VERITAS Observations of the Arrival Directions of the Highest Energy Cosmic Rays

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Abstract.

The recent discovery by the Pierre Auger collaboration of anisotropy in the arrival directions of the highest energy cosmic rays, correlated with the positions of nearby active galactic nuclei [1, 2], encourages the search for counterpart TeV gamma-ray emission. Approximately half of the sky viewed by the southern hemisphere Pierre Auger experiment is also visible at reasonable elevations for the northern hemisphere gamma-ray telescope array, VERITAS. We report on first observations by VERITAS of regions associated with the arrival directions of ultra-high energy cosmic ray events.

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INTRODUCTION

The principle of using gamma rays as “tracers” for the sources of cosmic ray acceleration was one of the original motivations behind the development of gamma-ray astronomy. If cosmic rays are accelerated to EeV energies in discrete sources, an enhanced flux of lower energy photons might also be observed from the direction of these sources. This could result either from interactions of the ultra-high energy cosmic ray (UHECR) particles with intergalactic matter and photon fields, in which case the source flux and size depend strongly on the unknown strength and structure of the intergalactic magnetic fields, or from lower energy particle acceleration and gamma-ray emission processes driven by the same central engine. The Pierre Auger Observatory sky map (modified from[1]) is reproduced in Figure 1, consisting of 27 events with energies above 57 EeV. Sources from the Veron-Cetty and Veron catalogue [3] with z<0.018 are shown by red stars, the Auger points are shown by black circles with a radius $\Psi$ = 3.1°.

VERITAS OBSERVATIONS

VERITAS [4] is an array of four, 12 m diameter imaging atmospheric Cherenkov telescopes located in Tucson, Arizona (31°40'30" N, 110°57'07" W, 1268 m above sea level). Of the 27 UHECR events, 7 have declinations $>-10°$, and so are visible to VERITAS at telescope elevations greater than 50°. Four arrive in two groups of two (labelled Pair A and Pair B in Figure[1]). The properties of the UHECR events in these pairs are summarized in Table[1].

VERITAS observed these regions of the sky in autumn, 2007. Table[2] lists AGN from the Veron-Cetty and Veron catalogue with z<0.05 which were within the field of view during these observations. The exposure time for Pair A was 200 minutes, for Pair B, 608 minutes. Observations consist of 20 minute runs in the standard “wobble” mode, wherein the putative source is offset by 0.5° sequentially to the North, South, East and West from the centre of the field of view. The mean source elevation angle for these observations was 52°.

RESULTS

The VERITAS observations were analysed using standard analysis tools ([5]) and gamma-ray selection cuts optimized for point sources with a flux of 1% of the Crab Nebula and a Crab-like spectrum. Figures[2] and[3] show the significance skymaps (left), and the distribution of significances over all bins in each map (right). No significant evidence for gamma-ray emission at any position in the field of view was found.

Table[3] shows the 99% confidence integral upper flux limits for point source emission at each of the AGN positions in the fields, calculated according to the method of Feldman & Cousins [6]. The upper limits are calculated

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1 http://www.auger.org/news/PRagn/AGN_correlation.html
FIGURE 1. The Pierre Auger Observatory sky map (modified from 1), showing the celestial sphere in galactic coordinates with circles of radius 3.1° centered at the arrival directions of the 27 cosmic rays with highest energy detected by the Pierre Auger Observatory [1]. The positions of the 472 AGN (318 in the field of view of the Observatory) with redshift $z \leq 0.018(D < 75 \text{ Mpc})$ from the 12th edition of the catalog of quasars and active nuclei [3] are indicated by red asterisks. The solid line draws the border of the field of view (zenith angles smaller than 60°). Darker color indicates larger relative exposure. Each colored band has equal integrated exposure. The dashed line is, for reference, the super-galactic plane. Centaurus A, one of our closest AGN, is marked in white. The two pairs of events of interest for the VERITAS observations are marked and labeled.

FIGURE 2. Significance map in the region of Pair A. AGN at $z \leq 0.018$ are indicated by square markers. More distant AGN out to $z \leq 0.05$ are indicated by triangles. PC 2207+0122 is at the centre of the field; observations were made with the camera centre offset by 0.5° from this position in four different directions.
for an assumed power-law energy spectrum with a differential spectral index of $\alpha = -2.5$, and a minimum energy of 500 GeV, close to the energy threshold of VERITAS for observations at this angle to the zenith and for the analysis cuts used.

**CONCLUSIONS**

We have searched for evidence of gamma-ray emission from two regions on the sky coincident with the arrival directions of pairs of ultra-high energy cosmic ray events detected by the Auger observatory. No significant evidence for emission has been found within a field of view of $\sim 1.7^\circ$ radius, and point source upper limits are given for close AGN in these fields.

Numerous mechanisms exist for the production of a GeV-TeV gamma-ray flux associated with the production and propagation of ultra-high energy cosmic rays (e.g. [3][8][9]). The lack of a detection by VERITAS is not surprising, however. The flux may be below the sensitivity of these observations, spatially very extended, located at a large angle to the cosmic ray arrival directions, or possibly time variable. Nevertheless, the search for a gamma-ray source population associated with the highest energy cosmic ray events is worthwhile, as the excellent angular resolution ($\sim 0.01^\circ$) of TeV instruments may allow for the unambiguous identification of the sites of acceleration of these particles. Ongoing observations by Auger will, in the future, provide clearer targets for gamma-ray source searches.

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FIGURE 3. Significance map in the region of Pair B. AGN at $z \leq 0.018$ are indicated by black square markers. More distant AGN out to $z \leq 0.05$ are indicated by triangles. The black circle indicates the centre of the field; observations were made with the camera centre offset by 0.5° from this position in four different directions.

TABLE 3. Results of VERITAS observations of AGN from the Véron-Cetty & Véron catalogue with $z \leq 0.05$. Upper limits are calculated for point source emission using the method of Feldman and Cousins [6]. The upper six sources are associated with Pair A (exposure=200 minutes), the lower three with Pair B (exposure=608 minutes).

| Source Name          | ON-source (events) | OFF-source (events) | Background Normalization | 99% confidence upper limits (events) | $\phi m^{-2} s^{-1} > 500$ GeV |
|----------------------|--------------------|---------------------|--------------------------|--------------------------------------|---------------------------------|
| Q 2207+0122          | 4                  | 78                  | 0.10                     | 4.6                                  | $8.6 \times 10^{-9}$            |
| Q 2207+0121B         | 4                  | 78                  | 0.10                     | 4.6                                  | $9.6 \times 10^{-9}$            |
| Q 2205+0120          | 7                  | 73                  | 0.10                     | 9.5                                  | $2.3 \times 10^{-8}$            |
| SDSS J2206+0106      | 7                  | 34                  | 0.10                     | 13.4                                 | $4.9 \times 10^{-8}$            |
| Q 2212+0215          | 3                  | 35                  | 0.10                     | 7.0                                  | $3.9 \times 10^{-8}$            |
| Q 2213+0218          | 0                  | 10                  | 0.10                     | 3.8                                  | $3.8 \times 10^{-8}$            |
| NGC 1358             | 26                 | 179                 | 0.10                     | 19.1                                 | $1.4 \times 10^{-8}$            |
| SDSS J03302-0532     | 13                 | 170                 | 0.10                     | 6.1                                  | $4.9 \times 10^{-9}$            |
| SDSS J03349-0548     | 13                 | 137                 | 0.10                     | 10.8                                 | $8.3 \times 10^{-9}$            |