A parameterized catalog of radio galaxies as ultra-high energy cosmic ray sources

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Many attempts have been made to provide catalogs of potential sources of ultra-high energy cosmic rays (UHECR) based on various astronomical tracers, such as observed radio or gamma-ray emission. A closer look reveals, however, that they all suffer from significant bias and selection effects. We present here a demo-version of a catalog for one often-discussed UHECR source class, radio galaxies (or radio-loud AGN), which is based on a complete theoretical description of jet-energetics, particle acceleration physics, relativistic beaming effects and nuclear composition, parametrized by a comprehensible set of adjustable physical quantities. As found in previous work, the FR-II galaxy Cygnus A at ≈250 Mpc distance is expected to be the strongest UHECR contributor in the sky, but in our new sample it is almost matched by the equally distant steep-spectrum radio quasar PKS 0521-36 if relativistic beaming effects are considered. Under the assumption that the contribution of Cygnus A is significantly diminished — because it is too young (≲10 Myr) for its cosmic rays to reach us due to their delay in the propagation through extragalactic magnetic fields (EGMF) — we find that the anisotropy signals expected from radio galaxies promise to be in good agreement with current observational findings. Yet, in particular the current lack of knowledge of the EGMF strength leaves big scope for predictions. We plan to provide a completed and improved version of this catalog in electronic form, to be used in more detailed UHECR propagation simulations. For immediate applications, we suggest a complete set of 15 strong UHECR sources which can contribute to UHECR anisotropy on the level which can be currently probed by experiment, and note that 5 of them have not been considered in any previous studies.

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1. Introduction

Ever since evidence for the existence of ultra-high energy cosmic rays (UHECR) up to about 100 EeV has been achieved, radio galaxies (RGs) belonged to the prime candidates for astrophysical sources able to explain them [1]. One of the first complete models for the origin of UHECR has been based on a particularly powerful subset of RGs [2], and more recently it was shown that also the current results on spectrum and the chemical composition of UHECR can be reproduced with RG sources ([3], hereafter Paper I). The main part of the contribution is hereby expected to arrive at Earth nearly isotropic, and thus can be described by a continuous source function [4].

Yet the most challenging test to the hypothesis that RGs are the dominant sources of UHECR is the comparison with the weak, but increasingly significant signatures of anisotropy in the arrival direction distribution of UHECR events. The most important structure to consider here is the dipole detected to 5σ significance by the Pierre Auger Observatory (hereafter “Auger”) [5], but also the less significant indications for intermediate scale anisotropy, seen by Auger and also the Telescope Array experiment (hereafter “TA”), have to be taken into account [6]. RGs are particularly suitable to generate such anisotropy, as they vary in their power by many orders of magnitude, but to compare this with data, a complete list of the “UHECR-brightest” sources is a precondition. Such a selection has to consider the physics connecting radio flux to UHECR production, as it has been described in Paper I, and provide adjustable parameters for all theoretical assumptions made. We present here a first version of such a “parametrized UHECR source catalog” based on radio galaxies, and discuss some of its immediate properties.

2. Source selection

For testing models of UHECR origin against observed anisotropies, a reliable and bias-free selection of the brightest sources of the considered model-class is vital. Unfortunately, applying astronomical selection criteria is quite bias-prone, as we can argue for the popular choice of gamma-ray brightness: although there is no doubt that cosmic rays have the potential to produce gamma-rays in interactions, gamma-ray flux (a) depends on the additional presence of a sufficiently dense target population that is not in a simple relation with the cosmic ray density; (b) can also be produced by non-hadronic processes like inverse Compton scattering; and (c) is observed in the GeV-TeV regime, while the cosmic rays we consider here are above EeV. Thus, without a detailed theoretical description how to link the two signals together, the relation between them remains obscure.

A more robust selection criterion is radio flux, because radio luminosity is known to be in a simple relation to the non-thermal power of an object, which in turn is a plausible scaling quantity for the power in cosmic rays (see also Rachen, these proceedings). Moreover, by relating it to another important non-thermal ingredient of astrophysical sources, magnetic fields, it sets a limit to the highest energy attainable in electromagnetic acceleration (see Paper I and references therein). Here we will adopt this relation in a very simple and pragmatic way as the “scaling paradigm for radio galaxies as UHECR sources”, focusing on the question: Assume RGs are the sources of UHECR, which objects contribute most?

2.1 Selection criteria

The scaling paradigm for radio galaxies as cosmic ray sources connects the power emitted in cosmic
rays at all energies, $L_{cr}$, and the nominal maximum energy $\hat{E}_{cr}$ up to which UHECR with charge number $Z$ can be accelerated, to observational quantities as

$$L_{cr} \propto L_{\text{jet}} \propto (P_1 d^2)^{\beta_L}$$

$$\hat{E}_{cr} \propto L_{\text{jet}}^{1/2} \propto Z \sqrt{v} (P_1 d^2)^{\beta_L}$$

(2.1)

Here, $P_1$ is the radio flux of the steep spectrum component (see Sec. 2.2) of the source at 1 GHz, and $d$ the source distance. The power law index $\beta_L$ stems from the relation of radio to jet power, values are assumed to be in the range $0.5 - 0.85$, potentially dependent on the Fanaroff-Riley class of the source (for references see Eichmann [4]). The impact of the acceleration physics is expressed by the dependency of $\hat{E}_{cr}$ on a characteristic velocity scale $v$, is likely higher in the collimated sub-Mpc scale jets of FR-II galaxies ($v \sim 0.3c$) than in FR-I galaxies ($v \sim 0.1c$).

To find out how much a source contributes to the ultra-high energy end of the cosmic ray spectrum, the spectral index $s$ of the cosmic ray spectrum ($dN/dE \propto E^{-s}$) enters as a key parameter. As the cosmic ray spectrum of a UHECR source extends over 10 orders of magnitude, even small variations of this index have huge effects on the energetics. As shown in Paper I, values for $s$ slightly smaller than 2 are preferred to produce the observed UHECR flux with RGs. However, if we just compare individual sources and decide to assign the same value for $s$ to all, we choose $s = 2$ for simplicity. Considering then the contribution to cosmic rays above 1EeV observed at Earth for the "optical case", i.e., disregarding all propagation effects and assume that their flux is simply $\propto L_{cr} d^{-2}$, we can define a source selection criterion

$$\left( \frac{P_1}{d/\text{Mpc}} \right)^{\frac{2}{3}} \ln \left( \frac{\bar{v} P_1 d^2}{14.9 \text{Jy Mpc}^2} \right) > X ,$$

(2.2)

where the choice of the positive dimensionless number $X$ determines the depth of the catalog. Here, we suppose that the predominant part of UHECRs is composed of protons, i.e. $Z = 1$, and define $\bar{v} \equiv v/0.1c$ as the case for typical FR-I galaxies. We have chosen the index $\beta_L = \frac{2}{3}$, a value which is supported by both the normalization of jet power on accretion disk properties [2] and on kinetic power of the lobes as summarized by Eichmann [4]. The logarithmic term is defined such that it is positive for sources which are powerful enough to accelerate protons up to at least 1 EeV.

### 2.2 Blazar-like sources and relativistic boosting

Our general scaling relation is based on total jet power, which is released into cosmic rays mostly on large scales, where velocities can be assumed at most weakly relativistic. It is therefore reasonable to assume that RGs emit their cosmic rays nearly isotropic. Nevertheless, observations of blazars, which are thought to be RGs with their jets aligned to the line of sight according to the common unification paradigm [7], strongly suggest that radio galaxy jets start up with relativistic velocities. The idea that hadronic processes are active in this region has been greatly substantiated by the observation of a cosmic neutrinos likely associated with blazars [8], but the connection to the much higher cosmic ray energies is still unclear. As we do not want to go into this discussion, we choose again a pragmatic approach: We assume that, additionally to the isotropic emission of a cosmic ray source, a fraction $f \ll 1$ of this power is emitted in UHECR from the compact jet, with the same spectrum and composition as that of the jet, and then boosted into a narrow cone of opening angle
$\Delta\Theta = \delta^{-2}$ with the relativistic Doppler factor $\delta = [\Gamma(1 - \cos\Theta)]^{-1}$, for a typical bulk Lorentz factor $\Gamma = 10$. For the borderline case where boosted and unboosted emission are comparable as it is the case for most sources in our sample, the jet is inclined by an angle $\Theta \approx 1/\Gamma$ and $\delta \approx \Gamma$. For an observer located in the beaming-cone, and assuming "optical propagation" again, the flux of cosmic rays per unit angle is then enhanced by a boosting factor $b = 1 + 2\pi f \delta^2$, where we account for the presence of two jets whereof only one is aligned to Earth. As a canonical choice, we use $f = 0.1$ and $\delta = 10$, thus $b \approx 64$.

What remains is how sources with "blazar properties" are selected. A characteristic feature of blazars is a flat ($\alpha \approx 0$) radio spectrum $S_\nu \propto \nu^{-\alpha}$, in particular at high radio frequencies. This is usually interpreted as a signature of a compact, partially self-absorbed relativistic jet, while at MHz frequencies and the steep lobe component (typically $\alpha \approx 0.7$) dominates. For sources showing such features, it is important that the radio flux of the lobes is determined from extending the power law of the low-frequency component to 1 GHz, and used in (2.1) for normalization. The boosting is then considered by increasing the resulting $L_{\text{cr}}$ by the factor $b$.

### 2.3 The demo-catalog and the strong UHECR source sample

As the selection criterion (2.2) is difficult to submit in standard catalog searches, we first pre-selected radio sources from their listed flux at or around 1 GHz. As a base catalog, we used the local radio source catalog by van Velzen et al. [9] (hereafter "vV12"), as we did in Paper I. As noted there already, this catalog suffers from severe deficits in particular in the regime of extremely powerful RGs, because it is based on the 2MRS catalog which selects on infrared flux, and powerful RGs tend to be comparatively dim in infrared. We therefore performed additionally a search for objects with radio flux >3Jy (and no other criteria applied) in NED [2], and then drew our sample from the joint list. Here we first selected a list of confirmed RGs with a 1 GHz flux above 10Jy and restricted their distance to 300Mpc, which was found to be a reasonable maximum distance for UHECR propagation above 10 EeV [10]. We then included a few weaker sources interesting to include for various other reasons, until we obtained a list of 42 sources.

In an a posteriori analysis, considering UHECR transport as described in the next sections, we then defined a sub-sample of "strong UHECR sources" which could significantly influence UHECR anisotropy. This selection, which is equivalent to applying (2.2) for $X = 5$, can be considered complete in the sense that (a) there exists no radio galaxy within 300Mpc with a comparable impact on UHECR anisotropy, (b) omission of sources of our demo-catalog not contained in it will hardly affect the results. We particularly note that 5 objects out of this list of 15 — Pictor A, Centaurus B, PKS 0521-36, PKS 1610-60 and PKS 1814-63 — are not contained in vV12.

### 3. Considering UHECR transport

The selection criteria applied so far treated cosmic rays analogous to radio photons — we called this the “optical scenario”. Of course, this view cannot hold for three reasons: (a) the presence of heavy

1We note that our normalization of UHECR power and maximum energy is done in the lab-frame, thus the boosting considered here is solely an effect of directed emission and not a Lorentz boost from the comoving frame of the jet.

2NASA/IPAC extragalactic database, https://ned.ipac.caltech.edu/

3This choice is based on the well-known fact that 42 is the answer to everything, so we cannot do wrong using it.
Table 1: The 42 sources of the demo catalog, with objects included in the strong UHECR source sample marked. Sources in this sub-sample can significantly influence UHECR anisotropy. Sources are generally named after radio-catalogs and radio naming conventions, in the order Constellation (Con) A/B, 3C, PKS, 4C, TXS, although several sources in the list are better known under other names, e.g., 4C +39.49 ≡ Mrk 501. The “type” column lists the Fanaroff-Riley type including borderline cases, and for beamed sources “BL” for BL Lac objects, “FR-I/BL” for weakly beamed sources with a significant steep spectrum component, and SSRQ for Steep-Spectrum Radio Quasar, which is the corresponding FR-II based source class [7].

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<th>Radio name</th>
<th>RA</th>
<th>DEC</th>
<th>P1/1yr</th>
<th>d/Mpc</th>
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<td>123</td>
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<td>167</td>
<td>—*</td>
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<td>14</td>
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*(†) Object included in the strong UHECR source sample; for sources marked with a b this applies only if boosting is applied.

(nuclei in the UHECR spectrum, as implied by Auger results [11], (b) energy losses of UHECRs and photodisintegration of nuclei in interactions with ambient extragalactic photon backgrounds, and (c) deflection of cosmic rays in extragalactic magnetic fields (EGMF). All these effects can be ideally treated in simulations with the cosmic ray propagation code CRPropa [12], where we use a set of possible EGMF models provided by Hackstein et al. [13], hereafter referred to as H+18a, H+18aR, H+18p, and H+18p2R using the same naming convention as Eichmann (these proceedings, see also for details).

3.1 Simulation setup and weighting

In order to obtain sufficient statistics from distant sources for all H+18 models within a reasonable CPU time we use the so-called inverted simulation setup introduced by Eichmann [4]. As the H+18 models are limited to a volume that does not include sources at distances \( \gtrsim 125 \text{ Mpc} \), we reflect the magnetic field structure at its boundaries, based on the assumption of a homogeneous Universe on large scales. An isotropically emitting source is placed at the center of ten concentric observer spheres, with radii chosen such that they represent source distances with \( \approx 10\% \). Each observer sphere records the CR properties each time it passes through its surface in any direction, until the particle is removed from the simulation when either the trajectory length exceeds 5000Mpc or its energy dropped to \(< 1 \text{ EeV} \). To obtain about equal statistics within the simulated energy range as well as the chemical composition, the source ejects a solar composition of particles enhanced by...
$Z^{2.5}$ with an energy spectrum between 1 EeV and 300 Z EeV with a spectral index $s = 1$. To exclude the impact of a particular source position in the EGMF structure, we run 50 different positional setups of 10,000 particles for each of the H+18 EGMF models.

From these data, the cosmic ray contribution of individual sources is obtained via (2.1), where we also re-weight to an $s = 2$ spectrum with $Z^2$ enhancement (see Paper I). In the case of blazar-like sources, particles that are emitted within an opening angle $\Delta \Theta = 0.1$ with respect to the line of sight obtain an additional boosting weight $b$. To consider a limited source age $T_s$, we allow to select only particles with trajectory lengths $d$ on a sphere with radius $r$ which satisfy $d - r < c T_s$.

As we want to determine the particle flux $dN/dA d\Omega dt$, we account for the angular dependence of effective area $dA$ in our setup by applying a weight $1/|\cos \theta|$, plus a weight $1/\sin \theta$ as $d\Omega \propto \sin \theta$.

4. Sky maps and comparison to anisotropy signals

The results presented here demonstrate some immediate properties of our source selection, but should not be taken as definite predictions of the “radio galaxy model” suitable to confirm or refute it. The maps are in galactic coordinates, and when we refer to individual sources in the text we add $(l, b)$ in degrees to allow their easy identification.

4.1 UHECR emission power and flux contribution

The upper left panel of Fig. 1 shows the source sample in symbols with their area proportional to their cosmic ray power ejected above 4 EeV. This figure clearly show that Cyg A ($76^\circ, +6^\circ$) is the main contributor of UHECR in general, as already pointed out in Paper I, but for the case of boosting, the source PKS 0521-36 ($241^\circ, -33^\circ$), which have so far never been mentioned in UHECR studies, on a similar level. In its right panel, the same sky plot is shown, but this time with symbol sizes weighted by observed particle flux. This considers UHECR transport for H+18aR fields, and the contribution of distant sources are diminished mostly because particles are delayed in their arrival time by more than 100 Myr. We have applied this upper bound as RGs are in fact transient objects on these time scales, but in special cases it might be much shorter. An example is Cyg A where the age of the current hot spots is thought to be significantly below 1 Myr [14]. For demonstrative purposes, we show here a case where propagation delays significantly reduce the contribution of Cyg A. Switching to the weaker H+18a fields, the contribution of Cyg A is already much less reduced, while essentially no cosmic rays are received from any distant sources in the H+18p/p2R scenarios.

4.2 Dipole contribution and hot spots in directed flux

Turning to anisotropy signatures in the UHECR flux, the lower panel of Fig. 1 shows the dipole contribution of our source sample. We see that the direction of its total dipole is in excellent agreement with Auger results, mostly caused by the strong contributions of PKS 0521-36 and Per A ($151^\circ, -13^\circ$). We note, however, that this agreement stands and falls with their contribution relative to Cyg A, which depends in the realistic case crucially on the EGMF strength.

\footnote{Effectively we set the maximum delay to zero, as the H+18 fields are either significantly too weak or too strong to show this effect. We note that, if the average EGMF strength would be as low as 1 pG (with no place where $B \ll \langle B \rangle$), the minimum delay obtained would be $\gtrsim$ Myr over the distance of Cyg A.}
Figure 1: Map of radio galaxies as UHECR sources, weighted by emitted (upper left) and observed (upper right) cosmic rays above 4 EeV. Unboosted emission of each source is shown by a circle, the relative contribution scales with the circle area – in some cases, where two source are too close in their lines of sight, triangles are used to distinguish them. For blazar-like sources with the potential of boosted emission, hexagons indicate their contribution for a canonical boosting factor given in text. Colors indicate the source distance, from violet for the closest source (Cen A) to deep-red for the most distant ones. The lower panel shows the dipole contribution above 8 EeV (left) and 32 EeV (right). The total dipole is calculated from adding the dipole vectors of all sources, with (red) or without (blue) consideration of boosting for blazar-like sources. Black are the positions of the Auger dipoles for these energies [5]. By the way, the tiny hexagon at (64,+39) is Mrk 501, the strongest contributor among TeV blazars.

Finally, Fig. 2 shows the situation for cosmic rays observed above 57 EeV, where we compare to the “hot spots” in directional flux reported by both leading experiments. It should be mentioned that our results do not include UHECR deflection in the Galactic magnetic field (GMF), which could for intermediate mass nuclei reach up to 30° or more. With this in mind, we emphasize that the strongest and most significant excess reported by Auger is almost identical to the position of the nearest strong radio galaxy, Cen A, while the TA hot spot and the Auger excess near the Galactic south pole are at about 30° distance of the strong RGs Vir A and For A, respectively. Clearly, and understanding of UHECR anisotropy at the highest energies requires additional experimental and theoretical research, but if current signals can be confirmed our results show that RGs have the potential to explain them.

5. Conclusions and Outlook

We presented a first demo version of a UHECR source catalog based on radio galaxies, including a “strong UHECR source sample” which can be regarded as the currently most reliable and complete selection of sources which could contribute to UHECR flux anisotropy on a level testable with

One might think that deflections could be easily included by applying the JF12 [15] lensing map contained in CRPropa. We did not do this here because creating sky maps of arrival directions is beyond the scope of this paper. Moreover, we note that the question of the GMF structure is far from being settled [16].
current statistics. We demonstrated that radio galaxies still have the potential to explain all currently claimed UHECR anisotropies. We will soon provide an extended and completed version of this catalog in electronic form, to be used with CRPropa to produce conclusive and high quality sky maps which can be compared with actual and future data.

References


