High Energy Cosmic Rays from Fanaroff-Riley Radio Galaxies

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Abstract. The extended jet structures of radio galaxies (RGs) represent an ideal acceleration sight for High Energy Cosmic Rays (HECRs) and a recent model showed that the HECR data can be explained by these sources, if the contribution by a certain RG, Cygnus A, is almost isotropically.

First, this work probes the isotropy assumption showing that the used extragalactic magnetic field model is either too weak or a contribution by a multitude of isotropically distributed sources is needed at these energies.

Secondly, the HECRs contribution by the bulk of RGs of different Fanaroff-Riley (FR) type is determined. Here, it is carved out that FR-II RGs provide a promising spectral behavior at the hardening part of the CR flux, between about 3\,EeV and 30\,EeV, but most likely not enough CR power. At these energies, FR-I RGs can only provide an appropriate flux in the case of a high acceleration efficiency and $\beta_L \gtrsim 0.9$, otherwise these sources rather contribute below 3\,EeV. Further, the required acceleration efficiency for a significant HECR contribution is exposed dependent on $\beta_L$ and the CR spectrum at the acceleration sight.

Keywords: ultra high energy cosmic rays, magnetic fields, radio galaxies

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1 Introduction

The origin of the High Energy Cosmic Rays (HECRs) is still one of the great enigmas of modern astrophysics. From observatories like the Pierre Auger Observatory (Auger) and the Telescope Array (TA) experiment at the highest energies as well as KASCADE, KASCADE-Grande and a few other detectors at lower energies, there are basically three main observational characteristics, that describe our current knowledge of the HECRs:

1. The energy spectrum, which changes at about $0.4 \text{EeV}$ — the so-called second knee — to a stepper power-law distribution with a spectral index of about 3.3 and flattens above about $3 \text{EeV}$ — the so-called ankle — to a spectral index of 2.6 and a sharp flux suppression above about $30 \text{EeV}$ [1–3].

2. The chemical composition, that shows a decrease of the fraction of heavier elements between about $0.1 \text{EeV}$ and $2 \text{EeV}$, changing to an increase at energies $> 2 \text{EeV}$ [4–7].

3. The arrival directions, that are usually expressed in terms of the multipoles of their spherical harmonics. Between about $0.01 \text{EeV}$ and $8 \text{EeV}$ there are no significant hints of anisotropy [8]. However, at higher energies Auger recently reported a $5\sigma$ detection of a dipole with an amplitude of $\approx 6.5\%$, while higher-order multipoles are still consistent with isotropy [9].

A likely source candidate of those extremely energetic particles are radio galaxies (RGs) due to their powerful acceleration sights within the jets, as already noted by Hillas in 1984 [10]. In particular the shocks caused by the backflowing material in the lobes of RGs represent an ideal acceleration sight for HECRs [11]. Fanaroff and Riley classified two major types of radio galaxies [12]: FR-I RGs, in which the jets are terminating within the galactic environment on scales of a few kiloparsec, so that the brightness decreases with increasing distance from the central object; and FR-II RGs, where the jets extend on scales of $> 100 \text{kpc}$ deep into extragalactic space causing an increased brightness with distance. This morphology distinction obviously correlates with radio power, so that sources with $L_{178} \lesssim 2 \times 10^{25} \text{W Hz}^{-1} \text{sr}^{-1}$ tend
to be FR-I galaxies, while sources with \( L_{178} \gtrsim 2 \times 10^{25} \text{W Hz}^{-1} \text{sr}^{-1} \) usually have a FR-II morphology.\(^1\)

In a recent study [13] — hereafter referred to as E+18 — it is shown that all of the observational characteristics of HECRs above the ankle, so-called Ultra High Energy Cosmic Rays (UHECRs), can be explained by Centaurus A, a FR-I RG, and Cygnus A, a FR-II RG, if the light CRs from Cygnus A are almost isotropically distributed over the whole sky due to significant deflections by the extragalactic magnetic field (EGMF), providing a rms deflection of \( \theta_{\text{rms}} \gtrsim 25^\circ (\bar{E}/100 \text{EeV})^{-1} \) for a mean energy \( \bar{E} \) of the propagating CR.

Unfortunately, the magnetic fields in extragalactic space and our Galaxy are poorly known, and the currently most sophisticated descriptions of the EGMF, given by Dolag et al. [14] — hereafter referred as D+05, is constrained to a maximal distance of about 120 Mpc. Therefore, a reliable test of the isotropy assumption is missing so far.

Another important outcome from E+18 has been the subdominance of the UHECR flux by the non-local RG population, i.e. the mean contribution from RGs beyond 120 Mpc, above the ankle. But, its spectral behavior has indicated that a significant contribution below the ankle is still possible. In addition, the description of the average non-local RG population has not differentiated between FR-I and FR-II types, however, FR type dependent radio luminosity functions [15] and radio luminosity to jet power correlations [16, 17] indicate the need for a more detailed investigation of the average HECR contribution from RGs.

The paper is organized as follows: In Sect. 2 the simulation setup is introduced that provides an estimate of the mean deflections of HECRs from Cygnus A in the EGMF of D+05 and subsequently the ‘isotropy assumption’ is probed. In Sect. 3 the continuous source function of HECRs is reinvestigated and the average contributions by the bulk of FR-I and FR-II RGs to the observed HECR flux is constrained. All simulations are carried out with the publicly available code CRPropa3 [18].

2 UHECRs from Cygnus A

To estimate the EGMF effect on HECRs from Cygnus A, a magnetic field structure up to at least 255 Mpc is needed as well as an efficient propagation algorithm to obtain sufficient statistics.

2.1 Inverted simulation setup

Due to the lack of reliable large-scale EGMF structures, the inner cube of the D+05 field, with an edge length \( l_D \approx 170 \text{Mpc} \), is used and continued reflectively at its boundaries. Hence, also the extended EGMF stays divergence free.

Subsequently, an inverted simulation setup is used, where the source is placed at the center of an observer sphere, whose radius is determined by the distance of Cygnus A as sketched in the left Fig. 1. All CR candidates that arrive at the spherical surface are collected and the proper arrival directions are estimated by using the zenith angle, as well as the proper spatial positions of the Earth and the source. Thus, a significant gain of statistics is obtained with respect to the regular simulation setup used in E+18, since all ejected particles will reach the observer, if they do not cool below the minimal energy constrain of 0.1 EeV. However, this method is obviously at the expanse of an EGMF structure that is able to represent the proper spatial distribution in the local Universe. But, in the case of large scale propagations

\(^1\)There are notable exceptions to this radio power distinction, like the very powerful FR-I galaxy Hydra A.
as well as the absence of extragalactic lenses close to the Earth, it is expected that the impact of the EGMF is determined by its large scale properties, so that the deflection rather depends on the distance to the source than on its certain spatial position. This assumption is verified by calculating the difference between the deflection $\theta_i$ of $10^4$ individual candidates and the corresponding mean value $\bar{\theta}$ that is obtained for $50$ arbitrary source positions within the expanded EGMF structure. Hence, the absolute error $\Delta \theta = \sum_i \| \bar{\theta} - \theta_i \|$ of CR candidates with different rigidities is computed $50$ times in the inverted simulation setup without the impact of energy losses. In particular at rigidities $> 1\, \text{EV}$ the Fig. 2 indicates by the narrow bands, that the spatial position of source and observer are negligible with respect to the resulting mean deflection. The inverted simulation setup necessarily provides the sum of all possible deflections dependent on the given distance to the source. However, the right Fig. 1 shows, that this approach causes for $95\%$ of the simulated CR candidates a maximal deflection error of about $4^\circ$ at $4\, \text{EV}$, that decreases to about $2^\circ$ at $8\, \text{EV}$. Only about $1\%$ of the sky provides significant deflections errors at the order of some tens of degree at these rigidities, which is in good agreement with the extrapolation results by D+05. Thus, a significant over- or underestimate of the mean deflections of the HECRs from the proper spatial position of Cygnus A is very unlikely.

### 2.2 Mean HECR deflection

If Cygnus A and Centaurus A are the dominant UHECR sources, as suggested by the E+18 model, the arrival directions of CRs from Cygnus A need to be almost isotropically distributed at $E > 3\, \text{EeV}$, corresponding to a mean deflection of $\bar{\theta}_{iso} \sim 45^\circ$. The Fig. 2 displays that only for a charge number $Z \sim 26$ the ejected CRs by Cygnus A are deflected by the EGMF in the necessary order of magnitude. However, such a scenario can clearly be ruled out, as heavy nuclei suffer from photo-disintegration, so that the CRs can hardly keep such a high charge number while propagating to Earth. Further, an iron dominated ejecta can hardly be

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2Note, that $\theta_i$ is evaluated using the initial and the final momentum of the particle, so that in the case of large deflections $\theta_i$ converges towards $45^\circ$. 

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Figure 1: Left figure: Sketch of the inverted simulation setup with the extended EGMF. The thin dashed line marks the inner cube of the original D+05 field. Right figure: Maximal absolute deflection error of a given percentage of the individual CR candidates. The bands refer to the scattering that results from the effect of 50 arbitrary source positions.
motivated physically. In the case of a light CR ejecta, i.e. solar like abundances, even source distances of several hundreds of Mpc yield a mean deflection in the extended D+05 magnetic field of only a few degrees at these energies. Thus, a few single, individual sources, like Cygnus A and Centaurus A, cannot be the only dominant HECR sources above the ankle. So, the dominant contribution up to $\sim 8\text{ EeV}$ needs to be provided by a multitude of isotropically distributed sources, as pursued in the following.

3 FR radio galaxies as HECR emitters

In the case of a weak EGMF with a root-mean-squared field strength $\lesssim 1\text{ nG}$ and a small filling factor\(^3\) above $\sim 1\text{ nG}$, like the D+05 model [19], only a homogeneous distribution of sources that provide a HECR flux at about the same order of magnitude can account for the high degree of isotropy of the arrival directions around the ankle. However, E+18 already showed that the average non-local source population according to the local radio luminosity function (RLF) from Mauch and Sadler [20] cannot explain the observed spectral behavior above the ankle. But this RLF does not cover the contribution of (rather distant) high-luminous FR-II sources, that dominates the RLF at $L_{151} \gtrsim 10^{26.5}\text{ W Hz}^{-1}\text{ sr}^{-1}$ in the non-local Universe [15]. In addition, the kinetic power of the jet most likely also depends on the FR classification of the source due to different lobe dynamics [17]. In order to constrain the HECR contribution by the bulk of the different types of FR RGs, an appropriate continuous source function (CSF) is needed.

Therefore, the calculations from E+18 are repeated using the RLF from Willott et al. [15] — hereafter referred as W+01 — that differentiates between the FR types and includes the redshift dependence according to the source evolution. In addition, the impact of different

\[^3\text{The filling factor indicates the fraction of the total volume filled with magnetic fields higher than a certain reference value.}\]
ratios of radio luminosity $L_{\text{radio}}$ to jet power $Q_{\text{jet}}$, also known as the radiative efficiencies, are investigated. Due to the lack of reliable empirical methods to measure the jet power [17], there are plenty of studies on this issue providing slightly different results. Willott et al. [21] — hereafter referred as W+99 — have derived a popular, model dependent predictor of the jet power of FR-II sources implying a systematic uncertainty $f^{3/2}$ with $1 \leq f \leq 20$. Other analysis have confirmed this $L_{\text{radio}} - Q_{\text{jet}}$ correlation even for FR-I sources [22] within the uncertainty band. However, most of the other predictions yield a rather high $f$ value [23] and a slightly different slope of the correlation [24, 25]. Godfrey and Shabala [16, 17] — hereafter referred as GS13 and GS16, respectively — investigated the hypothesis of a significant difference in the distribution of the energy budget between FR-I and FR-II sources that has not been taken into account so far: In FR-I RGs the energy budget is dominated by a factor of $\gg 100$ by non-radiating particles yielding a rather high $f$ value, while radiating particles dominate this budget in the lobes of FR-II RGs suggesting a low $f$ value. However, the expected difference in the normalization of the $L_{\text{radio}} - Q_{\text{jet}}$ correlation is not observed, and also the theoretically expected difference in the slope $\beta_L$ of the correlation, due to different jet dynamics, could not be verified so far.

The radio-to-CR correlation provides the energy density in CRs as

$$Q_{\text{cr}} = \frac{g_m}{1 + k} Q_{\text{jet}} = \frac{g_m}{1 + k} Q_0 \left( \frac{L_{151}}{L_p} \right)^{\beta_L}$$  \hspace{1cm} (3.1)

where $g_m$ denotes the fraction of jet energy found in leptonic and hadronic matter and the ratio of leptonic to hadronic energy density is given by $k$. Here, all of the introduced parameters differentiate between FR-I and FR-II. In principle, $g_m < 1$ and in the case of a minimum-energy magnetic field this parameter yields $g_m \simeq 4/7$ [26]. Note, that deviations from the given correlation (3.1) at the order of more than a magnitude occur only for individual sources. Based on the most recent models by Godfrey and Shabala the normalization $Q_0$ is estimated by equalizing the jet power at the pivot luminosity

$$L_p = \begin{cases} 
10^{21}/(4\pi) \text{ W Hz}^{-1} \text{ sr}^{-1} & \text{for FR-I at } 151 \text{ MHz} , \\
10^{27.6}/(4\pi) \text{ W Hz}^{-1} \text{ sr}^{-1} & \text{for FR-II at } 151 \text{ MHz} ,
\end{cases}$$  \hspace{1cm} (3.2)

taken from GS16, to the corresponding jet power given by the GS13 model, which yields

$$Q_0 \simeq \begin{cases} 
2.27 \times 10^{44} \text{ erg/s} & \text{for FR-I} , \\
3.04 \times 10^{45} \text{ erg/s} & \text{for FR-II} .
\end{cases}$$  \hspace{1cm} (3.3)

Here, a rather large normalization factor ($g = 2$) for the GS13 correlation model of FR-II RGs is supposed. GS16 showed that

$$\beta_L \simeq \begin{cases} 
0.5 & \text{for FR-I} , \\
0.8 & \text{for FR-II} ,
\end{cases}$$  \hspace{1cm} (3.4)

is expected from a theoretical point of view, but basically the whole range of $0.5 \lesssim \beta_L \lesssim 1.4$ is possible from observations [17]. The Fig. 3 shows that the W+99 model is in good agreement with the FR-II prediction by the GS16 model in the case of low $f$ values. Taking the upper limit of $f$ seriously, the normalization (3.3) cannot exceed $10^{46} \text{ erg/s}$ for FR-II. As expected from theory, the predicted jet power of low-luminous FR-I RGs by Godfrey and Shabala is
Figure 3: Different models of the radio to jet power correlation (left axis) and the RLF of W+01 derived for model A for an open cosmology ($\Omega_M = 0$) with a redshift $z \in [0, 2]$.

above the W+99 prediction, and the flat slope of the correlation yields a significant increase of the CR contribution by low-luminous FR-I.

In the large scale structures $\gtrsim 1$ pc of radio galaxies the dominant loss time scale is given by the escape time $\tau_{\text{esc}} \simeq r/\beta_{\text{sh}} c$ which is estimated by the shock or shear velocity $\beta_{\text{sh}} c$ and the size $r$ of the jet. For the common assumption of Bohm diffusion, the acceleration takes place on a timescale $\tau_{\text{acc}} = f_{\text{diff}} r_L/(c \beta_{\text{sh}}^2)$ for cosmic-ray particles with a Larmor radius $r_L R/B$, where $R$ is called the particle rigidity, and $8 \lesssim f_{\text{diff}} \lesssim 1$ encapsulates all details of the upstream and downstream plasma properties [27] in a strongly turbulent magnetic field for standard geometries [28]. In steady state, the equality of both time scales yields the maximal rigidity

$$\hat{R} \equiv E_{\text{max}} Z c \beta_{\text{sh}} f_{\text{diff}} B r = g_{\text{acc}} \sqrt{(1 - g_m) Q_{\text{jet}}/c},$$

where the magnetic field power of the jet $Q_B = c \beta_{\text{jet}} \pi r^2 B^2/8\pi = Q_{\text{jet}}(1 - g_m)$ is used. Here, the acceleration efficiency parameter

$$g_{\text{acc}} = \sqrt{8 \beta_{\text{sh}}^2 f_{\text{diff}}^2 / \beta_{\text{jet}}},$$

is introduced and in the case of the typical shock and jet velocities $\beta_{\text{sh}} \sim \beta_{\text{jet}} \sim 0.1$ in extended jets of radio galaxies yielding $0.01 \lesssim g_{\text{acc}} \lesssim 1$. Thus, the typical parameter values $g_{\text{acc}} = 0.1$ and $g_m = 4/7$ are used in the following unless otherwise stated.

3.1 Continuous Source Function

The number of radio sources per volume per power bin yields

$$\frac{d\tilde{N}}{dV dQ_{\text{cr}}} = \frac{\tilde{\Phi}_{\text{RG}}(L_{151}, z)}{2.3 \beta_L Q_{\text{cr}}},$$

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where $\Phi_{RG}$ denotes the RLF from W+01 of (i) low-luminous radio sources, including FR-I as well as FR-II sources with low-excited/weak emission lines, and (ii) high-luminous radio sources, composed almost exclusively of sources with FR-II radio structures, respectively. In the following, the differentiation of $\Phi_{RG}$ based on the FR type is simplified using

$$\frac{d\tilde{N}}{dV dQ_{cr}} = \begin{cases} \frac{\rho_{i0}}{2.3 \beta_{i} Q_{cr}} \left(\frac{Q_{cr}}{g_{m} Q_{*}}\right)^{-\alpha_{i}/\beta_{i}} \exp \left(-\left(\frac{Q_{cr}}{g_{m} Q_{*}}\right)^{1/\beta_{i}}\right) f_{I}(z), & \text{for FR-I}, \\ \frac{\rho_{i0}}{2.3 \beta_{i} Q_{cr}} \left(\frac{Q_{cr}}{g_{m} Q_{*}}\right)^{-\alpha_{i}/\beta_{i}} \exp \left(-\left(\frac{Q_{cr}}{g_{m} Q_{*}}\right)^{1/\beta_{i}}\right) f_{II}(z), & \text{for FR-II}, \end{cases} \tag{3.8}$$

where

$$Q_{*} = \begin{cases} \left(\frac{4 \pi L_{L}}{L_{p}}\right)^{\beta_{L}} Q_{0}, & \text{for FR-I}, \\ \left(\frac{4 \pi L_{L}}{L_{p}}\right)^{\beta_{L}} Q_{0}, & \text{for FR-II}, \end{cases}$$

$$f_{I}(z) = \begin{cases} \left(1 + z\right)^{k_{l}} & \text{for } z < z_{0}, \\ \left(1 + z_{0}\right)^{k_{l}} & \text{for } z \geq z_{0}, \end{cases} \tag{3.9}$$

$$f_{II}(z) = \begin{cases} \exp \left(-\frac{1}{2} \left(\frac{z - z_{a0}}{z_{a1}}\right)^{2}\right) & \text{for model A or models B and C at } z < z_{b0}, \\ 1 & \text{for model B at } z \geq z_{b0}, \\ \exp \left(-\frac{1}{2} \left(\frac{z - z_{b0}}{z_{b1}}\right)^{2}\right) & \text{for model C at } z \geq z_{b0}, \end{cases}$$

for two different cosmological models with $\Omega_{M} = 1$ and $\Omega_{M} = 0$ for three different parameter models A, B, C. The model dependent parameters $L_{Li}, L_{hL}, \rho_{i0}, \rho_{h0}, \alpha_{i}, \alpha_{h}, k_{l}, z_{l}, z_{h}$ are given in table 1 by W+01.

Thus, the redshift dependent CSF of FR-I and FR-II sources, respectively, is given by

$$\tilde{\Psi}_{i}(R, z) \equiv \frac{d\tilde{N}_{cr}(Z_{i})}{dV dR dt} = \int_{Q_{cr}}^{\tilde{Q}_{cr}} S_{i}(R, \tilde{R}(Q_{cr})) \frac{d\tilde{N}}{dV dQ_{cr}} dQ_{cr} \tag{3.10}$$

where $S_{i}(R, \tilde{R}(Q_{cr})) \equiv d\tilde{N}_{cr}(Z_{i})/dR dt$ denotes the cosmic ray spectrum of element species $i$ with charge number $Z_{i}$, emitted by a FR-I/II source with total cosmic ray power per charge number, $Q_{cr,i} \equiv Q_{cr}(Z_{i}) = f_{i} Z_{i} Q_{cr}/\tilde{Z}$, up to a maximal rigidity $\tilde{R}(Q_{cr})$. The limits of integration are the smallest, $\tilde{Q}_{cr}$, respectively largest, $Q_{cr}$, CR powers that need to be considered.

To solve this integral analytically, one has to suppose that the source spectra are given by

$$S_{i}(R, \tilde{R}(Q_{cr})) = \nu_{i}(a) Q_{cr} \left(\frac{R}{\tilde{R}}\right)^{-a} \Theta(\tilde{R}(Q_{cr}) - R), \tag{3.11}$$

with the Heaviside step function $\Theta(x)$ that introduces a sharp cutoff at

$$\tilde{R}(Q_{cr}) = g_{acc} \sqrt{\frac{1}{c} \left(\frac{1}{g_{m}} - 1\right) \left(1 + k\right) Q_{cr}} \tag{3.12}$$

according to Eq. (3.5). Analogous to the approach by E+18, the requirement

$$Q_{cr,i} = f_{i} Z_{i} Q_{cr}/\tilde{Z} = e Z_{i} \int_{R}^{\tilde{R}(Q_{cr})} dR \tilde{R} S_{i}(R, \tilde{R}(Q_{cr})) = e Z_{i} \int_{R}^{\tilde{R}(Q_{cr})} dR \tilde{R} S_{i}(R, \tilde{R}(Q_{cr})), \tag{3.13}$$

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yields the spectral normalization correction $\nu_i(a)$ as

$$
\nu_i(a) = \frac{f_i}{e Z R^2} \times \begin{cases} 
(2 - a) / (\rho_{ct}^{2-a} - 1), & \text{for } a \neq 2 \\
1/ \ln \rho_{ct}, & \text{for } a = 2 
\end{cases} 
$$

(3.14)

with the cosmic ray dynamical range $\rho_{ct} \equiv \tilde{R}(Q_{ct})/\bar{R}$. The approximate analytical solution to Eq. (3.10) is given by

$$
\tilde{\Psi}_i(R, z) \simeq \begin{cases} 
\rho_{0i} f_i \nu_i c 
& 
\frac{2}{2.3 e Z} \left[ \frac{g^{2}_{acc}}{g_{m} - 1} (1 + k) \right]^{-1} \left( \frac{R}{\tilde{R}_*} \right)^{-a} f_i(z) \\
\times \Gamma \left( \xi^l_{a,} \left( \frac{R}{\tilde{R}_*} \right)^{2/\beta_L} \right) - \Gamma \left( \xi^{II}_{a,} \left( \frac{\tilde{Q}_{ct}(k + 1)}{g_{m} Q_*} \right)^{1/\beta_L} \right), & \text{for FR-I}, \\
& 
\rho_{0i} f_i \nu_i c 
& 
\frac{2}{2.3 e Z} \left[ \frac{g^{2}_{acc}}{g_{m} - 1} (1 + k) \right]^{-1} \left( \frac{R}{\tilde{R}_*} \right)^{-a} f_i(z) \\
\times \Gamma \left( \xi^l_{a,} \left( \frac{g_{m} Q_*}{Q_{ct}(k + 1)} \right)^{1/\beta_L} \right) - \Gamma \left( \xi^{II}_{a,} \left( \frac{\tilde{R}_*}{\bar{R}} \right)^{2/\beta_L} \right), & \text{for FR-II}, 
\end{cases}
$$

(3.15)

for the three simplifying cases

$$
\nu_i = 2 - a; \quad \xi^l_{a,} = -\alpha_i + a \beta_L/2; \quad \xi^{II}_{a,} = \alpha_h - a \beta_L/2; \quad \text{for } a < 2, a \neq 2,
$$

$$
\nu_i = 1/ \ln \rho_{*}; \quad \xi^l_{a,} = -\alpha_i + \beta_L; \quad \xi^{II}_{a,} = \alpha_h - \beta_L; \quad \text{for } a \simeq 2,
$$

$$
\nu_i = (a - 2)\rho_{*}^{2-a}; \quad \xi^l_{a,} = -\alpha_i + \beta_L; \quad \xi^{II}_{a,} = \alpha_h - \beta_L; \quad \text{for } a > 2, a \neq 2
$$

where the critical rigidity

$$
\tilde{R}_* = g_{acc} \sqrt{\frac{(1 - g_{m}) Q_*}{c}} = \begin{cases} 
8.2 \times 10^{18} g_{acc}(1 - g_{m})^{1/2} g_l^{3/2} V, & \text{for FR-I}, \\
9.5 \times 10^{19} g_{acc}(1 - g_{m})^{1/2} g_h^{3/2} V, & \text{for FR-II}, 
\end{cases}
$$

(3.16)

is introduced with the RLF model dependent parameters

$$
g_l = \sqrt{\frac{4 \pi L_{l,*}}{L_p}} \simeq 39.77 - 61.6
$$

(3.17)

$$
g_h = \sqrt{\frac{4 \pi L_{h,*}}{L_p}} \simeq 1.68 - 2.88
$$

as well as the corresponding dynamic range $\rho_{*} = \tilde{R}_*/\bar{R}$.

The Fig. 4 shows that the critical rigidity $\tilde{R}_*$ of FR-I sources strongly depends on $\beta_L$, and in the case of the GS16 model

$$
\tilde{R}_* \sim \begin{cases} 
10^{18} V, & \text{for FR-I if } \beta_L \simeq 0.5, \\
10^{19} V, & \text{for FR-II if } \beta_L \simeq 0.8
\end{cases}
$$

(3.18)

for the typical parameter values.
Figure 4: The range of the critical rigidity dependent on $\beta_L$ for the different RLF models. Here and in the following the typical parameter values of $g_{acc} = 0.1$, $g_m = 4/7$ are used unless otherwise stated.

Figure 5: CSF of CR protons from FR-I and FR-II sources with an initial spectral index $a = 2$ for different $\beta_L$ in the case of $z = 0$ (middle) and $z = 2$ (right).

Analyzing the asymptotic spectral behavior of the CSF (3.15) of FR-I and FR-II sources one recognizes that

$$\tilde{\Psi}_i(R \ll \tilde{R}_s, z) \propto \left( \frac{R}{\tilde{R}_s} \right)^{-a},$$

$$\tilde{\Psi}_i(R \gg \tilde{R}_s, z) \propto \begin{cases} 
\left( \frac{R}{\tilde{R}_s} \right)^{-a + 2\xi^I/\beta_L - 2/\beta_L} \exp \left( - \left( \frac{R}{\tilde{R}_s} \right)^{2/\beta_L} \right) & \text{for FR-I}, \\
\left( \frac{R}{\tilde{R}_s} \right)^{-a - 2\xi^{II}/\beta_L} & \text{for FR-II},
\end{cases}$$

so that the spectral behavior of the CSF of FR-I sources is hardly able to explain the observed CR spectrum at $E \gg 1$ EeV for $\beta_L \simeq 0.5$ (see Fig. 5). These results are in good agreement with the results from the E+18 model. In contrast, the spectral behavior of the CSF of FR-II sources is in principle able to explain the data. However, its contribution at small redshifts is significantly smaller than the contribution by FR-Is at about 1 EeV, if the same parameters
of $g_{\text{acc}}$, $g_m$ and $a$ are supposed. But due to different jet dynamics [11] these parameters likely differ between FR-I and FR-II RGs. At large redshifts the CR production rate of FR-I and FR-II sources becomes comparable at about 1 EeV, but due to the magnetic horizon effect [29] at these redshifts the sources hardly contribute to the UHECR flux at Earth.

3.2 Constraints on the HECR contribution

Propagation effects need to be included in order to give an accurate estimate of the average contribution of the bulk of FR sources between $z = 0$ and $z = 2$ to the observed HECR data. Therefore, a 1D simulation is performed, as already introduced by E+18, where the production rate density (3.15) is used to obtain an absolutely normalized CR flux from the bulk of FR sources. In general, a solar-like initial composition is supposed, i.e. 92% H, 7% He, 0.23% C, 0.07% N, 0.5% O, 0.08% Si and 0.03% Fe in terms of number of particles at a given rigidity, and an initial spectral index $a = 2$ according to the first order Fermi acceleration theory at the sources. The chosen RLF model parameters hardly change the FR-I contribution, however, the FR-II contribution varies almost by an order of magnitude. Unless otherwise stated, the RLF model A for $\Omega_M = 1$ is used in the following, as this setup provides the maximal HECR contribution.

![Figure 6](image)

Figure 6: The HECR contribution in the limiting case of $k = 0$ and $g_m = 4/7$:
- Left: HECR spectra by FR RGs using the radio-to-CR correlation by GS16. The shaded areas indicate the results for $g_{\text{acc}} \in [1, 0.01]$ and $g_m \in [0.9, 0.1]$.
- Right: The required acceleration efficiency $g_{\text{acc}}$ of FR-I RGs dependent on $\beta_L$ for different spectral indexes $a$ of the initial CR spectrum. The shaded area indicates the uncertainty due to the different parametrization of the RLF of W+01.

In the case of the radio-to-CR correlations of GS16 (or GS13) the average HECR contribution by FR-II sources is even for a high acceleration efficiency and a high cosmic ray load at least a magnitude below the data, as shown in the left Fig. 6, although, its spectral behavior looks quite promising. Further, it can be shown that even for a hard initial CR spectrum, i.e. $a \ll 2$, the FR-II contribution stays below the data points. FR-I sources are for a flat radio-to-CR correlation index, i.e. $\beta_L = 0.5$, as suggested by GS16, at least able to provide the HECR flux below the ankle. In addition, the right Fig. 6 explores the required parameter space of FR-I RGs in order to provide a significant contribution of HECRs.

Based on a simple trial-and-error fitting method, the Fig. 7 introduces two scenarios that provide an accurate CR flux at $10^{18.7}$ eV $\lesssim E \lesssim 10^{19.5}$ eV by FR-I RGs (scenario I) and FR-II RGs (scenario II), respectively. For the scenario I, a rather high $\beta_L$ value and a
high acceleration efficiency are needed to obtain a critical rigidity (3.16) above $\sim 10^{19.5}$ V, so that the spectral behavior above the ankle becomes appropriate. For the scenario II, the jet power of FR-II RGs needs to exceed $10^{46}$ erg s$^{-1}$ at the pivot luminosity as well as $k \sim 0$ and $g_m \sim 4/7$ in order to provide enough UHECRs. Due to the impact of the Greisen-Zatsepin-Kuzmin (GZK) effect [30, 31] both scenarios fail at the highest energies. In contrast to scenario I, the scenario II also yields an appropriate HECR flux below the ankle due to the contribution by FR-I RGs. Note, that the necessary contribution from additional sources at higher and lower energies, respectively, most likely changes the given values of the fit parameters.

4 Conclusions

In this paper, an extended D+05 EGMF structure up to several hundreds of Mpc is developed in order to examine the mean deflection $\bar{\theta}$ of CRs from distant sources. In the case of Cygnus A, $\bar{\theta} \lesssim 5^\circ$ at rigidities $\gtrsim 3$ EV, so that this source cannot provide the bulk of light CRs at around the ankle, where the observational data features no significant anisotropy so far. This leaves two possible conclusions:

(i) The EGMF strength needs to be significantly higher than the one given by the D+05 model. In particular in the large-scale structures of voids, filaments and sheets where the model predominantly preserves the initial seed field. A significant UHECR contribution by Cygnus A requires an initial seed field strength $B_0 \gg 10^{-12}$ G or a sufficient amplification of the field in the filaments and sheets [32, 33].

(ii) Cygnus A does not contribute significantly to the UHECR data, but a multitude of isotropically distributed sources, most likely radio galaxies or starburst galaxies [34].

Figure 7: Proof of principle fit scenarios, where the blue/ red lines indicate the individual contributions by FR-I/ FR-II RGs and the shaded bands expose the uncertainty due to the different RLF models:

Left: Scenario I with $a = 1.8$, $g_m = 4/7$ for both FR classes; $\beta_L = 0.9$, $k = 12$, $g_{acc} = 0.8$ for FR-I RGs; and $\beta_L = 0.8$, $k = 0$, $g_{acc} = 0.1$ for FR-II RGs.

Right: Scenario II with $k = 0$, $g_m = 4/7$, $g_{acc} = 0.2$ for both FR classes; $a = 1.88$, $\beta_L = 0.5$ for FR-I RGs; and $a = 1.88$, $\beta_L = 0.8$, as well as a modified normalisation $Q_0 = 2.8 \times 10^{46}$ erg s$^{-1}$ for FR-II RGs.
Although, the latter source class might struggle to accelerate a nucleus up to the required rigidities [35].

Based on the common radio to jet power correlations, this work determines the average HECR contribution of the different types of FR RGs dependent on the CR load of the jet, given by \( g_m \) and \( k \), the acceleration efficiency \( g_{acc} \), as well as the spectral index \( \beta_L \) of the correlation and the spectral index \( a \) of the CRs at the sources. It turns out, that the bulk of FR-II RGs cannot provide enough HECR power to explain the observed HECR flux, if \( Q_{cr} < 10^{46} \text{ erg s}^{-1} \) at \( L_{151} = 10^{26.5} \text{ W Hz}^{-1} \text{ sr}^{-1} \) as suggested by the most recent correlation models. In contrast, there is a large variety of different parameter setups that enable a significant HECR contribution by FR-I RGs. It is shown for a maximal CR load of the jet, i.e. \( g_m \sim 4/7 \) and \( k = 0 \), which acceleration efficiency is required dependent on \( \beta_L \) and \( a \).

Finally, two proof of principle scenarios are introduced that enable an explanation of the hardening part of the CR flux at \( 10^{18.7} \text{ eV} \lesssim E \lesssim 10^{19.5} \text{ eV} \): First, by FR-I RGs, in the case of a low CR load, but a high acceleration efficiency \( g_{acc} \gtrsim 0.8 \) of these sources. However, also a large correlation index \( \beta_L \gtrsim 0.9 \) is needed, that disagrees with the theoretical expectations of the FR-I lobe dynamics [17]. Secondly, by FR-II RGs, in the case of a significantly higher CR power of these sources with a vanishing lepton fraction. But such an energetically dominant CR population is disfavored by some models [36–38], that suggest \( k \gtrsim 1 \) in the lobes of FR-II RGs. Nevertheless, such a scenario exhibits some strong implication with respect to the whole HECR data: Supposing that FR-I RGs provide a rather heavy CR contribution with respect to the FR-II class and an individual, close-by FR-I source like Centaurus A provides the observed CRs at energies \( \gtrsim 30 \text{ EeV} \) as shown by E+18, even the observed spectral behavior of the chemical composition, as well as the arrival directions are probably explainable. However, the northern hemisphere, as covered by the TA experiment, still misses a luminous, close-by FR source that provides the observed CRs above the GZK cut-off energy. Hence, further investigations, that are beyond the scope of this work, are needed in order to verify whether FR RGs are able to explain all HECR data.

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