PROCEEDINGS OF SCIENCE

ONLINE ICRC 2021 THE ASTROPARTICLE PHYSICS CONFERENCE Berlin | Germany 37th International Cosmic Ray Conference 12–23 July 2021

The Zettavolt Askaryan Polarimeter (ZAP) mission concept: radio detection of ultra-high energy cosmic rays in low lunar orbit.

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Probing the ultra-high energy cosmic ray (UHECR) spectrum beyond the cutoff at 40 EeV requires an observatory with large acceptance, which is challenging to implement with ground arrays. We present a concept for radio detection of UHECRs impacting the Moon's regolith from low-lunar orbit called the Zettavolt Askaryan Polarimeter (ZAP). ZAP would observe several thousands of events above the cutoff (40 EeV) with a full-sky field of view to test whether UHECRs originate from Starburst Galaxies, Active Galactic Nuclei, or other sources associated with the matter distribution of the local universe at a distance > 1 Mpc. The unprecedented sensitivity of ZAP to energies beyond 100 EeV would enable a test of source acceleration mechanisms. At higher energies, ZAP would produce the most stringent limits on super heavy dark matter (SHDM) via limits on neutrinos and gamma rays resulting from self-annihilation or decay.

37th International Cosmic Ray Conference (ICRC 2021)
July 12th – 23rd, 2021
Online – Berlin, Germany

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1. Introduction

The physical origin of ultra-high energy cosmic rays (UHECRs) beyond the well-established spectral cutoff energy of $\sim$ 40 EeV [1–3] is currently a topic of debate. While spatial clustering of events with astrophysical sources is an obvious way of identifying the sources, this is complicated by the fact that Galactic magnetic fields scatter the cosmic ray arrival directions [4]. At energies beyond the cutoff the scattering scale is $\Theta \sim 2.5^\circ Z\,(E/[40\,\mathrm{EeV}])^{-1}$, which does allow to test whether classes of sources are correlated to anisotropies in the distribution of UHECR arrival directions [5]. We present an observatory concept to survey a large target area ($\sim 5 \times 10^5$ km^2) visible from $\sim$ 100 km lunar orbit altitude at low radio frequencies (30-300 MHz) capable of detecting thousands of UHECR events above the cutoff in a two-year observing window.

2. ZAP Observatory Concept

2.1 Observatory Model

The basic observatory concept is shown in Figure 1. An ultra-high energy cosmic ray enters the lunar regolith to produce an air shower that will reach shower maximum within the first $\sim$ 5 m. While the regolith can be as thin as 3 m in certain regions of the lunar maria, UHECRs impact the surface preferentially at inclined angles ensuring that shower maximum is contained above the basalt layer. Note that this technique is not highly sensitive to depth of interaction in dense media since it only varies by $\sim$ 10% per decade in energy. Depth of interaction is, however, not a significant source of uncertainty in event reconstruction.

As the particle shower evolves in the regolith, a $\sim$ 20% charge excess develops resulting in Askaryan radio emission [7, 8]. This results in a 100% linearly polarized impulsive transient with a beam pattern that varies from dipole-like at low frequencies ($\lesssim$ 100 MHz) and transitions to a cone-shaped beam pattern peaking at the Cherenkov angle ($\sim 57^\circ$ for the lunar regolith) at higher frequencies (Figure 2). The key insight for ZAP is to target the lower frequencies (30-300 MHz) where the beam pattern is wide and the UHECR event can be detected from a wide range of view angles therefore significantly increasing the exposure. The fact that the peak signal strength is weaker at lower frequencies is compensated by the larger radio amplitude with increasing UHECR

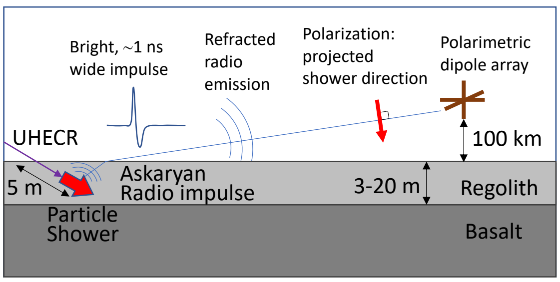

Figure 1: ZAP measures the energy and direction of arrival from UHECRs incident on the lunar surface with detection of the electric field strength, spectrum, and polarization (see text for details).

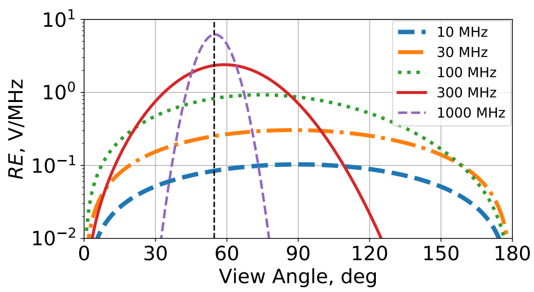

Figure 2: Askaryan radiation beam pattern cuts for a 10^{20} eV particle shower obtained with ZHAireS [6]. For $\lesssim$100 MHz, the beam pattern is dipole-like while at higher frequencies the beam pattern is cone-shaped.

energy resulting in an overall increased sensitivity to the lower fluxes at the end of the cosmic ray spectrum. It is also worth noting that the Cherenkov angle is complementary to the total internal reflection angle. Since UHECR interact within the first several meters in the regolith, this technique is limited to down-going events meaning that the range of view angles detectable at higher frequencies is severely limited further supporting the need for a low-frequency detector.

Refraction through the lunar surface reduces the signal strength due to the transmission coefficients through the dielectric boundary. These effects are taken into account in simulations using polarization-dependent Fresnel coefficients. The lunar surface roughness also needs to be taken into account. Fortunately, the shower maximum for most events of interest will be within a few meters of the surface. For an observatory at $\sim$ 100 km altitude, the first Fresnel zone is $\sim$ 3 m where the lunar surface is typically smooth compared to the 1 - 10 m wavelengths of interest. The main impact of surface slopes is that they can vary by $2.0^\circ - 7.5^\circ$ depending on whether the event occurs in the lunar mare (smooth) or highlands (rough) [9].

2.2 Event Reconstruction

The information required to reconstruct the direction and energy of the UHECR event is the location on the surface, polarization vector, and signal spectrum. The pulse detected by a polarimetric array will receive a 100% linearly polarized impulse with some small losses possibly due to fine-scale surface roughness on the Moon. To localize the signal, the observatory requires an array of antennas with baseline separations that are sufficiently long to localize the direction of the radio impulse. Assuming a detection amplitude SNR of 5 in electric field, the antenna separations B need to be $B \gtrsim 5.7\ \mathrm{m} \times \left(\frac{\delta\theta}{3^\circ}\right) \times \left(\frac{SNR}{5}\right)$ to localize the signal with a directional uncertainty of $\delta\theta = 3^\circ$. The detector can be tuned to improved localization by either increasing the required SNR or the antenna separation length.

Once the radio signal can be projected back onto the surface of the Moon, the direction of the cosmic ray shower can be reconstructed using the polarization vector, which traces the direction of shower projected along the line of sight, and the signal spectrum, which depends on the shower axis view angle (Figure 2). The polarization angle uncertainty for a polarimetric array $\Delta\theta_{\mathrm{pol}} \simeq \frac{1}{SNR}$ in radians, implying a polarization angle uncertainty of 10° for an SNR of 5.8. This is smaller than the scale of the Galactic magnetic field scattering for nuclei in the C-N-O group for energies >40 EeV. Note that the uncertainty is primarily in the azimuthal direction of the cosmic ray (with respect to the line of sight).

The view angle uncertainty of the UHECR will depend on the spectrum, which is expected to be constrained to $\sim 5^\circ$ for a signal with SNR=5. The deviation in view angle $\Delta\theta_{\mathrm{view}}$ due to refraction on a surface with slope scale $\Delta\theta_{\mathrm{slope}}$ can be approximated by $\Delta\theta_{\mathrm{view}} \simeq (\Delta\theta_{\mathrm{slope}}/n)\cos\theta_{\mathrm{ref}}$ where θ_{ref} is the refracted angle estimated by assuming a smooth surface and the index of refraction $n \simeq 1.5$ for the lunar regolith. This results in a typical multiplier in uncertainty on view angle of $\simeq 0.4$ resulting in $0.8^\circ - 3^\circ$ view angle uncertainty in the cosmic ray.

Altogether, we expect the direction uncertainty of the cosmic ray to be determined within 12° in azimuth and 6° in view angle. For anisotropy analyses, the relevant uncertainty is the geometric mean which is 8°, below the expected scattering due to Galactic magnetic fields for C-N-O mass group cosmic rays an energies > 40 EeV.

The uncertainty in energy will most likely be dominated by statistical uncertainties. At a threshold SNR=5, the uncertainty in the amplitude is 20%. Direction uncertainties of 5° in view angle do not significantly affect the energy uncertainty because, as can be seen from Figure 2, the low frequency portion of the emission is wide and relatively insensitive to view angle near the most probable direction of observation ($\theta_{\rm view} \simeq 90°$ based on Monte Carlo simulations).

2.3 Expected event rates

An implementation of ZAP in low lunar orbit ($\sim$ 100 km altitude) can achieve sufficiently high exposure (Figure 3) resulting in a projected event rate of $> 2,000$ for energies $>$ 40 EeV in two years of operation (Figure 4). The event rates and sensitivity to energies below the cutoff (needed for calibration against ground arrays) can be tuned by a combination of orbit altitude and the number of antennas in the receiver array. Higher altitude of 200 km increase the exposure to higher energies while lower altitudes of 100 km increase the sensitivity to lower energies. The sensitivity to suit the objectives of a future ZAP mission can also be tuned using elliptical orbits that sample a range of orbital altitudes.

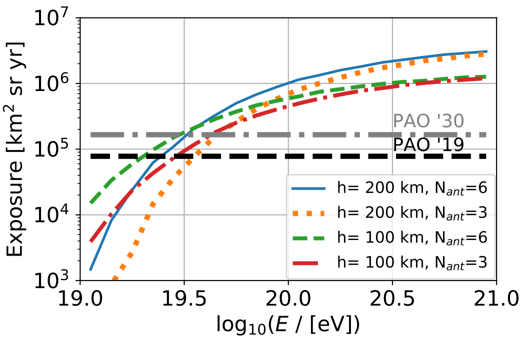

Figure 3: Projected exposures for a 2-year ZAP mission for different orbit altitudes and number of antennas per polarization $N_{\rm ant}$. Horizontal dashed lines indicate the current and 2030-projected exposures of the Pierre Auger Observatory (PAO).

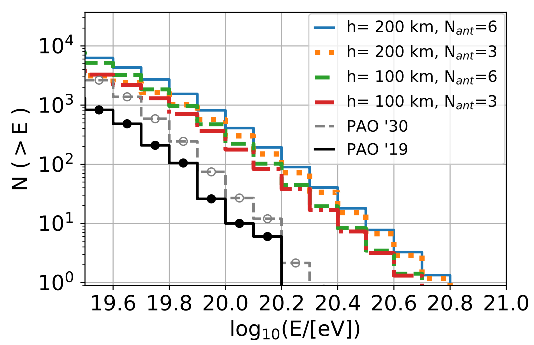

Figure 4: Cumulative event rates for exposures shown in Figure 3 and UHECR the flux of Auger [10]. Higher orbit altitude increases event rates at the highest energies while more antennas (greater sensitivity) increase event rates near the cutoff.

3. Scientific Capabilities

3.1 Anisotropy

One of the main scientific drivers for ZAP is to provide a full-sky observatory to determine whether the sources of cosmic rays are starburst galaxies (SBGs), active galactic nuclei (AGNs), or a broader class associated with the matter distribution in the local universe at distance $>$ 1 Mpc (for example gamma-ray bursts, newly born pulsars and magnetars). ZAP could achieve this goal by leveraging the full-sky coverage available to a lunar orbiter and comparing the arrival direction distribution of UHECRs above the cutoff energy of 40 EeV to predictions based on the source distributions of AGN, SBGs, and the large-scale structure (2MRS catalogue). Figure 5 shows predicted probability density maps for these source classes, including CR propagation effects and the expected scale of Galactic magnetic field scattering. The limited sky coverage of ground arrays is one of the major limitations to achieving this objective. ZAP would observe the full-sky in a single experiment.

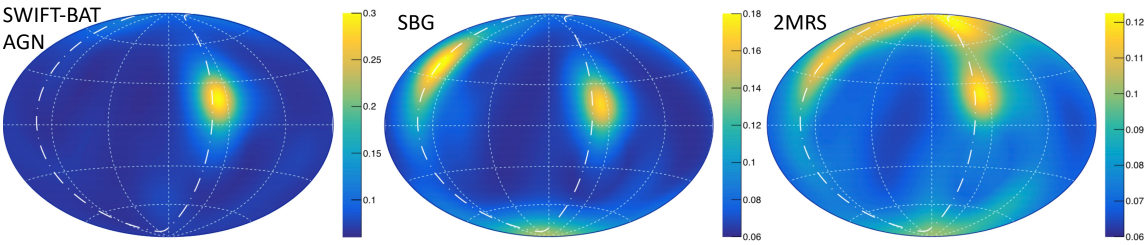

Figure 5: Source distributions assuming a scattering angle of 15°, as expected from Galactic magnetic fields, with an anisotropic fraction of UHECR events of 20%. From left to right the source catalogues are SWIFT-BAT Active Galactic Nuclei, Starburst Galaxies, and the 2MRS [5]. Note that the color scales in each map (in Galactic coordinates) have different ranges.

Table 1: Anisotropy measurement requirements (see text for definitions and details).

f_{sig}	Θ	AGN	SBG	2MRS
10%	20°	1,240	2,060	>5,000
10%	15°	920	1,910	4,830
15%	20°	680	1,000	2,550
15%	15°	660	870	2,280
20%	20°	<650	<650	1,520
20%	15°	<650	<650	1,320

We have estimated the number of events with energy above 40 EeV required to obtain correlations with 5 σ significance (with > 95% success rate in simulated realizations) for each scenario. We assume a range of anisotropic event fractions (f_{sig}) and magnetic field scattering scales (Θ) from [5, 11, 12]. The values summarized in Table 1 shows that with ~2,000 events, AGN and SBG can be confidently identified as the sources even for low anisotropic fractions ($f_{sig} \simeq 10\%$) and large scattering angles ($\Theta \simeq 20°$). The correlation to large scale structure (2MRS) can be achieved with ~2,000 events for the upper range $f_{sig} \simeq 20\%$ in Table 1.

3.2 Suppression at the end of the cosmic ray spectrum

The unprecedented sensitivity of ZAP to UHECRs at energies > $10^{20.2}$ eV, currently inaccessible to ground arrays, would allow for the determination of whether the suppression at the end of the cosmic ray spectrum is due to a source energy cutoff or propagation losses in surrounding photon fields at the source. The suppression mechanism can be tested using the global spectrum where a source energy cutoff (maximum energy for CR accelerators) predicts no events beyond $10^{20.2}$ eV. The alternative hypothesis is that losses due to surrounding photon fields at the source, which preferentially act on heavier nuclei, allow for a spectral recovery from protons escaping the source. Flux recovery predictions [13] allowed by composition bounds from Auger ($\lesssim$ 20% protons) are shown in Figures 6 and 7. A ZAP mission with 2-year duration would provide unprecedented sensitivity at the highest energies to discriminate between suppression mechanism scenarios (Figure 7).

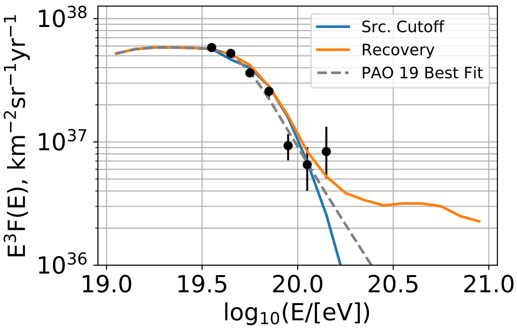

Figure 6: Flux measurements of Auger (points with error bars) and best fit (dashed gray line) compared to models for a source cutoff (solid blue line) and spectral recovery (solid orange line), adapted from [13].

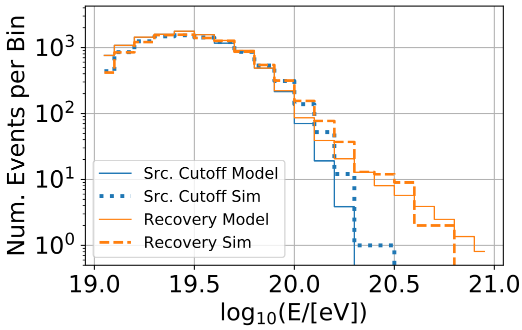

Figure 7: Simulated event rates for a 2-year mission using fluxes in Figure 6 including 30% energy uncertainty predict distinguishable measurements. ZAP is expected to do better with energy uncertainty of 20%.

3.3 Superheavy Dark Matter

ZAP would probe the origin of dark matter by detecting decay products of superheavy dark matter [14] at energies $> 10^{21}$ eV or place an upper limit on mass $> 10^{21}$ eV and lifetime $> 10^{22}$ yr. This goal would be achieved using the radio technique in solid dielectric media, which is particularly sensitive to identifying showers from electrons produced by ν_e interactions at extremely high energies because they produce structured radio impulses [15] distinct from the hadronic showers produced by UHECRs. In addition, SHDM events would correlate to the Galactic center because this is where most of the nearby dark matter is concentrated. The range of UHE photons is limited to 10 – 100 Mpc limiting extragalactic contributions. This allows for discrimination against other proposed sources of UHE particles [16], which are isotropic.

4. Conclusions

We have presented a lunar orbiting cosmic-ray observatory concept that could expand the energy frontier probing the mechanisms that accelerate the highest energy particles observed in the universe and exploring the nature of dark matter. The detector concept applies the developments of radio-detection of ultra-high energy particles in the last decades with NASA's ANITA sub-orbital detector [6] to a space-based platform at low frequencies.

Acknowledgements: The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004). ©2021 California Institute of Technology. All rights reserved. This work was sponsored under NASA grant 17-APRA17-0066. J. AM and E.Z. thank the following. This work has received financial support from Xunta de Galicia (Centro singular de investigación de Galicia accreditation 2019-2022), by European Union ERDF, by the "María de Maeztu" Units of Excellence program MDM-2016-0692, the Spanish Research State Agency and from Ministerio de Ciencia e Innovación PID2019-105544GB-I00.

References

[1] **HiRes** Collaboration, Abbasi, R. et al, "First observation of the Greisen-Zatsepin-Kuzmin suppression," *Phys. Rev. Lett.* **100** (2008) 101101, arXiv:astro-ph/0703099.

[2] **Pierre Auger** Collaboration, Abraham, J. et al, "Observation of the suppression of the flux of cosmic rays above 4×10^{19}eV," *Phys. Rev. Lett.* **101** (2008) 061101, arXiv:0806.4302 [astro-ph].

[3] Anchordoqui, L.A., "Ultra-High-Energy Cosmic Rays," *Phys. Rept.* **801** (2019) 1–93, arXiv:1807.09645 [astro-ph.HE].

[4] Farrar, G.R. and Sutherland, M.S., "Deflections of UHECRs in the Galactic magnetic field," *JCAP* **05** (2019) 004, arXiv:1711.02730 [astro-ph.HE].

[5] Aab, A. et al, "An Indication of Anisotropy in Arrival Directions of Ultra-high-energy Cosmic Rays through Comparison to the Flux Pattern of Extragalactic Gamma-Ray Sources," *The Astrophysical Journal Letters* **853** no. 2, (Feb., 2018) L29, arXiv:1801.06160 [astro-ph.HE].

[6] Anita Collaboration et al, "The Antarctic Impulsive Transient Antenna ultra-high energy neutrino detector: Design, performance, and sensitivity for the 2006-2007 balloon flight," *Astroparticle Physics* **32** no. 1, (Aug., 2009) 10–41, arXiv:0812.1920 [astro-ph].

[7] Askaryan, G., "Excess negative charge of an electron-photon shower and its coherent radio emission," *Sov. Phys. JETP* **14** no. 2, (1962) 441–443.

[8] Askaryan, G., "Coherent radio emission from cosmic showers in air and in dense media," *Sov. Phys. JETP* **21** (1965) 658.

[9] Rosenburg, M.A. et al, "Global surface slopes and roughness of the Moon from the Lunar Orbiter Laser Altimeter," *Journal of Geophysical Research (Planets)* **116** no. E2, (Feb., 2011) E02001.

[10] **Pierre Auger** Collaboration, Aab, A. et al, "The Pierre Auger Observatory: Contributions to the 36th International Cosmic Ray Conference (ICRC 2019)," *arXiv e-prints* (Sept., 2019) arXiv:1909.09073, arXiv:1909.09073 [astro-ph.HE].

[11] Caccianiga, L., "Anisotropies of the Highest Energy Cosmic-ray Events Recorded by the Pierre Auger Observatory in 15 years of Operation," in *36th International Cosmic Ray Conference (ICRC2019)*, vol. 36 of *International Cosmic Ray Conference*, p. 206. July, 2019.

PoS(ICRC2021)403

[12] Abbasi, R.U. et al, "Evidence for a Supergalactic Structure of Magnetic Deflection Multiplets of Ultra-high-energy Cosmic Rays," *The Astrophysical Journal* **899** no. 1, (Aug., 2020) 86.

[13] Muzio, M.S., Unger, M. and Farrar, G.R., "Progress towards characterizing ultrahigh energy cosmic ray sources," *Physical Review D* **100** no. 10, (Nov., 2019) 103008.

[14] Chung, D.J.H., Kolb, E.W. and Riotto, A., "Nonthermal Supermassive Dark Matter," *Physical Review Letters* **81** no. 19, (Nov., 1998) 4048–4051, arXiv:hep-ph/9805473 [hep-ph].

[15] Alvarez-Muñiz, J. and Zas, E., "Cherenkov radio pulses from Eev neutrino interactions: The LPM effect," *Phys. Lett. B* **411** (1997) 218–224, arXiv:astro-ph/9706064.

[16] Berezinsky, V., Sabancilar, E. and Vilenkin, A., "Extremely high energy neutrinos from cosmic strings," *Physical Review D* **84** no. 8, (Oct., 2011) 085006, arXiv:1108.2509 [astro-ph.CO].

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