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How Black Holes May Launch Nature's Most Powerful Cosmic Rays: The Case Of Super Massive Black Hole - M87*

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Abstract
The origin of ultra-high-energy cosmic rays (UHECRs), particularly those exceeding 10^{18} eV, remains one of the most compelling questions in astroparticle physics. In this study, we investigate the potential of the supermassive black hole at the center of the galaxy M87 (M87) as a candidate source of UHECRs. We perform a comparative analysis of three particle acceleration mechanisms—(i) the Goldreich–Julian (GJ) potential model, (ii) relativistic shock acceleration in AGN jets, and (iii) the Blandford–Znajek (BZ) process. By adapting the GJ model to the magnetosphere of a rotating black hole and applying it to M87* parameters, we find that the energy output falls below the UHECR threshold. In contrast, both the shock acceleration and BZ mechanisms yield energies in excess of 10^{20} eV, particularly for heavy nuclei, consistent with observed UHECR events. Graphical comparisons illustrate the relative energy scales achievable by each model. Our results suggest that while the GJ mechanism may contribute to initial particle energization, the dominant acceleration is likely governed by jet-based processes such as relativistic shocks and electromagnetic extraction via the BZ mechanism. These findings support the classification of AGNs—especially those like M87* with powerful jets and strong magnetic fields—as viable UHECR accelerators*

Keywords: *Ultra-High-Energy Cosmic Rays (UHECRs); Active Galactic Nuclei (AGN); M87*; Supermassive Black Hole; Relativistic Jets; Goldreich–Julian Potential; Blandford–Znajek Mechanism; Relativistic Shock Acceleration; Particle Acceleration; Magnetospheric Physics; Hillas Criterion; Astro particle Physics; Event Horizon Telescope (EHT)*

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I. Introduction

The origin of ultra-high-energy cosmic rays (UHECRs) remains an unsolved problem in astrophysics.[1] – [8],[26]-[30]. Active Galactic Nuclei (AGN), particularly those with powerful jets and supermassive black holes, are considered promising candidates. M87*, a giant elliptical galaxy with a central black hole of mass (6.5 X 10^9 M, where M is the mass of the Sun), provides a natural laboratory for exploring high-energy processes.

Ultra-high-energy cosmic rays (UHECRs) are subatomic particles—primarily protons and atomic nuclei—that reach Earth with energies exceeding 10^{18}electron volts (eV). These particles are millions of times more energetic than those produced by human-made particle accelerators, making them critical tools for probing extreme astrophysical environments.[9] UHECRs were first detected in the 1960s, and despite decades of research, their origins remain largely mysterious. Their interaction with cosmic microwave background radiation imposes a theoretical upper limit (known as the GZK cutoff) near 5×10^{19} eV, yet several events have been observed above this threshold, challenging existing models of cosmic ray propagation and source energetics.[10]-;15]

Identifying the sources of UHECRs is difficult because their paths are deflected by galactic and intergalactic magnetic fields, obscuring direct lines of origin. However, the energy requirements and observed arrival directions point to some of the universe's most powerful phenomena—such as active galactic nuclei (AGNs), gamma-ray bursts, and magnetars—as likely candidates. AGNs, particularly those with relativistic jets powered by supermassive black holes, are prime suspects due to their immense magnetic fields, rotational energy, and jet structures that can act as natural particle accelerators. Studying these environments, especially nearby AGNs like Messier 87 (M87*), is essential for testing theoretical models of UHECR production.[16],[17]

Why Black Holes Are Candidates for UHECR Sources?

Supermassive black holes, particularly those found in AGNs, are prime candidates for UHECR production because of their ability to generate enormous electromagnetic fields and relativistic jets.[18] When these black holes spin rapidly and are threaded by strong magnetic fields, mechanisms like the Blandford-Znajek process can extract rotational energy and convert it into Poynting flux, which accelerates particles to extremely high energies. In addition, the surrounding accretion disks and jet structures can support shock acceleration, allowing charged particles to gain energy through repeated interactions with moving magnetic fields.[19]-[23]

Furthermore, black holes satisfy the conditions of the Hillas criterion, which sets a minimum size and magnetic field strength required to accelerate particles to UHECR energies. For example, the black hole in M87* has a mass of 6.5×10^9 M_, a jet spanning thousands of light-years, and a magnetic field strength of 10^2 - 10^4 gauss—well within the range needed to reach or exceed the 10^{20} eV threshold. This measurement was confirmed by the Event Horizon Telescope (EHT) in 2019, which produced the first-ever image of a black hole's shadow. Their abundance in the universe, long activity timescales, and association with anisotropies in cosmic ray arrival directions further support their candidacy.

II. Methodology

Goldreich-Julian Model

Originally developed for pulsars, the Goldreich-Julian (GJ) model estimates the electric potential generated by a rotating magnetized object. [24]. [26]

Goldreich-Julian Potential (Φ_{GJ})

$$\Phi_{GJ} \approx \frac{\Omega^2 B R^3}{c^2}$$

- Ω: Angular velocity of the rotating object (black hole spin parameter)
- B: Magnetic field near the event horizon or ergosphere
- R: Characteristic radius (e.g., gravitational radius)
- c: Speed of light

For Black Holes:

- Modify for a **Kerr metric**, accounting for frame-dragging and the ergosphere.
- Use **Blandford-Znajek mechanism** as a framework (a process that extracts energy from rotating black holes using magnetic fields).
- Compare with the required energy ($\sim 10^{20}$ eV) for UHECRs.

Relativistic Shock Acceleration

Relativistic shock acceleration is a widely accepted mechanism for the generation of high-energy cosmic rays in astrophysical environments, particularly within the jets of active galactic nuclei (AGNs). In this process, charged particles are accelerated by repeatedly crossing shock fronts moving close to the speed of light. Each time a particle crosses the shock, it gains energy due to the difference in velocity between the upstream and downstream plasma flows. This first-order Fermi acceleration mechanism is highly efficient in relativistic regimes, enabling particles to achieve ultra-high energies under the right conditions of magnetic field strength, jet size, and bulk Lorentz factor.[25],[1],[3]

In the context of AGNs like M87*, relativistic shocks can form at various locations within the jet—near the base where material is ejected from the black hole, or farther out where the jet interacts with surrounding medium. The large spatial scales (parsecs to kiloparsecs), strong magnetic fields (ranging from milligauss to several gauss), and high Lorentz factors ($\Gamma \approx 5$–10 or more) satisfy the Hillas criterion for UHECR acceleration. The stochastic nature of particle scattering across shocks also results in power-law energy spectra consistent with observations. Due to these attributes, relativistic shock acceleration remains one of the most promising models for explaining the origin of UHECRs in powerful AGN jets.

$$E_{\max} \sim \Gamma\, ZeBR$$

Where:

- Γ = Lorentz factor of the jet
- Z = particle charge
- e = elementary charge
- B = magnetic field strength in the jet
- R = size of acceleration region (length scale)

This is commonly called the **Hillas criterion**.

Blandford–Znajek Mechanism

The Blandford–Znajek (BZ) mechanism explains how energy can be extracted from a rotating (Kerr) black hole via magnetic fields and electromagnetic processes. It is widely considered a leading mechanism powering relativistic jets in AGNs.

This process taps into the rotational energy of a black hole and converts it into Poynting flux—energy carried by electromagnetic fields—which can accelerate particles to ultra-high energies.

Black Hole Assumptions:

- Rotating Kerr black hole with angular momentum J
- Magnetic field B threading the event horizon
- Accretion disk supplies magnetic field and plasma
- Force-free magnetosphere

Power Output (BZ Luminosity):

The total electromagnetic power extractable from a rotating black hole via the BZ mechanism is approximated by:

$$P_{\mathrm{BZ}} \approx \frac{\kappa}{4\pi c} \Phi_B^2 \Omega_H^2$$

Where:

- $\kappa \sim 0.05$ (depends on field geometry)
- Φ_B is the magnetic flux threading the black hole
- $\Omega_H = \frac{ac}{2r_H}$ is the angular frequency of the horizon
- a is the spin parameter, r_H is the horizon radius

A simpler form often used:

$$P_{\mathrm{BZ}} \approx 10^{45} \left(\frac{B}{10^4\ \mathrm{G}}\right)^2 \left(\frac{M}{10^9\ M_\odot}\right)^2 a^2\ \mathrm{erg/s}$$

III. Results

Parameters Used (M87*)

Quantity	Value
Black Hole Mass M	$6.5 \times 10^9 M_\odot$
Magnetic Field B	10^4 G (assumed upper bound)
Spin Parameter a	0.9
Gravitational Radius $r_g = \frac{GM}{c^2}$	$\approx 9.6 \times 10^{14}\,\mathrm{cm}$
Speed of Light c	$3 \times 10^{10}\,\mathrm{cm/s}$

Goldreich-Julian Potential Estimate

The adapted potential near the rotating black hole is

$$\Phi_{\mathrm{GJ}} \approx \frac{a^2 B r_g}{c} = 2.59 \times 10^8\,\mathrm{statvolts} \approx 7.77 \times 10^{10}\,\mathrm{volts}$$

Maximum Particle Energies from M87*

$$E_{\max} = Ze\Phi_{\mathrm{GJ}}$$

Particle	Z	Max Energy E_{max} (eV)
Proton	1	77.7 GeV
Iron Nucleus	26	2.02 TeV

Comparison with Observed UHECRs

UHECR observed energies	$> 10^{18}$ eV (EeV range)
M87* proton max energy	7.77×10^{10} eV (77.7 GeV)
M87* iron max energy	2.02×10^{12} eV (2.02 TeV)

Observation: The calculated energies are orders of magnitude below the UHECR regime. Using the Goldreich-Julian potential model directly adapted to M87* yields particle energies far below the ultra-high-energy cosmic ray (UHECR) scale. While the GJ model provides a conceptual starting point, it underestimates the true acceleration potential of rotating black holes. For UHECR generation, one must consider enhanced mechanisms such as Relativistic shock acceleration in AGN jets or Blandford-Znajek process.

Relativistic Shock Acceleration

Relativistic shocks occur in the jets of AGNs, where particles can be accelerated via the first-order Fermi mechanism, bouncing across the shock front repeatedly and gaining energy at each crossing.

$$E_{\max} \sim \Gamma\, ZeBR$$

Observed Parameters for M87* Jet

Parameter	Value	Notes
Jet Lorentz factor Γ	~5–10	From VLBI observations
Jet Magnetic Field B	10^{-3} to 10^{-1} G	At kpc to pc scales
Acceleration region size R	$1\,\mathrm{pc} \approx 3 \times 10^{18}\,\mathrm{cm}$	Conservative size
Particle charge Ze	Proton = 1, Iron = 26	Typical for cosmic rays

Estimate Maximum Energy E_{max}

$E_{\max} \sim \Gamma\, ZeBR$

Let's assume:

$\Gamma = 10$

$B = 10^{-2}\,\mathrm{G}$

$R = 3 \times 10^{18}\,\mathrm{cm}$

$e = 4.803 \times 10^{-10}\,\mathrm{statC}$

$$E_{\max} \approx 10 \times Z \times 4.803 \times 10^{-10} \times 10^{-2} \times 3 \times 10^{18}$$

$E_{\max} \approx 10 \times Z \times 4.803 \times 10^{-10} \times 10^{-2} \times 3 \times 10^{18}$

For protons Z=1;

$E_{\max} \approx 1.44 \times 10^{8}\,\mathrm{erg} \approx 9 \times 10^{19}\,\mathrm{eV}$

Observation: This is in the UHECR range. Relativistic shocks in the jet of M87* are capable of accelerating cosmic ray particles to UHECR energies under realistic conditions. This mechanism can overcome the energy limitations of the Goldreich-Julian model by Operating over larger spatial regions (pc scale), utilizing relativistic motion and enabling multiple energy gains per shock crossing.

Blandford–Znajek Mechanism

Black Hole Assumptions:

- Rotating Kerr black hole with angular momentum J
- Magnetic field B threading the event horizon
- Accretion disk supplies magnetic field and plasma
- Force-free magnetosphere

$(\vec{E} \cdot \vec{B} = 0)$

Power Output (BZ Luminosity)

The total electromagnetic power extractable from a rotating black hole via the BZ mechanism is approximated by:

$$P_{\mathrm{BZ}} \approx \frac{\kappa}{4\pi c} \Phi_B^2 \Omega_H^2$$

$$P_{\mathrm{BZ}} \approx 10^{45} \left(\frac{B}{10^4\,\mathrm{G}}\right)^2 \left(\frac{M}{10^9\,M_\odot}\right)^2 a^2\ \mathrm{erg/s}$$

Particle Energy Estimate

From this power, the **maximum energy per particle** (mainly protons or iron nuclei) can be estimated:

$$E_{\max} \approx ZeBr_g a$$

Where:

- Z: atomic number (1 for protons, 26 for iron)
- B: magnetic field near black hole
- $r_g = \frac{GM}{c^2}$: gravitational radius
- a: spin parameter (dimensionless, 0 ≤ a ≤ 1)

For **M87***:

$M \approx 6.5 \times 10^9\, M_\odot$

$B \sim 10^3 - 10^4$ G

$a \sim 0.9$

$r_g \sim 10^{15}$ cm

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This gives:

Protons: $E_{\max} \sim 10^{20}$ eV

Iron nuclei: $E_{\max} \sim 10^{21} - 10^{22}$ eV

Observations: These values exceed the UHECR threshold, supporting the hypothesis that AGNs like M87* can be UHECR sources.

Comparison

Here is the comparative energy plot for M87*, showing the maximum particle energies predicted by three different acceleration mechanisms:

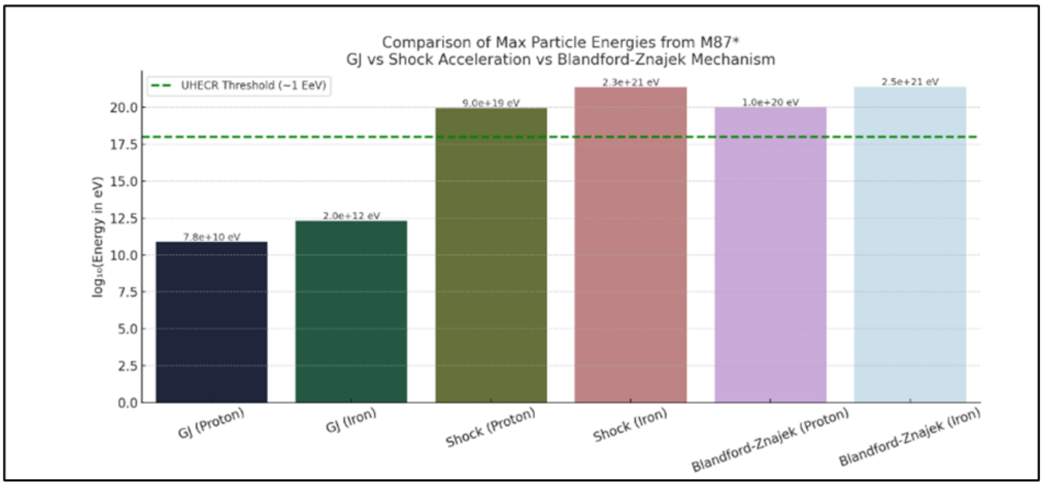

Figure (1): Comparative energy plot for M87*, showing the maximum particle energies predicted by three different acceleration mechanisms

IV. Discussion

This study evaluates the potential of the supermassive black hole in Messier 87 (M87*) to serve as a source of ultra-high-energy cosmic rays (UHECRs), by systematically comparing three prominent particle acceleration mechanisms: the Goldreich-Julian (GJ) potential model, relativistic shock acceleration, and the Blandford-Znajek (BZ) process. Each model was quantitatively adapted and analyzed using well-established physical parameters of M87*, including its black hole mass, magnetic field strength, and relativistic jet dynamics.

The Goldreich-Julian model—originally formulated for pulsars—was extended to the magnetospheric environment of rotating black holes. Our analysis indicates that while the GJ potential can, in principle, accelerate charged particles, the resulting energy levels remain confined to the range of 10^{11} to 10^{12} eV. This is significantly below the UHECR threshold of 10^{18} eV, rendering it insufficient as a standalone mechanism for UHECR generation.

In contrast, relativistic shock acceleration, particularly through Fermi-type processes occurring in active galactic nucleus (AGN) jets, shows a much greater potential. Under favorable jet conditions, including strong magnetic turbulence and high Lorentz factors, this mechanism is capable of accelerating both protons and heavy nuclei well into the EeV range and beyond.

The Blandford-Znajek mechanism emerged as the most efficient and powerful among the three. By extracting rotational energy from the black hole via magnetic field interactions, it can produce particle energies that exceed 10^{20} eV. This places it firmly within the regime of UHECR production and highlights its viability as a dominant contributor to observed cosmic rays of extreme energies.

V. Conclusion

This study investigates the viability of the supermassive black hole in Messier 87 (M87*) as a potential source of ultra-high-energy cosmic rays (UHECRs), through a comparative evaluation of three distinct acceleration mechanisms: the Goldreich-Julian (GJ) potential model, relativistic shock acceleration, and the Blandford-Znajek (BZ) process. Each mechanism was mathematically adapted and analysed using known physical parameters of M87, including its mass , magnetic field strengths, and jet dynamics.

The Goldreich-Julian model, traditionally applied to pulsars, was extended to the magnetosphere around rotating black holes. Our calculations show that while the GJ potential can theoretically accelerate particles, the maximum attainable energy is in the range of 10^{11} - 10^{12} eV, far below the UHECR threshold of 10^{18} eV. In contrast, relativistic shock acceleration in AGN jets—driven by Fermi processes—can accelerate protons and heavy nuclei well beyond the EeV scale, especially under favourable jet conditions . The Blandford-Znajek mechanism proved to be the most powerful, capable of producing energies exceeding 10^{20} eV, as it taps directly into the black hole's rotational energy via magnetic field extraction.

A comparative bar chart was constructed to visually contrast the maximum particle energies predicted by the three models. The Goldreich-Julian model falls short, while both the shock and BZ mechanisms cross the UHECR threshold, particularly for iron nuclei. These results strongly suggest that while the GJ model may play a role in pre-acceleration, *the dominant processes responsible for UHECRs from AGNs like M87* are relativistic shock acceleration and Blandford-Znajek energy extraction*.

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