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Searching for Ultrahigh Energy Neutrinos with PUEO

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PUEO, the Payload for Ultrahigh Energy Observations, is a long duration balloon-borne experiment with the primary science goal of detecting the impulsive Askaryan emission from ultrahigh energy (UHE, >1 EeV) neutrinos interacting in the ice sheet of Antarctica. The ultrahigh energy neutrino flux is yet to be detected, and so a successful measurement by PUEO will give us information about the where and how these neutrinos are produced; this may be through a process called the GZK effect when ultrahigh energy cosmic rays interact with the cosmic microwave background, or it may be directly within the environment of cosmic ray accelerators.

In order to detect radio Askaryan emission, PUEO consists of a broadband interferometric radio detector of 96 antennas which point down at the ice. Additionally, it has a drop-down low-frequency subsystem which will deploy after launch. This improves PUEO's ability to detect tau neutrinos and charged cosmic rays, which can both produce geomagnetic air shower emission. This contribution will outline PUEO's science case, present its expected sensitivity, and share status updates from our preparation to launch PUEO from McMurdo Station, Antarctica in December 2025.

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1. Introduction

The sources of acceleration for the most energetic cosmic rays in the universe remain elusive. Though ultrahigh energy (UHE) >1 EeV) cosmic rays (CRs) have been detected up to hundreds of EeV, to further study these particles, a different technique is required. Searching for cosmic ray accelerators through neutrinos has several advantages in the UHE regime. First, UHE CRs will tend to interact after some (cosmologically) short distance. For protons, this is through the GZK effect, in which they interact with the cosmic microwave background over an interaction length of ~50 Mpc to produce neutrinos; for heavier nuclei, this is through photodisintegration. Secondly, neutrinos will arrive unimpeded and undeflected at Earth, and due to the cosmological distances at which they are produced, will point back roughly (to within several degrees) of the accelerator on the sky.

PUEO, the Payload for Ultrahigh Energy Observations, is a Pioneer-class NASA funded balloon payload designed to detect neutrinos by utilizing the Antarctic ice sheet as a detector medium. It will be launched from McMurdo Station, Antarctica in December of 2025. PUEO builds on the heritage of the successful ANITA program, which over four flights set the best limits on the UHE neutrino flux. While ANITA did not make a positive detection of any UHE neutrinos, it did observe many charged cosmic rays through the geomagnetic emission from their extensive air showers during each of its flights; observing more of these air shower events is thus a secondary science goal for PUEO.

This contribution will detail the science case of PUEO, discussing the production of ultrahigh energy neutrinos, both astrophysical and cosmogenic, as well as their detection through the Askaryan effect in the Antarctic ice. It will briefly discuss the hardware implementation of PUEO; for more details on this, see [1].

2. Ultrahigh energy neutrinos

UHE neutrinos are the primary target of observation for PUEO. Because neutrinos are uncharged and weakly interacting, they are a unique messenger for the UHE regime as compared to charged cosmic rays, which are deflected in the galactic and extragalactic magnetic fields, and thus don't track back to their original sources. UHE neutrinos may be produced either through the GZK effect, in which case they are called cosmogenic neutrinos, or they may be produced directly in sources, in which case they are called astrophysical neutrinos.

2.1 Cosmogenic Neutrinos

Through the GZK effect [2, 3], UHE protons will interact through the delta resonance with the cosmic microwave background (CMB) ($p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow \pi \rightarrow \nu$). Because the CMB permeates the entire universe, the interaction length for UHE cosmic rays through the GZK effect is about 50 Mpc – this means that direct observations of charged cosmic rays are limited to sources from within this horizon.

The fluxes of UHE cosmic rays from the Pierre Auger Observatory and Telescope Array imply a low flux of UHE neutrinos, since these can be jointly fit [4, 5]. However, it is not necessarily straightforward to extrapolate the UHE CR flux into neutrinos, as there may very likely be source evolution which results in accelerators existing predominantly at older epochs; thus, the majority

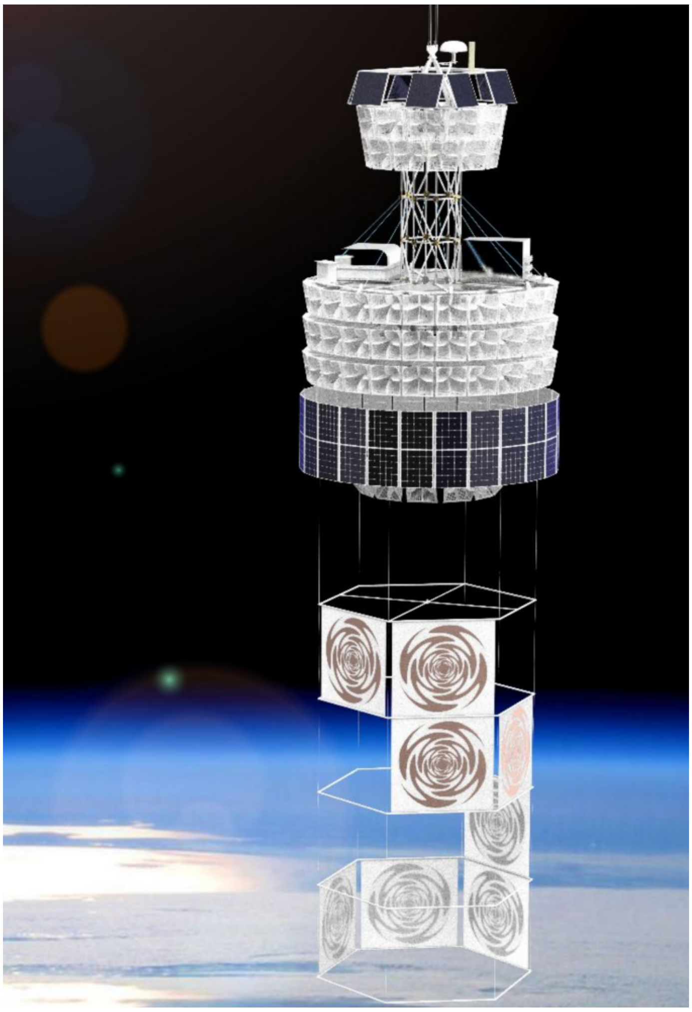

Figure 1: CAD rendering of PUEO, with the low frequency instrument hanging below the main instrument

of UHE cosmic rays would be shielded from us by the GZK horizon and the neutrino flux would be much higher than the predictions based solely on UHE CR observations.

2.2 Astrophysical Neutrinos

Alternatively, UHE neutrinos may be produced directly within sources, such as active galactic nuclei [6], pulsars [7], or gamma-ray bursts (GRBs) [8]. The astrophysical neutrino flux has been measured by IceCube up to ~10 PeV; this flux may extend into the EeV regime. These astrophysical UHE neutrinos are typically produced through $p\gamma$ interactions with radiation fields local to the accelerator environment, rather than an external field as in the case of cosmogenic neutrinos. For example, in the GRB model, if UHE CRs are accelerated by the initial burst, then they may interact with the gamma-ray afterglow. These neutrinos fluxes may be persistent, or they may be transient; in the latter case, source identification may be possible with simultaneous multimessenger observations of the photons.

2.3 In-ice Askaryan emission

PUEO is designed to detect UHE neutrinos through their Askaryan emission in ice. The Askaryan Effect [9] details how an electromagnetic shower will produce a coherent radio emission in a dielectric medium. The electromagnetic shower has a diameter on the order of tens of centimeters, and the collective Cherenkov emission from all of the particles coherently sums; the peak frequency of this coherent pulse scales with energy, and in the UHE regime it is in the radio band. The neutrino interacting with an atom in the dielectric material may produce either an electromagnetic shower, or a hadronic shower; in the latter case, the hadrons will initiate further EM showers, and so Askaryan emission is still produced. In the range $\sim$1 EeV to 10 EeV, the Askaryan channel sensitivity is dominated by electron neutrinos, while at higher energies all three flavors are roughly equal.

The Askaryan emission in ice takes the form of a radially polarized cone with an opening angle equal to the Cherenkov angle in ice, 56°. When the cone of Askaryan emission reaches the ice-air interface, the top arc, which is close to vertically polarized with respect to the interface, will transmit, while the rest of the cone, which is roughly horizontally polarized, will be reflected and remain in the ice. Thus, the Askaryan signal that reaches the payload is predominantly vertically polarized, which helps to differentiate Askaryan from background as well as air shower events.

Due to the size and quality of the ice sheet in Antarctica, it is an ideal dielectric medium to search for UHE neutrinos; the attenuation length is about 1 km, and from a balloon floating at $\sim$40 km altitude above Antarctica, there is roughly a million cubic kilometers of ice visible.

2.4 Tau neutrinos

In addition to Askaryan emission, tau neutrinos can produce emission through extensive air showers. By this mechanism, a tau neutrino traveling through the Earth can undergo a charged current interaction in the Earth's crust or ice and produce a tau lepton. When this lepton decays in the air it will produce an extensive air shower. This extensive air shower undergoes charge separation and produces a radio signal. [10] Because the Earth's magnetic field is near vertical in Antarctica, the produced radio signal is predominantly horizontally polarized.

3. Charged cosmic rays

Over the course of the ANITA program, 71 cosmic ray air shower events were observed. Similar to tau neutrino events, these charged cosmic rays induce an extensive air shower which produces geomagnetic radio emission. This occurs for cosmic rays coming from a range of incident angles; if the cosmic ray is steeply down-going, its radio emission will reflect off the ice and come to PUEO from below the horizon. Alternatively, a cosmic ray at a shallow upward angle will skim the atmosphere, and appear unreflected from above the horizon, which is at about $-6°$. Of the 71 observed cosmic ray events in ANITA, 64 were classified as direct, and 7 were classified as reflected. Table 1 summarized the differences between the two types of cosmic ray events, reflected and direct, and the two types of neutrino events, Askaryan and tau air shower.

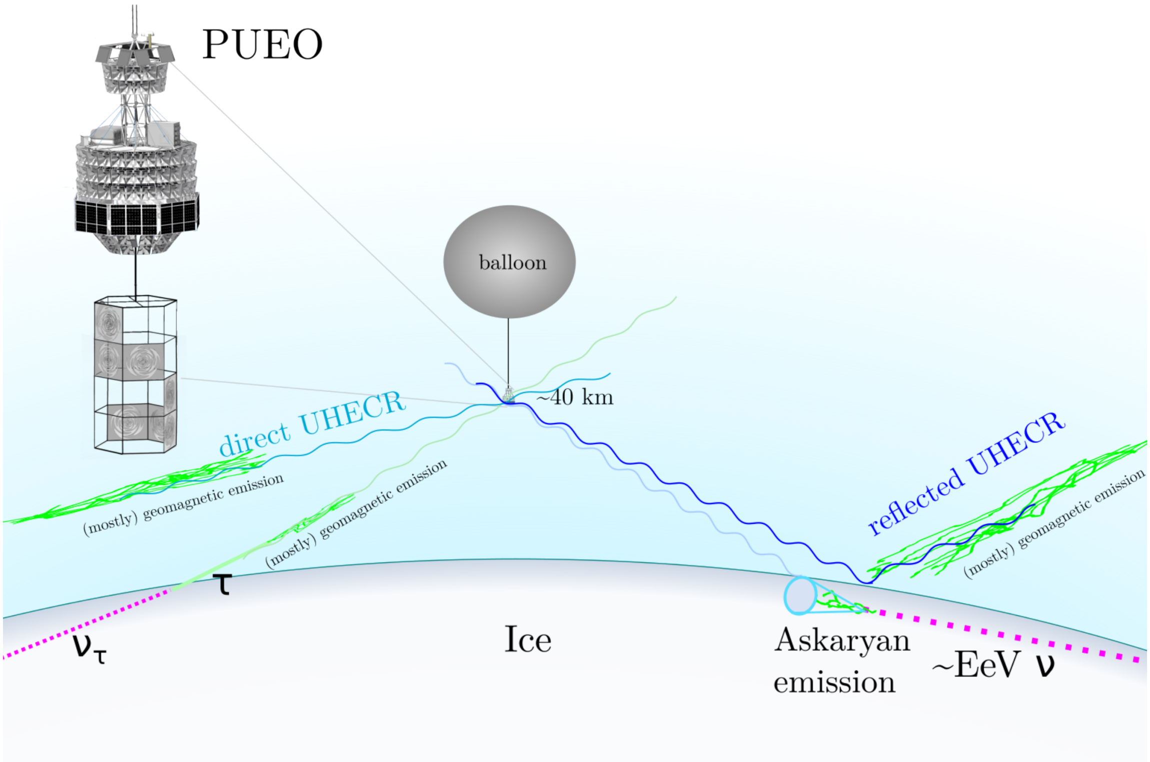

Figure 2: Diagram showing all of the detection channels for PUEO: Askaryan emission from UHE neutrinos, geomagnetic emission from Earth-skimming tau neutinos, geomagnetic emission from direct cosmic rays, and geomagnetic emission from reflected cosmic rays

Event type	polarization	polarity	Below/above horizon
Askaryan neutrino	horizontal	non-inverted	below
Tau neutrino air shower	vertical	non-inverted	below
Direct cosmic ray air shower	vertical	non-inverted	above
Reflected cosmic ray air shower	vertical	inverted	below

Table 1: Events are classified based on their incoming angle, polarization, and polarity as detailed here.

4. The PUEO Instrument

There are 96 dual-polarized quad ridged horns on PUEO, covering a band of 300 MHz to 1200 MHz; this is double the number of antennas on ANITA-IV, which is part of the reason for PUEO's increased sensitivity. These are vertically separated into four rings of 24 antennas that cover 360° in azimuth. The antennas are all canted down at $-10°$ to point just below the horizon.

The other main upgrade over ANITA is that the data acquisition system is implemented on RFSoCs (Radio frequency system-on-chip). These allow for a real-time phased array trigger, which significantly improves PUEO's performance over ANITA.

To maximize PUEO's sensitivity to air shower events from cosmic rays and tau neutrinos, there is a low-frequency dropdown instrument. This consists of sinuous antennas of conductive fabric and will deploy beneath the payload once it reaches altitude. It is sensitive to the 50 MHz to

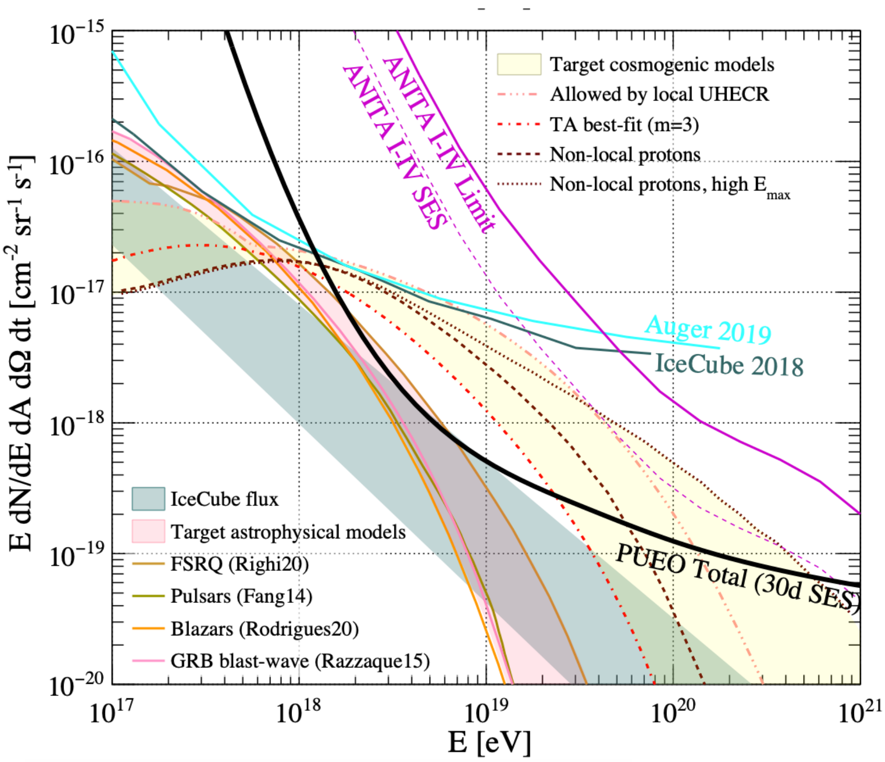

Figure 3: Predicted single event sensitivity of PUEO over a 30 day flight, as compared to the limits set by ANITA, as well as IceCube and Auger. Also shown are some of the astrophysical models that PUEO would be sensitive to.

300 MHz range which contains the peak of the geomagnetic pulse.

5. Predicted performance of PUEO

PUEO's performance is predicted using the simulation packages `nicemc` and `pueoSim`, which are custom-built libraries to simulate the production of Askaryan radiation in the ice, its propagation to the payload, and its processing through the instrument signal chain. Using assumptions that the flight path will be similar to ANITA-IV and will last for 30 days, we find the sensitivity shown in Figure 3. PUEO will be able to distinguish cosmogenic models as shown in the yellow band, as well as astrophysical models shown in the pink band.

6. Conclusion

PUEO is on track to fly from McMurdo, Antarctica, in December 2025. It will undergo its final compatibility test with the ballooning equipment, such as communications and commanding interfaces, during the week of July 7th, after which it will be disassembled, packed, and shipped to Antarctica. Once there, it will be reassembled during November, and launch in December for a roughly 30 day flight, where it will hopefully make the first detection of ultrahigh energy neutrinos.

Acknowledgments

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References

[1] K. Hughes, Q. Abarr, P. Allison, J. Alvarez-Muñiz, J. Ammerman Yebra, T. Anderson et al., *The Payload for Ultrahigh Energy Observations (PUEO): Detector Design and Implementation*, *PoS* **ICRC2025** (2025) .

[2] K. Greisen, *End to the Cosmic-Ray Spectrum?*, *PhRvL* **16** (1966) 748.

[3] G.T. Zatsepin and V.A. Kuz'min, *Upper Limit of the Spectrum of Cosmic Rays*, *Soviet Journal of Experimental and Theoretical Physics Letters* **4** (1966) 78.

[4] A. van Vliet, R.A. Batista and J.R. Hörandel, *Determining the fraction of cosmic-ray protons at ultrahigh energies with cosmogenic neutrinos*, *Phys. Rev. D* **100** (2019) 021302.

[5] D. Bergman, *Combined Fit of the Spectrum and Composition from Telescope Array*, *PoS* **ICRC2019** (2019) 190.

[6] X. Rodrigues, J. Heinze, A. Palladino, A. van Vliet and W. Winter, *Active Galactic Nuclei Jets as the Origin of Ultrahigh-Energy Cosmic Rays and Perspectives for the Detection of Astrophysical Source Neutrinos at EeV Energies*, *PhRvL* **126** (2021) 191101 [2003.08392].

[7] K. Fang, K. Kotera, K. Murase and A.V. Olinto, *Testing the newborn pulsar origin of ultrahigh energy cosmic rays with EeV neutrinos*, *Phys. Rev. D* **90** (2014) 103005 [1311.2044].

[8] S. Razzaque and L. Yang, *PeV-EeV neutrinos from GRB blast waves in IceCube and future neutrino telescopes*, *PhRvD* **91** (2015) 043003 [1411.7491].

[9] G.A. Askar'yan, *Coherent Radio Emission from Cosmic Showers in Air and in Dense Media*, *Soviet Journal of Experimental and Theoretical Physics* **21** (1965) 658.

[10] J.L. Feng, P. Fisher, F. Wilczek and T.M. Yu, *Observability of Earth-Skimming Ultrahigh Energy Neutrinos*, *PhRvL* **88** (2002) 161102 [hep-ph/0105067].

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