CHANDRA OBSERVATIONS OF AGN-CANDIDATES CORRELATED WITH AUGER UHECRS

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ABSTRACT

The Auger observatory has observed a possible correlation between Ultrahigh Energy Cosmic Rays (UHECRs) above 57 EeV and nearby candidate Active Galactic Nuclei (AGN) from the Veron-Cetty Veron catalog (VCV). In this paper we report on Chandra X-ray observations of 10 unconfirmed VCV AGN-candidates and luminous IR galaxies correlating with the first set of Auger UHECRs, to determine whether or not they have active nuclei. The X-ray data, when combined with optical luminosities, show that in fact none of the 10 galaxies have a significant AGN component; if there is any nuclear activity at all, it is weak rather than obscured. This reduces the number of UHECRs in the original Auger dataset possibly correlating with AGNs from 20 of 27 down to 14 of 27. We also used Chandra to measure the X-ray luminosity of ESO 139-G12, an AGN which correlates with 2 of the Auger UHECRs, to obtain the first estimate of its bolometric luminosity; this completes the determination of the bolometric luminosities of all correlating AGNs. Taking our results into account, only one of the 27 UHECRs in the original Auger data-release is correlated on a few-degree angular scale with an identified AGN that is powerful enough in its steady-state to accelerate protons to the observed energies, according to conventional acceleration mechanisms. Intriguingly, ≈ 60% of the UHECRs with $|b| > 10^\circ$ do correlate with genuine AGNs, but these are too weak to meet the acceleration criterion for protons; this may be an indication that AGNs experience transient high-luminosity states which can accelerate UHECRs. To determine the source(s) and composition of UHECRs through statistical correlation studies requires reliable, complete and uniform catalogs of identified AGNs; our a posteriori inspection of ambiguous source candidates underscores the inadequacies of the VCV catalog in this respect.

1. INTRODUCTION

Identifying the sources of ultra-high energy cosmic rays (UHECRs) is one of the major outstanding goals in astrophysics. Progress has proven difficult due to the rarity of high energy events and because the deflections of the cosmic rays as they travel through intergalactic magnetic fields mean that the cosmic ray arrival directions do not point back to their origins. The very most energetic cosmic rays ($E \gtrsim 6 \times 10^{19}$ eV) have attracted attention as a
promising path forward. The energy loss due to the GZK mechanism means that CRs with such energies typically have traveled about 100 Mpc, significantly limiting the possible sources for such high energy particles. Furthermore, at these energies magnetic deflections of protons may be small enough to allow the identification of the progenitor type based on statistical associations.

By 2007, the Pierre Auger Collaboration (2007, 2008) had compiled enough events to begin drawing statistical correlations between UHECR events and possible sources, and reported a strong correlation between UHECRs and the nearby galaxies listed in the Véron-Cetty and Véron (2006) Catalog of Quasars and Active Galactic Nuclei (12th Ed.) (The Pierre Auger Collaboration 2007). The scan procedure that was used steps through UHECR energy threshold, maximum angular separation, and maximum VCV galaxy redshift to find the values giving the lowest chance probability compared to an isotropic distribution, then evaluates the likelihood of such a correlation occurring by chance by performing the same analysis on many isotropic datasets. In the following, the term “correlated” referring to a galaxy with respect to a UHECR simply means that the given galaxy falls within the angular and redshift limits returned by applying the scan method with that galaxy catalog.

Of the 27 cosmic rays with energies above $57 \times 10^{18}$ eV that Auger detected before Aug. 31, 2007, twenty correlate within 3.2° with VCV galaxies having $z < 0.018$, about 75 Mpc (The Pierre Auger Collaboration 2008). Since more than one galaxy can be correlated with a UHECR and vice versa, there are 21 VCV galaxies correlated with these 20 UHECRs. Galaxy catalogs such as VCV are incomplete in the Galactic Plane, so a better comparison is obtained by restricting to $|b| > 10^\circ$ where the VCV catalog is more complete. With this restriction there are 22 UHECRs of which 19 UHECRs correlate with 20 galaxies (Zaw et al. 2009). This is a much higher correlation than would be expected by chance from an isotropic source distribution, and higher than can be explained by nearby galaxy clustering alone (Zaw et al. 2011). More recent Auger data continue to show a significant, albeit less strong, correlation with VCV galaxies (Abraham et al. 2009).

An important question is whether the observed correlation with VCV galaxies implies that AGNs are the sources of some or all UHECRs. The VCV catalogue is a list of AGN candidates, so first it must be established whether the correlating galaxies (i.e., the VCV galaxies within 3.2° of a UHECR) are actually AGNs or not. Zaw et al. (2009) looked at existing observations of the galaxies in VCV that were correlated with the first set of UHECRs and found that only 14 of the 21 galaxies show unambiguous evidence of AGN activity. Three show no signs of AGN activity, while the other four have ambiguous optical spectra. A widely used technique for optical identification of AGNs, so-called BPT line ratios, compares the relative strengths of diagnostic spectral lines (Baldwin et al. 1981). The BPT line ratios of the 4 ambiguous galaxies fall within the ranges classified by Kauffmann et al. (2003) as AGNs but they do not fall within the line-ratio ranges adopted by Kewley et al. (2001) as indicative of an active nucleus. AGN activity can often be obscured in the optical bands by dust obscuration, and the Kewley test excludes some known AGNs. Additionally, as many as half of AGNs that are selected based on radio or X-ray properties would not be identified by looking only at their BPT line ratios (Reviglio and Helfand 2006). Thus, determining whether these 4 ambiguous VCV galaxies have active nuclei requires observations outside of optical wavelengths.

The VCV galaxies are not the only population of nearby galaxies found to correlate with the Auger UHECRs. Berlind et al. (2010) find an anomalously large correlation between the Auger galaxies and nearby Luminous IR galaxies in the PSCz catalog. Restricting to $|b| > 10^\circ$ where PSCz is complete, 13 galaxies of $L_{IR} > 10^{10.5}L_{sun}$ correlate within 2.1° with one or more of the 22 Auger UHECR events. Some LIRGs contain
an active nucleus with dust absorbing the AGN radiation and re-emitting it thermally, giving rise to large IR luminosities. This raises the question of whether the LIRGs found to correlate may actually be AGNs. Berlind et al. (2010) showed that 6 of the 13 correlating IR galaxies are also in VCV and 5 of these do in fact host AGNs. The other 7 correlating IR galaxies lacked the observations needed to differentiate between star-formation and obscured nuclear activity.

A key distinguishing feature of active galaxies is that accretion-driven radiation produces a nearly flat spectrum from the IR to the X-ray, known as the broad-band continuum. Normal and starburst galaxies, on the other hand, have broadened blackbody spectra peaked sharply in the UV/optical. This means the X-ray to optical flux ratios are considerably harder for AGNs than for normal/starburst galaxies. If the active nucleus is obscured, the X-ray to optical ratio becomes even harder since dust absorbs UV and optical photons more readily than X-rays (Comastri et al. 2003). This makes X-ray observations, particularly when combined with observations in the near-IR, optical or UV, a powerful tool for identifying obscured AGNs.

In this paper we use X-ray observations to determine whether the 4 ambiguous VCV galaxies, and the 7 indeterminate PSCz galaxies, have active nuclei. We observed ten of these possible UHECR source galaxies using the Chandra X-ray satellite, while for IC 5169 we used data from a recent XMM-Newton observation.

Another interesting question is whether AGNs that correlate with UHECRs have any characteristic features which distinguish them from the AGNs that do not seem to correlate with UHECRs. A particularly relevant property is the luminosity of the AGN, as this helps to constrain the possible cosmic ray acceleration mechanisms (Farrar and Gruzinov 2008). Previously, reliable luminosities have been established for all but one of the correlating AGNs (Zaw et al. 2009, Berlind et al. 2010).

We observed the remaining AGN, ESO 139-G12, in order to obtain the first robust estimate of its bolometric luminosity.

2. OBSERVATIONS AND DATA REDUCTION

Each target was observed on the Chandra ACIS-I detector for 5 kiloseconds between January and August 2009. Data analysis was performed using the ciao data analysis software. All of the targets corresponded to an X-ray source. (Table 1).

For the Chandra observations, we used two different methods to estimate the X-ray energy flux. The direct method sums the energy received per unit time in the band of interest (2-10 keV) in a 2 arcsec window around the source using the eff2evt tool which takes into account both the quantum efficiency and the effective area corrections of the satellite. The flux is typically dominated by higher energy and less frequent events, making this technique vulnerable to Poisson fluctuations when the count rates are small. The second technique considers only the total counts received from the compact nuclear source, ignoring the energies of the photons, and assumes that the spectrum follows a power law with a spectral index of 2. Then webPIMMS can estimate the corresponding flux, including Galactic extinction from webPIMMS and assuming no intrinsic extinction. For the galaxies which are diffuse sources, we report only the direct measurement of the flux within 2 arcsec of the galactic center, as an upper limit on the possible nuclear emission.

We also analyzed the XMM-Newton observation of IC 5179. Using the source imaging PPS processing provided by XMM, we took the count rate on the EPIC pn camera (0.5-12 keV) and used webPIMMS to estimate the corresponding 2-10 keV flux of the source.

3. ANALYSIS AND RESULTS

X-ray to optical flux ratios provide a useful way to classify galaxies according to their nuclear activity. Barger et al. (2002) show that for AGNs, the ratio of the 2-10 keV flux to the R-band magnitude is typi-
The results are summarized in Table 1. The X-ray to optical ratios are far below what is expected from AGNs ($log(f_x/f_R) > -1$) for ten of the ambiguous or indeterminate galaxies: nine we observed with Chandra, and IC 5179 for which we used an XMM-Newton observation. This holds even when the larger of the two X-ray flux determinations is used to calculate the X-ray to optical flux ratios. Since our measure of nuclear activity depends on $log_{10}(f_x)$, it is relatively insensitive to the uncertainties inherent in the determination of the flux at these low count rates. We conclude that none of these galaxies have active nuclei.

The last of the indeterminate galaxies (2MASX J1 754-60) lacks the optical observations needed for the $log(f_x/f_R)$ test, but its X-ray emission is diffuse and weak, and its near-IR properties are similar to the other galaxies. Therefore we conclude that it is unlikely to host an AGN, certainly not one expected to be capable of UHECR acceleration.

Obscured AGN in X-ray surveys are often identified by the hardness ratio of the source. The hardness ratio is defined as $H - S / H + S$ where $H$ is counts from 2-8 keV and $S$ is counts from 0.5-2 keV. Typically, nearby AGN with column densities greater than $N_H \approx 10^{22}$ have positive hardness ratios, while unobscured sources have negative hardness ratios (Fiore et al. 2000). Table 1 gives counts from 0.5-10 keV and 2-10 keV. These can be used to estimate the hardness ratio since the small effective area of Chandra at high energies meant that no photons with

| Source Name | Obs ID | Total Counts (0.5-10 keV) | Hard Counts (2-10 keV) | Flux (Direct) | Flux (webPIMMS) | Rmag | Log($f_x/f_R$) | $L_{2-10}$ |
|-------------|-------|--------------------------|------------------------|--------------|-----------------|------|----------------|-----------|
| IC 5169     | 10265 | 17                       | 6                      | 3.3 E-14     | 1.4 E-14        | 12.5 | -3.0          | 7.4 E 39  |
| NGC 7591    | 10264 | 17                       | 2                      | 6.6 E -15    | 1.4 E -14       | 12.4 | -3.4          | 8.6 E 39  |
| NGC 1204    | 10256 | 13                       | 4                      | 1.3 E -14    | 1.2 E -14       | 13.6 | -2.9          | 5.8 E 39  |
| NGC 2989    | 10255 | 5                        | 2                      | 2.3 E -14    | 4.9 E -15       | 12.5 | -3.1          | 8.8 E 39  |
| IC 4523     | 10261 | 6                        | 5                      | 6.5 E -14    | 6.5 E -15       | 13   | -2.5          | 3.8 E 40  |
| ESO 270-G007| 10260 | 14                       | 5                      | 2.2 E -14    | –               | 13   | -3            | 8.4 E 39  |
| IC 5186     | 10259 | 5                        | 0                      | 5.8 E -16    | –               | 12.3 | -3.8          | 3.4 E 39  |
| ESO 565-G006| 10258 | 21                       | 8                      | 5.5 E -14    | 2.4 E -14       | 12.7 | -2.7          | 3.2 E 40  |
| NGC 7648    | 10257 | 5                        | 1                      | 3.0 E -15    | –               | 12.2 | -4.4          | 9.7 E 38  |
| 2MASX J1 754-60 | 10262 | 3                        | 1                      | 2.7 E -15    | –               | 12.3 | -4.4          | 9.7 E 38  |
| IC 5179     | XMM-Newton | 2685          | –                      | 9.1 E -14    | 11.4            | 12.9 | -0.2          | 2.9 E 43  |
| ESO 139-G12 | 10263 | 1070                     | 666                    | 4.7 E -12    | –               | 12.9 | -0.2          | 2.9 E 43  |

TABLE 1
Table listing source properties

REFERENCES. — (1) Lauberts and Valentijn (1989), (2) Doyle et al. (2005), (3) de Vaucouleurs and Longo (1988)

Note. — Fluxes are for 2-10 keV and are in cgs units (erg cm$^{-2}$ s$^{-1}$); only the direct flux determination method is used for diffuse sources. The 2-10 keV luminosity, $L_{2-10}$, is in units of erg s$^{-1}$ and is derived from the direct flux measurement; it is the total X-ray luminosity in the central region and thus an upper limit on X-ray luminosity of a possible AGN. The first four rows are the correlating host galaxies found in VCV. The following six are those from PSCz. The next row was observed by XMM-Newton: the counts are from 0.5-10 keV and the observation lasted 25000 secs. The last row is a known AGN whose X-ray luminosity had not previously been measured, needed to assess its ability to accelerate UHECRs.

(a) No counts above 2 keV. (b) Johnson magnitude rather than Cousins. This does not affect the result. (c) Derived from fit, see Figure 1.

$log(f_x/f_R) \equiv log_{10}(f_x) + 5.5 + A * R_{mag}$ where $f_x$ is the 2-10 keV flux.
Although *ESO 139-G12* is the only galaxy we observed which appears to have nuclear activity, it is always possible that the host galaxy simply dominates the AGN energetically, making the AGN impossible to detect. Therefore the 2-10 keV luminosity is given for the other galaxies as well. With an appropriate conversion factor, this can be used to get an upper limit on possible weak nuclear activity in the galaxy which may be of interest in other studies of UHECR sources.

5. CONCLUSIONS

These *Chandra* observations complete the task of determining which galaxies found to correlate with UHECRs by *The Pierre Auger Collaboration* (2007) and *Berlind et al.* (2010) have active nuclei, and of determining the bolometric luminosities of the AGNs correlating with UHECRs. The X-ray fluxes of the ten unclassified correlating galaxies we studied all fall within the range typical of normal and starburst galaxies of the same optical magnitude, hence we find no evidence of AGN activity in any of them.

Thus only 14 out of 27 UHECRs (13 out of 22 UHECRs with $|b| \geq 10^\circ$) correlate within 3.2$^\circ$ with an actual AGN, using the Auger scan method to correlate UHECRs with VCV galaxies but discarding candidate sources which are not in fact AGNs. Of the 13 highly luminous IR galaxies ($L_{IR} \geq 10^{11.5} L_\odot$) found to correlate within 2.1$^\circ$ with one (or more) of the 22 UHECRs with $|b| \geq 10^\circ$, we find that only five are also AGNs. Five of the 27 UHECRs, and one of the 22 UHECRs with $|b| \geq 10^\circ$, have neither an AGN nor a LIRG within 3.2$^\circ$ or 2.1$^\circ$ respectively. These uncorrelated UHECRs do not preferentially have low energies, for which sources are typically more distant, so the lack of correlation cannot be attributed entirely to incompleteness of the VCV or PSCz catalogs at larger distances.

2 Of course, it is impossible to rule out the possibility of very low luminosity nuclear activity which is energetically dominated by the host galaxy, but such weakly active AGN are not well-motivated candidates for UHECR acceleration.

3 We could not run this correlation for the full 27 UHECRs because IRAS does not observe within the Galactic plane.
redshifts.

The degree of correlation with VCV galaxies was found to be lower in the second Auger data release (Abraham et al., 2009). It has also been shown recently that the scan method itself is subject to large sample-to-sample variance and that it systematically tends to overestimate the degree of correlation (Farrar et al., 2011, in preparation). These facts may suggest that other candidate sources not associated preferentially with AGNs may be responsible for some, most, or all UHECRs. But other factors can contribute to a lack of correlation between UHECRs and AGNs as well, even if active galaxies are an important source of UHECRs: incompleteness of source catalogs (especially within the Galactic plane), magnetic deflection that obliterates angular correlation between the CRs and their true source (particularly for UHECRs with charge $Z > 1$), or transient production of UHECRs via exceptional, powerful flares in very weakly or non-active galaxies (Farrar and Gruzinov, 2009).

Another possibility raised by our results is that the VCV catalog may be so badly contaminated with non-AGNs, that the correlation analyses applied to the data up to now, c.f., Abraham et al., 2009), may be thrown off. The “spot check” of VCV provided by this work combined with (Zaw et al. 2009) is the most thorough to date, by providing definitive identifications of AGN candidates; if it gives a representative picture of the full VCV catalog, a third of the galaxies in the VCV catalog are not true AGNs. Earlier spot-checks using (incomplete) data available in the literature, but considering a larger angular region around UHECRs and/or later UHECR catalogs, e.g., Zaw et al., 2011, find that 1/4 - 1/3 of the AGN candidates in VCV are not AGNs. The impact of a contamination of this magnitude on statistical correlation analyses such as Auger’s scan method needs to be examined with simulations – it may bias the results in unpredictable ways.

The one established AGN which we observed in order to determine its bolometric luminosity, $ESO\ 139-G12$, proves to have $L_{bol}$ comparable to most of the other 13 correlated AGNs (Zaw et al., 2009). Knowledge of $L_{bol}$ and the energies of the correlated UHECRs (89 and 59 EeV) allows us to evaluate $\lambda_{bol} \equiv 10^{-45} L_{bol} E^{-2}_{100}$, the figure-of-merit introduced by Zaw et al., 2009) to quantify the ability of an AGN to accelerate a proton to the energy of the correlated UHECR. A value of $\lambda_{bol} \geq 1$ satisfies the acceleration criterion for protons (c.f., Farrar and Gruzinov, 2009). With $\lambda_{bol} \equiv 0.1$, $ESO\ 139-G12$ is weak for standard UHECR acceleration mechanisms.

6. Summary

Our observations and analysis using the Chandra X-ray satellite and other data establish that one-third of the 21 galaxies in the Veron-Cetty Veron catalog of AGN candidates found by The Pierre Auger Collaboration (2007) to correlate with UHECR arrival directions, do not in fact have active nuclei. Combining this with our measurement of the X-ray luminosity of $ESO\ 139-G12$, an AGN correlating with 2 UHECRs, implies that only one of the 27 UHECRs in that first Auger data-release correlates with an AGN that is powerful enough in its steady-state to accelerate protons to the observed energies, according to conventional acceleration mechanisms. However 60% of the UHECRs with $|b| > 10^\circ$ do correlate with genuine but weak AGNs, consistent with the possibility that AGNs may have a flaring state that can accelerate UHECRs (Farrar and Gruzinov, 2009). These results, along with the second Auger data release showing a lower correlation even with weak AGNs (Abraham et al., 2009), underscore the fact that the source(s) of the highest energy cosmic rays, as well as their composition, remains an open question.

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