Cosmic Ray Acceleration in Active Galactic Nuclei
- On Centaurus A as a possible UHECR Source.

Frank M. Rieger
(1) Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany
(2) European Associated Laboratory for Gamma-Ray Astronomy (CNRS/MPG)

Abstract

We discuss a representative selection of particle acceleration mechanisms believed to be operating in Active Galactic Nuclei. Starting from direct electrostatic field acceleration in the vicinity of the black hole up to Fermi-type particle acceleration in the jet and beyond, possible efficiency constraints on the energization of ultra-high energy cosmic rays (UHECR) are evaluated. When paradigmatically applied to Cen A, the following results are obtained: (i) Proton acceleration to energies of $E_c = 5 \times 10^{19}$ eV and beyond remains challenging and most likely requires the operation of an additional mechanism capable of boosting energetic seed protons up by a factor of $\sim$ten. It is argued that shear acceleration along the large-scale jet in Cen A could be a promising candidate for this. (ii) Heavier elements, like iron nuclei, are more easily accelerated (by, e.g., shocks or direct electrostatic fields) and may not need additional boosting to reach $E > E_c$; (iii) If Cen A indeed proves to be an UHECR source, the cosmic ray composition might thus be expected to become heavier above energies of a few times $10^{19}$ eV.

1 Introduction

The observation of variable, non-thermal high emission from Active Galactic Nuclei (AGN) reveals that efficient particle acceleration can take place on different length scales. It is widely believed, for example, that diffusive shock acceleration of electrons can produce the power-law particle distributions that are needed to account for the observed nuclear synchrotron and inverse Compton emission features in AGN jets. While efficient electron acceleration is in most cases strongly limited by radiative losses, this is much less the case for protons and heavier nuclei, suggesting that these particles could reach much higher energy via the same acceleration process. Motivated by the indication of a possible correlation between the Pierre Auger (PAO)-measured ultra-high energy cosmic ray (UHECR) events and the nearby AGN distribution [1, 2, 3], this contribution analyzes the conditions under which efficient cosmic ray acceleration to UHECR energies may become possible. Particular attention is given to the radio galaxy Cen A, which, based on its proximity, could represent a promising UHECR source candidate, e.g., [4, 5, 6].

2 Centaurus A

Given the possible association of some of the PAO measured UHECR events with Centaurus A (Cen A) [3], an application to it may appear most instructive.
Being the nearest ($d \sim 3.4$ Mpc) FR I source, Cen A is among the best studied AGN. Radio observations show a complex morphology with a sub-pc-scale jet and counter-jet, a one-sided kpc-jet, two radio lobes and extended diffusive emission. VLBI observations suggest that Cen A is a non-blazar source with its jet inclined at a rather large viewing angle $i \gtrsim 50^\circ$ and characterized by a relatively modest bulk flow speed $u_j \sim 0.5 \, c$ \cite{7, 8}. The center of its activity is a supermassive black hole with mass inferred to be in the range $m_{\text{BH}} = (0.5 - 3) \times 10^8 M_\odot$ \cite{10, 11}. With a bolometric luminosity output of the order of $L_\text{b} \sim 10^{43}$ erg/s \cite{12}, Cen A is rather under-luminous and accreting at sub-Eddington rates. If the inner disk in Cen A remains cooling-dominated (standard disk), accreting rates $\dot{m} \sim 10^{-3} \dot{m}_{\text{Edd}}$ and equipartition magnetic field strengths close to the black hole of order $B_0 \sim (2L_\text{b}/r_g^2 c)^{1/2} \sim 2 \times 10^3$ G might be expected (where $r_g = GM/c^2 \simeq 1.5 \times 10^{13}$ cm is the gravitational radius for a $10^8 M_\odot$ black hole). If the disk switches to a radiatively inefficient mode, characteristic magnetic field strengths may be somewhat higher, possibly reaching $B_0 \sim 2 \times 10^4$ G.
3 Particle acceleration in the vicinity of the black hole

Rotating magnetic fields, either driven by the disk or the black hole itself, can produce energetic charged particles emerging from the vicinity of the black hole.

3.1 Direct electrostatic field acceleration

If a black hole is embedded in a poloidal field of strength $B_p$ and rotating with angular frequency $\Omega_H$, it will induce an electric field of magnitude $|\vec{E}| \sim (\Omega_H r_H) B_p/c$. This corresponds to a voltage drop across the horizon $r_H$ of magnitude $\Phi \sim r_H \frac{|\vec{E}|}{c}$. In terms of the electric circuit analogy, a rotating black hole thus behaves like a unipolar inductor (battery) with non-zero resistance, so that power can be extracted by electric currents flowing between its equator and poles. Using parameters appropriate for Cen A, the voltage drop is of the order of

$$\Phi \sim 3 \times 10^{19} a \left( \frac{m_{BH}}{10^8 M_\odot} \right) \left( \frac{B_p}{10^4 G} \right) [V], \quad (1)$$

where $0 \leq a \leq 1$ denotes the dimensionless Kerr parameter. If a charged particle (with charge number $Z$) can fully tap this potential, particle acceleration to ultra-high energies

$$E = Z e \Phi \sim 3 \times 10^{19} Z eV \quad (2)$$

may become possible. This would suggest a rather heavy composition instead of a light one (e.g., iron nuclei instead of protons) for cosmic ray events above $E_c = 5 \times 10^{19}$ eV. Yet, whether such energies can, in fact, be achieved, seems questionable: (i) In the plasma-rich environment of AGN (where the typical charge number density is much larger than the Goldreich-Julian one), a non-negligible part of the presumed electric field is expected to be screened and therefore not available for particle acceleration. (ii) Even if this would not be the case, curvature losses would constrain achievable proton energies in sources like Cen A to values of $\lesssim 10^{19}$ eV \[14\]. (iii) Large-scale poloidal fields threading the horizon with strengths of $B_p \sim 10^4$ G would be required. This may appear overly optimistic, at least in the case of a standard disk \[15\]. (iv) A highly spinning black hole with $a \sim 1$ would be required (also, if one wishes to account for the power output solely via a Blandford-Znajek-type-process), although rather modest spins may be expected for FR I sources \[16\]. Taken together, this suggests that direct acceleration of protons to energies of $E_c$ and beyond in Cen A is rather unlikely, while it could be (marginally) possible for heavy elements.

3.2 Centrifugal acceleration

Even if the charge density would be such that effective electric field screening does occur, particle acceleration due to inertial effects (i.e., centrifugal acceleration along rotating magnetic fields) could still be possible, e.g. \[17\], \[18\]. The requirement that the associated acceleration timescale remains larger than the inverse of the relativistic gyro-frequency, however, then implies a maximum Lorentz factor for cosmic rays \[18\], which in the case of Cen A is of the order of

$$\gamma \lesssim 2 \times 10^7 \frac{r_L}{10^{14} \text{cm}} \left( \frac{m_p}{m_0} \right)^{2/3} \left( \frac{r_L}{10^{14} \text{cm}} \right)^{2/3} \quad (3)$$
where $r_L$ denotes the light cylinder radius (typically of the order of a few times the Schwarzschild radius). This suggests that centrifugal acceleration in Cen A will be unable to account for the production of ultra-high energy cosmic rays.

4 Fermi-type particle acceleration in the jets and beyond

Stochastic processes in the turbulent AGN environment (e.g., in the jets or lobes) could well lead to the production of non-thermal particle distributions. In the classical Fermi picture [19], for example, particle acceleration occurs as a consequence of multiple scattering off moving magnetic turbulence structures, with a small energy change in each scattering event. The characteristic energy gain per scattering event for an energetic charged particle (velocity $v \sim c$), elastically scattering off some magnetic irregularity moving with typical velocity $\vec{v}$, is given by

$$\Delta \epsilon := \epsilon_2 - \epsilon_1 = 2\Gamma^2 (\epsilon_1 u^2/c^2 - \vec{p}_1 \cdot \vec{u}), \quad (4)$$

where $\Gamma = (1 - u^2/c^2)^{-1/2}$ is the Lorentz factor of the scatterer, $\vec{p} = \epsilon \vec{v}/c^2$ the particle momentum and the indices 1 and 2 denote particle properties before and after scattering. A particle can thus gain or lose energy depending on whether it suffers head-on/approaching ($\vec{p}_1 \cdot \vec{u} < 1$) or following/overtaking ($\vec{p}_1 \cdot \vec{u} > 1$) collisions. Based on this, one can distinguish the following Fermi-type particle acceleration processes, cf. [20, 21, 22].

4.1 Diffusive shock (Fermi I) acceleration

Diffusive shock acceleration assumes that energetic particles (with gyro-radius much larger than width of the shock, $|\vec{p}_1| \simeq \epsilon_1/c$) can pass unaffected through a shock, and, by being elastically scattered in the fluid on either side, cross and re-cross the shock several times. Sampling the difference $\Delta u$ in flow velocities across a shock (always head-on), the characteristic energy gain for a particle crossing the shock, cf. eq. (4), becomes first order in $\Delta u/c$, i.e., $\Delta \epsilon/\epsilon_1 \propto (\Delta u/c)$.

As this energy gain is acquired during a shock crossing time $t_c \sim \lambda/u_s$ (with $u_s$ the shock speed and $\lambda$ the scattering mean free path), the characteristic acceleration timescale (for a non-relativistic shock) is of the order of

$$t_{acc} \sim \epsilon \left(\frac{d\epsilon}{dt}\right) \sim \frac{\epsilon_1/\Delta \epsilon}{t_c} \sim \frac{\lambda c}{u_s^2}. \quad (5)$$

If radiative losses are negligible, we can equate the timescale for acceleration with the one for cross-field diffusion out of the system, $t_c \sim r_g^2/(\lambda c)$, or the dynamical timescale, $t_d \sim z/u_s$ (whichever is smaller), to derive an estimate for the maximum achievable particle energy, cf. [23]

$$E_{max} \sim Z e B r_{gyro}/\beta_s \sim 2 \times 10^{19} Z \left(\frac{B_0}{10^4 G}\right) \left(\frac{\beta_s}{0.1}\right) \ eV,$$

(6)

taking $\lambda \sim r_{gyro}$ to be of the order of the gyro-radius, $\beta_s = u_s/c$, and $B(z) \sim 4 B_0 (r_g/z \alpha_j)$ (allowing for some magnetic field compression), with $B_0$ the field strength close to the black hole and $\alpha_j$ the jet opening angle. The observed (radio) jet speeds in Cen A are only mildly relativistic with $u_j \sim 0.5 \ c$. If representative for the general flow, then typical internal shock speeds (of the order of
the relative velocity between colliding shells) are expected to be rather moderate with \( \beta_s \sim 0.1 \) or less. Such low shock speeds are as well suggested by the nuclear SED of Cen A, showing an electron synchrotron peak below \( 10^{20} \) Hz (already assuming the 2nd peak to be due to synchrotron and not inverse Compton, cf. \[24\]): synchrotron-limited electron shock acceleration would imply a (magnetic field-independent) peak at \( \sim 3 \times 10^{19} (\beta_s/0.1)^2 \) Hz and thereby support rather modest shock speeds. Equation \( [6] \) suggests that if shock acceleration would be responsible for UHECR production in Cen A, then the expected composition should be rather heavy, i.e., efficient shock acceleration of protons to energies of \( \sim E_c \) and beyond seems unlikely (see also below, \( \S 5 \)). This might be compared with a recent analysis of the PAO measurements suggesting that the cosmic ray composition becomes heavier towards the highest measured energies \[25\].

### 4.2 Stochastic Fermi II acceleration

According to eq. \[4\], particle acceleration due to scattering off randomly moving magnetic inhomogeneities is accompanied by an average energy gain which is second order in \((u/c)^2\). Efficient acceleration thus obviously requires that the velocity of the scatterers is sufficiently large. As the energy gain is acquired over a scattering time \( t_s \sim \lambda/c \), the associated acceleration timescale is of the order of

\[
t_{\text{acc}} \sim \left( \frac{c}{v_A} \right)^2 \frac{\lambda}{c},
\]

assuming that the scattering is due to Alfvén waves moving with a speed \( u = v_A = B/\sqrt{4\pi \rho} \). If we again neglect radiative losses, achievable particle energies are limited by escape via cross-field diffusion, resulting in an upper limit of

\[
E_{\text{max}} \sim 2 \times 10^{19} Z \left( \frac{R}{100 \, \text{kpc}} \right) \left( \frac{v_A}{0.1 \, c} \right) \left( \frac{B}{10^{-6} \, \text{G}} \right) \, \text{eV},
\]

on scales of \( R \sim 100 \) kpc appropriate for the giant radio lobes in Cen A. For relativistic Alfvén speeds (>0.3 c), 2nd order Fermi effects could thus potentially allow proton acceleration up to ultra-high energies \[26\]. Yet, whether such conditions could be realized seems questionable, cf. \[27\]. For if some of the observed X-ray emission in the giant lobes of Cen A is indeed thermal in origin, e.g., \[28\], this would imply a thermal plasma density of the order of \( n_{\text{th}} \sim (10^{-5} - 10^{-4}) \) cm\(^{-3}\), so that expected Alfvén speeds would be of the order of \( v_A \sim 0.003 \) c, i.e., well below the ones required. Such (relatively high) thermal plasma densities are in fact consistent with recent, independent estimates based on Faraday rotation measurements in the radio lobes of Cen A \[29\]. Given current evidence, it may thus seem rather doubtful whether efficient UHECR acceleration could take place in its giant radio lobes.

### 4.3 Shear acceleration

If the flow, in which the scatterers are thought to be embedded, has a smoothly changing velocity profile in the direction perpendicular to the jet axis (e.g., a shear flow or layer with \( \vec{u} = u_z(r) \hat{e}_z \)), then energetic particles, scattered across it, may well be able to sample the flow difference \( du \) and thereby get accelerated \[30\] \[31\]. Like stochastic 2nd order Fermi acceleration, the average energy gain would be proportional to \((du/c)^2\), although the physical origin is now different.
The velocity difference in the flow, experienced by a particle scattered across it, is of the order of \( du \sim (du_z/dr) \lambda \), where \( \lambda \) is the scattering mean free path. Again, this energy change is acquired over a mean scattering time \( \tau_s \sim \lambda/c \), so that the characteristic acceleration timescale becomes

\[
t_{\text{acc}} \sim \frac{\epsilon_1}{\Delta \epsilon / \tau_s} \sim \frac{1}{(du_z(r)/dr)^2 \lambda}.
\]

Compared to eq. (5) and eq. (7), the acceleration timescale is now inversely proportional to \( \lambda \). Thus, as a particle increases its energy (so that the mean free path \( \lambda \) becomes larger), the acceleration timescale decreases. Shear acceleration will, therefore, preferentially pick up high energy seed particles for further energization, and act more easily on protons than on heavier nuclei. It seems well possible that shocks, operating in the jet (either on smaller scales or within a spine), could provide the energetic seed protons required for further shear acceleration along the jet [32]. If so, then the maximum achievable energies might be expected to be essentially determined by the confinement condition that the gyro-radius remains smaller than the width of the shear layer. The large-scale jet in Cen A has a projected length of \( \sim 4.5 \) kpc and towards its end a width of about \( \sim 1 \) kpc [9, 33]. If we take a characteristic magnetic field strength of \( B \sim 10^{-4} \) G on kpc-scale and assume the width of the shear to become comparable to the width of the jet, achievable maximum energies would be of the order of

\[
E \sim ZeB(\Delta r) \sim 10^{20}b_jZ \text{ eV},
\]

suggesting that shear acceleration might be able to boost energetic seed protons (produced by shock acceleration) up to energies beyond \( E_c \). Note that in the presence of sufficient internal shear, the magnetic field within the layer may well be expected to fall more slowly with distance along the jet, \( b_j > 1 \), due to amplification by stretching and folding of magnetic field lines, e.g. [34, 35]. A shear dynamo effect could possibly also explain why in Cen A the magnetic field direction seems to be almost parallel along the kpc jet [8]. If such an amplification takes place, the situation may be even more favorable.

5 Constraints from jet power requirements

If efficient UHECR acceleration would take place in the jet of Cen A, one could estimate the magnetic energy flux carried by the jet, and therefore the minimum jet power required. For the magnetic flux carried by the jet in Cen A, we have

\[
L_m \sim \int dr \ 2\pi r u_z (B_\perp^2 / 8\pi) = r^2 B_\perp^2 u_z/8,
\]

where \( B_\perp \) is the magnetic field component perpendicular to the direction of the bulk outflow velocity \( u_z \) (assumed to be non-relativistic), and where the second equality holds provided \( B_\perp \) and \( u_z \) (or more precisely, the product \( B_\perp^2 u_z \)) are independent of the jet radius \( r \). If we assume \( r \sim r_w/2 \) and use eq. (8) to find an expression for the magnetic field in terms of \( E_{\text{max}} \), efficient cosmic ray acceleration by internal shocks would require a jet power of at least \( L_j \sim 2L_m \), i.e.

\[
L_j \sim 10^{44} \left( \frac{u_z}{0.5c} \right) \left( \frac{0.1}{\beta_s} \right)^2 \left( \frac{E_{\text{max}}}{10^{19}\text{eV}} \right)^2 \frac{1}{Z^2} \ \text{erg/s}.
\]
This would support the previous conclusion that proton acceleration beyond a few times $10^{19}$ eV would require a jet power well in excess of the one expected for Cen A as an FR I source, e.g., [36]. On the other hand, UHECR acceleration of heavy elements like iron may still remain possible. In the case of shear acceleration, the parameters employed above for efficient proton acceleration ($B \sim 10^{-4}$ G, $r \sim 0.5$ kpc, $u_z \sim 0.5$ c) may, at first sight, as well imply a jet power of $L_j \sim r^2 B^2 \perp u_z/4 \sim 10^{44}(E_{\text{max}}/10^{20}\text{eV})^2 Z^{-2}$ erg/s. However, this ignores the $r$-dependence of the bulk flow and (probably) the magnetic field, and when properly accounted for, a smaller jet power may already well be sufficient.

6 Conclusions

The above analysis suggests that efficient acceleration of protons to UHECR energies in Cen A is challenging and may require the operation of an additional acceleration mechanism like shear to further boost achievable particle energies beyond $E_c = 5 \times 10^{19}$ eV. Efficient shear acceleration in Cen A would require high energy seed particles which, however, could be provided by, e.g., shock acceleration. A fraction of these seed protons may then be picked up and accelerated to the maximum energy given by the confinement limit. If such a two-step process would indeed take place, spectral changes in the cosmic ray energy spectrum may not just simply be due to propagation effects. The situation is much more relaxed for heavier elements like iron nuclei, which could possibly be directly accelerated (either by shocks or within the black hole magnetosphere) to energies of $E_c$ and beyond. If Cen A would indeed be an efficient UHECR accelerator one may thus expect the composition to become heavier above energies $\sim 10^{19}$ eV.

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