GALAXIES CORRELATING WITH ULTRA-HIGH ENERGY COSMIC RAYS

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ABSTRACT

The Pierre Auger Observatory reported that 20 of the 27 highest energy cosmic rays have arrival directions within 3°2 of a nearby galaxy in the Veron-Cetty and Veron (VCV) Catalog of Quasars and Active Galactic Nuclei (12th ed.), with a 1% probability that this would be due to chance if the cosmic ray directions were isotropic. In this paper, we examine the correlated galaxies to gain insight into the possible ultra-high energy cosmic ray (UHECR) sources. We find that 14 of the 21 correlated VCV galaxies are active galactic nuclei (AGNs) and we determine their bolometric luminosities. The remaining seven are primarily star-forming galaxies. The bolometric luminosities of the correlated AGNs are all greater than 5 \times 10^{42} \text{ erg s}^{-1}. This may explain the absence of UHECRs from the Virgo region in spite of the large number of VCV galaxies in Virgo, since most of the VCV galaxies in the Virgo region are low-luminosity AGNs. Interestingly, the bolometric luminosities of most of the AGNs are significantly lower than that required to satisfy the minimum condition for UHECR acceleration in a continuous jet. If a UHECR–AGN correlation is substantiated with further statistics, our results lend support to the recently proposed “giant AGN flare” mechanism for UHECR acceleration.

Key words: acceleration of particles – cosmic rays – galaxies: active

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1. INTRODUCTION

The origin of ultra-high energy cosmic rays (UHECRs), with energies greater than 10^{19} \text{ eV}, has been an important question in astrophysics for many decades. The sources of UHECRs must be both very powerful, in order to be able to accelerate cosmic rays to such high energies, and nearby (D \sim \mathcal{O} (100 \text{ Mpc})), since the cosmic rays from more distant sources would lose energy by interacting with cosmic microwave background (CMB) photons, in what is known as the Griszen–Zatsepin–Kuzmin (GZK) effect. Efforts to find angular correlations between UHECR arrival directions and candidate astrophysical sources have been bedeviled, until recently, by inadequate statistics. The task is further complicated by the fact that UHECRs, being charged particles, are deflected by magnetic fields en route from their sources. Discovering and understanding which astrophysical sites are capable of accelerating UHECRs will be of fundamental importance for our understanding of extreme astrophysical systems, such as gamma-ray bursts (GRBs) and active galactic nuclei (AGNs) which are two of the leading candidates for UHECR acceleration.

The Pierre Auger Observatory has recently reported a significant correlation between the highest energy cosmic rays and nearby galaxies in the Véron-Cetty & Véron (VCV; 2006) Catalog of Quasars and Active Galactic Nuclei (12th edition; The Pierre Auger Collaboration 2007, 2008; Auger07a,b below). A prescription was established by scanning on UHECR energy threshold, maximum angular separation, and maximum VCV object redshift, using UHECR data above 40 EeV through 2006 May 27 and VCV galaxies out to z = 0.024. The most significant correlation was found for angular separation less than 3°1, UHECR energy threshold 56 EeV and maximum VCV galaxy redshift 0.018, for which 12 of 15 events correlate with VCV galaxies. (A correlation is simply defined as a UHECR falling within the specified angular separation of a VCV galaxy.) A prescription was designed (Auger07a,b) such that with different possible trials and at most 34 new events accumulated, the overall chance probability would be less than 1% of satisfying the prescription by chance with an isotropic source distribution. Then, independent data taken after 2006 May 27 was used to do an a priori correlation study with the same energy threshold, maximum redshift, and angular separation. The prescription was first satisfied on 2007 May 25 with six out of eight event correlating. Auger continued to take data until 2007 August 31, and eight of 13 new events above 56 EeV were found to correlate, with ~2.7 expected by chance. (The probability that eight of 13 events selected at random and observed with the Auger exposure would fall within 3°1 of VCV galaxies with z < 0.018 is 1.7 \times 10^{-3}, lower than the 1% which takes into account the different possible trials.) With the prescription firmly established, Auger repeated the scan procedure on the full data set. The optimal scan parameters were an energy threshold of 57 EeV, a maximum angular scale of 3°2, and a maximum VCV galaxy redshift of z < 0.018 (about 75 Mpc), consistent with the original parameters. In the full data set, there are 27 UHECR total events with energy above 57 EeV and 20 of them are within 3°2 of VCV galaxies with z < 0.018 \footnote{Restricting to |b| > 10, where the VCV catalog is more complete, there are 22 UHECRs of which 19 are correlated.} (Auger07a,b). The full data set and the parameters from the final scan form the basic sample for our study.

This Auger result is of fundamental importance to particle astrophysics, because the correlation with nearby extragalactic structure clearly demonstrates that UHECRs are of extragalactic origin and that the highest energy cosmic rays have a horizon, consistent with the GZK effect. (The downturn in the spectrum might merely be due to a maximum energy of the accelerators.) However, as stressed by the Pierre Auger Collaboration, the observed correlation may not mean that the correlated UHECRs...
are produced by galaxies with which they are correlated: the VCV galaxies may just be tracers of the true sources. Further data will be required to determine whether the correlation between UHECRs and VCV galaxies observed by the Pierre Auger Collaboration is due to AGNs being the sources of most or all UHECRs. The analysis presented here makes a contribution to deciding this question by investigating the purity of the VCV catalog, and, if the answer is affirmative, is a first step to identifying key properties of AGNs that accelerate UHECRs.

Our purpose here is to examine the VCV galaxies that correlate with the 20 Auger UHECRs. We emphasize that the correlation observed by Auger is only statistical. We cannot be confident that any given one of the correlated VCV galaxies is a source. However, the sample as a whole likely contains sources of UHECRs and examining them is an important step toward elucidating the properties of the sources of UHECRs. First, we determine whether they contain a known energetic astrophysical object potentially capable of accelerating UHECRs. In principle, each VCV galaxy should contain an active nucleus. However, the VCV catalog is a list of the AGN, quasar, and BL Lac candidates reported in the literature, based on heterogeneous selection criteria. While it is the largest available catalog of known AGNs, especially for the southern hemisphere where most of Auger’s exposure lies, it has several deficiencies compared to an ideal catalog. The VCV catalog is known to be incomplete and nonuniform. Furthermore, it is not pure. Therefore, we verify whether the correlated VCV galaxies meet rigorous AGN criteria based on optical emission line ratios. Second, for each galaxy confirmed to be an AGN, we determine its bolometric luminosity, which is an important diagnostic of the maximum UHECR energy an AGN can produce in conventional jet acceleration. Finally, we compare the bolometric luminosities of the correlated AGNs to those in the Virgo Cluster, which contains a large number of AGNs but from which no UHECRs were detected. We find that most of the Virgo AGNs have much lower bolometric luminosity than the AGNs which are correlated with UHECRs. The lack of UHECRs from the direction of Virgo may indicate an empirical minimum bolometric luminosity for UHECR acceleration. Based on this, we estimate the fraction of low-luminosity AGNs (LLAGNs, taken here to have \( L_{\text{bol}} \leq 5 \times 10^{42} \text{ erg s}^{-1} \)) in the VCV catalog in the HiRes exposure region, finding that about half the AGNs are below the luminosity threshold of AGNs correlated with Auger UHECRs. The fraction of known LLAGNs in VCV is higher in the HiRes field of view than in Auger’s, due to the sensitive northern hemisphere survey by Ho et al. (1995); this may contribute to HiRes’ not observing a significant correlation between VCV galaxies and their UHECR data (Abbasi et al. 2008).

2. UHECR ACCELERATION

The motivation and agenda for our study derive from theoretical considerations of UHECR acceleration. No astrophysical system has been conclusively demonstrated theoretically to be capable of accelerating cosmic rays to the observed energies of \( \gtrsim 10^{20} \text{ eV} \). GRBs have been argued to be responsible for UHECRs (Waxman 1995, 2004b) on the basis of their energy injection rate and theoretical plausibility: they are known to produce high-energy photons and the GRB internal-shock model can be viable for UHECR acceleration as well. Other possible accelerators include internal shocks in the jets of AGNs—analagous to those in GRBs but with much lower bulk Lorentz factors (for an early suggestion see Biermann & Strittmatter 1987), external shocks in the lobes of powerful radio galaxies, and magnetars (Arons 2003), to name some of the more popular. A GRB could satisfy the requirements of UHECR acceleration for \( \Gamma \sim 10^3 \) (Waxman 1995), while for AGN jet acceleration \( \Gamma \sim 10 \) few would be envisaged. Assuming that the correlation between UHECRs and VCV galaxies observed by Auger is real, AGNs become the favored sources and we focus here on testing AGN-based acceleration models.

A very general requirement to accelerate a cosmic ray proton of energy \( E \equiv E_{20} \times 10^{20} \text{ eV} \), in a relativistic jet of bulk Lorentz factor \( \Gamma \), is that the Poynting luminosity of the jet, \( L_P \), satisfy \( L_P \gtrsim 10^{45} \Gamma^2 E_{20}^{\frac{2}{3}} \text{ erg s}^{-1} \) (Waxman 2004a; Farrar & Gruzinov 2009). This follows because the Larmour radius of the UHECR,\(^5\) \( R_{\text{L}} \equiv 2.8 \times 10^{20} \times \frac{E_{20}^{\frac{2}{3}}}{B\mu} \) cm, must be less than the characteristic size of the acceleration region, \( R \), leading to \( R B \gtrsim 3 \times 10^{17} \Gamma^{-1} E_{20} \text{ G cm} \), which translates to a lower bound on the Poynting luminosity of the jet, \( L_P \sim \frac{1}{2} c \eta^2 B^2 R^2 \). For a conventional AGN jet the Poynting luminosity is supplied by accretion, so the jet and accretion disk must satisfy the quoted luminosity constraint, as discussed in greater detail by Farrar & Gruzinov (2009). Therefore, the bolometric luminosity of the accretion disk of an AGN capable of accelerating a proton to \( E_{20} \times 10^{20} \text{ eV} \) must satisfy

\[
L_{\text{bol}} \gtrsim 10^{45} \Gamma^2 E_{20}^{\frac{2}{3}} \text{ erg s}^{-1}.
\]

If the timescale of variation of the accelerator is large compared to the cosmic ray travel time, estimated to be \( \lesssim 10^5 \) yr for the correlated Auger cosmic rays (Farrar & Gruzinov 2009), then the required luminosity should be evident when observing the sources today. In conventional AGN jet acceleration or acceleration in radio lobes, the timescale for variation of the source is of the order of the lifetime of an AGN, i.e., \( \gtrsim 10^7 \) yr. Thus, an AGN capable of accelerating UHECRs should either have powerful radio lobes or have an accretion disk luminosity consistent with the bound on \( L_{\text{bol}} \) in Equation (1).

An alternative to the conventional continuous jet model of AGN acceleration has recently been proposed by Farrar & Gruzinov (2009). In this “giant AGN flare” mechanism, an instability of the accretion disk—perhaps initiated by the tidal disruption of a passing star—produces an intense flare lasting of order a day to a month. During the flare the luminosity condition for UHECR acceleration is easily satisfied (Farrar & Gruzinov 2009), but afterward the emission subsides quickly because the cooling time is short and the material which fuels the flare is largely consumed. Therefore, the system as observed today need not satisfy the luminosity condition (1). In Section 5, we determine, for each AGN–UHECR pair, the figure-of-merit \( \lambda_{\text{bol}} \equiv \lambda_{\text{bol}} 10^{-45} E_{20}^{-2} \). \( \lambda_{\text{bol}} \) should be \( \gtrsim 1 \) for conventional continuous jet acceleration of protons, but has no such constraint for the giant flare scenario. We find that at least half of the correlated AGNs do not satisfy the bolometric luminosity requirement, favoring the giant AGN flare scenario.

A question raised (but not yet answered) by the giant AGN flare model is whether the AGNs responsible for UHECR production, as observed today, show a threshold \( \lambda_{\text{bol}} \). In the AGN flare model, an accretion disk is required prior to the flare, but the observed value of \( L_{\text{bol}} \), reflects the properties of the remnant system, which depends on how much material is left after the period of rapid accretion, and how cool the accretion disk has become in the intervening time. In Section 6, we find empirical evidence for a threshold \( \lambda_{\text{bol}} \gtrsim 5 \times 10^{42} \text{ erg s}^{-1} \).

\(^5\) Assumed here to be a proton.
There are a number of diagnostics used to identify an ac-
creting supermassive black hole (SMBH) from optical spec-
troscopy. Broad permitted emission lines (e.g., Hβ) with line
widths $\gtrsim 1000$ km s$^{-1}$ strongly suggest that we are seeing
the Keplerian velocities of gas orbiting the BH. This dense orbit-
ing gas, known as the broad-line region (BLR), has a typical
size of light days, and thus is never spatially resolved in astro-
nomical observations. Objects with observable broad emission
lines, for which we have an unobstructed view of the nucleus,
are known as broad-line AGNs (or, at low luminosities, Seyfert
1 galaxies). In some cases, our view of the central engine and
broad-line region are obscured. AGNs may still be identified by
using log($[O\text{ iii}]/\lambda H\beta$) evaluated individually. Figure 1 is a BPT diagnostic diagram
for AGN developed by Kewley et al. (2001), indicated by the solid line. The Seyfert 2 galaxies are shown as diamonds. They
lie well within the Seyfert region of the diagram. The demarcation line used by
Kauffmann et al. (2003) is shown (dashed) for comparison. The horizontal line
shows the boundary between Seyferts (above the line) and LINERs (below the line).

Figure 1. BPT diagram showing the line ratios, log($[O\text{ iii}]/\lambda H\beta$) vs.
log($[N\text{ ii}]/\lambda H\alpha$), for 11 of the 15 VCV galaxies correlated with UHECRs which
are not broad-line AGNs or radio galaxy. NGC 5244 and NGC 7135 are not plotted
since they show almost no [O ii] emission, nor are NGC 4945 and ESO 139-G12 since their identification as AGNs is made on other grounds. The dwarf
galaxy, Q 2207+0122, is indicated by the asterisk. NGC 2989, IC 5169, NGC
1204, and NGC 7591 are shown as triangles. These fall to the left and below
the theoretical classification line for AGN developed by Kewley et al. (2001),
indicated by the solid line. The Seyfert 2 galaxies are shown as diamonds. They
lie well within the Seyfert region of the diagram. The demarcation line used by
Kauffmann et al. (2003) is shown (dashed) for comparison. The horizontal line
shows the boundary between Seyferts (above the line) and LINERs (below the line).

We now turn to our task; our first objective is to identify the
AGNs among the correlated VCV galaxies.

3. IDENTIFICATION OF ACTIVE GALACTIC NUCLEI

There are a number of diagnostics used to identify an ac-
creting supermassive black hole (SMBH) from optical spec-
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nomical observations. Objects with observable broad emission
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are known as broad-line AGNs (or, at low luminosities, Seyfert
1 galaxies). In some cases, our view of the central engine and
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Two-dimensional line ratio diagnostics have been developed to
effectively discriminate between various emission mecha-
nisms, e.g., star formation, shock, or photoionization by an ac-
creting BH. See Baldwin et al. (1981; BPT below), (Veilleux &
Osterbrock 1987; Kewley et al. 2001; Kauffmann et al. 2003).
Baldwin, Phillips, and Terlevic (BPT) diagnostic diagrams
are based on the relative strengths of prominent emission lines (e.g.,
$[O\text{ iii}]/\lambda H\beta$ versus $[N\text{ ii}]/\lambda H\alpha$) that are close together in wave-
length space, to minimize the impact of reddening. A typical
BPT diagram is shown in Figure 1, along with various boundary
lines between different types of galaxies with narrow-line emis-
sion. Kewley et al. (2001) developed a conservative boundary
between star formation and AGN activity based on theoretical
modeling, shown as a solid curve in Figure 1; galaxies lying
above and to the right of the Kewley line are unambiguously
AGNs. A looser, empirical boundary was used by Kauffmann
et al. (2003) to identify Sloan Digital Sky Survey (SDSS) star-
forming galaxies by their line ratios; it is shown as a dashed curve in Figure 1. There is a further distinction for the ob-
jects which fall outside the star formation boundary: those with
log($[O\text{ iii}]/\lambda H\beta$) $> 0.48$, are known as high-ionization Seyfert
galaxies, and those with log($[O\text{ iii}]/\lambda H\beta$) $\leq 0.48$ are known as low-ionization nuclear emission regions (LINERs; Heckman 1980). The Seyfert–LINER boundary is indicated by the hori-
zontal line in Figure 1. While many LINERs have been demonstr-
ated to be powered by accretion activity, there are other pro-
cesses such as shocks that can lead to LINER-like line ratios
(see review in Ho 2008). Caution and auxiliary data are often
required to determine the nature of distant LINERs.

It is, of course, important to remember that all AGN selection
techniques are biased in different ways, and depend on the
depths and apertures of individual surveys. Since UHECR
source candidates are closer than about 100 Mpc, and star-
forming regions with enough emission to be confused with an
AGN are larger than $\sim 10$ pc, X-ray observation with Chandra
resolution can decide whether a UHECR candidate source is
an AGN or not. In the radio, detection of jets unambiguously
identifies an AGN. If no jets are seen, the presence of an
AGN can be inferred if there is a compact source at the
center of the galaxy whose radio emission exceeds that which
would be expected for a nuclear star burst region based on the
far infrared–radio relation (Condon 1992). For nearby AGNs,
optical emission line surveys are probably the most complete
(e.g., Heckman et al. 2005; Ho 2008). Note, however, that
Reviglio & Helfand (2006) find that about half the AGNs
detected in their sample using radio or X-ray selection are not
identified by the BPT criteria discussed above.

4. UHECR-CORRELATED VCV GALAXIES

Auger has published 27 UHECRs with energies above 57
EeV, 20 of which are correlated with a VCV galaxy closer than $z = 0.018$ (Auger07a,b). That is our basic UHECR sample for this study. The 20 UHECRs are correlated with 21 VCV galaxies. Table 1 shows the 20 correlated UHECRs and the 21 associated VCV galaxies. For each VCV galaxy, we verify the VCV classification using both the literature and the available optical spectra. Six of the galaxies show unambiguous signatures of nuclear activity: five broad-line
AGNs and NGC 5128 (Cen A), a well-known FRI radio galaxy with a possible BL Lac nucleus (Israel 1998). The remaining
15 galaxies are potential narrow-line AGNs and have to be
evaluated individually. Figure 1 is a BPT diagnostic diagram
using log($[O\text{ iii}]/\lambda H\beta$) versus log($[N\text{ ii}]/\lambda H\alpha$), for 11 of the 15
galaxies. The four galaxies which cannot be plotted in Figure 1 consist of two AGNs, NGC 4945 and ESO 139-G12, and two
without nuclear activity, NGC 5244 and NGC 7135. The optical emission from NGC 4945 is highly obscured but its hard X-ray
spectrum clearly identifies AGN activity (Madejski et al. 2000).
ESO 139-G12 shows a hint of a broadened Hα line (Marquez et al.
2004) and is an AGN. NGC 5244 (Moran et al. 1996) and
NGC 7135 (Joguet et al. 2001) have almost no [O iii] emission;
they cannot be identified as AGNs from their optical spectra.

Eleven galaxies appear in Figure 1 of which six, shown as diamonds on the BPT diagram, fall comfortably in the Seyfert

Some VCV galaxies have two UHECRs within 3/2 and some UHECRs
have multiple VCV galaxies within 3/2.
region of the BPT diagram; these are clear AGNs. Two of the 11 (NGC 7591 and Q 2207+0122), shown as a triangle and an asterisk, fall below the Kauffmann et al. (2003) empirical star formation line and are not AGNs. The remaining three (NGC 2989, NGC 1204, IC 5169) are predominantly star-forming galaxies but may have limited AGN activity, contributing \( \lesssim 25\% \) of the total luminosity. Detailed information on each of the correlated VCV galaxies is given in Appendix A and summarized in Tables 2 and 3.

Figure 2 shows Auger’s 27 highest energy cosmic rays with the correlated UHECRs represented by 3\( \times \)2 circles and the uncorrelated ones represented by 8-point stars. The confirmed AGNs are shown as triangles and the other correlating VCV galaxies are shown as squares. Auger’s exposure cutoff at \( \delta = 25^\circ \) is indicated (cyan line) as is the Galactic plane band (|\( b | \) = \( \pm 10^\circ \)), where VCV is especially incomplete. The rest of the VCV galaxies with \( z \lesssim 0.018 \) are shown as points, color-coded in bins of redshift. In all, 14 of the 21 VCV galaxies, correlated with 14 UHECRs, are AGNs, while seven show limited or no sign of AGN activity. Radio or X-ray observations of these seven VCV galaxies which do not appear to be AGN are needed to determine whether they are, in fact AGNs.\(^7\) Sufficiently complete and well-characterized AGN catalogs will be crucial determining whether AGNs are the sources of most or all UHECRs.

### 5. BOLOMETRIC LUMINOSITIES

Under the widely used assumption of a universal spectral energy distribution (SED) for active galaxies, the bolometric luminosities may be estimated from measurements of a single line or in a single band. In most cases, we have flux measurements in only one waveband. In this paper, we use the following bolometric corrections for [O\( \text{iii} \)] and broad He\( \alpha \) emission:

\[
L_{\text{bol}} = 3500L_{[\text{O\( \text{iii} \)]}} \times (0.38 \text{dex variance})
\]

The conversion factor from the 2–10 keV X-ray luminosity to the bolometric luminosity, as determined by Vasudevan &

\(^7\) **Notes.** This table lists each Auger UHECR (with \( E > 57 \text{ EeV} \)) whose arrival directions are within 3\( \times \)2 of a nearby \((z \lesssim 0.018) \) VCV galaxy, along with the correlated VCV object. The year and the Julian day when the UHECRs were recorded are given, as well their energies and positions (equatorial and galactic) in degrees, from Auger07b. This is followed by the name of the VCV galaxy, its position in degrees, and its separation from the UHECR in degrees, its redshift, and the VCV classification (Note: Star-forming regions are also known as H\( \text{ii} \) regions because young stars ionize the hydrogen around them (neutral hydrogen is known as HI)). The last column shows the correct optical classification, taken from the literature where available and confirmed in every case.

**References.** (1) Schneider et al. 1994; (2) Kewley et al. 2001; (3) Sturm et al. 2006, Veilleux et al. 1995; (4) Israel 1998; (5) Moran et al. 1996; (6) Gonçalves et al. 1999; (7) Sturm et al. 2006, Veilleux et al. 1995; (8) Joggie et al. 2001.
Fabian (2007), is dependent upon the level of AGN activity; it is 15–25 for AGNs with Eddington ratios \((L_{\text{bol}}/L_{\text{Edd}})\) below \(-0.1\), and 40–70 for those with Eddington ratios above \(-0.1\). The Eddington luminosity, \(L_{\text{Edd}}\), is related to the SMBH mass, \(M\), by the relation \(L_{\text{Edd}} = 3.3 \times 10^{4} (M/M_{\odot}) L_{\odot}\). We were able to obtain SMBH mass estimates for four AGNs in our sample; two can be found in the literature and we derive two from the broad \(H\alpha\) luminosity and line width following Greene & Ho (2005). (See details in Appendix A.) All four have low Eddington ratios: 0.006, 0.015, 0.029, and 0.1. Therefore, in the absence of SMBH mass measurements for the rest, we use \(L_{\text{bol}} = 20 L_{2–10 \text{ keV}}\) for all.

In order to test the AGN-based UHECR acceleration models, we determine the bolometric luminosities for the correlated AGNs from \([\text{O} \text{ iii}]\), broad \(H\alpha\), or 2–10 keV emission. For the broad-line AGNs, the \([\text{O} \text{ iii}]\) and \(H\alpha\) luminosities are taken from published data when possible, or fit from available optical spectra. (See Appendix A for details.) We use multicomponent Gaussian models to fit for the broad \(H\alpha\) luminosities. When fitting for \([\text{O} \text{ iii}]\) luminosities, we assume only a single Gaussian. The 2–10 keV X-ray luminosities are collected from literature. There is one AGN (ESO 139-G12), for which neither a calibrated spectrum nor an X-ray detection is available, and we use the upper limit for the X-ray luminosity. The AGNs and their bolometric luminosities are given in Table 2.

For each AGN–UHECR pair, the figure-of-merit \(\lambda_{\text{bol}} \equiv L_{\text{bol}} 10^{-45} E_{20}^{-2}\) is determined. Out of the 13 UHECRs which are correlated with AGNs for which we were able to determine the bolometric luminosities, we see that only one UHECR correlates with an AGN having a value of \(\lambda_{\text{bol}} \geq 1\). Another five UHECRs are correlated with AGNs whose luminosity is within a factor of 2 of the minimum. Given the rough nature of the \(\lambda_{\text{bol}}\) bound, these AGNs may have sufficient power to accelerate their associated UHECRs. However, seven correlated UHECRs are associated with AGNs that fall far short of the minimum power. This poses a serious problem for conventional models of UHECR acceleration in continuous AGNs, although it is compatible with the recently proposed giant AGN flare scenario of Farrar & Gruzinov (2009).

6. POSSIBLE THRESHOLD IN BOLOMETRIC LUMINOSITY

We have seen in Section 5 that only one of the AGNs correlated with UHECRs satisfies the naive limit for UHECR acceleration. We seek in this section to determine whether correlated AGNs show any threshold bolometric luminosity—such a threshold would elucidate the nature of the UHECR acceleration mechanism, and as we shall argue, can account for puzzling features of present observations.

One puzzling aspect of the observed correlation of Auger UHECRs with nearby VCV galaxies is the lack of UHECRs from the Virgo Cluster, which contains M87, a well-known radio galaxy (Auger07b). While this may simply be a statistical fluctuation, it seems surprising due to the Virgo Cluster’s proximity, and the very large number of VCV galaxies in the Virgo region (Gorbunov et al. 2008). The possibility that the lack of correlated events from Virgo is not a statistical fluctuation motivates us to further investigate the AGN-as-UHECR-source ansatz by looking for some systematic difference(s) in the properties of the Virgo VCV galaxies compared to the AGNs which correlate with UHECRs. Therefore, we have conducted the same analysis for VCV galaxies in Virgo. We examined the VCV galaxies within a circle of radius 15° centered on the Virgo Cluster at \(\alpha_{2000} = 12:26:32.1, \delta_{2000} = +12:43:24\) (Binggeli et al. 1987) and \(z \leq 0.009\), which are in the Virgo Cluster\(^8\). There are a total of 30 VCV galaxies which satisfy

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\(^8\) We take galaxies which are listed as belonging to the Virgo Cluster by Ho et al. (1997a) or are not in the Ho et al. (1997a) survey sample.
these criteria. VCV classifies five of them as H ii galaxies. One other galaxy was also found to be an H ii galaxy. We can determine the bolometric luminosities of 23 out of the remaining 24. In 18 cases we use the measured 2–10 keV X-ray luminosities (Ho et al. 2001; Terashima et al. 2002; Satyapal et al. 2005; González-Martín et al. 2006; Panessa et al. 2006; Horst et al. 2008; Kandalyan 2005), and for the five for which X-ray luminosities are not available we use the measured [O iii] luminosity (Shields et al. 2007; Höf et al. 1997a). There is some evidence that the [O iii] to bolometric luminosity conversion depends on luminosity or Eddington ratio (e.g., Netzer et al. 2006). Since optical emission line fluxes, particularly Hα, may be contaminated by non-nuclear sources (e.g., Ho et al. 2001) we have chosen to use the hard X-ray flux as a bolometric indicator whenever possible.

The bolometric luminosities of the Virgo AGNs, listed in Appendix B, are systematically lower than those of the AGNs correlated with UHECRs (which span the range $5 \times 10^{42}$ to $1 \times 10^{46}$ erg s$^{-1}$). Of the Virgo AGNs, only two have bolometric luminosities in the range of the correlated AGNs (NGC 4338 and NGC 3976, with luminosities of $1.1 \times 10^{45}$ erg s$^{-1}$ and $4.6 \times 10^{45}$, respectively) and three others (NGC 4486 [M87], NGC 4579, and NGC 4698) have bolometric luminosities within a factor of 5 lower. The remaining 18 have bolometric luminosities ranging from $10^{43}$ erg s$^{-1}$ to $10^{44}$ erg s$^{-1}$, far below the bolometric luminosities of AGNs correlated with UHECRs. A histogram of the bolometric luminosities of the Virgo AGNs, compared with that of the AGNs correlated with UHECRs, is shown in Figure 3. The abundance of known low-luminosity AGNs in Virgo is due to the sensitive Palomar spectroscopic survey of nearby galaxies in the northern hemisphere by Ho et al. (1995), which found AGNs in ~60% of bulge-dominated galaxies (Ho et al. 1997b; Ho 2008).

It may be that the accretion activity of these very low-luminosity AGNs is too low for them to be sources of UHECRs.

A lower bound on the quiescent accretion rate might be expected if UHECRs are accelerated in intense, month-long, giant AGN flares, triggered when the tidal stream of a star disrupted by an SMBH interacts with an existing accretion disk, as proposed by Farrar & Gruzinov (2009). Note that if there is a threshold accretion luminosity, it may be larger than $L_{bol,min}$ of the correlated AGNs, since ~3 of the correlated AGNs are presumably chance associations, and the AGN luminosity function increases at low luminosities (Ho et al. 1995).

Another puzzle is the lack of significant correlation between UHECRs and VCV galaxies reported by the HiRes Collaboration (Abbasi et al. 2008). If UHECRs are preferentially accelerated by AGNs above a threshold bolometric luminosity, then one would expect a reduced degree of correlation significance.
observed by northern hemisphere experiments such as AGASA and HiRes, compared to what is seen by Auger in the southern hemisphere. This is because a substantial fraction of the VCV northern hemisphere AGNs are LLAGNs (Ho et al. 1995) and 14% of Auger’s exposure and 84% of HiRes’ exposure are from the northern hemisphere. We can estimate the degree of dilution in the VCV catalog for $z \leq 0.018$ in the HiRes exposure compared to that in the Auger exposure as follows. The Ho et al. (1995) survey included 417 emission line galaxies with $z \leq 0.018$. They report that about 50% are AGN, with median $L(\text{H}\alpha) = 2 \times 10^{39} \text{erg s}^{-1}$, which roughly corresponds to our empirical UHECR threshold $L_{\text{bol,min}} = 5 \times 10^{42} \text{erg s}^{-1}$. Thus, at least $\approx 105$ of the VCV galaxies in the northern hemisphere with $z \leq 0.018$ are LLAGNs. The exposure-weighted average fraction of LLAGNs and H II galaxies compared with total VCV galaxies is $\approx 0.443$ for HiRes, but only $\approx 0.193$ for Auger. This is a concrete illustration of the systematic differences in completeness and purity, between the portions of the VCV catalog used by the two UHECR experiments.

7. INFRARED LUMINOSITIES

An interesting question is whether the correlated VCV galaxies which are not optical AGNs have any common properties. One relevant property could be the total infrared luminosity, which is sensitive to both star formation and nuclear activity. In fact, there is circumstantial evidence that accretion is accompanied by significant star formation (e.g., Sanders & Mirabel 1996; Kauffmann et al. 2003), although the temporal coincidence of the two is a matter of debate (Ho 2005). It is certainly theoretically plausible that the large gas accretion episodes leading to AGN activity are accompanied by significant star formation events, and correspondingly elevated dust levels. Sufficiently dense and dusty star formation, such as that seen in ultra-luminous infrared galaxies, may in principle completely obscure AGN activity.

We determine the IR luminosities of the seven VCV galaxies that are not AGNs from IRAS fluxes following the prescription of Sanders & Mirabel (1996):

$$ F_{\text{IR}} = 1.8 \times 10^{-14} \left[13.48 f_{12} + 5.16 f_{25} + 2.58 f_{60} + f_{100}\right] \text{W/m}^2, $$

$$ L_{\text{IR}} = 4\pi D_L^2 F_{\text{IR}}, $$

where $D_L$ is the luminosity distance of the galaxy, and $f_{12}$ to $f_{100}$ are the IRAS fluxes. One of these nonoptical-AGN galaxies is a luminous infrared galaxy (LIRG) (high rate of star formation: $11 < \log\left[L_{\text{IR}}/L_\odot\right] < 12$), four are starburst galaxies ($10 < \log\left[L_{\text{IR}}/L_\odot\right] < 11$), one is a quiescent galaxy ($\log\left[L_{\text{IR}}/L_\odot\right] < 10$), and one has very low luminosity—it is in fact a dwarf galaxy. The infrared luminosities and classifications of these galaxies are listed in Table 3. For completeness, we also calculate the IR luminosities of the AGN and include them in Table 2. Sanders & Mirabel (1996) report that about 15% of LIRGs are Seyferts and another 35% are LINERs, whereas for starburst galaxies the LINER fraction is about the same but $\lesssim 5\%$ are Seyferts.

8. NOTE ADDED—MOSKALENKO ET AL. (2009)

While this paper was being reviewed by the Pierre Auger Collaboration Publication Committee (submitted on April 27, approved on 2008 May 28) a paper appeared by Moskalenko et al. (2009; MSPC below), which takes a complementary approach to ours, examining the radio morphology and luminosity of galaxies that might be the sources of the Auger UHECRs. MSPC extend the set of candidate sources to include 27 galaxies: 19 of the 21 VCV galaxies considered here, plus eight more galaxies with $z \leq 0.018$ that are also candidate AGNs according to the NASA Extragalactic Database (NED) but which do not appear in the VCV catalog, plus an additional 27 galaxies from VCV and NED in the redshift range $0.018-0.037$. The 19 VCV $z \leq 0.018$ galaxies that MSPC consider are those in our Table 1, less SDSS J03349–0548 and ESO 383-G18. The former is removed because they exclude SDSS galaxies (except that SDSS J053302–0532 is in their sample as NGC 1346) but we do not understand why they do not include ESO 383-G18.

Of the 54 galaxies considered, MSPC reports that four of them display the powerful jets or radio lobes expected for UHECR sources: two in each of their redshift bins. One of the two in the lower redshift bin, Cen A (NGC 5128) with $\lambda_{\text{bol}} = 0.03$, is in our sample and the other, PKS 1343–60, is not. We examine the optical properties of PKS 1343–60 found in the literature. Although it has a bright optical nucleus, the emission is highly absorbed and it could not be classified as an AGN using optical criteria, which most likely explains its absence from the optically

### Table 3

| AGN     | Auger Year, Day | $E$ (EeV) | $r$ (deg) | $z$ | $\log([\text{N} II]/\text{H}\alpha)$ | $\log([\text{O} III]/H\beta)$ | $\log(L_{\text{IR}}(8–1000 \mu\text{m}))$ | Type         |
|---------|----------------|-----------|-----------|-----|----------------------------------|-----------------------------|---------------------------------|-------------|
| NGC 2989| 2007, 84       | 64        | 3.00      | 0.013| $-0.28$                          | $0.23$                     | $10.48$                         | Starburst (AGN $\lesssim 20\%$) |
| NGC 7591| 2006, 185      | 83        | 3.04      | 0.017| $-0.32$                          | $-0.35$                    | $11.07$                         | LIRG        |
| NGC 1204| 2007, 145      | 78        | 1.57      | 0.014| $-0.11$                          | $-0.47$                    | $10.83$                         | Starburst (AGN $\lesssim 25\%$) |
| NGC 5244| 2006, 299      | 69        | 2.70      | 0.008| ...                              | ...                        | ...                             | Starburst   |
| IC 5169 | 2005, 295      | 57        | 2.13      | 0.010| $-0.17$                          | $0.20$                     | $10.36$                         | Starburst   |
| NGC 7135| 2007, 193      | 90        | 2.12      | 0.007| ...                              | ...                        | 9.42                            | Quiescent   |
| Q 2207+0122| 2005, 63    | 71        | 3.16      | 0.013| $-1.58$                          | $0.82$                     | ...                             | Dwarf Galaxy|
|         | 2007, 51       | 58        | 1.58      |       |                                  |                            |                                 |             |
identified VCV catalog. We note that while Cen A has the largest radio flux of their candidate sources, 54 Jy, its extreme proximity makes it a weaker radio source than PKS 1343−60 with 23 Jy.

For completeness, we have extended the study reported in Section 4, to include the eight new AGN candidates with $z \leq 0.018$ within 3°2 of an Auger UHECR introduced by MSPC. Only two have published optical line fluxes, WKK 4374 (IGR J14515−5542) and NGC 7626. The former, WKK 4374, is a narrow-line Seyfert (S2) with $L_{bol} = 1.9 \times 10^{44}$ erg s$^{-1}$ (Masetti et al. 2006) and $\lambda_{bol} = 0.46$; intriguingly, it correlates with a previously uncorrelated UHECR (Auger year, day = 2007, 186; $E = 64$ EeV). The latter, NGC 7626, is a LINER with $L_{bol} = 1.2 \times 10^{42}$ erg s$^{-1}$ (Ho et al. 1997a), $\lambda_{bol} = 0.002$. It is also radio loud, confirming that it is an AGN. Two of the UHECRs whose VCV-correlated galaxies were found here to not be identifiable AGNs, (2006, 185; 83 EeV, correlated with NGC 7591) and (2007, 84; 64 EeV; correlated with NGC 2989), correlate with the new “MSPC” source candidates NGC 7626 and NGC 2907, respectively. NGC 2907 is determined to have LINER-like emission lines (Mauch & Sadler 2007) but further data are needed to determine whether it meets optical AGN criteria. The remaining five also do not have enough published optical emission line information to establish them as optical AGNs.

The main result of MSPC is that apart from the four galaxies with powerful jets or radio lobes, their other source candidates have no special features that distinguish them from generic Seyferts and LINERs. On that basis, they conclude that the UHECR–AGN correlation must be due to chance, under the assumption that UHECR acceleration is not episodic in nature.

9. SUMMARY AND CONCLUSIONS

We have examined the 21 galaxies from the VCV catalog with $z \leq 0.018$ which are within 3°2 of the 27 highest energy cosmic rays, and eight additional AGNs from NED introduced by Moskalenko et al. (2009). We find that 14 of the 21 VCV galaxies are AGNs and the other seven are either star-forming or quiescent galaxies. X-ray or radio observations are needed to find out if any of these seven have obscured nuclear activity at an interesting level. Two of the eight additional NED galaxies can be optically established as AGNs (one is a Seyfert 2, one a LINER, and six do not have adequate optical spectra to make a determination). The new optically identified AGN, WKK 4374, increases by one the number of UHECR-AGN correlations, because it is within 2°8 of a previously uncorrelated UHECR.

We have determined the spectral type and bolometric luminosity of the 14 VCV AGNs and the newly identified AGN. Their luminosities range from $5 \times 10^{42}$ erg s$^{-1}$ to $1 \times 10^{46}$ erg s$^{-1}$. Five are broad-line, nine are narrow-line, and one is an FRI radio galaxy. Hao et al. (2005b) find that the numbers of broad-line and narrow-line AGNs are comparable at low and moderate luminosity, while at high luminosity, broad-line AGNs far outnumber narrow-line ones. Thus, the AGNs possibly producing the observed UHECRs are representative of the population of moderate luminosity AGNs both in luminosity and type.

We have also identified and determined the bolometric luminosities of the Virgo AGNs and LINERs. Most have luminosities more than an order of magnitude below the lowest luminosity of any AGN correlated with a UHECR. (A large number of low-luminosity AGNs and LINERs are known in Virgo, due to the Ho et al. (1995) high-sensitivity spectroscopic survey of the near-by galactic nuclei in the northern hemisphere.) A minimum bolometric luminosity requirement for UHECR-accelerating systems may therefore explain the absence of UHECRs correlated with Virgo AGNs. If there is such a threshold, the significance of correlations between UHECRs observed by northern hemisphere observatories and VCV galaxies would be reduced in comparison to that observed by Auger South, due to a greater dilution of the VCV catalog in the northern hemisphere by large numbers of known very low luminosity AGNs. A threshold in the bolometric luminosity is consistent with the giant AGN flare scenario (Farrar & Gruzinov 2009), but is not predicted by it, since the properties of the remnant have not yet been modeled.

Altogether, 21 of the 27 Auger UHECRs are within 3°2 of a VCV galaxy or the newly identified AGNs. Of these, 17 of the 21 correlated UHECRs can be attributed to an identified AGN within 3°2 and $z \leq 0.018$. However, few of the correlated AGNs satisfy the condition $L_{bol} \geq 10^{45} E^{2/3}_y$ erg s$^{-1}$, required to confine a cosmic ray as it is accelerated (Farrar & Gruzinov 2009). If correlated AGNs with inadequate bolometric luminosities are in fact the sources of most of these UHECRs, their luminosities present a puzzle to the conventional picture of AGN acceleration in a continuous jet. The recent analysis of Moskalenko et al. (2009) finds that few of the correlated AGNs have powerful radio jets or lobes, corroborating this conclusion. If the AGN–UHECR correlation is a real one, these results provide evidence in favor of the new mechanism of UHECR acceleration by giant AGN flares proposed by Farrar & Gruzinov (2009), in which a modest AGN has an intense flare producing a jet of the required luminosity (initiated for instance by a stellar tidal disruption rapidly heating the accretion disk) and then reverts to a mild-mannered existence.

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APPENDIX A

NOTES ON INDIVIDUAL OBJECTS

The 21 VCV galaxies correlated with Auger UHECRs with energy above 57 EeV are comprised of one FRI radio galaxy (Centaurus A), five broad-line AGNs (Seyfert 1 galaxies), eight narrow-line AGNs (Seyfert 2 galaxies), and seven (non-optical-AGN) emission line galaxies. In this section, we give detailed information on the identification and properties of each of these galaxies.

A.1. Centaurus A

Centaurus A (NGC 5128) is a well-known, near-by (3.4 Mpc) FRI radio galaxy. Its nuclear activity is manifested by large radio/X-ray jets—radio plumes extending to 250 kpc, and a compact circumnuclear disk. The multiwavelength variability of the nucleus, its polarization, and ionization of the optical filaments suggest that Cen A contains a misaligned BL Lac/blazar nucleus (Israel 1998). Rothschild et al. (2006) report a 2–10 keV X-ray flux which varies between 1.69 and $3.23 \times 10^{-10}$ erg s$^{-1}$ cm$^{-2}$ in six observations between 1996 August and 2004 February with the PCU instrument on Rossi X-ray Timing Explorer RXTE.
A.2. Broad-Line AGNs (Seyfert 1 Galaxies)

SDSS J03302−0532 (J033013.26−053235.9). The optical spectrum shows broadened Hα and Hβ lines. We fit multi-Gaussian models to the spectrum. Galaxy subtraction is performed using the principle component analysis code of Hao et al. (2005a), and the narrow lines are modeled as outlined in Greene & Ho (2004); see also Ho et al. (1997c). Following Greene & Ho (2005), the AGN luminosity is measured from the Hα line and the velocity dispersion is measured from the Hα line width (for details see Greene & Ho 2007). The black hole masses for the SDSS objects are estimated from the broad Hα luminosity and line width using the relation $M_{\text{BH}} = 2.0 \times 10^6 \frac{L_{\text{H} \alpha}}{10^{43} \text{erg s}^{-1}} 0.55^{\text{FWWHM}_{\text{H} \alpha}}^{-2.06} M_{\odot}$ following Greene & Ho (2005). We find: FWHM(Hα) = 5340 km s$^{-1}$, log($L$(Hα)) = 40.83 erg s$^{-1}$, log($L$(O iii)) = 39.50 erg s$^{-1}$, $M_{\text{BH}} = 7.2 \times 10^7 M_{\odot}$, $L_{\text{bol}}/L_{\text{Edd}} = 0.006$.

SDSS J03349−0548 (J033458.00−054853.2). The optical spectrum shows broadened Hα and Hβ lines. We fit the spectrum as described for SDSS J03302−0532 and find: FWHM(Hα) = 4390 km s$^{-1}$, log($L$(Hα)) = 40.10 erg s$^{-1}$, log($L$(O iii)) = 39.30 erg s$^{-1}$, $M_{\text{BH}} = 6.6 \times 10^7 M_{\odot}$, $L_{\text{bol}}/L_{\text{Edd}} = 0.015$.

$\text{Zw 374.029 (CGCG 374−029)}$. A broadened Hα line can be seen in the optical spectrum with a broad Hα FWHM of 2048 km s$^{-1}$ (Kollatschny et al. 2000). We have fit a single Gaussian to the narrow [O iii] line and find $F$(O iii) = 2.74 $\times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$.

NGC 424. The broad Hα and Hβ lines were detected in polarized emission by Moran et al. (2000). They report an Hα FWZI of 4400 km s$^{-1}$. They classify it as an intermediate Seyfert (S1.5) due to the absence of a broadened Hβ line. They report a dereddened broad Hα flux of $F$(Hα) = 3.3 $\pm$ 0.8 $\times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$, and a 2–10 keV X-ray flux of $F_{2–10\text{keV}}$ = 3.6 $\times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$.

A.3. Narrow-Line AGNs (Seyfert 2 Galaxies)

NGC 5506. The optical spectrum for NGC 5506 has strong [O iii] and [N ii] narrow lines. The log($L$(O iii)/Hβ) and log($L$(N ii)/Hα) line ratios, 0.88 and −0.09 respectively (Kewley et al. 2001), place it firmly in the Seyfert 2 region of the BPT diagram. Gu et al. (2006) report an [O iii] flux, $F$(O iii) = 1614.0 $\times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$ and an X-ray luminosity, log($L_{2–10\text{keV}}$) = 42.89 erg s$^{-1}$.

IC 5135 (NGC 7130). The optical spectrum for IC 5135 has strong [O iii] and [N ii] narrow lines. The log($L$(O iii)/Hβ) and log($L$(N ii)/Hα) line ratios, 0.6990 and −0.0231 respectively (Vaceli et al. 1997), place it in the Seyfert 2 region of the BPT diagram. Shu et al. (2007) report an [O iii] luminosity, log($L$(O iii)) = 42.55 erg s$^{-1}$.

MRK 607 (NGC 1320). The log($L$(O iii)/Hβ) and log($L$(N ii)/Hα) line ratios for MRK 607, 1.0458 and −0.1498 respectively (Vaceli et al. 1997), place it in the Seyfert 2 region of the BPT diagram. Shu et al. (2007) report an [O iii] luminosity, log($L$(O iii)) = 41.05 erg s$^{-1}$.

IC 4518A. We fit for the narrow lines in the optical spectrum of IC 4518A (courtesy of N. Masetti). The log($L$(O iii)/Hβ) and log($L$(N ii)/Hα) line ratios (courtesy of J. Moustakas), 0.839 and −0.199 respectively, place it in the Seyfert 2 region of the BPT diagram. We fit a single Gaussian to the [O iii] line and obtain a flux of $F$(O iii) = 1.20 $\times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$.

NGC 1358. The log($L$(O iii)/Hβ) and log($L$(N ii)/Hα) line ratios, 1.0542 and 0.3032 respectively (Ho et al. 1997a), place it in the Seyfert 2 region of the BPT diagram. Shu et al. (2007) report an [O iii] luminosity, log($L$(O iii)) = 40.86 erg s$^{-1}$. The SMBH mass is determined to be 6.56 $\pm$ 2.50 $\times 10^7 M_{\odot}$ (Wu & Han 2001). This implies an Eddington ratio of 0.029.

ESO 383-G18. The log($L$(O iii)/Hβ) and log($L$(N ii)/Hα) line ratios for ESO 383-G18, 0.9289 and −0.6327 respectively (de Grijp et al. 1992), place it in the Seyfert 2 region of the BPT diagram. Gu et al. (2006) report an [O iii] flux, $F$(O iii) = 360.9 $\times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$.

NGC 4945. Optical emission from NGC 4945 is highly obscured. Even X-rays below 10 keV are absorbed by a column of $N_H = 4.5 \times 10^{24}$ cm$^{-2}$, but NGC 4945 is one of the brightest Seyfert galaxies at 100 keV, indicating an active nucleus (Madejski et al. 2000). From its 1–500 keV X-ray luminosity, Madejski et al. (2000) estimate the bolometric luminosity to be $\sim 2 \times 10^{43}$ erg s$^{-1}$. The mass of the SMBH has been determined from circumnuclear H$_2$O masers to be $\sim 1.4 \times 10^6 M_{\odot}$, which implies that the Eddington ratio of NGC 4945 is $\sim 0.1$ (Greenhill et al. 1997).

ESO 139-G12. The optical spectrum for ESO 139-G12 (Márquez et al. 2004) does not extend to [O iii] and Hβ wavelengths, but the hint of a broadened Hα line indicates that it is an AGN. Since the spectrum is not flux calibrated, we use the upper limit for the X-ray luminosity from Pelletta et al. (1996), $L_{2–10\text{keV}} < 47.56 \times 10^{42}$ erg s$^{-1}$.

A.4. Non-AGN Emission Line Galaxies

NGC 2989. VCV identifies NGC 2989 as an H ii galaxy, Gonçalves et al. (1999) (NB: co-authors are Veron-Cetty and Veron) classify this as a pure H ii galaxy. Since the spectrum is not flux calibrated, we use the upper limit for the X-ray luminosity from Pelletta et al. (1996), $L_{2–10\text{keV}} < 47.56 \times 10^{42}$ erg s$^{-1}$.
and LINER and classify it as a Seyfert even though no radio core was detected and the radio continuum is dominated by star formation. They place a limit on the AGN component of 25% of the total emission of the galaxy.

**NGC 5244.** While the optical spectrum for NGC 5244 (Moran et al. 1996) has [N ι] and Hα emission lines, [O ι] and Hβ lines are not apparent. Moran et al. (1996) classify it as an H ι galaxy and VCV also identifies it as an H ι galaxy.

**IC 5169.** Kewley et al. (2001) classify this as an H ι galaxy based on the following line ratios, log([O ι]/Hβ) = 0.20, log([N ι]/Hα) = −0.170, log([O ι]6300/Hα) = −1.49, and log([S ι]6717,31/Hα) = −0.55. While it falls between the Kauffmann et al. (2003) and Kewley et al. (2001) lines in the log([O ι]/Hβ) versus log([N ι]/Hα) diagram, it falls well within the star formation line in log([O ι]/Hβ) versus log([S ι]6717,31/Hα) and log([O ι]/Hβ) versus log([O ι]6300/Hα) diagrams, confirming that it is not an optical AGN.

**NGC 7135.** Joguet et al. (2001) classify NGC 7135 as a star forming galaxy based on the fact that the [O ι] emission line is very weak, EW([O ι]) = −0.7 A, and that strong stellar absorption features are visible, determining it to be “an early-type galaxy with no active nucleus.”
emission line fluxes, particularly Hα, may be contaminated by non-nuclear sources (e.g., Ho et al. 2001) we have chosen to use the hard X-ray flux as a bolometric indicator whenever possible.

**APPENDIX C**

**NOTES ON THE AGNs FROM THE NASA EXTRAGALACTIC DATABASE**

Moskalenko et al. (2009) lists eight additional AGNs within 3/2 of the Auger CRs with $z \leq 0.018$, based on the classifications in the NED. Some of them were determined to be AGNs after the publications of the VCV 12th edition. Others were selected as AGNs mainly via X-ray, infrared, or radio criteria and list their optical properties below.

**PKS 1343−60** (Centaurus B). Cen B is a well-known FRI radio galaxy. However, while an optical counterpart for the active nucleus has been detected (West & Tarenghi 1989), the optical emission is highly absorbed and no clear emission lines or line ratios could be obtained from the optical spectrum beyond the detection of the Hα−[N II] complex.

**NGC 5064**. Bonatto et al. (1989) reported a [N II]/Hα value of 1.051 and [S II]/Hα value of 0.461. No [O II], Hβ or [O I] line fluxes were reported. This indicates that NGC 5064 is a LINER. The authors determined this LINER to be nuclear powered rather than shock powered.

**IRAS 13028−4909**. This galaxy is from a set of X-ray and IR-selected AGNs (Kirhakos & Steiner 1990). An [N II]/Hα ratio of 1.28 was reported. No other line fluxes or ratios were given.

This casts doubt on the strength of its nuclear activity based on optical data. Data from other wavelengths have not been published.

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