiRes measured UHECR spectra, the AGASA spectrum at high energies exhibits no GZK suppression; this may be indicative of poorer energy resolution at these energies. The HiRes collaboration has not yet published their event list containing the energy and direction information together. For this reason, it is not possible for us to analyze their results as we did for Auger and AGASA. However, it is intriguing that HiRes has already reported a potential correlation of their stereo events with distant BL Lac objects, well beyond the GZK horizon [15]. This correlation cannot be explained by conventional physics models.

In the next section we will review the search for the source of the Fly's Eye highest energy event. In section 3 we describe our search for source of the Auger highest energy event. Then follows the analysis for AGASA's events. In section 5 we discuss exotic models which may allow cosmic rays to reach us from such faraway sources.

2. The highest cosmic ray event ever detected

The highest energy cosmic ray event was detected by the Fly's Eye collaboration [11], which determined the energy to 3.2×10^{20} eV. A thorough search for its source was done by Elbert and Sommers (ES) [10], who looked for strong radio sources with strong magnetic fields and large fluxes of energetic particles in the direction of the Fly's Eye event. These sources were targeted since in order to accelerate particles to ultra high energies, a high magnetic field moving with high velocity is required [16]. Powerful radio galaxies are therefore good UHECR source candidates. Their search was limited to a region within an angular distance of 10° from a two sigma error box centered in the event arrival direction.

From the four sources that fell into this region, the quasar 3C 147 was the only one within one sigma from the event arrival direction. It is also the only one which meets the necessary requirements for particle acceleration. It is listed in a catalog of 173 powerful radio luminosity sources [17]. Its total radio luminosity is about 10^{45} ergs s^{-1} being among the 28 brightest ones in this catalog. It is also included in a list of 96 plausible candidates for having very large Faraday rotations (FR) [18], having one of the top four largest FR [19]. The redshift of this source is however 0.545, which puts it at a distance of 2 Gpc away from us for current cosmological parameters.

3. The Auger Highest Energy Event

From the 27 high energy events published by the Auger collaboration [1], only one is above 10^{20} eV, having an energy of 148 EeV. Events of these energies are expected to have its origin outside of our Galaxy [16]. As ordinary galaxies do not meet the requirements for accelerating particles to such high energies, we searched for high luminosity radio sources in the direction of the highest energy Auger event (HEA).

We define high luminosity according to the criterion established by Wall & Peacock [20], requiring a minimum flux density of 2 Jy at a frequency of 2.7 GHz. We then use the "advanced all-sky survey" of the NASA/IPAC Extragalactic Database (NED) [21] to produce a list of such objects. As the Auger search [1] did not find a nearby correlation for this event, we look for objects that have a redshift greater than 0.024, and therefore beyond the GZK radius. The GZK radius is the maximum distance from which a particle can travel through the cosmic microwave background radiation (CMB) and reach the Earth at ultra high energies. For a proton this distance is about 100 Mpc. We also require the sources to be within the Auger field of view and away from the galactic plane ($|b| > 12^\circ$) where astrophysical catalogs are incomplete. The Auger exposure [1] for events with zenith angle below 60° is roughly constant in right ascension and is a function of declinations, being nonzero for $\delta < 24.8^\circ$.

The NED search results in 164 strong radio luminosity objects. We further reduce this list by requiring sufficient luminosity to accelerate particles to 10^{20} eV. It has been shown [26] that a solid lower bound on the source luminosity in order to achieve such an acceleration, is of $10^{45} Z^{-2}$ erg/s, where Z is the charge of the cosmic ray nucleus. In order to account for measurement uncertainties, we require a minimum source luminosity of $L = 10^{44}$ erg/s. One can roughly translate this to a minimum flux density $S_{\rm min}$ at a certain frequency ν in Hz [10]:

$$S_{\rm min} \approx \frac{L H_0^2}{4\pi \nu c^2 z^2} = \frac{5 \times 10^9}{\nu z^2} \tag{3.1}$$

where c/H_0 is the Hubble length, z is the source's redshift, and $S_{\rm min}$ is given in Jansky. From the 164 NED sources, only 57 meet this luminosity requirement, among which 48 are quasars and 9 are galaxies.

In order to correlate the HEA to a faraway source, we assume the cosmic ray is electrically neutral. As for these energies the Auger angular resolution is about 1° [1], we require that the angular distance between the source and the event is at maximum 1.5°. The equatorial coordinates for the HEA are right ascension $\alpha = 192.7°$ and declination $\delta = -21°$. From our 57 objects catalog, only one fell in this angular region. It is the quasar (QSO) PKS1245-19, with an angular distance of 1.2° from the HEA. The chance probability for this to happen from an isotropic distribution is 0.008.

The QSO PKS1245-19 is also included in a sample of the most powerful radio sources [22] from the Molonglo catalog [23]. Molonglo is a 408-MHz survey looking for sources with flux densities above 0.7 Jy. This catalog covers 7.85 sr of the sky, over declinations $+18°.5 \geq \delta \leq -85°.0$ and $|b| \geq 3°$. No other powerful radio sources are found in this catalog in the direction of the HEA[1]. PKS1245-19 is also among 96 sources selected as good candidates for having high Faraday Rotation [18]. It has also been listed as an energetic gamma-ray source detected by the Egret telescope [27].

This source candidate is therefore very much like the one found in the Fly's Eye event direction (QSO 3C147). Its total radio luminosity can be determined as [17]

$$L = 4\,\chi^2\,(1+z)^2\,S_{bol,obs}\,h^{-2} \tag{3.2}$$

where χ is the comoving distance and $S_{bol,obs}$ is the observed radio spectrum integrated from 10 MHz to 100 GHz. The flux density at various frequencies can be obtained from the NED catalogue. An integration of the PKS1245-19 radio spectrum gives a radio luminosity of $\sim 3\times10^{46}$ erg/s. Proceeding in the same way, the 3C147 radio luminosity is $\sim 1\times10^{45}$ erg/s. As both QSOs are also listed as having high Faraday Rotation measurement, they are excellent candidates for accelerating particles to ultra high energies. Just as the case with 3C147, PKS1245-19 is very far away, at a redshift of 1.275 (3.8 Gpc for current cosmological constants).

4. AGASA High Energy Events

The Akeno Giant Air Shower Array (AGASA) has detected 11 events with energies above 10^{20} eV. Although there is a $\sim$ 30% discrepancy among their energy measurement and HiRes' [14], we take their results as published [13].

We proceed in the same way as described in the previous section. We search for very high luminosity (above 10^{45} erg/s) objects in the direction of any of these 11 events. The

[1]If we modify our search to look for objects within $z < 0.024$, we find 19 sources which fulfill our initial requirement of at least 2 Jy at a frequency of 2.7 GHz. From these only one has an angular distance α of less than 15° from the HEA.It is the galaxy pair VV201 [24] at $z = 0.015$ or a distance of about 61 Mpc, and $\alpha = 8.5°$ from the event direction. If a 1 Mpc magnetic field coherence length is assumed, an rather large extragalactic magnetic field of ~ 4 nG is necessary to bend a proton to the event direction [25]. The radio luminosity of this pair of interacting galaxies is $\sim 5 \times 10^{41}$ erg/s, much lower than the 10^{45} erg/s required for UHECR sources. This source does not fulfill the $S_{\rm min}$ requirement, Eq. 3.1.

only difference is that due to the poorer AGASA angular resolution, we look for a high luminosity source within a 3° angular distance from each event direction. This will of course increase the chance probability of having an incorrect source in the direction of an event, if sources positions are sampled from an isotropic distribution. The AGASA latitude is $35°47'$ and its field of view covers approximately between $-10° < \delta < 80°$ in Equatorial coordinates. Our final catalogue of high luminosity sources in the AGASA field of view consists of 50 objects. From these the QSO 3C380 is at an angular distance of 2.5° from AGASA's 1.06×10^{20} eV event. This event has $\alpha = 281.25°$ and $\delta = 48.3°$. The chance probability for a 3° correlation from an isotropic distribution is of 0.047.

Estimating the radio luminosity of this quasar from Equation 3.2, one gets $\sim 10^{46}$ erg/s. It is also listed in the same large Faraday Rotation list [18] as the above QSOs. Just as the previous candidate sources, QSO 3C380 is an excellent source for acceleration of UHECR. It is also faraway, at a redshift of 0.692 (2.4 Gpc for current cosmological parameters).

5. Exotic candidates

As described in the previous sections, QSOs PKS1245-19, 3C147 and 3C380 whose positions are well-correlated with the directions of Auger's, Fly's Eye's highest energy events, and to one of AGASA's high energy events, are very good UHECR source candidates. The only question then relates to their large distance from the Earth.

Below we describe two candidates that could account for this huge distance. One important remark is that although the GZK feature has been observed, high energy exotic events can certainly compose a small fraction of the UHECR spectrum. They could maybe even account for most of the composition at the highest end of the spectrum above 10^{20} eV.

Two possible candidates would be axions [28] and exotic massive hadrons [29, 30]. Photons would convert into axions at the source, due to their interaction with the source's magnetic field. They would then propagate through intergalactic space without scattering on the CMB or other extragalactic background photons, and convert back to photons in the Milky Way. Their air shower would thus be initiated by a photon. However, as we will describe below, the photon-axion conversion probability is low at such high energies. Alternatively, exotic massive hadrons would be the primary particle in the atmospheric shower development [30]. These showers can be distinguished from showers initiated by standard particles [31].

5.1 Axions

Axion-like particles [28] would be excellent candidates to propagate through cosmological distances without scattering. They might also explain the possibly anomalous transparency of the universe to TeV gamma rays observed in air Cherenkov telescopes [33, 34]. In models of photon-axion mixing, an UHE gamma is produced as a byproduct of acceleration of hadronic cosmic rays in the astrophysical source. This gamma coherently interacts with background magnetic fields and is converted into a UHE axion which can then propagate cosmological distances without scattering. Upon entering the magnetic field of the Milky Way, the axion reconverts into a UHE gamma which induces a detectable cosmic ray air shower. Due to low statistics at the highest energies, experimental constraints on a possible gamma-induced fraction of observed air showers are still rather weak, with upper bounds ranging from the $20\% - 60\%$ level for UHECR of energies greater than a few 10^{19} eV (see for example [36]). It has also been shown that the longitudinal profile of the most energetic Fly's Eye event is compatible with that expected of a photon-initiated air shower at the 1.5σ level [37]. Morever, due to the poorer composition sensitivity in UHECR detected by surface detectors [35, 36], it is not possible to unambigously distinguish between hadronic or photon-initated showers for either the Auger event or the AGASA events. In particular, the correlated AGASA event did not have composition-sensitive muon flux information. So it is possible for all three of the correlated events discussed here to be photon-initiated.

The interaction term between the axion field a and photons is

$$\mathcal{L}_{\rm int} = -\frac{1}{4} g a F \tilde{F} = g \vec{E} \cdot \vec{B} \tag{5.1}$$

where g is the axion-photon coupling, F represents the photon field, and $\vec{E}$ and $\vec{B}$ represent the electric and magnetic fields respectively. In the presence of a background magnetic field of strength B, this interaction term becomes an off-diagonal term in the effective flavor mixing matrix, coupling axions to the photon polarization component aligned with the magnetic field direction. At sufficiently high photon energies $\omega > (m_a^2 - m_\gamma^2)/(2gB)$, the photon-axion system is in a regime of maximal mixing, and the probability of conversion from photons to axions and vice-versa is $P \sim (gBL)^2/4$. This probability becomes of order unity in regions where $BL \sim 1/g$.

The UHE photons are expected to be produced as secondary particles in the accleration of UHE protons. In order to accelerate cosmic ray protons to $E_{\rm proton} = 10^{20}$ eV energies, the sources must have magnetic field regions which satisfy $B_0 L = E_{\rm proton}$. This coincides with the results of galactic magnetic field models [32] which arrive to a comparable magnetic baseline for the poloidal magnetic field, $B_0 L \sim (6\mu{\rm G}) \cdot (4 \text{ kpc}) = 3 \times 10^{19}$ eV. So an axion model with $g \sim 10^{-11}$ GeV^{-1} would predict efficient conversions via oscillation both at the source, and in the galaxy [33, 34]. Alternatively conversions could occur in propagation over sufficiently large coherent domains of the weaker extragalactic magnetic fields [38].

However when considering photon-axion oscillations at ultra high energies, effects from magnetic birefringence might dominate implying in an insignificant oscillation probability [39]. At energies $E >>$ TeV, magnetic birefringence due to quantum electrodynamics alters the photon dispersion relationship and induces a large diagonal component into the effective mixing matrix. As a result the effective photon-axion mixing angle becomes too small to produce efficient photon-axion conversion. A previous paper proposing photon-axion mixing as the source of the correlations between HiRes cosmic ray events and distant BL Lac objects [15] did not account for the QED birefringence effect [40], so here we will investigate the effect in detail.

The formulation of the birefringence of the vacuum, was first quoted by Adler [41], following numerical evaluations by Toll [42]. In the presence of a constant background magnetic field B, the indices of refraction for photon polarizations perpendicular and parallel to the B are given by:

$$n_{\perp,\parallel} = 1 + \frac{\alpha}{\pi}\left(\frac{B\sin\theta}{2B_{\rm cr}}\right)^2 N_{\perp,\parallel}(x) \tag{5.2}$$

where α is the fine-structure function, x parameterizes the center of mass energy as

$$x = \frac{\omega}{2m}\frac{B\sin\theta}{B_{\rm cr}}, \tag{5.3}$$

θ is the angle between the photon propagation and the direction of the background field B, and the critical magnetic field is

$$B_{\rm cr} = m_e^2/e = 4.41 \times 10^{13}\ {\rm G}. \tag{5.4}$$

The function $N_{\perp,\parallel}(x)$ is determined by Toll [42], by numerically evaluating the dispersion, averaged over a series of absorption resonances in which the external magnetic field absorbs the excess energy-momentum in the process $\gamma \rightarrow e^+e^-$. The numbers given by Adler, and subsequently widely quoted, including in [43] are [2]

$$N_{\perp} = 8/45, \tag{5.5}$$

$$N_{\parallel} = 14/45. \tag{5.6}$$

Most subsequent astrophysical photon-axion mixing papers [44, 45, 46, 47] primarily concern themselves with mixing at low energies, and therefore do not explicitly quote Adler's admonition that these values only represent a particular asymptotic limit of Toll's calculations when $B \ll B_c$ and $\omega < 2m_e$. This is the limit when the available energy in the interaction between the photon and magnetic field is far below the first pair production resonance, a regime of normal dispersion. In Toll's thesis, it is illustrated that as x increases through the series of pair production resonances, whose effects can be averaged over, the photon enters a regime of anomalous dispersion where the index of refraction decreases through $n = 1$ before becoming slightly negative. In the limit $B \ll B_{\rm cr}$, the numerical predictions of the asymptotic behavior at high x far beyond the resonances are

$$N_{\perp} = -0.4372/x^{4/3}, \tag{5.7}$$

$$N_{\parallel} = -0.6558/x^{4/3}. \tag{5.8}$$

This approximation is valid when $x > 500$ or $B_{\rm mG}\ \omega_{12} > 10^{13}$, where magnetic field is measured in milliGauss, and photon energy in units of TeV.

The axion-photon mixing matrix is given by [39]

$$\left[\omega - i\partial_z - \begin{pmatrix} \Delta_\perp^{\rm QED} & 0 & 0 \\ 0 & \Delta_{\rm pl} + \Delta_\parallel^{\rm QED} & \Delta_{\rm B} \\ 0 & \Delta_{\rm B} & \Delta_a \end{pmatrix}\right]\begin{pmatrix} A_\perp \\ A_\parallel \\ a \end{pmatrix} = 0. \tag{5.9}$$

[2]Note that we use here the conventional definition of photon polarization using the electric field vector rather than the opposite definition used by both Toll and Adler.

Where $A_\perp$ and $A_\parallel$ are orthogonal components of the photon field. The elements of the dispersion matrix are defined and estimated [39] as

$$\Delta_a = \frac{m_a^2}{2\omega} \simeq 2.5 \times 10^{-20}\ m_{\mu\mathrm{eV}}^2 \omega_{12}^{-1}\ \mathrm{cm}^{-1}, \tag{5.10}$$

$$\Delta_\mathrm{B} = \frac{gB}{2} \simeq 1.7 \times 10^{-21}\ g_{11} B_\mathrm{mG}\ \mathrm{cm}^{-1}, \tag{5.11}$$

$$\Delta_\mathrm{pl} = \frac{\omega_\mathrm{pl}^2}{2\omega} \simeq 3.5 \times 10^{-26} \left(\tfrac{n_e}{10^3\ \mathrm{cm}^{-3}}\right) \omega_{12}^{-1}\ \mathrm{cm}^{-1}, \tag{5.12}$$

$$\Delta_\parallel^\mathrm{QED} \simeq -\frac{\alpha}{\pi}\left(\frac{B}{2B_\mathrm{cr}}\right)^2 N_\parallel \omega = -1.3 \times 10^{-21}\ B_\mathrm{mG}^2 \omega_{12}\ \mathrm{cm}^{-1} \tag{5.13}$$

where $m_{\mu\mathrm{eV}} \equiv m_a/\mu\mathrm{eV}$, $g_{11} \equiv g \times 10^{11}$ GeV, ω_pl^2 is the plasma frequency for an electron density n_e. As we have now seen, the last equation holds only for low magnetic field and low energy photons such that $x \ll 10^{-1}$ or $B_\mathrm{mG} \cdot \omega_{12} \ll 10^{10}$.

Since the sign of the QED birefringence term $\Delta_\parallel^\mathrm{QED}$ is negative, indicating a regime of normal dispersion, and Δ_pl is negligible, there is no possibility to achieve the resonance condition $\Delta_\parallel^\mathrm{QED} = \Delta_a$ where the mixing angle $\theta = (1/2)\arctan(2\Delta_\mathrm{B}/(\Delta_\mathrm{QED} + \Delta_\mathrm{pl} - \Delta_a))$ becomes maximal. The best that can be hoped for is that both $\Delta_\parallel^\mathrm{QED}, \Delta_a \ll \Delta_\mathrm{B}$ so the configuration is sufficiently close to resonance that a large mixing angle can still be achieved. Suppose that the initial conversion from photons to axions occurs in the galaxy hosting the astrophysical photon source, and the regeneration of photons occurs in the Milky Way galaxy. Then, the highest energy photons that can penetrate the wall of extragalactic background light can be estimated using $g_{11} = 10$, $B_\mathrm{mG} = 10^{-4}$, and $L \sim 30$ kpc for both source and destination galaxy so that the mixing probability is of order unity in each. In this case, the maximum photon energy for which this process can occur efficiently is 10^{17} eV, for which $\Delta_a \sim 10^{-25}$ cm^{-1}, $\Delta_\parallel^\mathrm{QED} \sim \Delta_\mathrm{B} \sim 10^{-24}$ cm^{-1}.

The only remaining possibility to obtain efficient mixing at even higher energies is to enter the regime of anomalous QED dispersion, in which the indices of refraction are parameterized by Eqs. 5.8. In this case, $\Delta_\parallel^\mathrm{QED} > 0$, and so an exact resonance is possible. To achieve this condition, the center of mass energy must be well above the energy required to produce on-shell pairs, $B_\mathrm{mG} \cdot \omega_{12} > 10^{13}$ [42]. For photon energies of 10^{19} eV, the magnetic field required is then 10^4 G. Such high fields may indeed be present in the high energy photon sources, and induce resonant conversion of photons into axions, or even efficient conversion by adiabatic level-crossing. However, there are no such fields in the Milky Way, and the resulting ultra-high-energy axions cannot be efficiently reconverted into detectable photons.

5.2 Exotic Massive Hadrons

Before the high energy end of the cosmic ray spectrum was established, a class of exotic massive hadrons was proposed [29] to account for the events beyond the GZK cutoff. This generic class was coined as "uhecron", and is composed of colored, strongly interacting massive particles.

Uhecrons are modeled in a way that it loses much less energy than protons while traveling through the CMB. In short, their heavy mass shifts the threshold for photoproduction of pions to much higher energies. They can propagate distances of gigaparsecs through the CMB before losing most of its energy [29]. The strong interaction is necessary in order to produce a hadronic shower in the atmosphere [30]. It is also taken as electrically neutral particles in order to avoid deflections by magnetic fields.

Simulations of uhecron induced air showers [30] show that uhecrons with masses up to 50 GeV are compatible with UHECR events. The shower generated by the interaction of an uhecron with the atmosphere, can resemble the longitudinal profile of the highest energy cosmic ray detected by Fly's Eye [11].

One of the best candidates for an uhecron is the heavy gluino lightest supersymmetric particle (LSP), proposed by Stuart Raby [48]. It fits all the uhecron requirements. Experimental limits set the heavy gluino LSP mass between 25 and 35 GeV [49].

As uhecrons can account for the large distances between faraway QSOs and the Earth, the heavy gluino LSP is a candidate for the highest energy cosmic rays analyzed here.

It has also been showed that it is possible to distinguish uhecron from proton or heavy nuclei induced showers [31]. Uhecrons with masses in the 25 to 35 GeV window can be discriminated from the bulk of the cosmic ray spectrum,which might be composed by protons or iron. An enhancement of this discrimination can be achieved by correlating the event direction with the far away source.

However, the acceleration mechanism to produce uhecrons at these energies is not well established. It has been pictured generically [29] as originating from proton collisions with hadronic matter in the source. This requires protons being accelerated to energies slightly above 10^{20} eV. It was pointed out [29] that even if uhecrons are originated in proton collisions, it is hard to explain the lack of lower energies uhecrons. This remark does not hold here, since uhecrons would constitute a small fraction of the UHECR spectrum, and the lower energy ones would be hidden by the larger fraction of standard particles. Information from the Large Hadron Collider on the heavy gluino LSP will contribute to the possibility of uhecrons accounting for the long distances between QSOs and Earth.

6. Conclusions

We have described our search for the source of the highest energy cosmic ray detected by the Pierre Auger Observatory. We show that given requirements on the acceleration capabilities of the source, one faraway quasar is located at 1.2° from the event arrival direction. The chance probability for this correlation from an isotropic distribution is of 0.008.

In this search we look for sources with radio luminosities above 10^{45} erg/s, which are required in order to be able to accelerate particles to energies of 10^{20} eV. The quasar PKS1245-19 found in the direction of the Auger event, has a luminosity of 4×10^{46} erg/s. It is included in a catalogue of the most powerful radio sources [23] and among 96 sources selected to be good candidates for having large Faraday Rotation [18]. It is also listed as an energetic gamma-ray source by the Egret telescope [27]. PKS1245-19 is therefore very much like quasar 3C147 found [10] at one sigma from the direction of the highest energy cosmic ray ever detected [11].

As no obvious astrophysical source within the GZK cutoff was found in the direction of either the Auger or the Fly's Eye event, the faraway quasars are so far the best observed candidate sources for these high energy cosmic rays. In this case the only explanation for these particles being able to reach us, is that they are composed of non-standard particles, at least during their transit.

Two plausible candidates are axions and exotic massive hadrons. As was shown in this work, the probability for photon-axion conversion at these high energies is probably too small for this effect to produce a significant contribution to the UHECR flux. Uhecrons could account for these events. However accelerating protons to even higher energies above 10^{20} eV is required in order to originate uhecrons at the required energy. One should however bear in mind that the acceleration mechanism for standard particles is not well understood either. Furthermore, it could be that the energies of these exotic uhecron-induced showers are systematically overestimated since the energy scale of the various detectors is calibrated to the average, presumably hadronic, cosmic ray. If either the shower profile or the invisible energy carried by neutral shower particles differs from that expected from typical hadronic showers, then the energy measurement can be biased [50] for a small fraction of the cosmic ray flux composed of exotic particles.

As we are analysing events at energies well beyond that produced in Earth based accelerators, there could still be some unknown exotic phenomena involved in the cosmic ray production and propagation. It is clear that there exist faraway quasars in the direction of these ultra high energy events and that only new physics can account for a particle propagating from their distance to us. The alternative of course, is that UHECR sources are nearby, but transient and not readily apparent in current observations of the sky.

We thank the members of the Auger collaboration at Fermilab, for valuable discussions. IA was partially funded by the U.S. Department of Energy under contract number DE-AC02-07CH11359 and the Brazilian National Counsel for Scientific Research (CNPq). AC is also supported by the U.S. Department of Energy under contract No. DE-AC02-07CH11359. This work made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

[1] J. Abraham *et al.*, Astropart. Phys. **29**, 188 (2008) [Erratum-ibid. **30**, 45 (2008)]; J. Abraham *et al.*, Science **318**, 938 (2007).

[2] R. U. Abbasi *et al.*, Astropart. Phys. **30**, 175 (2008).

[3] R. Abbasi *et al.*, Phys. Rev. Lett. **100**, 101101 (2008).

[4] J. Abraham *et al.*, Phys. Rev. Lett. **101**, 061101 (2008)

[5] K. Greisen, Phys. Rev. Lett. **16**, 748 (1966); G. T. Zatsepin, V. A. Kuz'min, JETP Lett. **4**, 78 (1966); ZhETF Pis'ma Eksp **4**, 114 (1966).

[6] E. Waxman, Nucl. Phys. Proc. Suppl. **151**, 46 (2006) [arXiv:astro-ph/0412554].

[7] M. Lemoine and E. Waxman, JCAP **0911**, 009 (2009) [arXiv:0907.1354 [astro-ph.HE]].

[8] G. R. Farrar and A. Gruzinov, Astrophys. J. **693**, 329 (2009) [arXiv:0802.1074 [astro-ph]].

[9] E. Waxman and A. Loeb, JCAP **0908**, 026 (2009) [arXiv:0809.3788 [astro-ph]].

[10] J. W. Elbert and P. Sommers, Astrophys. J. **441**, 151 (1995).

[11] D. J. Bird *et al.*, Astrophys. J. **441**, 144 (1995).

[12] M.-P. Véron-Cetty and P. Véron, Astron. & Astrophys. **455**, 773 (2006).

[13] M. Takeda *et al.*, Astrophys. J. **522**, 225 (1999)

[14] D. De Marco, P. Blasi and A. V. Olinto, Astropart. Phys. **20**, 53 (2003).

[15] R. U. Abbasi *et al.* [HiRes Collaboration], Astrophys. J. **636**, 680 (2006) [arXiv:astro-ph/0507120].

[16] A. M. Hillas, Ann. Rev. Astron. Astrophys. **22**, 425 (1984).

[17] T. Herbig and C. S. Readhead, The Astrophys. Journ. Supp. Series **81**, 83 (1992).

[18] M. Inoue, H. Tabara, T. Kato and K. Aizu, Publ. Astron. Soc. Japan **47**, 725 (1995)

[19] T. Kato, H. Tabara, M. Inoue and K. Aizu, Nature **341**, 720 (1989).

[20] J. V. Wall and J. A. Peacock, Mon. Not. R. astr. Soc. **216**, 173 (1985).

[21] Mazzarella, J. M., & The NED Team, Astronomical Data Analysis Software and Systems XVI, **376**, 153 (2007); Proceedings Edited by Richard A. Shaw, Frank Hill and David J. Bell, Conference 15-18 October 2006, Tucson, Arizona, USA.

[22] P. R. Best, H. J. A. Rottering and M. D. Lehnert, Mon. Not. R. astr. Soc. **310**, 223 (1999).

[23] M. I. Large *et el.*, Mon. Not. R. astr. Soc. **194**, 693 (1981).

[24] Vorontsov-Velyaminov, Astr. Ap. Suppl. **28**, 1 (1977).

[25] Auger Collaboration, "The Pierre Auger Project Design Report," FERMILAB-PUB-96-024 (1996).

[26] M. Lemoine and E. Waxman, arXiv:0907.1354 [astro-ph.HE].

[27] C. E. Fichtel *et el.*, The Astrophysical Journal Supplement Series, **94**, 551 (1994).

[28] S. J. Asztalos *et el.*, Ann. Rev. Nucl. Part. Sci. **56**, 293 (2006).

[29] D. J. H. Chung, G. R. Farrar and E. W. Kolb, Phys. Rev. D **57**, 4606 (1998).

[30] I. F. M. Albuquerque, G. R. Farrar and E. W. Kolb, Phys. Rev. D **59**, 015021 (1999).

[31] I. F. M. Albuquerque and W. R. Carvalho, Phys. Rev. D **80**, 023006 (2009).

[32] D. Harari, S. Mollerach and E. Roulet, JHEP **9908**, 022 (1999).

[33] D. Hooper and P. D. Serpico, Phys. Rev. Lett. **99**, 231102 (2007)

[34] M. Simet, D. Hooper and P. D. Serpico, Phys. Rev. D **77**, 063001 (2008).

[35] M. Risse *et al.*, Phys. Rev. Lett. **95**, 171102 (2005) [arXiv:astro-ph/0502418].

[36] J. Abraham *et al.* [Pierre Auger Collaboration], Astropart. Phys. **29**, 243 (2008) [arXiv:0712.1147 [astro-ph]].

[37] M. Risse, P. Homola, D. Gora, J. Pekala, B. Wilczynska and H. Wilczynski, Astropart. Phys. **21**, 479 (2004) [arXiv:astro-ph/0401629].

[38] A. De Angelis, O. Mansutti and M. Roncadelli, Phys. Rev. D **76**, 121301 (2007) [arXiv:0707.4312 [astro-ph]].

[39] K. A. Hochmuth and G. Sigl, Phys. Rev. D **76**, 123011 (2007).

[40] M. Fairbairn, T. Rashba and S. Troitsky, arXiv:0901.4085 [astro-ph.HE].

[41] S. L. Adler, Annals Phys. **67**, 599 (1971).

[42] J. S. Toll, PhD. Thesis, Princeton University (1952).

[43] G. Raffelt and L. Stodolsky, Phys. Rev. D **37**, 1237 (1988).

[44] D. Chelouche, R. Rabadan, S. Pavlov and F. Castejon, Astrophys. J. Suppl. **180**, 1 (2009) [arXiv:0806.0411 [astro-ph]].

[45] D. Chelouche and E. I. Guendelman, Astrophys. J. **699**, L5 (2009) [arXiv:0810.3002 [astro-ph]].

[46] M. A. Sanchez-Conde, D. Paneque, E. Bloom, F. Prada and A. Dominguez, Phys. Rev. D **79**, 123511 (2009) [arXiv:0905.3270 [astro-ph.CO]].

[47] P. Jain and S. Mandal, arXiv:0910.3036 [astro-ph.CO].

[48] S. Raby, Phys. Lett. B **422**, 158 (1998).

[49] A. Mafi and S. Raby, Phys. Rev. D **62**, 035003 (2000).

[50] A. S. Chou, Phys. Rev. D **74**, 103001 (2006) [arXiv:astro-ph/0606742].