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Correlating Fermi gamma-ray sources with ultra-high energy cosmic rays

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ABSTRACT
The origin of ultra-high energy cosmic rays (UHECRs) is one of the enduring mysteries of high-energy astrophysics. To investigate this, we cross-correlate the recently released *Fermi* Large Area Telescope First Source Catalog (1FGL) with the public sample of UHECRs made available by the *Pierre Auger* collaboration. Of the 27 UHECRs in the sample, we find 12 events that arrived within 3.1° of *Fermi* sources. However, we find similar or larger number of matches in 63 out of 100 artificial UHECR samples constructed using positions randomly drawn from the BATSE 4B catalog of gamma-ray bursts (GRBs) collected from 1991 until 1996. Based on our analysis, we find no evidence that UHECRs are associated with *Fermi* sources. We conclude with some remarks about the astrophysical origin of cosmic rays.

Key words: acceleration of particles, cosmic rays, galaxies: active, gamma rays: observations

1 INTRODUCTION

Ultra-high energy cosmic rays (UHECRs) are energetic particles ($> 10^{19}$ eV) that must originate in the most powerful particle accelerators in the Universe. These extreme events have fascinated scientists from the time of their discovery in 1962 (Linsley 1963). Since then, speculation about their origin has flourished (Pierpaoli & Ferrar 2005; Ghisellini et al. 2008; Cuesta & Prada 2009). Theoretically, active galactic nuclei (AGN) have long been favored as the best candidates for particle acceleration to these extreme energies (Ginzburg & Syrovatskii 1964; Hillas 1984). Unfortunately, no firm astrophysical association has been established.

Possibly the most intriguing suggestion of an association between UHECRs and AGN was put forward by the *Pierre Auger* collaboration (Abraham et al. 2004) that found a possible correlation between the arrival direction of 27 events collected in their Southern Observatory and the position of nearby ($\leqslant$ 75 Mpc) AGN from the Verón-Cetty catalog (Abraham et al. 2007). The correlation remains but has weakened slightly with the inclusion of additional UHECR events (for a grand total of 58) collected between 2004 January and 2009 March (Abraham et al. 2009). Nonetheless, questions remain about the likelihood of the reported correlation (Abbasi et al. 2008a).

It is expected that if AGN are responsible for UHECRs, these must be preferentially placed within a distance of 100 Mpc (Abraham et al. 2007). Interactions with Cosmic Microwave Background (CMB) photons should starve UHECRs arriving from larger distances through the Greisen-Zatsepin-Kuzmin (GZK) effect (Greisen 1966; Zatsepin & Kuzmin 1966). In fact, a combination of recent observations appear to corroborate the existence of a suppression of UHECRs above 4×10^{19} eV consistent with a GZK horizon (Abbasi et al. 2008b; Abraham et al. 2008b). It is important to note that recent results from the *Pierre Auger* collaboration point to a transition to heavier composition with increasing energies (Unger 2007). If indeed iron nuclei are the dominant component of UHECRs, the large deviation angles expected for heavy nuclei would render the detection of astrophysical counterparts even the nearest ones nearly impossible (Abraham et al. 2008a).

Here, we present a cross-correlation study of UHECRs and the recently released *Fermi* Large Area Telescope First Source Catalog (1FGL) in the 100 MeV to 100 GeV energy range (Abdo et al. 2010a). In contrast with previous studies, our cross-correlation analysis is unique in that the *Fermi* catalog comprises a wide range of *bona fide* particle accelerators with gamma-ray production above 100 MeV directed in the Earth's direction. The Large Area Telescope on board *Fermi* offers a major improvement in sensitivity over previous GeV detectors (Atwood 2007). In its survey observation mode, the LAT observes the entire sky every 3 hours. For individual sources, *Fermi* provides nearly uniform sky coverage down to a photon flux of 4×10^{-10} cm^{-2} s^{-1} between 1 and 100 GeV, except for sources at low Galactic

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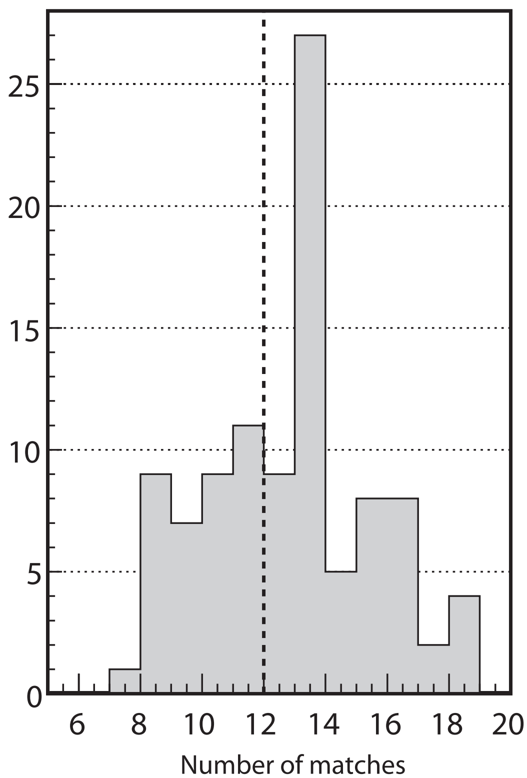

Figure 1. Distribution of total matches with the 1FGL catalog for 100 random sample drawn from the BATSE 4B catalog. The vertical line indicates the number of matches between UHECRs detected by the *Pierre Auger* Observatory and the 1FGL catalog.

latitude ($|b| \leqslant 10°$) where the diffuse emission dominates (Abdo et al. 2010a). Throughout the paper, we assume an H_0 =71 km s^{-1} Mpc^{-1}, $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$ cosmological model.

2 CROSS-CORRELATION OF *Pierre Auger* UHECRS WITH *Fermi* SOURCES

As of 2007 November, the public catalog of UHECRs released by the *Pierre Auger* collaboration contains 27 events with energies above 55 EeV collected at their site in Malargüe, Argentina (Abraham et al. 2004). The *Fermi* LAT 1FGL catalog consists of 1451 sources characterized in the 100 MeV–100 GeV energy range (Abdo et al. 2010a). The data were obtained in an all-sky scanning mode during 2008 August–2009 July and represents the most extensive map of the gamma-ray sky ($\geqslant$ 100 MeV) ever obtained. The entire catalog includes 689 blazars, two starburst galaxies, two radio galaxies, 56 pulsars, 50 supernova remnants, and 630 unidentified sources (Abdo et al. 2010a).

Since we are interested in testing for possible correlations of UHECRs with various classes of gamma-ray emitters in the MeV-GeV energy range without any *a priori* assumption, we take advantage of the complete 1FGL catalog without any redshift or type discrimination.

To test for a possible cross-correlation between UHECRs and *Fermi* sources in the 1FGL catalog, we checked whether the individual UHECR positions in the *Pierre Auger* sample are clearly contained within the error circle of individual sources listed in the 1FGL catalog. Specifically, we count correlations whenever an UHECR event is within a circle of 3.1° radius around a particular *Fermi* source. This radius is in line with the value predicted by conventional models of cosmic ray trajectories that consider the full effect of the Galactic magnetic field (Abraham et al. 2008a). In order to avoid "multiple" counts, we only consider one match per individual UHECR event.

Within the 27 UHECR events, we find 12 matches with 1FGL sources. To examine the likelihood of such correlation, we used the BATSE 4B gamma-ray burst (GRB) catalog (Paciesas et al. 1999) in place of a random generator of isotropic sky positions that allows us to generate artificial samples of simulated UHECRs. The BATSE 4B catalog consists of 1637 GRB positions localized by the BATSE instrument on board the Compton Gamma Ray Observatory (CGRO) in the period between 1991 April 19 and 1996 August 29. For our work, we restricted our analysis to events that would be accessible from the *Pierre Auger* southern site at a declination $< 24.8°$ (Abraham et al. 2004). In addition, we assume that the fraction of exposure is the same accross the declination range as stated in Abraham et al. (2008a). After the proper cuts were applied, we drew 100 random sets of 27 events from the resulting "southern" BATSE 4B catalog to match the UHECR sample. We next proceeded to correlate each of the 100 random sets with the 1451 *Fermi* sources in the same manner as with the original *Pierre Auger* dataset.

Figure 1 shows the distribution of matches between the artificial samples of UHECRs constructed from the BATSE 4B catalog and the 1FGL catalog. In particular, 63% of the artificial samples have 12 or more matches consistent with *Fermi* positions. Allowing for larger circles (6° and 8° radii) only increases the number of false positives when compared with the BATSE sample to 71% and 73% respectively. If the position of *Pierre Auger* events were strongly correlated with *Fermi* sources, we would expect a greater number of coincidences when compared with the outcomes of randomly-generated artificial sets of UHECR events drawn from the BATSE 4B GRB catalog. We find no evidence for such an association and subsequently cannot claim a positive cross-correlation between UHECRs and the 1FGL catalog.

3 DISCUSSION AND CONCLUSIONS

In summary, we find no cross-correlation between UHECRs and 1FGL sources that cannot be reproduced by chance alignment. This differs from the findings reported by Abraham et al. (2009), using a different AGN sample (see also Abraham et al. 2007). Examining the matches between the *Pierre Auger* events and the 1FGL catalog in closer detail, we notice that the sample includes one pulsar, two unidentified sources, and eight AGN. Four of the AGN have measured well beyond the GZK horizon with redshifts as high as $z = 1.843$. The lowest redshifts correspond to Centaurus A ($z = 0.002$) and NGC 4945 ($z = 0.002$), as we shall discuss later. The remaining two AGN associations have no spectroscopic redshifts.

One could argue that the aforementioned AGN without spectroscopic redshifts could potentially form a parent population for UHECRs. If it was, these AGN would most likely lie at distances closer than 100 Mpc (Abraham et al. 2008a). Optical imaging studies of BL Lac reveal that the host galaxies of nearby AGN with jets pointed in our direction tend to cluster around a mean absolute magnitude in the R band equivalent to $M_R = -22.8$ (Sbarufatti, Treves & Falomo 2005). For distances closer than 100 Mpc, this would correspond to an apparent R-band magnitude $R = 12.2$ or brighter. A quick analysis of optical Digitized Sky Survey images centered on the positions of the two matched AGN without spectroscopic redshifts reveals no optical sources brighter than $R = 12.2$ at the derived AGN positions (Abdo et al. 2010b). Therefore, it is unlikely that any of the paired UHECRs/AGN are located within the hypothesized GZK horizon at 100 Mpc.

Interestingly, we do recover the two UHECRs previously associated with the radio galaxy Centaurus A (Abraham et al. 2008a) and one UHECR consistent with the position of the starburst/Seyfert 2 NGC 4945 (Moskalenko et al. 2009). Both Centaurus A (1FGL J1325.6−4300) and NGC 4945 (1FGL J1305.4−4928) are detected by *Fermi*. However, NGC 4945 only stands out as one of the two Seyfert 2 galaxies in the 1FGL catalog rather than for its qualifications as a UHECR accelerator (Abdo et al. 2010b). On the other hand, radio galaxies such as Centaurus A could potentially account for the acceleration of some UHECRs to energies > 55 EeV (Dermer et al. 2009). As a result, it is important to continue to explore the connection (if any) between UHECRs and Centaurus A. However, it is troubling that 24 UHECR events detected by *Pierre Auger* remain without an apparent *Fermi* gamma-ray counterpart within 100 Mpc (we dub these "orphan" UHECRs).

In fact, there seems to be an apparent dearth of nearby AGN detected in gamma rays at distances less than 100 Mpc ($z \leqslant 0.025$). To see this more clearly, Figure 2 shows the distribution for *Fermi* AGN in the redshift range $z = 0 - 0.1$ (Abdo et al. 2010b). In total, there are only five objects with $z \leqslant 0.025$ that would be accessible to the *Pierre Auger* southern site namely NGC 253 ($z = 0.001$), NGC 4945 ($z = 0.002$), Centaurus A ($z = 0.002$), M 87 ($z = 0.004$), and ESO 323-G77 ($z = 0.015$). NGC 4945 (being generous) and Centaurus A could potentially account for 3 of the 27 UHECR events as discussed above. However, we remark that there are no additional identified *Fermi* sources in the 100 MeV-100 GeV energy band to account for the bulk of UHECRs seen by *Pierre Auger* so far.

It is possible that other AGN remain unidentified in the 1FGL catalog, as implied by the observed north-south anisotropy of the associated sources, which might reflect the incompleteness of the existing AGN catalogs in other bands (Abdo et al. 2010b). However, the remainder is expected to lie in the lower end of the gamma-ray flux distribution, and therefore in principle not represent the most efficient particle accelerators. In addition, some AGN are known to be highly variable, therefore we cannot fully discard that some sources have escaped *Fermi* detection and possible correlation with UHECRs because of a low state.

Accordingly, one must admit one or all of the following

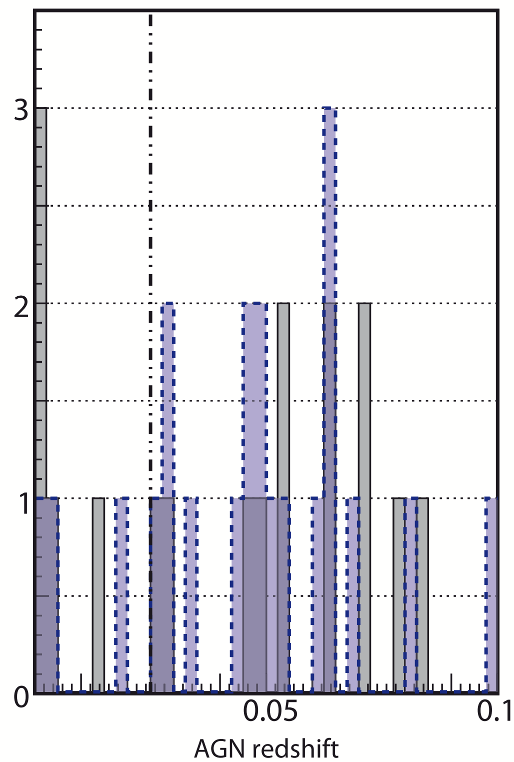

Figure 2. Redshift distribution of *Fermi* AGN between $z = 0$ and $z = 0.1$. Northern (decl $> 24.8^{\circ}$) and southern (decl $< 24.8^{\circ}$) samples are shown in blue (dashed line) and grey (solid line) respectively. Only five identified *Fermi* sources have $z < 0.025$ and are accessible to the *Pierre Auger* southern site. The vertical line marks a distance of 100 Mpc.

possibilities: 1) if UHECRs are truly accelerated within the current sample of detected *Fermi* sources, their trajectories must experience deviations greater than 3.1° from their actual astrophysical origin, making the identification of UHECRs nearly intractable. In particular, the absence of astrophysical counterparts could be well justified if UHECRs are dominated by heavy nuclei including iron since the deviation scales linearly the atomic number Z, 2) there could potentially exist an undetected population of nearby AGN – the so called proton blazars? (Mannheim 1993) – that only emit in a very narrow band above 100 GeV to be discovered by future VHE experiments such as the Cherenkov Telescope Array (CTA) or the Advanced Gamma Imaging System (AGIS), and 3) the absence of obvious particle accelerators in the MeV-GeV energy band leaves some room for the exploration of additional forms of particle acceleration and even exotic possibilities.

Trying to narrow down future observational directions, it is important to search for possible timing/directional correlations of the arrival direction of cosmic ray with AGN flares. Such exercise currently lacks the dedicated sky monitoring that could potentially identify the majority of AGN flares in real time. It would also require the rapid release of UHECR detections (including position) in real time. The existing fleet of MeV-TeV telescopes including *AGILE*, *Fermi*

H.E.S.S., MAGIC, and VERITAS could help trace strong flares in the gamma-ray band. However, groundbreaking progress into the gamma-ray variability domain might have to wait for the next generation of VHE experiments. In the theoretical front, it is critical to improve existing models of cosmic ray propagation. In particular, based on current cross-correlation studies, the initial expectation that cosmic ray trajectories at energies $> 10^{19}$ eV should be fairly rigid does not appear to be so obvious.

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