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The UHECR contribution of radio galaxies with a finite life-time

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The observational data on ultrahigh energy cosmic rays (UHECR), in particular their mass composition, show strong indications for extremely hard spectra of individual mass groups of CR nuclei at Earth. It has been shown that such hard spectra can be the result of the finite life-time of UHECR sources, if only a few individual sources dominate the UHECR flux at the highest energies. In this work we investigate the requirements on their CR power and life-time dependent on the characteristics of a purely turbulent, extragalactic magnetic field (EGMF). Without accounting for the anisotropy data, we are able to draw some robust constraints on the contribution of the brightest local radio galaxies, if the initial source spectrum at the acceleration side is soft, i.e. with a spectral index $\alpha \gtrsim 2$, as expected from conventional shock-acceleration theory. Moreover, we show that a local source could provide a dominant UHECR contribution which agrees with the mass composition at energies $E \gtrsim 40\,\mathrm{EeV}$ data only in the case of a strong EGMF.

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1. Introduction

Since the first observation of CRs with energy close to 10^{20} eV [1], the revelation of their origin has been a key-driver in the field of cosmic ray (CR) physics. Due to observations by the Pierre Auger Observatory (PAO) and the Telescope Array (TA) experiment considerable progress has been made in recent years (see e.g. [2–4]), such as the precise determination of the diffuse energy spectrum [5–7] of ultrahigh energy cosmic rays (UHECRs), a better determination of the mass composition, and the discovery of a dipolar anisotropy with an amplitude $\delta \simeq 6.5\%$ in the arrival directions of UHECRs exceeding 8×10^{18} eV [8]. In particular this dipole anisotropy — whose amplitude seems to increase as $\delta \propto E^{0.8}$ with energy [9] — reveals the prospect of identifying the sources of the CRs at the highest energies. But despite multiple efforts (see e.g. [10–13]) the original quest remains unsolved (or at most ambiguously solved), which is predominantly a consequence of the lack of knowledge on the Galactic and extragalactic magnetic field (EGMF) as well as on the individual source characteristics.

Nevertheless, the contribution of certain astrophysical sources to the observed UHECR signal can be constrained: Hereby, an important observational information results from the variance of the mass composition with energy, indicating that the dominating element groups to the flux are surprisingly well separated [7] above about 10 EeV. This introduces the need for extremely hard spectra, i.e with a positive slope. Such a slope could either be realized at the sources by a certain type of acceleration mechanism — that, however, needs to be considerably different from the conventional shock-acceleration — or during propagation to Earth by the magnetic horizon suppression. In its original version, the magnetic horizon effect was used to explain the suppression of the diffuse extragalactic cosmic ray flux below few $\times 10^{17}$ eV [14–16]. Later, the same effect was studied for the case of a mixed composition showing that the suppression of low-energy cosmic rays helps to reconcile the measured composition data [17]. More recently, Refs. [18–20] studied the magnetic horizon effect for local sources with a finite life-time.

In this work, we continue on this line of thought and constrain the necessary source and EGMF characteristics required for a dominant flux contribution at energies $E \gtrsim 40$ EeV. We suppose a purely turbulent EGMF, while the additional elongation of the propagation length by the Galactic magnetic field can be neglected. Our driving question can be summarized as follows: What is the necessary CR power and life-time of these UHECR sources? In Sect. 2 we introduce two theoretical constraints that are subsequently, in Sect. 3, applied and compared to the observational data. In Sect. 4 we conclude and discuss our findings.

2. Constraints

The elongation of the CR's propagation length by an isotropic Gaussian random magnetic field of rms strength $B_{\rm rms}$, with a coherence length $l_{\rm coh}$ and a Kolmogorov spectrum, can be characterised by the diffusion length

$$l_D \simeq l_{\rm c} \left[4 \left(\frac{R}{B_{\rm rms}\, l_{\rm coh}} \right)^2 + 0.9 \left(\frac{R}{B_{\rm rms}\, l_{\rm coh}} \right) + 0.23 \left(\frac{R}{B_{\rm rms}\, l_{\rm coh}} \right)^{1/3} \right] , \qquad (1)$$

where $R \equiv E/Ze$ denotes the particle's rigidity. This provides the length scale on which the CR particle experiences the diffusive motion by the magnetic field. Hence, CR particles with small rigidity need more time to reach Earth than those with higher rigidity. Therefore, we obtain a diffusive enhancement of CRs in case of a steady source at a distance $d \gg l_{\mathrm{D}}$. But if the source has a finite life-time $\tau_{\mathrm{act}} < \infty$ not all CRs manage to reach Earth in time yielding a suppression of CRs with small rigidity — the so-called magnetic horizon effect. It has been numerically determined by Ref. [19] that the so-called enhancement factor

$$\xi(R, d, \tau_{\mathrm{act}}) = \frac{3d\, \exp\left(-\left(d^2/[0.6\,(c\tau_{\mathrm{act}} + d) l_{\mathrm{D}}]\right)^{0.8}\right)}{l_{\mathrm{D}}\,[1 - \exp(-3(d/l_{\mathrm{D}}) - 3.5(d/l_{\mathrm{D}})^2)]} \tag{2}$$

comprises these two effects on the observed UHECR intensity. Note that we define the source life-time τ_{act} with respect to the observation at Earth, so that the maximal distance traveled by the observed UHECRs equals $ct_{\mathrm{act}} + d$. The magnetic horizon suppression is associated to the exponential function in the numerator.

In addition to the impact by magnetic fields, UHECRs also suffer from energy losses by interactions with photons from the cosmic microwave background (CMB) and the extragalactic background light. The details of this interaction depends on the UHECR nuclei species i. But in any case its impact reduces the unaffected UHECR intensity by a modification factor $\eta_i(R, d) \leq 1$, so that the total UHECR intensity from a source with a finite life-time τ_{act} at distance d can be constrained to

$$J_s(R, d, \tau_{\mathrm{act}}) \equiv \frac{\mathrm{d}N_{\mathrm{cr}}}{\mathrm{d}R\, \mathrm{d}A\, \mathrm{d}t\, \mathrm{d}\Omega} \leq \frac{c}{4\pi}\, n_s(R, d, \tau_{\mathrm{act}}) = \frac{c}{4\pi}\, n_0 \left(\frac{R}{\check{R}}\right)^{-\alpha} \exp\left(-\frac{R}{\hat{R}}\right) \xi(R, d, \tau_{\mathrm{act}})\,. \tag{3}$$

Here, we adopted a source spectrum with a spectral index α between the minimal rigidity $\check{R}$ and the maximal rigidity $\hat{R}$, where the exponential cut-off sets in. The total CR power of all nuclei species i is given by

$$Q_{\mathrm{cr}} = \sum_i Z_i \int_{\check{R}}^{\hat{R}} \mathrm{d}R\; R\, \frac{\mathrm{d}N_{\mathrm{cr,i}}}{\mathrm{d}R\, \mathrm{d}t}\,, \tag{4}$$

so that the normalization yields

$$n_0 \simeq \frac{Q_{\mathrm{cr}}}{2\pi c\, d^2}\, \frac{\check{R}^{-\alpha}\,(2-\alpha)}{(\hat{R}^{2-\alpha} - \check{R}^{2-\alpha})}\,. \tag{5}$$

Here we incorporated that the nuclei-dependent modification factor (that accounts for the interactions with the photon fields) can be approximated by a nuclei averaged modification factor $\bar{\eta}$ according to $\eta_i \simeq A_i\, \bar{\eta} \simeq 2Z_i\, \bar{\eta}$ (see Ref. [11] for more details). Note that also $\bar{\eta} < 1$, so that the inequality in Eq. (3) holds. As shown in the left panel of Fig. 1, the initial spectral power-law behavior is changed by the impact of ξ yielding a distance dependent exponential suppression towards small rigidities. Thus, the energy spectra of different nuclei specie can become clearly separated, see e.g. Ref. [20], so that with increasing energy the mass composition becomes on average heavier, but its variance remains small.

2.1 Total Flux Cut

Independent of the supposed hadronic interaction model, the total observed flux above $E_0 = 40\,\mathrm{EeV}$ yields

$$\int_{R_0}^{\infty} \mathrm{d}R\; J_{\mathrm{obs}}(R) \simeq 7 \times 10^{-3}\, \mathrm{km}^{-2}\, \mathrm{yr}^{-1}\, \mathrm{sr}^{-1}\,.$$

The corresponding lower limit $R_0 = E_0/Z_0 e \simeq 2E_0/\exp(\langle \ln A(E_0)\rangle) e$ can be estimated only considering the observed mass composition, i.e. the inferred mean logarithm of the mass number at E_0, which however, is not independent of the hadronic interaction model. For instance, R_0 ranges from about 5 EV in case of Sibyll2.3c up to 19 EV in case of QGSJetII-04. In the following, we use an intermediate value of $R_0 = 9\,\mathrm{EV}$ that results from using the EPOS-LHC model. Hence, we obtain from Eq. (3) as minimal CR power

$$\check{Q}_{\mathrm{cr}} \simeq \frac{5.3 \times 10^{40} \left(\frac{d}{1\,\mathrm{Mpc}}\right)^2 \left(\hat{R}^{2-\alpha} - \check{R}^{2-\alpha}\right)\,\mathrm{yr}^{-1}}{\check{R}^{-\alpha}\,(2-\alpha) \int_{R_0}^{\infty} \mathrm{d}R\,\left(\frac{R}{\check{R}}\right)^{-\alpha} \exp\left(-\frac{R}{\hat{R}}\right)\,\xi(R, d, \tau_{\mathrm{act}})}\,. \tag{6}$$

The distance dependence of $\check{Q}_{\mathrm{cr}}$ is predominantly given by $\xi(R, d, \tau_{\mathrm{act}})$. At small source distances, i.e where the magnetic horizon suppression is negligible, $\check{Q}_{\mathrm{cr}} \propto d^2$ in case of a fixed maximal rigidity $\hat{R}$. Note that for $\hat{R} \propto \sqrt{Q_{\mathrm{cr}}}$ we obtain at small distances $\check{Q}_{\mathrm{cr}} \propto d$ for $\alpha \sim 2$, and the necessary CR power decreases with increasing acceleration efficiency, i.e. increasing $\hat{R}$, as shown in the right panel of Fig. 1. At large source distances, where the magnetic horizon suppression becomes relevant, the necessary CR power $\check{Q}_{\mathrm{cr}}$ increases exponentially in both cases.

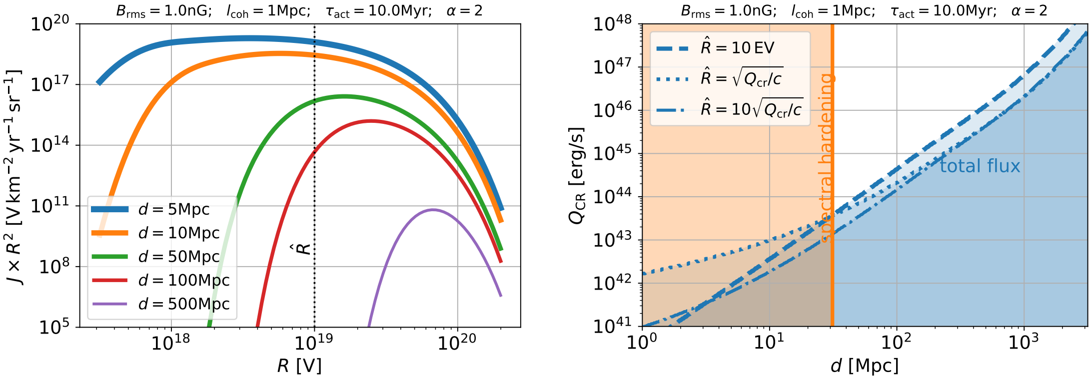

Figure 1: *Left:* The spectral UHECR intensity for different source distances adopting a maximal rigidity $\hat{R} = 10\,\mathrm{EV}$ and a CR power $Q_{\mathrm{cr}} = 10^{44}\,\mathrm{erg\,s^{-1}}$. *Right:* The minimal CR power $\check{Q}_{\mathrm{cr}}$ dependent on the source distance for different assumptions on the maximal rigidity $\hat{R}$.

2.2 Spectral Hardening Cut

In addition to a sufficient CR power, the resulting flux at Earth also needs to exhibit the proper spectral behavior. Supposing a soft spectral behavior with $\alpha \gtrsim 1.5$ at the sources—which is expected from the conventional shock-acceleration scenarios—the flux needs to harden significantly by propagation effects to agree with the observational data. It is hard to imagine any other effect except for the magnetic horizon suppression that is able to yield such a strong hardening as needed at energies $\gtrsim 10\,\mathrm{EeV}$. According to the enhancement factor (2) we thus have to demand that

$$d \gtrsim \sqrt{0.6\,(c\,\tau_{\mathrm{act}} + d)\,l_{\mathrm{D},0}} \quad \Rightarrow \quad d \gtrsim 0.3\,l_{\mathrm{D},0} + \sqrt{0.6\,c\,\tau_{\mathrm{act}}\,l_{\mathrm{D},0} + 0.09\,l_{\mathrm{D},0}^2} \tag{7}$$

with $l_{\mathrm{D},0} \equiv l_\mathrm{D}(R_\mathrm{hor})$ to obtain a sufficient flux suppression at rigidities $R \lesssim R_\mathrm{hor}$. Hence, independent of the actual source life-time, the source distance has to be at least of the order of $0.6\, l_{\mathrm{D},0}$. According to the spectral features and the observed mass composition we expect that $3\,\mathrm{EV} \lesssim R_\mathrm{hor} \lesssim 10\,\mathrm{EV}$. We adopt $R_\mathrm{hor} = 3\,\mathrm{EV}$ in the following, which keeps the minimal source distance as small as possible. Still, we obtain that—independent of the source life-time—the UHECR source needs to be at a distance of *at least* 29 Mpc in case of an EGMF with $B_\mathrm{rms} = 1\,\mathrm{nG}$ and $l_\mathrm{coh} = 1\,\mathrm{Mpc}$. As shown in the left Fig. 1, this yields an additional constraint, that is quite useful to exclude close-by CR sources which are hardly constrained from Eq. (6).

3. Results

To apply our previously introduced constraints (6) and (7) to actual sources, we need an estimate of their CR power. AGN with collimated jets, also referred to as "radio galaxies", exhibit a large size, longevity and a sufficiently high power as to plausibly be able to accelerate UHECRs [21]. The so-called radio-jet power correlation, se e.g. [22], provides an order-of-magnitude estimate of their total jet power Q_jet, whereof some fraction is emitted in form of CRs, yielding [11]

$$Q_\mathrm{cr} = \frac{g_\mathrm{m}}{1+k}\, Q_\mathrm{jet} \simeq \frac{g_\mathrm{m}}{1+k}\, Q_0 \left(\frac{L_{151}}{L_p}\right)^{\beta_L} . \tag{8}$$

Here $g_\mathrm{m} < 1$ denotes the fraction of jet energy in relativistic particles and k the ratio of leptonic to hadronic energy density. Thus, based on the distance as well as the observed radio flux at 151 MHz of brightest local radio galaxies as composed by Ref. [23], we can determine an upper limit of their CR power (as given by the black data points in Fig. 2) using the resulting jet power.

Furthermore, some part of the remaining fraction is stored in the magnetic field, which can be used to constrain the maximal rigidity [11]

$$\hat{R} = g_\mathrm{acc}\sqrt{(1-g_\mathrm{m})\, Q_\mathrm{jet}/c} = g_\mathrm{acc}\sqrt{(1+k)\left(g_\mathrm{m}^{-1}-1\right)\, Q_\mathrm{cr}/c}$$

introducing the acceleration efficiency parameter which lies in the range $0.01 \lesssim g_\mathrm{acc} \lesssim 1$. In total, we expect that $g_\mathrm{acc}\sqrt{(1+k)\left(g_\mathrm{m}^{-1}-1\right)} \lesssim 10$, so that even in the most conservative[1] scenario $\check{Q}_\mathrm{cr}$ is only a factor of about 3 times smaller (as can be seen in the right Fig. 1) than the case for a fixed (and also conservative) value of $\hat{R} = 10\,\mathrm{EV}$—referring to the idea that the exponential cut-off in the observed flux spectrum is associated to the maximal energy of the accelerator. In the following we stick to this idea and use a conservative, fixed value of $\hat{R} = 10\,\mathrm{EV}$, as current observations indicate that $\hat{R} \lesssim 10\,\mathrm{EV}$ of the CR protons, which is significantly below the expected GZK cut-off [24, 25] energy.

Moreover, we adopt an initial source spectrum with $\alpha \sim 2$—as expected from conventional shock acceleration mechanisms—but stay agnostic with respect to the source and acceleration details. This is necessary as in the case of very hard source spectra, $\alpha \ll 2$, the previously introduced constraints (6) and (7) become irrelevant and unjustified, respectively. In addition, we use a minimal CR rigidity $\check{R} = 1\,\mathrm{GV}$ as expected from the thermal-leakage models and used previously by Ref. [11]. Note that the necessary CR power increases with decreasing $\check{R}$, but for $\alpha \simeq 2$ its impact is marginal.

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[1] Conservative in the sense that the resulting $\check{Q}_\mathrm{cr}$ value becomes minimal.

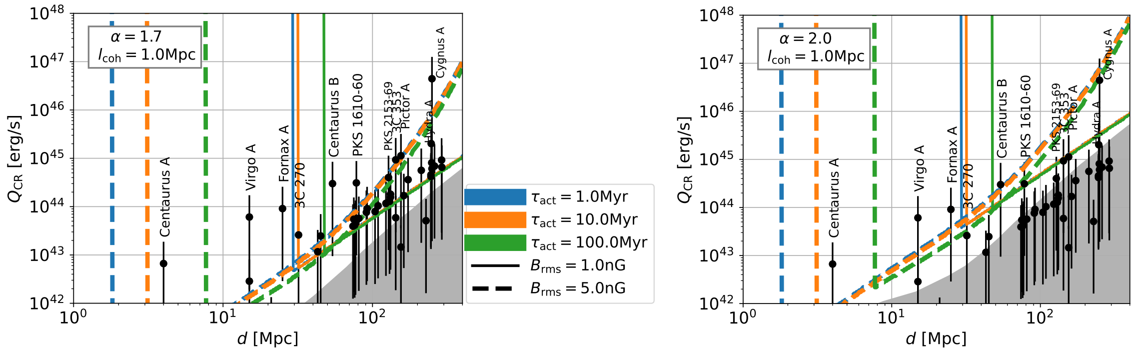

Figure 2: The allowed parameter space (within the “knife-shaped” regions) dependent on the EGMF strength and the source life-time as well as the maximal CR power (black dots) of the brightest local radio galaxies. The grey shaded region indicates the parameter space that can be excluded independent of the choosen B_{rms} and τ_{act} values. A coherence length $l_{\mathrm{coh}} = 1$ Mpc as well as an initial spectral source index of $\alpha = 1.7$ (*left*) and $\alpha = 2$ (*right*), respectively, is supposed.

Figure 2 shows taking into account the previouse conservative assumptions, the potential maximal CR power of the radio sources as well as the allowed, “knife-shaped” regions of the parameter space—dependent on the EGMF strength and the source life-time—that enable a single sources to explain the observed flux above 40 EeV. Thus, the huge majority of sources can be excluded in general (grey shaded region) in case of an initial source spectrum $\alpha > 2$. But even for slightly harder source spectra, rather tight constraints on the EGMF strength and source life-time have to be imposed to allow a dominating UHECR source. Close-by sources such as Centaurus A, Virgo A or Fornax A, generally need an EGMF with an rms strength $\gtrsim 1$ nG or a coherence length $\gg 1$ Mpc. Note that we have used conservative presumptions so far and the number of potential UHECR sources is reduced considerably by increasing the value of R_{hor} or decreasing the value of $\hat{R}$.

4. Conclusions and Discussion

In this work, we discussed the potential UHECR sources at energies > 40 EeV under the presumption of a soft, initial energy spectrum, with $\alpha \sim 2$, as expected from conventional shock-acceleration scenarios. We accounted for the finite life-time of the sources as well as deflections by a non-vanishing, turbulent EGMF. Under these conditions, the impact of the magnetic horizon effect suppresses CRs towards small rigidity, an effect favoured by the observational data of the energy spectrum and mass composition, as recently shown in Refs. [18–20].

Based on these assumptions we determined the necessary minimal CR power dependent on the source distance and life-time as well as the EGMF characteristics to be the dominating UHECR source above 40 EeV. Finally, we used as a specific example the case of local radio galaxies showing that (i) only few radio galaxies—in particular Virgo A, Fornax A, Centaurus A and B—are powerful enough to contribute a significant amount of UHECRs; and (ii) nearby sources (with distances $\lesssim 50$ Mpc) need a strong local EGMF. For an EGMF with a rms strength $\ll 1$ nG all of the *present* nearby sources can be excluded, as their spectral behavior is not effected by the hardening from the magnetic horizon suppression. Still, there is the chance that ancient sources (that are no longer visible by any electromagnetic signatures) have a significant contribution to the observed UHECR signal, as they have an enlarged effective distance. But to provide a sufficient intensity the bulk of emitted CRs needs to reach Earth with a temporal delay that is similar to the time span on which the source is no longer visible.

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