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POEMMA-Balloon with Radio, towards a space-based Multi-Messenger Observatory

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The Ultra-High-Energy Cosmic Ray (UHECR) community outlined the current status, open questions, and roadmap for the field of UHECRs in the white paper titled "Ultra-High Energy Cosmic-Rays: The Intersection of the Cosmic and Energy Frontiers" (Astropart. Phys. 147 (2023) 102794 - arXiv:2205.05845). In this paper, the community identified two types of next-generation detectors: (1) high-accuracy detectors and (2) detectors that maximize exposure at the highest energies such as the Probe Of Extreme Multi-Messenger Astrophysics (POEMMA), a proposed dual satellite mission for observing UHECRs and Very High Energy Neutrinos (VHENs). A key milestone towards such a mission is POEMMA-Balloon with Radio (PBR), designed as a payload for a NASA suborbital Super Pressure Balloon that will circle over the Southern Ocean for up to 100 days. PBR aims to achieve three major science goals: (1) to observe UHECRs via the fluorescence technique from suborbital space; (2) to study high-altitude horizontal air showers (HAHAs) with energies above the cosmic ray knee (E > 3 PeV) using optical and radio detection for the first time; and (3) to follow astrophysical event alerts in the search for VHENs. With a telescope design almost identical to POEMMA, PBR will validate the POEMMA design and proposed analysis strategies. This contribution presents a brief overview of the PBR detector design, its expected performance, and the current status of the mission.

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1. Introduction

The community roadmap for Ultra-High-Energy Cosmic Ray (UHECR) [1] describes the significant advancements achieved over the past decade, but also describes the remaining open questions such as the sources and accelerating mechanisms of UHECR, the most energetic particles known to exist. To address and collect the data necessary to answer these questions, the community proposes two types of next-generation detectors: (1) high-accuracy detectors and (2) detectors that maximize exposure at the highest energies. One such detector is the proposed dual satellite mission, Probe for Multi-Messenger Astrophysics (POEMMA) [2], which could address some limitations of ground-based observations by monitoring the Earth's atmosphere from above, providing a significantly increased exposure at the highest energies. This represents the next frontier in UHECR and VHE neutrino physics.

Before constructing and launching an ambitious space-based detector, it is highly beneficial to develop pathfinder missions to improve technological readiness and validate targeted detection techniques. A stratospheric balloon offers an opportunity for such investigations in a near-space environment without the risk and cost of a fully realized space mission. The POEMMA-Balloon with Radio (PBR) payload is such a pathfinder mission, built on the design study of the POEMMA and previous balloon missions, such as EUSO-SPB1 [3] and EUSO-SPB2 [4]. These earlier missions laid the groundwork for PBR by attempting to observe the fluorescence emission of Extensive Airshowers (EASs) produced by ultra-high-energy cosmic rays (UHECRs) from suborbital altitudes and measure the background for VHE neutrino oscillations. Despite facing challenges with balloon stability, these missions provided valuable insight and technical advancements that PBR will leverage.

The primary science goals of PBR are threefold and illustrated in Fig. 1:

1. Investigating the Origin of UHECRs: PBR will observe, for the first time, the fluorescence emission of EASs produced by UHECRs from sub-orbital altitudes. This goal builds on the efforts of previous missions, such as EUSO-SPB1 and EUSO-SPB2, whose balloons faced challenges in achieving stable long-duration flights.

2. Studying High-Altitude Horizontal Air-Showers (HAHAs): PBR will observe a significant number of HAHAs, providing valuable data to invesitgate this rarly measured phenomena. PBR will be able to use HAHAs to measure the cosmic-ray spectrum and discriminate cosmic ray composition around PeV energies. Additionally, PBR will detect the simultaneous optical Cherenkov and radio emissions of EASs, providing a multi-hybrid picture crucial for understanding these high-energy phenomena.

3. Searching for Astrophysical Neutrinos: PBR will search for neutrinos from multi-messenger events, such as gamma-ray bursts and binary coalescence of compact objects. By detecting EASs arriving from below the Earth's limb, PBR aims to identify tau-neutrinos interacting within the Earth, which produce tau-leptons that decay and generate EASs.

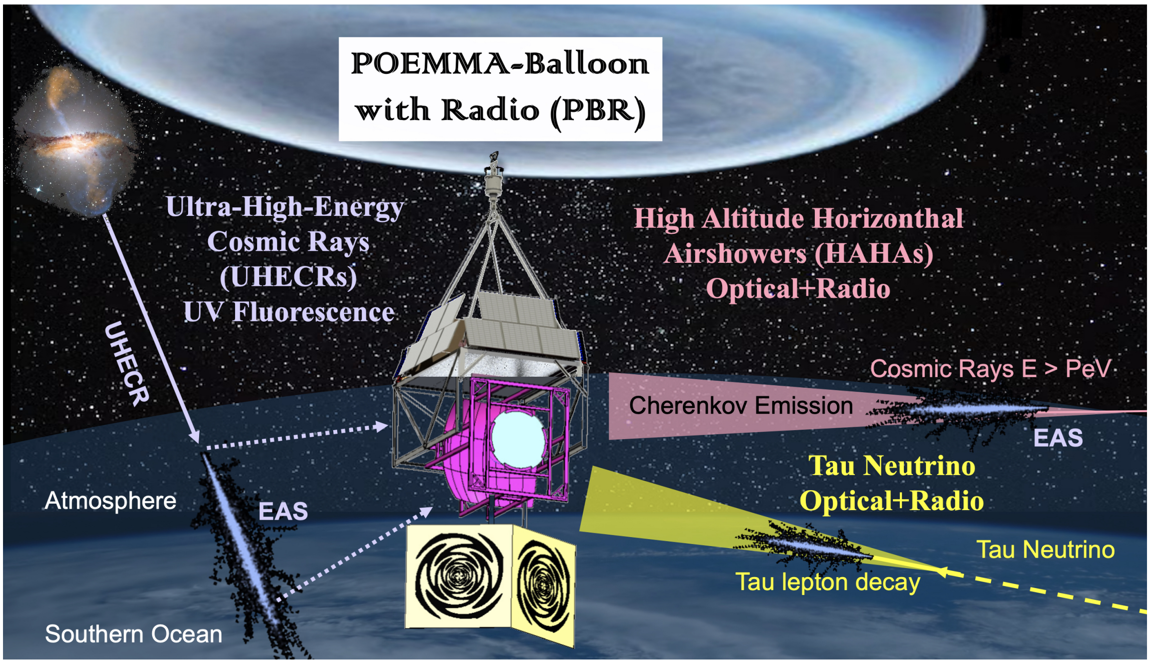

Figure 1: Sketch of the PBR main Science goals: first observation of UHECRs via fluorescence from above; study of HAHAs; and follow up on astrophysicsl event in the search of astrophysical neutrinos.

2. The POEMMA-Balloon with Radio Payload

The PBR payload is designed to fly on a NASA Super Pressure balloon and is equipped to support a flight of up to 100 days. The mission is planned to launch from Wanaka, NZ in the first half of 2027 and will circulate the Southern Ocean. It consists of one, large, tiltable telescope housing a hybrid focal surface and a Radio Instrument (RI) of two antennas mounted beneath the telescope. A drawing of the overall payload and its various components is shown in the left panel of Fig. 2.

The PBR **optical design** builds on the successful modified Schmidt design flown on EUSO-SPB2 with an increased entrance pupil diameter of 1.1 m to collect more photons and lower the energy thresholds for the Fluorescence Camera (FC) and Cherenkov Camera (CC). The primary mirror has a ∼1.6 m radius of curvature, built from 12 mirror segments and measures roughly 2×2 m in size, providing a FoV of approximately 36°by 30°with a expected PSF (95% containment) of 3 mm in diameter. The reflective surface is vacuum-deposited aluminum with a film thickness chosen to optimize reflectivity in the UV, which is protected by a silicon dioxide coating. The Aspheric Corrector Plate (ACP) covers the entrance pupil and corrects for spherical aberration inherent to a wide-field Schmidt telescope. The ACP will be made from polymethyl methacrylate (PMMA) and shaped by a diamond-turning process followed by polishing.

The pointing system is another crucial part of the PBR payload need to achieve its scientific goals and has 2 components. A NASA rotator will aim the telescope at night towards azimuth directions of astrophysical interest, using feedback from a differential global positioning system (GPS). A tilting mechanism will adjust the telescope's elevation angle about its center of mass, ranging from nadir to 12° above horizontal. This capability will enable periodic in-situ checks of

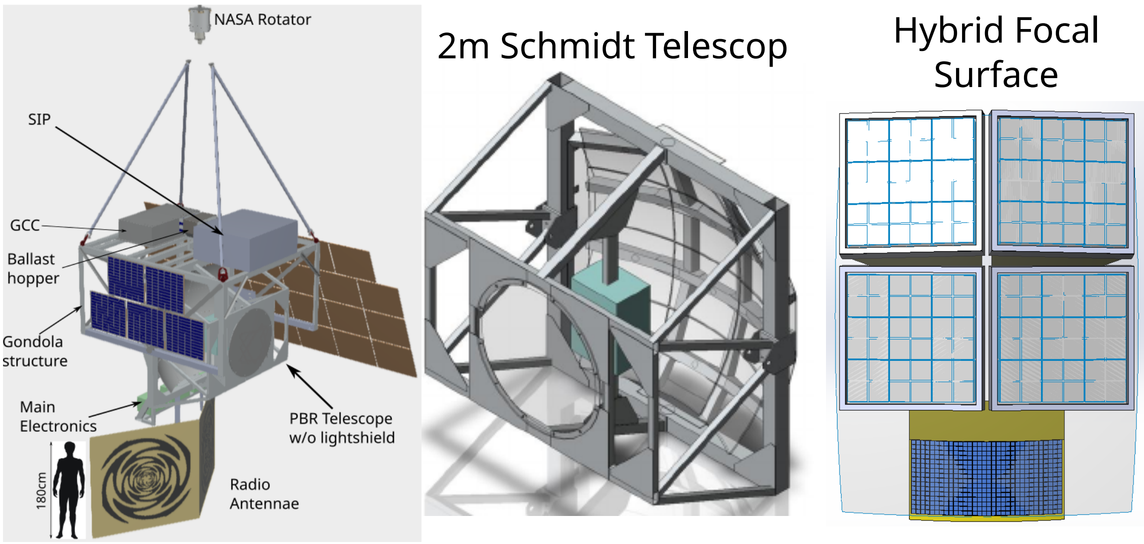

Figure 2: Left: Design of the PBR payload. Center: Mechanical drawing of the telescope structure. Right: Drawing of the Hybrid focal surface consisting of the FC and the CC.

optical focus across the FoV of the camera using stars.

The **Fluorescence Camera(FC)** structure follows a proven modular design flown in previous missions. PBR will feature four Photo Detection Modules (PDM), each consisting of 2304 individual pixels capable of single photo electron counting with a double pulse resolution of 6 ns and an integration time of 1 μs. In addition, a charge integration mode combining the signal of eight pixels, is available to extend the dynamic range of the camera. BG3 filters in front of the PDM will constrain the observed wavelength range to between 290 and 430 nm, to reduce background light. The combined FoV of all 4 PDM will be around 24°by 24°with an instantaneous FoV of 0.2°per pixel. A successful EAS measurement will raise FC Technical Readiness Level (TRL) to level 6 for POEMMA.

The **Cherenkov Camera (CC)** contains four rows of 8 SiPM arrays (Hamamatsu S13361-3050), each array consisting of 64 channels of 3×3 mm^2 pixels, totaling 2048 pixels for the entire camera. These arrays are mounted on a structure that shapes the photosensitive plane to approximate the spherical curvature required by the telescope optics. The total FoV spans 12°by 6°, with each pixel covering 0.2°. The sensitive wavelength range is 320 - 900 nm. The readout electronics will be either based on RadioROC or MIZAR ASICs, which are in development by the INFN group in Turin, Italy, providing a sampling frequency of 200 MHz. Both solution are currently being evaluated in parallel. A bi-focalizing optics will be mounted in front of the camera to reduce noise trigger by requiring two coincident spots on the camera for triggering.

The **Radio Instrument (RI)** comprises two radio receivers, each featuring dual-polarized sinuous antennas, a two-stage front-end RF signal conditioning chain, and associated power systems. This design draws heavily from the PUEO LF instrument [5]. PBR's sinuous antennas, which are two meters wide, provide a broadband gain of 5 dBi ranging from 50 MHz to 500 MHz in both vertical and horizontal polarizations with a 60°× 60°FoV. The two antennas are positioned below the optical telescope and angled 120°from each other, with their center line aligned with the CC to

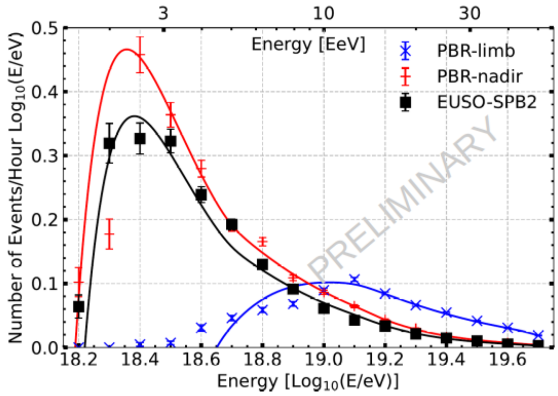

Figure 3: Preliminary event rate of PBR for two different pointing scenarios. In red for point straight down and in blue for the case the CC is pointed at the limb. Also the event rate as estimated for EUSO-SPB2 is drawn in black for comparison.

ensure overlapping FoVs (see left panel of Fig. 2).

In addition to these main instruments, PBR will be equipped with an IR camera to monitor clouds in the instruments FoV. and will for the first time include a γ and X-ray detectors, opening yet another detection channel to investigate a wide range of phenomena.

3. Science Goal #1: Investigating the Origin of UHECRs

The main goal for the fluorescence camera is the measurement of a high quality UHECR signal via fluorescence from suborbital space, and thereby proving this detection technique as viable for future space-based missions, such as POEMMA. A high-quality event is defined as one that allows the reconstruction of the arrival direction, energy and potentially composition of the primary cosmic ray. A large scale Monte-Carlo simulation is used to determine the expected performance of the PBR FC using the EUSO-Offline framework [6]. The underlying idea was already developed for EUSO-SPB1 and EUSO-SPB2 and needed only adaptation in regard to the new detector parameters. Details of the simulation approach can be found for example in [7].

The expected event rate (see Fig. 3) obtained by integrating over the entire energy span, is approximetly 0.23 events per hour observed when looking to nadir or 0.07 events per hour observed when looking towards the limb. Due to the increased distance to an observed event, the energy threshold rises from 1.8 EeV in the nadir to 4 EeV for the limb case. A pre-flight trained neural network will provide an on board prioritization of these events, to guarantee the download of the most promising event candidates even under limited bandwidth condition of a balloon missions.

4. Science Goal #2: Studying HAHAs

Cosmic rays that skim the Earth's atmosphere inducing an EAS and traverse the telescope FoV while never intersecting the ground are referred to as High-Altitude Horizontal Air Showers (HAHAs). This will be the most frequent event class observed by PBR. HAHAs can propagate over hundred of kilometers as the majority of the shower development happens in rarefied atmosphere

(above 20 km). Some example trajectories are shown in the left panel of Fig. 4. The extended path lengths combined with the unique atmospheric properties at high altitudes provide PBR a unique science potential. Additionally, HAHAs present a guaranteed proxy signal by which to evaluate and refine the detection technique toward spaced-based observation of neutrinos for the POEMMA mission.
The instrument mainly used to measure these HAHAs will be the Cherenkov Camera (CC) in conjunction with the Radio Instrument (RI).

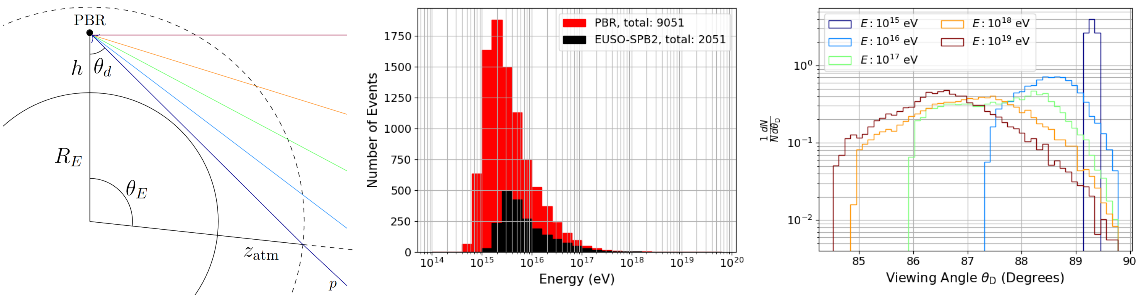

Figure 4: Left: Different HAHA trajectories, visualizing the vast distance in the atmosphere they traverse. Center: Expected event rate for a 30 day flight (red PBR and black EUSO-SPB2 for comparision). Right: angular distribution for different primary cosmic ray energies.

The EASCherSim [8, 9] optical Cherenkov simulation code is used to evaluate the performance of the PBR CC. The resulting event rate assuming a 20% duty cycle for a 30 day flight is shown in the center panel of Fig. 4 and the normalized angular distribution of accepted events as a function of energy is given in the right panel. As is shown, we expect a rate of more than 60 events per hour with an energy threshold at around 500 TeV and a peak sensitivity at 2 PeV. Due to the atmospheric attenuation, higher energy primaries with a HAHA trajectory have a wide range of angles while the lower energetic (more frequent) events are mainly concentrated in the upper part of the CC FoV. This can be used as a geometric energy filter. The impact of adding the radio measurement of these events into the reconstruction is still under investigation but could provide a handle to constrain composition of the primary cosmic ray.

5. Science Goal #3: Searching for Astrophysical Neutrinos

When the PBR telescope is pointed below the Earth's limb, the CC's sensitivity to the Cherenkov radiation from EAS makes it a pioneering instrument to study astrophysical sources of energetic neutrinos. The detection of such neutrinos would reveal insights into cosmic ray acceleration and interactions. Additionally, together with observations from other messengers, VHEN would help to further the understanding of the environments UHE accelerators (see for example [11]). One group of potential high energy neutrino point sources are transients including supernovae, binary neutron star mergers, tidal disruption events, blazar flares, and gamma-ray bursts.

The left panel of Fig. 5 shows PBR's 100 day flight sensitivity for Binary Neutron star mergers [10] scaled for a distance of 0.8 Mpc and 3 Mpc. Possible sources in this distance range could be located in M31, and NGC 253 and M82 (a star burst galaxy) respectively. The time-averaged effective area is color coded on the sky map in the right panel of Figure 5. In Fig. 5, a 100 day

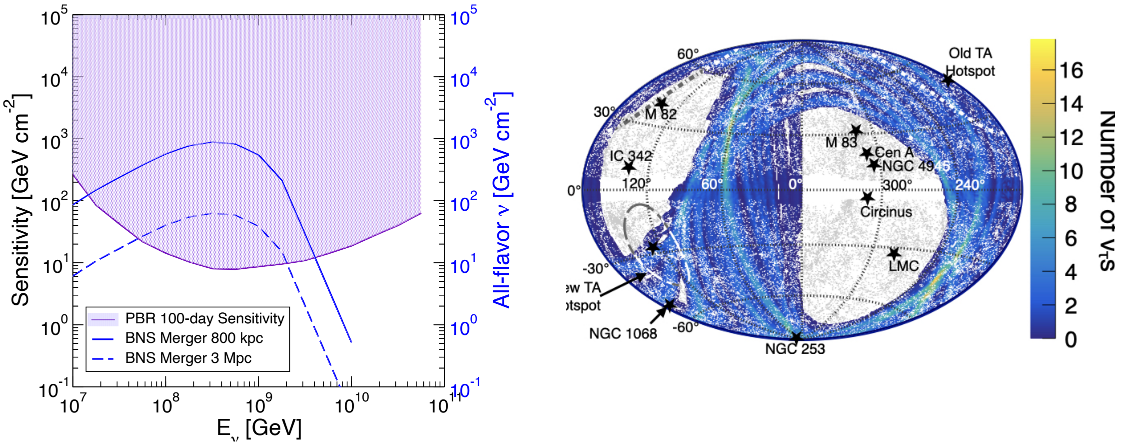

Figure 5: Left: All-flavor sensitivity of PBR for a 100-day flight. Blue lines are all-flavor neutrino fluences of binary neutron star (BNS) mergers [10] (solid: 800 kpc, dashed: 3 Mpc). Right: PBR's 100-day average number of ν_τ's observed depending on source location assuming a BNS merger model [10] at 3 Mpc distance. Black stars are some nearby sources.

flight with a launch in April 2027 is assumed and the Sun and Moon's effects on exposure are taken into account. Details on the methodology can be found in [12].

Finally, we would like to note that due to the duration of the mission and the narrow field of view, PBR has very limited sensitivity to the diffuse cosmogenic neutrino flux. Even with optimistic UHECR source evolution, its sensitivity is not sufficient, as shown by IceCube and Auger. For detailed sensitivity estimation, see [8].

6. Summary and Conclusion

The PBR instrument represents the next generation of stratospheric balloon payloads and is designed to measure fluorescence light from UHECRs from above for the first time. It also aims to study high-altitude horizontal air showers and detect Earth-skimming neutrinos by following up on astrophysical event alerts. Additionally, PBR's design, similar to that of POEMMA, features a hybrid focal surface, which will enhance its technical readiness for future space missions. The newly added radio instrument will provide an independent detection channel for most measurements and allow PBR to observe for the first time the radio and optical Cherenkov signal combined. The mission is planned as a NASA super pressure balloon payload, set to launch from Wanaka, New Zealand, in the first half of 2027.

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