*IOSR Journal Of Applied Physics (IOSR-JAP)*
*e-ISSN: 2278-4861.Volume 17, Issue 3 Ser. 1 (May. – June. 2025), PP 62-65*
*www.Iosrjournals.Org*

# Can Pulsars Power Ultra-High-Energy Cosmic Rays? A Theoretical Simulation And Comparison With Observational Data From The Pierre Auger Observatory

Premlal P.D
*Samgama Grama Madhavan Academy Of Sciences, Kerala, India*

***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 >*$10^{1}$ *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.*

---

Date of Submission: 15-05-2025 Date of Acceptance: 25-05-2025

---

Keywords : cosmic rays, pulsars, neutron stars, UHECR

## 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 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 $10^{1}$ 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 |

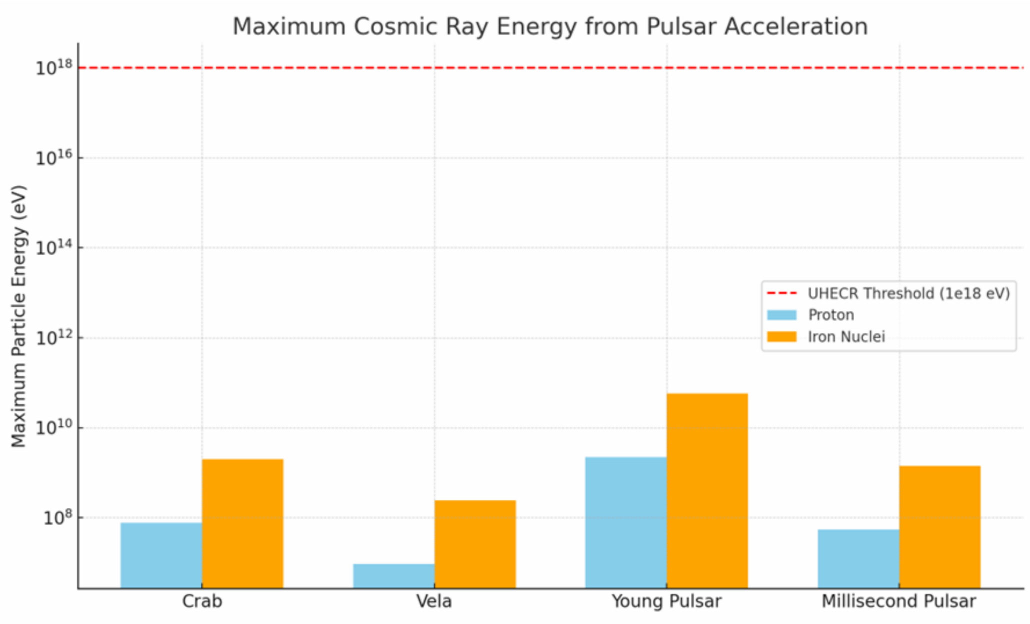


**Figure (1): Maximum cosmic ray energy from Pulsar acceleration.**

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 | $7.65 \times 10^{7}$ | $2.00 \times 10^{9}$ |
| Vela | $9.41 \times 10^{6}$ | $2.45 \times 10^{8}$ |
| Young Pulsar | $2.19 \times 10^{9}$ | $5.70 \times 10^{10}$ |
| Millisecond Pulsar | $5.48 \times 10^{7}$ | $1.43 \times 10^{9}$ |

**Observed Pulsar Energies (Pierre Auger Observatory)**

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

## IV. Discussion

Standard pulsars (Crab, Vela) produce iron nuclei with energies up to ~10 eV (1 GeV), far below the observed UHECR range ($\geq 10^{1}$ eV). The young, extreme pulsar model in your simulation accelerates iron nuclei to $\sim 5.7 \times 10^{1}$ eV, still 7–8 orders of magnitude lower than the most energetic UHECRs observed ($\sim 10^{2}$ 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 $>10^{1}$ 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.

## References


[1] C. Guépin, B. Cerutti, And K. Kotera, "Proton Acceleration In Pulsar Magnetospheres," Astronomy & Astrophysics, Vol. 636, A84, 2020.A&A Astronomy & Astrophysics+1a&A Astronomy & Astrophysics+1

[2] A. Aab Et Al., "The Pierre Auger Observatory: Contributions To The 36th International Cosmic Ray Conference (Icrc 2019)," Arxiv Preprint Arxiv:1909.09073, 2019.Arxiv+1arxiv+1

[3] A. Aab Et Al., "Observation Of A Large-Scale Anisotropy In The Arrival Directions Of Cosmic Rays Above $8 \times 10^{1}$ Ev," Science, Vol. 357, No. 6537, Pp. 1266–1270, 2017.Arxiv

[4] K. Kotera And A. V. Olinto, "The Astrophysics Of Ultrahigh Energy Cosmic Rays," Annual Review Of Astronomy And Astrophysics, Vol. 49, Pp. 119–153, 2011.Arxiv

[5] M. Lemoine, K. Kotera, And J. Pétri, "On Ultra-High Energy Cosmic Ray Acceleration At The Termination Shock Of Young Pulsar Wind Nebulae," Journal Of Cosmology And Astroparticle Physics, Vol. 2015, No. 11, 2015.Arxiv

[6] A. Neronov And D. V. Semikoz, "Origin Of Tev Galactic Cosmic Rays," Astroparticle Physics, Vol. 89, Pp. 14–28, 2017.

[7] J. Abraham Et Al., "Measurement Of The Energy Spectrum Of Cosmic Rays Above $10^{1}$ Ev Using The Pierre Auger Observatory," Physics Letters B, Vol. 685, No. 4–5, Pp. 239–246, 2010.

[8] A. Aab Et Al., "Depth Of Maximum Of Air-Shower Profiles At The Pierre Auger Observatory. Ii. Composition Implications," Physical Review D, Vol. 90, No. 12, 122006, 2014.

[9] R. Aloisio, D. Boncioli, A. F. Grillo, S. Petrera, And F. Salamida, "Simprop: A Simulation Code For Ultra High Energy Cosmic Ray Propagation," Arxiv Preprint Arxiv:1204.2970, 2012.Arxiv

[10] B. Eichmann Et Al., "Ultra-High-Energy Cosmic Rays From Radio Galaxies," Arxiv Preprint Arxiv:1701.06792, 2017.Arxiv

[11] L. J. Watson, D. J. Mortlock, And A. H. Jaffe, "A Bayesian Analysis Of The 27 Highest Energy Cosmic Rays Detected By The Pierre Auger Observatory," Arxiv Preprint Arxiv:1010.0911, 2010.Arxiv+1arxiv+1

[12] A. Khanin And D. J. Mortlock, "A Bayesian Analysis Of The 69 Highest Energy Cosmic Rays Detected By The Pierre Auger Observatory," Arxiv Preprint Arxiv:1601.02305, 2016.Arxiv

[13] P. Blasi, R. I. Epstein, And A. V. Olinto, "Ultra–High-Energy Cosmic Rays From Young Neutron Star Winds," The Astrophysical Journal Letters, Vol. 533, No. 2, L123, 2000.

[14] D. Allard Et Al., "Implications Of The Cosmic Ray Spectrum For The Mass Composition At The Highest Energies," Astronomy & Astrophysics, Vol. 443, No. 1, Pp. L29–L32, 2005.

[15] A. De Angelis And M. Persic, "Gamma-Ray Astrophysics: The High Energy Frontier," European Physical Journal Plus, Vol. 133, No. 8, 2018.

[16] T. K. Gaisser, T. Stanev, And S. Tilav, "Cosmic Ray Energy Spectrum From Measurements Of Air Showers," Frontiers Of Physics, Vol. 8, No. 6, Pp. 748–758, 2013.Wikipedia

[17] A. M. Hillas, "The Origin Of Ultra-High-Energy Cosmic Rays," Annual Review Of Astronomy And Astrophysics, Vol. 22, Pp. 425–444, 1984.Wikipedia

[18] J. Linsley, "Evidence For A Primary Cosmic-Ray Particle With Energy $10^{2}$ Ev," Physical Review Letters, Vol. 10, No. 4, Pp. 146–148, 1963.

[19] T. Abu-Zayyad Et Al., "The Cosmic-Ray Energy Spectrum Observed With The Surface Detector Of The Telescope Array Experiment," The Astrophysical Journal Letters, Vol. 768, No. 1, L1, 2013.

[20] S. Ostapchenko, "Monte Carlo Treatment Of Hadronic Interactions In Enhanced Pomeron Scheme: Qgsjet-Ii Model," Physical Review D, Vol. 83, No. 1, 014018, 2011.

[21] R. Engel, D. Heck, And T. Pierog, "Extensive Air Showers And Hadronic Interactions At High Energy," Annual Review Of Nuclear And Particle Science, Vol. 61, Pp. 467–489, 2011.

[22] D. Heck Et Al., "Corsika: A Monte Carlo Code To Simulate Extensive Air Showers," Forschungszentrum Karlsruhe Report Fzka, Vol. 6019, 1998.Wikipedia

[23] T. Huege, M. Ludwig, And C. W. James, "Simulating Radio Emission From Air Showers With Coreas," Aip Conference Proceedings, Vol. 1535, No. 1, Pp. 128–132, 2013.Wikipedia

[24] A. Aab Et Al., "Searches For Ultra-High-Energy Photons At The Pierre Auger Observatory And Implications For Astrophysical Scenarios," Universe, Vol. 8, No. 11, 579, 2022.Mdpi

[25] Pierre Auger Collaboration, "The Pierre Auger Observatory: Contributions To The 37th International Cosmic Ray Conference (Icrc 2021)," Arxiv Preprint Arxiv:2201.07170, 2022.

[26] Premlal.P.D," Impact Of Cosmic Rays On Satellite Communications: A One-Year Analysis Using Satellite And Observatory Data", Iosr Journal Of Electronics And Communication Engineering,.Volume 19, Issue 2, Ser. I (Mar. – Apr. 2024), Pp 33-37

[27] Premlal.P,D," Analysis Of Cosmic Ray Modulation By Solar Wind", Ournal Of Electronics And Communication Engineering Research Volume 9 ~ Issue 9 (2023) Pp: 26-30

[28] Premlal.P.D," Dynamics Of Solar Wind And Cosmic Ray Interactions At The Edge Of Interstellar Space: Insights From Voyager 1 And Ibex Data Analysis, Iosr Journal Of Electronics And Communication Engineering, Volume 19, Issue 5, Ser. 1 (Sept. – Oct. 2024), Pp 19-25

[29] Premlal.P,D," A Comprehensive Analysis Of Intense Solar Activity From Noaa Region 13664 (Ar3664) And Its Impact On Multiple Systems In May 2024, Journal Of Electronics And Communication Engineering Research Volume 10 ~ Issue 5 (2024) Pp: 16-20