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Fornax A, Centaurus A, and other radio galaxies as sources of ultrahigh energy cosmic rays

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ABSTRACT

The origin of ultrahigh energy cosmic rays (UHECRs) is still unknown. It has recently been proposed that UHECR anisotropies can be attributed to starburst galaxies or active galactic nuclei. We suggest that the latter is more likely and that giant-lobed radio galaxies such as Centaurus A and Fornax A can explain the data.

Key words: acceleration of particles – astroparticle physics – cosmic rays – galaxies: active – galaxies: jets – galaxies: starburst.

1 INTRODUCTION

Although their origin is unclear, ultrahigh energy cosmic rays (UHECRs) have often been posited to come from radio galaxies, the subclass of active galactic nuclei (AGNs) that is luminous at radio frequencies. One fundamental reason for this is that radio galaxies allow the Hillas (1984) criterion to be met; they are large, produce fast, energetic outflows, and have reasonably high magnetic fields. They are also known to produce high-energy electrons (e.g. Hargrave & Ryle 1974; Croston et al. 2009), thought to be mostly accelerated by diffusive shock acceleration (DSA; Axford, Leer & Skadron 1977; Krymskii 1977; Bell 1978; Blandford & Ostriker 1978) at termination shocks, which create the hotspots seen in Fanaroff & Riley (1974) (FR) type II sources.

Beyond this general physical reasoning, observational results from CR observatories have also hinted at an association between AGNs and UHECRs. Initial results from the Pierre Auger Observatory (PAO) indicated a tantalizing correlation between UHECR arrival directions and AGN source catalogues (Pierre Auger Collaboration et al. 2007). However, this correlation declined in significance as more data were obtained (Abreu et al. 2010) and subsequent studies found only low-significance departures from isotropy (e.g. Pierre Auger Collaboration et al. 2012).

Recently, results from the PAO indicated a large-scale anisotropy in the arrival directions of UHECRs (Pierre Auger Collaboration et al. 2017). Departures from anisotropy were also confirmed on intermediate angular scales (Pierre Auger Collaboration et al. 2018, hereafter A18), leading to a 4σ association with starburst galaxies (SBGs) and a slightly weaker association with γ-ray AGN from the second catalogue of hard *Fermi*-LAT sources (2FHL; Ackermann et al. 2016a). The radio galaxy Fornax A does not appear in the 2FHL catalogue. In this Letter, we show that including Fornax A in the analysis could explain the observed excess at southern Galactic latitudes, which could increase the significance of the γ-AGN association. We also outline the physical reasoning behind this and discuss parallels with Centaurus A and other sources. In addition, we show that the minimum power needed to accelerate protons up to 10 EeV can be supplied by jet outbursts in radio galaxies but not by starburst winds.

2 UHECR ARRIVAL DIRECTIONS

A18 analysed the PAO data set consisting of 5514 events above 20 EeV, finding that a number of models can provide a better fit than isotropy. In particular, a model involving SBGs is favoured over isotropy at the 4σ level, while their alternative models involving AGN attain lower significance (2.7σ–3.2σ). The threshold energy above which the correlation is evaluated is scanned by A18 to find the best value and the relevant statistical penalty is taken into account when evaluating the above significance levels. A18 find threshold energies of 39 EeV for SBGs and 60 EeV for γ-AGN.

The observed excess map above 60 EeV from A18 has two fairly clear hotspots (see their fig. 7). We do not have access to the A18 data set, but we can estimate the approximate positions of the hotspot centroids in Galactic coordinates as ($l = 308°$, $b = 26°$) (HS1) and ($l = 275°$, $b = -75°$) (HS2). We show the two hotspots in Fig. 1 using the same projection as used by A18, together with the 16 brightest radio galaxies from the van Velzen et al. (2012, hereafter vV12) radio catalogue. In the A18 SBG fit, HS1 can be attributed to combined UHECR emission from M83 and NGC 4945, while HS2 can be explained by NGC 253. In their γ-AGN fit, Centaurus A dominates the map with a small contribution from M87 (Virgo A); HS1 is associated with Centaurus A, while HS2 is unaccounted for.

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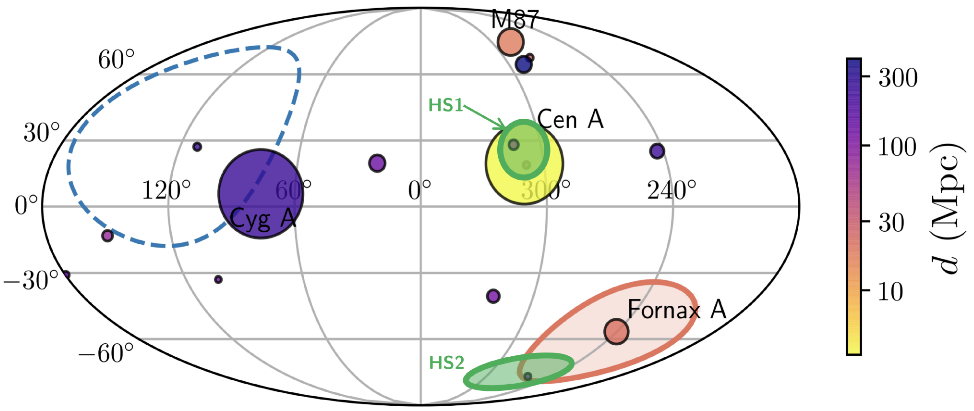

Figure 1. The positions of the 16 brightest radio galaxies in Galactic coordinates, with the area of the points proportional to 1.1 GHz radio flux and colour corresponding to distance from the Earth. The radio flux is calculated from table 2 of vV12. The orange circle around Fornax A illustrates a deflection angle of 22.5°, while the green shaded regions mark the approximate PAO excesses above 60 EeV (HS1 and HS2) from A18 as described in the text. The blue dashed line marks the area of the sky inaccessible to PAO. The projection is the same as that of fig. 7 of A18, with image coordinates (x, y) mapped to Galactic coordinates in degrees (l, b) by $x = \lambda \cos\theta$, $y = b$ where $\sin\theta = b/90°$ and $\lambda = -l$ (for $l \leq 180$), $\lambda = 360° - l$ (for $l \geq 180$).

2.1 Fornax A

Fornax A (NGC 1316) is one of the brightest radio galaxies in the sky at 1.4 GHz (Schweizer 1980), with a flux density of 150 Jy (Brown et al. 2011) and at a distance of 20.9 Mpc (vV12). It has giant lobes ~300 kpc across, which are bright in radio (Ekers et al. 1983; Geldzahler & Fomalont 1984), as well as being one of the two objects whose lobes are high-energy γ-ray sources (Ackermann et al. 2016b) – the other is Centaurus A (Abdo et al., 2010a,b). However, Fornax A does not appear in the 2FHL catalogue as it is an extended source with a 0.15° offset between the radio and γ-ray position (Ackermann et al. 2016b), although it is present in 3FHL Ajello et al. (2017). The absence from 2FHL meant that it was not included in the A18 analysis. Fornax A lies at a southern Galactic latitude, with the position of its radio core at ($l = 240.16°$, $b = -56.69°$) (Geldzahler & Fomalont 1984). It can be seen to the lower right of Fig. 1. The angular separation between Fornax A and our estimated HS2 position is 22.5°.

2.2 Magnetic deflection

The magnetic deflection of UHECRs depends on the magnetic field encountered – its strength and topology – and the *magnetic rigidity* of the UHECR, given by $\mathcal{R} = E/Ze$, where E is the CR energy and Ze is the charge on the nucleus. The deflection magnitude can then be written as $\theta_d = K/\mathcal{R}$, where K is a constant depending on the magnetic field between the source and Earth. Using the Jansson & Farrar (2012) model for the Galactic magnetic field, Smida & Engel (2015) find $K = 242°$EV (degree exa-Volts) for Fornax A. For a nucleus of $\mathcal{R} = 10$ EV, this corresponds to a deflection of 24.2°, very close to the offset between the PAO excess and Fornax A.

The deflection angle in an extragalactic turbulent field can also be estimated assuming some coherence length for the magnetic field, typically 1 Mpc. Sigl, Miniati & Ensslin (2003, 2004) and Eichmann et al. (2018) find deflections of 12°–24° are reasonable for a nucleus of $\mathcal{R} = 10$ EV travelling 20.9 Mpc in a 1–2 nG magnetic field. The fact that Centaurus A, at a distance of only 3.7 Mpc (Tully et al. 2015) is offset from HS1 by 7° again implies that large deflections are feasible for Fornax A at the greater distance of 20.9 Mpc. Further detailed modelling work is possible, using tools such as CRPROPA (Alves Batista et al. 2016); however, for the purposes of this Letter we note that a deflection of ≈20°–25° is highly plausible for a source at 20.9 Mpc, as shown by Sigl et al. (2004) and Smida & Engel (2015).

Table 1. γ-ray fluxes for the three sources discussed in Section 2.3.

Source	2FHL	3FHL
	(10^{-12} erg cm^{-2} s^{-1})	
Cen A core	3.90 ± 2.29	7.40 ± 1.90
M87	5.12 ± 3.47	9.55 ± 3.26
Fornax A	–	2.59 ± 1.27

2.3 Attenuation and fluxes

The γ-ray fluxes of Centaurus A, M87 and Fornax A from the 2FHL and 3FHL catalogues are given in Table 1, obtained from Ackermann et al. (2016a) and (Ajello et al. 2017). A18 use the 2FHL γ-ray luminosity as a proxy for UHECR luminosity, with a choice of three scenarios for UHECR attenuation during propagation. This attenuation is due to the Greisen–Zatsepin–Kuzmin (GZK; Greisen 1966; Zatsepin & Kuz'min 1966) effect and photodisintegration (Stecker & Salamon 1999). The SBGs in their sample are nearby and the choice of attenuation scenario makes little difference. Strong attenuation (scenario A) is favoured in their AGN analysis since (i) it accounts for the negligible UHECR signal from the direction of M87 that is at five times the distance of Centaurus A (ii) Fornax A, at a distance of 20.9 Mpc, is not included and might otherwise account for the HS2 hotspot if attenuation were weaker.

Given that M87 and Fornax A are at similar distances and that there is an Auger hotspot close to Fornax A but not M87, a successful model for the observed PAO anisotropy requires the attenuation to be less severe than scenario A of A18 and that M87 is intrinsically less luminous in UHECRs than Fornax A as we argue in Section 3. Less severe attenuation would be consistent with results from the CRPROPA code as given in fig. 1 of Alves Batista et al. (2015), as well as canonical values of the GZK length of 50–100 Mpc (e.g. Dermer et al. 2009; De Domenico & Insolia 2013). Sensitivity to composition and source energy spectrum makes the adoption of a single attenuation length difficult; for example, protons at 10 EeV and 100 EeV have approximate GZK lengths of 1000 and 100 Mpc, respectively (Dermer et al. 2009). Approximate attenuation lengths for N^{14} and Fe^{56} nuclei at 100 EeV are 6 and 300 Mpc, respectively (Alves Batista et al. 2015).

The correlation with an AGN in A18 would also be improved by including the contribution from the lobes of Centaurus A, which are estimated to be at least as bright as the core in γ-rays (Abdo et al. 2010b). Furthermore, although there may be a direct relation between the observed γ-rays and UHECRs (Sahu, Zhang & Fraija 2012; Yang et al. 2012; Joshi et al. 2018), γ-ray luminosity may not be the best proxy for UHECR luminosity.

3 FADING RADIO LOBES AS UHECR RESERVOIRS

As shown by Waxman (1995); Waxman (2001) and Blandford (2000), there is a minimum power requirement for particle acceleration to high energy at shocks. This can be derived just from considering the magnetic energy density, $U_{\rm mag} = B^2/(2\mu_0)$, and the Hillas energy $E_{\rm H} = uBLZe$, where B is the magnetic field strength, u is the shock velocity, and L is a characteristic size. The maximum magnetic power delivered through a shock is then roughly $uL^2U_{\rm mag}$, meaning we can write an equation for the minimum power needed to accelerate a nucleus to a given rigidity, $\mathcal{R}$:

$$P_{\rm min} = \frac{\mathcal{R}^2}{2\mu_0 u}, \quad (1)$$

which is equivalent to

$$P_{\rm min} \sim 10^{43} {\rm erg\,s^{-1}} \left(\frac{u}{0.1c}\right)^{-1} \left(\frac{\mathcal{R}}{10\,{\rm EV}}\right)^{2}. \quad (2)$$

Here we conservatively assume maximum efficiency and adopt $u = 0.1c$ due to the difficulties with accelerating UHECRs at highly relativistic shocks (Bell et al. 2018). This equation is quite general and places a fundamental constraint on UHECR sources. We note that starburst winds struggle to meet this constraint as they have powers of the order of 10^{42} erg s^{-1} and low shock velocities ($\sim$1000 km s^{-1}; Heckman, Armus & Miley 1990; Anchordoqui 2017; Romero, Müller & Roth 2018).

To examine which nearby radio galaxies meet the $P_{\rm min}$ requirement, we estimate a 'cavity power', $\bar{P}_{\rm cav}$, using the mean empirical relationship of Cavagnolo et al. (2010). This is quoted in their section 5 and given by

$$\bar{P}_{\rm cav} \approx 5.8 \times 10^{43} \left(\frac{P_{\rm radio}}{10^{40} {\rm erg\,s^{-1}}}\right)^{0.7} {\rm erg\,s^{-1}}, \quad (3)$$

where we take the 1.1 GHz luminosity from vV12 as our $P_{\rm radio}$. This estimate should be thought of as a rough proxy for average kinetic power, since we make use of the current radio luminosity but Cavagnolo et al. (2010) relate this to kinetic power using work done excavating a cavity. Fig. 2 shows $\bar{P}_{\rm cav}$ plotted against distance, with the power requirement from equation (2) marked for two rigidities. Centaurus A, Fornax A, and M87 are three of only a handful of sources within a characteristic GZK radius of 50–100 Mpc capable of accelerating UHECRs to $\mathcal{R} = 10$ EV and above. However, the actual current jet power in these sources is likely lower, with approximate estimates in the literature of 10^{42} erg s^{-1} (Fornax A; Russell et al. 2013) 6–8 $\times$ 10^{42} erg s^{-1} (M87; Rafferty et al. 2006; Russell et al. 2013) and 10^{43} erg s^{-1} (Cen A; Russell et al. 2013; Wykes et al. 2013). These estimates are uncertain and rely on the enthalpy ($4PV$) calculated from thermal pressure acting as a reliable

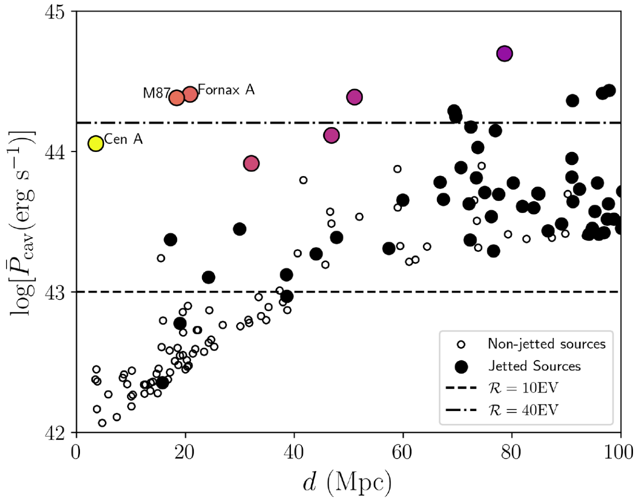

Figure 2. The logarithm of estimated cavity power for local radio galaxies plotted against distance, calculated as described in Section 3. The filled circles represent AGN observed to have jets and the coloured circles are the subset of these that are shown in Fig. 1, also with matching colours to Fig. 1. The two horizontal lines show $P_{\rm min}$ for two different rigidities.

estimate of energy content, when in actual fact the CR and magnetic energy densities may dominate (e.g. Mathews & Brighenti 2008).

Based on the UHECRs arriving at Earth with energies above 55 EeV and directions clustered around Centaurus A, Joshi et al. (2018) estimate an UHECR luminosity of $\sim10^{39}$ erg s^{-1}. The jet powers in Centaurus A, Fornax A, and M87 exceed this value by orders of magnitude. However, it seems that the current jet powers in these sources struggle, similarly to starburst winds, to meet the power requirements (equation 2) for particle acceleration to high energy. Despite this, the *average* powers in radio galaxies can be greater than $P_{\rm min}$, and the peak powers still greater, suggesting that past jet activity is important.

3.1 Enhanced activity in the past?

Based on the current energetics and distances alone, we might expect M87 to contribute a similar UHECR flux to Fornax A, but there is not a clear hotspot close to M87 in the observed UHECR data. However, the jet powers in local radio galaxies could feasibly have been different in the past. Acceleration during a more luminous phase aids with power requirements and allows DSA to operate at fast shocks, which is important since the shocks associated with the currently active Centaurus A jet struggle to accelerate the highest energy CRs (Croston et al. 2009). There is evidence in Centaurus A and Fornax A for enhanced activity within the last $\sim$100 Myr. Both show giant lobes with linear sizes greater than 250 kpc, whose energy contents are large compared to the current power of the jet; $\sim5 \times 10^{58}$ erg in Fornax A (Lanz et al. 2010) and as high as 10^{59-60} erg in Centaurus A (Wykes et al. 2013; Eilek 2014). The energy content of the lobes in M87 is lower, $\sim8 \times 10^{57}$ erg (Mathews & Brighenti 2008) and the lobes only extend $\sim$80 kpc across (Owen, Eilek & Kassim 2000). The M87 lobes are generally consistent with being inflated by the current jet (Owen et al. 2000), whereas Fornax A and Centaurus A hint at a more violent past.

In Centaurus A, Wykes et al. (2013) estimate the buoyancy time at $\tau_{\rm buoy} = 560$ Myr, which places a lower limit on the jet power to inflate the giant lobes of 5×10^{43} erg s^{-1}. This jet power could feasibly have been much higher. Fornax A shows direct evidence of declining AGN activity (Iyomoto et al. 1998; Lanz et al. 2010), and *both* sources are thought to have undergone mergers (Mackie & Fabbiano 1998; Horellou et al. 2001), with Fornax A showing evidence for merger activity within 3 Gyr (Goudfrooij et al. 2001a,b), and potentially as recently as 0.1 Gyr (Mackie & Fabbiano 1998). Mergers can trigger AGN activity as they provide fuel that can subsequently accrete onto a central black hole (e.g. Blundell & Rawlings 1999; Hopkins et al. 2008; Silverman et al. 2011).

Both Centaurus A and Fornax A seem promising candidates for a scenario in which a merger-triggered AGN outburst produced more powerful jets in the past, accelerating UHECRs that are still escaping from the giant lobe reservoirs. The Larmor radius of an UHECR proton is

$$r_g \approx \frac{E}{10\mathrm{EeV}} \left(\frac{B}{10\mu\mathrm{G}}\right)^{-1} \mathrm{kpc}, \quad (4)$$

indicating that long-term containment in the much-larger 100 kpc-scale lobes is likely. The magnetic field lines advected with the jet material that ultimately produces the lobes do not connect to the ambient medium. UHECRs are confined to local magnetic field lines, so UHECR escape requires the crossing of field lines, which is a slow process (e.g. Ozturk 2012; Zweibel 2013). It is therefore not safe to assume that the UHECRs are accelerated in the present source state; it is the history of the source over the shorter of the GZK time and the UHECR escape time that matters. This also means that the energy content of the lobes could make a good estimate of UHECR luminosity since it is an integrated measure over past activity. The sound-crossing time – the time-scale for adiabatic losses – in Centaurus A is of the order of τ_{buoy} (Wykes et al. 2013). This is longer than the GZK time of $r_{\mathrm{GZK}}/c \approx 300$ Myr, which implies that adiabatic losses are unimportant. GZK and hadronic γ-ray losses might still matter for γ-ray emission. In fact, UHECRs in the Centaurus A lobes are thought to produce some of the observed γ-ray flux (Sahu et al. 2012; Joshi et al. 2018). Overall, it seems reasonable that the UHECRs are escaping on a time-scale roughly comparable to the time since the outburst ended, but shorter than a GZK time.

It has been suggested that the UHECRs can also be accelerated by an *in-situ*, ongoing process in the lobes, such as second-order Fermi (Fraschetti & Melia 2008; Hardcastle et al. 2009). However, Hardcastle (2010) notes that this would require relativistic turbulence to reach the required energies.

4 CONCLUSIONS

We have shown that the observed excesses in the UHECR arrival directions measured with the PAO is more naturally explained by association with radio galaxies than with SBGs. Although SBGs are favoured in the A18 analysis, we argue that the increased significance they report compared with their γ-AGN sample is largely driven by one source near the south Galactic pole (NGC 253) and an increased flux estimate in the vicinity of Centaurus A due to the nearby SBGs M83 and NGC 4945. If Centaurus A were more luminous, as indeed it is in the 3FHL catalogue or if the lobes contribution is accounted for, and Fornax A were included, then this can increase the significance of the γ-AGN result, provided that we allow for reasonable magnetic deflection of around 20° and decreased attenuation compared to A18 scenario A.

We suggest that radio galaxies are likely candidates for UHECR production. Building on previous work (e.g. Norman, Melrose & Achterberg 1995; Romero et al. 1996; Fraschetti & Melia 2008; Rachen 2008; Eichmann et al. 2018), we have introduced a physical scenario to account for UHECR production in fading giant radio lobes from a recent jet 'outburst'. This scenario could be further developed to apply to SBGs with past AGN activity; radio galaxies and SBGs need not be unrelated populations. Further work from PAO coupled with more detailed modelling work should help to discriminate further.

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