CORRELATIONS BETWEEN ULTRAHIGH ENERGY COSMIC RAYS AND INFRARED-LUMINOUS GALAXIES

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ABSTRACT

We confirm the ultrahigh energy cosmic ray (UHECR) horizon established by the Pierre Auger Observatory using the heterogeneous Véron-Cetty–Véron (VCV) catalog of active galactic nuclei by performing a redshift–angle–IR luminosity scan using point-source catalog with redshift (PSCz) galaxies having infrared luminosity greater than $10^{10} L_\odot$. The strongest correlation—for $z < 0.016$, $\psi = 21$, and $L_{ir} \geq 10^{10.5} L_\odot$—arises in fewer than 0.3% of scans with isotropic source directions. When we apply a penalty for using the UHECR energy threshold that was tuned to maximize the correlation with VCV, the significance degrades to 1.1%. Since the PSCz catalog is complete and volume-limited for these parameters, this suggests that the UHECR horizon discovered by the Pierre Auger Observatory is not an artifact of the incompleteness and other idiosyncrasies of the VCV catalog. The strength of the correlation between UHECRs and the nearby highest-IR-luminosity PSCz galaxies is stronger than in about 90% of trials with scrambled luminosity assignments for the PSCz galaxies. If confirmed by future data, this result would indicate that the sources of UHECRs are more strongly associated with luminous IR galaxies than with ordinary, lower IR luminosity galaxies.

Key words: acceleration of particles – astroparticle physics – infrared: galaxies

1. INTRODUCTION

The Pierre Auger Observatory has reported (The Pierre Auger Collaboration 2007; Abraham et al. 2008) a correlation between the arrival directions of the highest energy cosmic rays and the positions of galaxies in the Véron-Cetty–Véron (VCV) “Catalog of Quasars and Active Galactic Nuclei” (12th ed.: Véron-Cetty & Véron 2006). Of the 27 cosmic rays above 57 EeV recorded by the Pierre Auger Observatory prior to 2007 August 31, 20 are within 3/2 of a VCV galaxy with $z \leq 0.018$ (about 75 Mpc). Restricting to $|b| > 10$ to avoid regions in which galaxy catalogs are incomplete due to Galactic extinction leaves 22 ultrahigh energy cosmic rays (UHECRs) of which 19 are within 3/2 of a VCV galaxy (Zaw et al. 2010). The existence of a correlation between UHECRs and VCV galaxies clarifies the nature of UHECRs by establishing that UHECRs are extragalactic in origin and that they have an energy-dependent horizon consistent with the Greisen–Zatsepin–Kuzmin (GZK) prediction. However, the VCV catalog is not complete, homogeneous, or pure, and its completeness drops with redshift (Véron-Cetty & Véron 2006; Zaw et al. 2009, 2010). Thus, VCV is not suitable for statistical analyses as would be required for establishing quantitative bounds on the contribution of various possible sources to the population of UHECRs, and its suitability for establishing the GZK horizon can be a source of concern.

Here, we study the correlation between UHECRs and infrared-luminous galaxies with two aims. First, we use the IRAS point-source catalog with redshifts (PSCz; Saunders et al. 2000), which is homogeneous and complete to beyond the GZK distance, to replicate the Auger result of a UHECR horizon and correlation with extragalactic matter. Second, we investigate whether the strength of a galaxy’s correlation with UHECRs is related to its infrared luminosity, $L_{ir}$. In the absence of an active nucleus, infrared luminosity is a good proxy for star formation, and thus galaxies with strong IR emission should have an enhanced concentration of massive stars, whose lifetimes are short on the timescale of star formation episodes. A number of proposed UHECR sources are associated with the death of massive stars or birth of their progeny, e.g., collapsars, gamma-ray bursts (GRBs), or magnetars, so the probability of such events occurring in a given galaxy could increase roughly in proportion to $L_{ir}$ of the galaxy. These considerations motivate a study of the correlation between UHECRs and high $L_{ir}$ galaxies. Of course, some high $L_{ir}$ galaxies host active galactic nuclei (AGNs), so discovering that correlations are enhanced with a high $L_{ir}$ sample does not by itself demonstrate a non-AGN source population and further investigation is needed. In particular, low-redshift GRBs occur primarily in relatively rare low-metallicity star-forming regions (Stanek et al. 2006), especially found in dwarf galaxies, so a UHECR correlation with high-luminosity IR galaxies would not necessarily be indicative of GRB sources. The correlation between AGASA UHECRs and PSCz galaxies was investigated by Smialkowski et al. (2002) and the clustering of Auger UHECRs was compared to that of PSCz by Cuoco et al. (2008).

We use the technique employed by Auger, of scanning over the maximum angular separation, $\psi$, and over the maximum redshift of the galaxies (also see Tinyakov & Tkachev 2001). We also scan on the threshold infrared luminosity of galaxies. Since only events with $E > 57$ EeV have been published, we do not perform a full scan on energy, but we do a partial scan in one direction (toward higher energy) in order to estimate the penalty associated with adopting the 57 EeV threshold. To assess the significance of the correlation compared to isotropy, as relevant to establishing the existence of a UHECR horizon, we perform the same scans on mock isotropic UHECR data sets. To test the significance of a possible correlation with infrared luminosity, we compare to the results of scans using mock catalogs obtained by scrambling the luminosities of the PSCz galaxies.

2. SCAN ANALYSIS WITH INFRARED-LUMINOUS GALAXIES

IRAS is an all-sky survey of infrared galaxies, and the PSCz catalog provides the redshifts of IRAS point sources. Sanders & Mirabel (1996) give the relationship between the IRAS observed

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3 Note that the terms “luminous infrared galaxy” (LIRG) and “ultra-luminous infrared galaxy” (ULIRG) commonly denote galaxies with $\log[L_{ir}/L_\odot] \in$ the ranges 11–12 and $\geq 12$, respectively, but we are not using those conventional categories here.
The choice of energy cut \((E > 57 \text{ EeV})\) made by Auger in releasing the data was tuned to maximize the correlation of UHECRs with VCV AGN. While this analysis is independent of the VCV analysis performed by Auger, VCV and PSCz galaxies both trace the same underlying matter density field. It is thus reasonable to worry that the choice of energy cut will bias our results. In order to estimate a penalty for this, we include a scan in the energy threshold in one direction, toward higher energy. We find that the minimum value of \(P\) occurs for the original energy cut of 57 EeV and the same values of \(\psi\), \(z_{\text{max}}\), and \(\log[L_{\text{ir}}/L_{\odot}]_{\text{min}}\). We then use \(5 \times 10^4\) catalogs of 22 random UHECR directions in new scans that include the energy scan in one direction. We find that the probability of finding as good or better correlation by chance from an isotropic source distribution is \((1.10 \pm 0.05) \times 10^{-2}\). In other words, the significance of our result degrades from 0.3% to 1.1% when we include the energy penalty.

As can be seen from Figure 2, the PSCz catalog is complete to redshift 0.024 for \(\log[L_{\text{ir}}/L_{\odot}] \geq 10.6\), to 0.02 for \(\log[L_{\text{ir}}/L_{\odot}] \geq 10.5\), and for \(z \leq 0.016\) it is complete down to \(\log[L_{\text{ir}}/L_{\odot}] < 10.3\). The scan minimum \((\log[L_{\text{ir}}/L_{\odot}]_{\text{min}} = 10.5, z_{\text{max}} = 0.016)\) is thus comfortably inside the domain of PSCz completeness and is thus established with a volume-limited sample. Although the whole scan range includes regions for which the PSCz catalog is not complete, the simulations measuring the chance probability for isotropically distributed UHECRs to give as low or lower a value have the same incompleteness, and therefore give a reliable estimate of the significance. Therefore, the analysis presented here suggests that the arrival directions of UHECRs correlate with nearby extragalactic objects and establishes the UHECR horizon.

3. INFRARED LUMINOSITY AND UHECR CORRELATION

One next wants to know if this correlation of UHECRs with luminous PSCz galaxies is stronger than if the galaxies were selected from the PSCz catalog without regard to their IR luminosities.
luminosity. To find out, we follow the same scan procedure as above, but scrambling the values of \( \log(L_{\text{ir}}/L_{\odot}) \) first. The \( P \) values obtained in 700 such trials are shown in the upper panel of Figure 3. Six percent of the cases have a \( P \) value as low as in the scrambled data set. Since that explicitly eliminates some correlations, we find an upper bound on the a priori chance probability. The lower panel of Figure 3 shows the distribution of \( P \) values for the reduced UHECR data set and scrambled IR luminosity values; the vertical line is the \( P \) value found using the reduced UHECR data set and scanning on the true IR luminosity. The observed \( P \) value is lower than in the scrambled data sets in 11.7% of the cases, allowing us to bracket the chance probability for the UHECR–LIRG correlation not being \( L_{\text{ir}} \) dependent to be in the range 6%–12%. This result suggests that UHECRs are more strongly correlated with highly luminous PSCz galaxies than lower luminosity galaxies, but it is not statistically significant and remains to be confirmed with future data.

Table 1 gives the name, right ascension, and declination of the PSCz galaxies that correlate with UHECRs for the scan parameters that minimize \( P \left( z \lesssim 0.016, \psi \lesssim 2^\circ,1,\text{and log}[L_{\text{ir}}/L_{\odot}] \gtrsim 10.5\right) \), followed by the year, Julian day, and energy of the correlated UHECR. This is followed by the angular separation between galaxy and UHECR, and the redshift and derived infrared luminosity of the galaxy. In some cases, PSCz reports multiple values of \( L_{\text{ir}} \); in such cases, these are listed separated by a comma. Thirteen distinct PSCz galaxies correlate with 13 different UHECRs within 2°, with two UHECRs correlating with more than one PSCz galaxy and two PSCz galaxies correlating with more than one UHECR: 2MASX J17544125–605440 (\textit{IRAS} 17501–6054) and ESO 270-G007 (\textit{IRAS} 13203–4317). Of course, a given cosmic ray can have only one source, and the presence of two source candidates within the scanning prescription is a useful reminder of the limitations of the scanning method.

It must be emphasized that a correlation in the scan procedure does not imply a correct identification of the cosmic ray source: the true source for that cosmic ray may not even be in the catalog or may be beyond the \( z_{\text{max}} \) which minimizes \( P \). Only a significant excess of correlations compared to chance, for the ensemble of correlations, is evidence for a concentration of sources in the catalog. The Generalized Maximum Likelihood method (Farrar
which allows the GZK redshift information to be imposed on an event-by-event basis, is distinctly superior to the scan method in this regard (N. G. Busca & G. R. Farrar 2010, in preparation) but we have adopted the scan method for the present work to allow direct comparison to the Auger analysis with the VCV catalog. Use of the new Generalized Maximum Likelihood method should significantly improve the sensitivity of future correlation studies (I. Zaw et al. 2010, in preparation).

Since PSCz is complete for the redshift and $L_\odot$ range of interest, and outside its mask the PSCz catalog does not suffer from the inhomogeneity issues plaguing the VCV catalog, detailed statistical studies to gain further insight into the origin of the correlation will be possible.

Both AGN activity and star formation lead to a high $L_\odot$ after reprocessing by dust, and indeed 5 of the 13 correlated PSCz galaxies have optically identified active nuclei by the criteria described in Zaw et al. (2009). This is a much larger portion than for randomly chosen high-$L_\odot$ luminosity galaxies, since studies show that 4% of galaxies with $\log[L_\odot/L_\odot] \in [10-11]$ are Seyferts, i.e., confirmed optical AGNs (Sanders & Mirabel 1996). Only about half of all active nuclei can be identified in the optical (Reviglio & Helfand 2006), so an important question is whether any of the seven correlated PSCz galaxies that do not appear in VCV have active nuclei as well. Upcoming X-ray observations of these galaxies with Chandra will help settle this question. For the moment, we cannot determine whether the UHECR correlation with IR-luminous galaxies may result from AGNs they contain, or may represent evidence for a second class of sources.

4. CONCLUSIONS

The scan analysis performed here shows a significant correlation between the published Auger cosmic rays and nearby moderately to highly luminous infrared galaxies. This provides a valuable independent corroboration of the UHECR horizon with a homogeneous, volume-limited catalog. The correlation is maximized for $z \leq 0.016$, $\psi = 2.1$, and $\log[L_\odot/L_\odot]_{\min} = 10.5$. The probability that isotropic sources would show such a high degree of correlation by chance is 0.3%. The PSCz catalog is complete to $z = 0.024$ for $\log[L_\odot/L_\odot] \geq 10.5$, thus we establish the UHECR horizon with a volume-limited catalog, removing the concern that the horizon found in the Auger analysis with VCV galaxies could be an artifact of VCV’s increasing incompleteness with distance (Zaw et al. 2010).

The angular separation maximizing the correlation in the PSCz luminosity scan, $\psi = 2.1$, is lower than the $\psi = 3:2$ optimizing the VCV scan. The relationship between $\psi$ and the spectrum of magnetic deflections is subtle and depends on the source sample size and completeness, since $\psi$ is determined by minimizing $P$. Nonetheless, this difference may be evidence that the incompleteness and inhomogeneity of VCV exaggerates the angular separation between source and UHECR arrival direction, and thus one must be cautious about inferring the typical magnetic deflection at this time.

The correlation observed between the published Auger UHECRs and highly luminous PSCz galaxies is stronger than between UHECRs and randomly chosen PSCz galaxies within the same redshift and angular region, in 6%-12% of the trials. If confirmed by future data, such a correlation between UHECRs and high-$L_\odot$ luminosity galaxies would show that luminous IR galaxies have an increased abundance of sources of UHECRs compared to randomly chosen galaxies in the PSCz catalog. It does not, however, resolve the question of whether UHECRs are produced by AGNs or some other mechanism, perhaps associated with the demise of stars as in GRBs or magnetars, since many of the correlated infrared galaxies are known to contain AGNs. A program of Chandra observations is underway to find out which of the other correlated high-$L_\odot$ luminosity galaxies may also have active nuclei.

We note that new Auger data (since the published 2007 science results of The Pierre Auger Collaboration) show a weaker correlation with the VCV AGN (Hand 2010), highlighting that the published UHECR data set may be too small to place robust constraints on cross-correlations with extragalactic sources. It is thus especially important to repeat the present analysis with a new and larger data set.

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