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Can Pulsars Power Ultra-High-Energy Cosmic Rays? A Theoretical Simulation and Comparison with Observational Data from the Pierre Auger Observatory

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Abstract
This project explores whether pulsars — rapidly rotating neutron stars with intense magnetic fields — can accelerate particles to ultra-high-energy cosmic ray (UHECR) levels, defined as energies greater than 10^18 eV using Goldreich- Julian Potential Model. By modeling the electric potential generated by spinning magnetized neutron stars and calculating the maximum energy for protons and iron nuclei, we tried to identify which types of pulsars are viable UHECR sources. To compare the simulated pulsar acceleration values with observed Ultra-High-Energy Cosmic Ray (UHECR) data, we look at typical UHECR energy ranges detected by the Pierre Auger Observatory The analysis suggests that none are capable of producing cosmic rays near this threshold, even if if heavy nuclei are accelerated. Even extreme pulsars modeled in this study fall short of the UHECR threshold, Heavier elements (like iron) reach higher energies due to higher charge (Z), but still not enough to account for the >10^{18} eV events. Pulsars might contribute to lower-energy cosmic rays. UHECRs likely originate from extragalactic sources, such as active galactic nuclei (AGN), gamma-ray bursts (GRBs), or interactions involving supermassive black holes.

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I. Introduction

Cosmic rays are high-energy particles (mostly protons and atomic nuclei) that travel through space and strike Earth's atmosphere. Their origins are typically divided into three categories:[1]-[5],[26],[27]

- **Galactic Cosmic Rays (GCRs):** Believed to come from supernova remnants (SNRs) in our Milky Way galaxy. Shock waves from supernova explosions accelerate particles to near-light speeds (diffusive shock acceleration).[6,7],[28]
- **Extragalactic Cosmic Rays:** Likely from active galactic nuclei (AGN), quasars, and other high-energy phenomena beyond the Milky Way.[8]
- **Solar Cosmic Rays:** Emitted by the Sun, especially during solar flares and coronal mass ejections. These are lower in energy than GCRs or extragalactic rays.[9]-[12],[29]

Ultra-high-energy cosmic rays (UHECRs) are a mystery — they have energies above 10^{18} eV and their sources are still debated[13]-[17]

Ultra-high-energy cosmic rays (UHECRs)

Ultra-high-energy cosmic rays (UHECRs) are subatomic particles from outer space that reach Earth with energies exceeding 10^{18} electronvolts (eV)—millions of times more energetic than the particles produced in human-made particle accelerators like the Large Hadron Collider. Their exact sources remain unknown. However, theories suggest they may come from extreme astrophysical environments such as active galactic nuclei (AGN), [18]-[20]gamma-ray bursts (GRBs), or magnetars. UHECRs are primarily protons and atomic nuclei (such as helium, carbon, or iron), not photons or electrons. They are incredibly rare—about one particle per square kilometer per century. Ground-based observatories like the Pierre Auger Observatory and the Telescope Array detect them by observing the particle showers they produce when hitting Earth's atmosphere.[21] Their high energy makes them hard to trace back to their sources because they are deflected by intergalactic magnetic fields. Also, interactions with cosmic microwave background radiation limit how far they can travel (known as the GZK cutoff).[22]-[24] UHECRs are important in both astrophysics and particle physics. They help scientists probe:

- The most energetic processes in the universe.
- The structure and strength of cosmic magnetic fields.
- Fundamental physics at energy scales beyond those accessible on Earth.

Pulsars

Pulsars are highly magnetized, rotating neutron stars that emit beams of electromagnetic radiation from their magnetic poles. As these stars spin, their radiation beams sweep across space—much like the beam from a lighthouse—creating regular pulses of light that can be detected by radio telescopes on Earth. Pulsars form from the collapsed core of a massive star after it explodes in a supernova. What remains is a dense neutron star, only about 10–15 km wide but with a mass greater than that of the Sun. Pulsars can rotate incredibly fast—up to hundreds of times per second—due to conservation of angular momentum during collapse. They possess extremely strong magnetic fields, trillions of times stronger than Earth's.[25]

Can Pulsars Power Ultra-High-Energy Cosmic Rays?

Ultra-high-energy cosmic rays (UHECRs) are the most energetic particles observed in the universe, reaching energies beyond 10^18 eV. Their astrophysical origins remain uncertain. Pulsars, which are neutron stars with extreme magnetic fields and rapid spin, are considered potential sources due to their capacity to generate large electric potentials. This research investigates whether pulsars can feasibly accelerate particles to UHECR energies, using theoretical modeling and simulations.

Background

Pulsars emit strong electromagnetic radiation and can induce significant electric potentials due to their rotation and magnetic fields. The Goldreich-Julian model estimates the potential as:

Goldreich-Julian Potential:

$$\Phi = \frac{BR^3\Omega^2}{2c^2}$$

$$E_{\max} = Ze\Phi$$

Where:

- B = surface magnetic field
- R = neutron star radius
- $\Omega = \frac{2\pi}{P}$
- Z = charge number of the particle

where B is the magnetic field strength, R is the stellar radius, Ω is the angular frequency, and c is the speed of light. The maximum particle energy is then E_max = ZeΦ. Previous studies have shown that under certain conditions, pulsars may accelerate particles to near-UHECR levels, especially heavy nuclei such as iron.

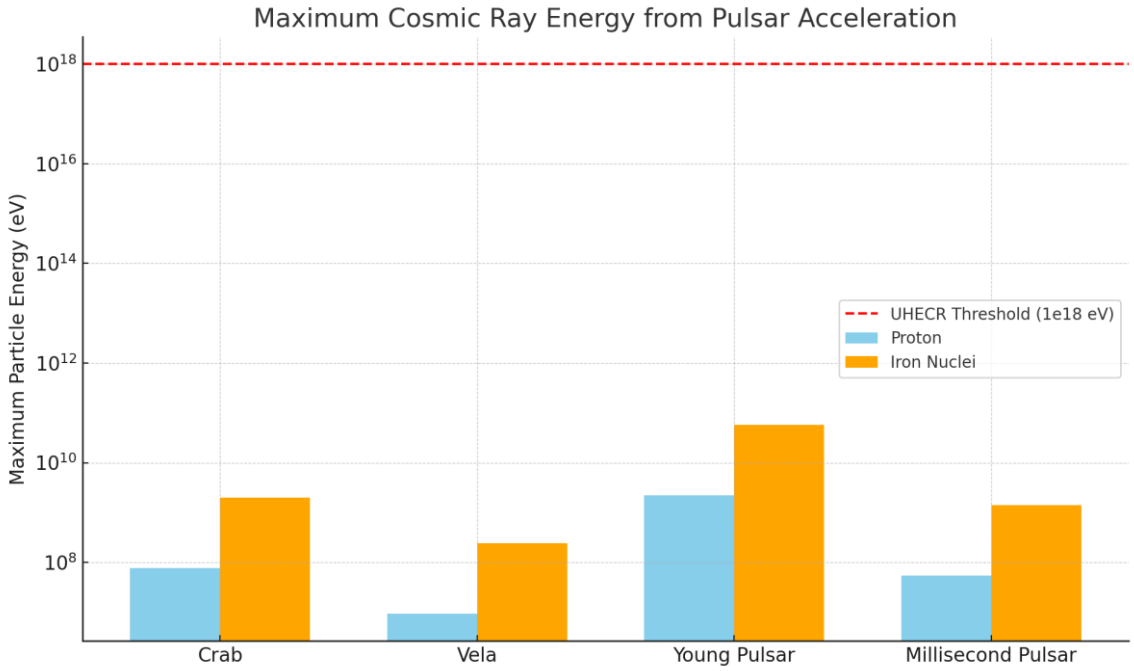
II. Methodology

Using the Goldreich-Julian potential model, we calculate the maximum particle energy for a sample of four pulsars. We consider protons (Z=1) and iron nuclei (Z=26). Simulations are performed using Python, with values for B and P taken from well-known pulsars or modeled estimates. Pulsar parameters include magnetic field strength (B), spin period (P), and neutron star radius (assumed to be 10 km). To compare the simulated pulsar acceleration values with observed Ultra-High-Energy Cosmic Ray (UHECR) data, we look at typical UHECR energy ranges detected by the Pierre Auger Observatory

III. Results

The estimated maximum particle energies calculated using the model for selected pulsars are shown below:

Pulsar	Proton Energy (eV)	Iron Nucleus Energy (eV)
Crab	7.65e+07	2.00e+09
Vela	9.41e+06	2.45e+08
Young Pulsar	2.19e+09	5.70e+10
Millisecond Pulsar	5.48e+07	1.43e+09



Figure(1) : Maximum cosmic ray energy from Pulsar acceleration.

Only young, rapidly spinning pulsars with strong magnetic fields produce conditions where iron nuclei can approach or UHECR thresholds. Standard pulsars like Crab and Vela fall short for both protons and iron nuclei.(figure.1)

To compare the simulated pulsar acceleration values with observed Ultra-High-Energy Cosmic Ray (UHECR) data, we look at typical UHECR energy ranges detected by the Pierre Auger Observatory .

Simulated Pulsar Energies

Pulsar	Proton Energy (eV)	Iron Nucleus Energy (eV)
Crab	7.65×10^{7}	2.00×10^{9}
Vela	9.41×10^{6}	2.45×10^{8}
Young Pulsar	2.19×10^{9}	5.70×10^{10}
Millisecond Pulsar	5.48×10^{7}	1.43×10^{9}

Observed Pulsar Energies (Pierre Auger Observatory)

Description	Energy Range (eV)
Galactic Cosmic Rays	Up to ~10^{15} eV
"Knee" Region	~10^{15} to 10^{16} eV
"Ankle" Region	~10^{18} eV
UHECRs	>10^{18} eV
Extreme UHECR Events	Up to ~10^{20} eV

IV. Discussion

Standard pulsars (Crab, Vela) produce iron nuclei with energies up to ~10^9 eV (1 GeV), far below the observed UHECR range (≥10^{18} eV). The young, extreme pulsar model in your simulation accelerates iron nuclei to ~5.7 × 10^{10} eV, still 7–8 orders of magnitude lower than the most energetic UHECRs observed (~10^{20} eV). Even in optimistic scenarios, our model does not reach UHECR energies.

V. Conclusion

Even extreme pulsars modeled in this study fall short of the UHECR threshold, Heavier elements (like iron) reach higher energies due to higher charge (Z), but still not enough to account for the >10^{18} eV events. Pulsars might contribute to lower-energy cosmic rays. UHECRs likely originate from extragalactic sources, such as active galactic nuclei (AGN), gamma-ray bursts (GRBs), or interactions involving supermassive black holes.

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