

The Roadmap to the POEMMA mission

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The Probe Of Extreme Multi-Messenger Astrophysics (POEMMA) is designed to observe ultrahigh-energy cosmic rays (UHECRs) and cosmic neutrinos from space with sensitivity over the full celestial sky. Developed as a NASA Astrophysics Probe-class mission, POEMMA consists of two identical telescopes orbiting the Earth in a loose formation designed to observe extensive air showers (EAS) via air fluorescence and Cherenkov emissions. UHECRs and UHE neutrinos above 20 EeV are observed with the stereo fluorescence technique, while tau neutrinos above 20 PeV are observed via the optical Cherenkov signals produced by up-going EAS generated by the decay of Earth-emerging tau-leptons. The POEMMA satellites are designed to quickly re-orientate to follow up transient cosmic neutrino candidate sources and obtain unparalleled neutrino flux sensitivity. Both observation techniques and the instrument design are being validated by current and upcoming missions, such as Mini-EUSO and EUSO-SPB as part of the JEM-EUSO program, and the Terzina instrument onboard the NUSES SmallSat mission. We discuss the POEMMA science performance and the current roadmap to the POEMMA mission.

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1. Introduction

The Probe Of Extreme Multi-Messenger Astrophysics (POEMMA) is one of the probe mission proposals selected for a conceptual study funded by NASA in preparation for the Astro2020 decadal survey. The POEMMA design optimizes the observation of extensive airshowers (EASs) from space by observing the ultraviolet emission from atmospheric fluorescence and the Cherenkov emission from upward going EASs. The stereo fluorescence technique enables precise observations of ultrahigh-energy cosmic rays (UHECRs) and ultrahigh-energy cosmic neutrinos above about 20 EeV. The Cherenkov technique enables the observation of tau-neutrinos from upward going EASs produced by tau-lepton decay generated by tau neutrinos that traverse the Earth and convert into tau-leptons. The Cherenkov technique is optimized for following targets-of-opportunity (ToO) transient astrophysical events that may emit neutrinos above 20 PeV. A detailed description of the POEMMA instrument, mission, and science can be found in Ref. [1] and references therein.

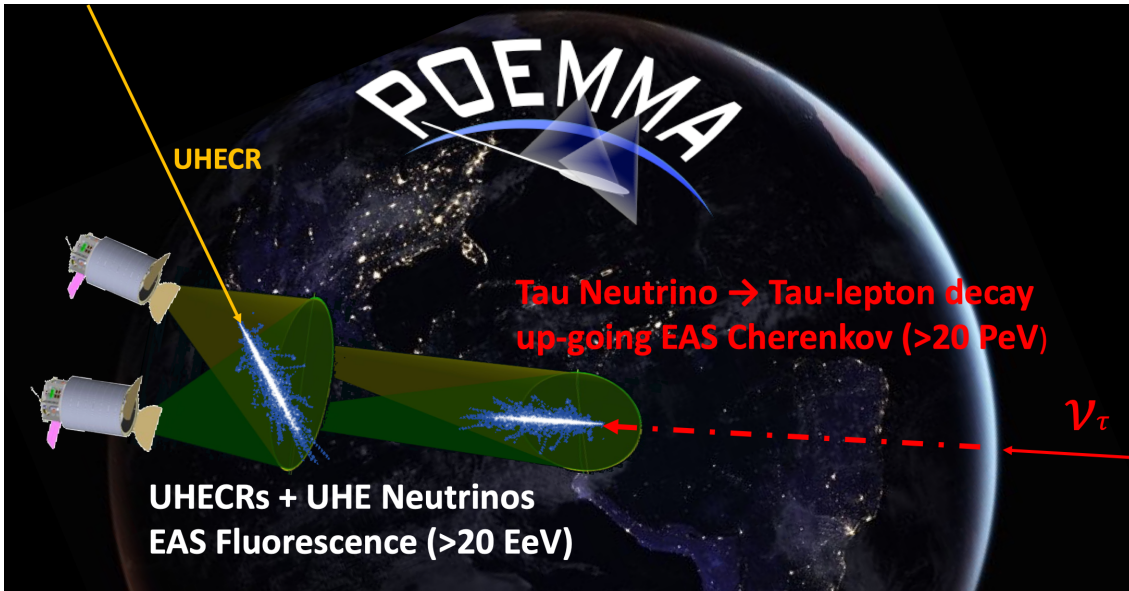


Figure 1: POEMMA Observation Modes: UHECRs and UHE neutrinos with energies above 20 EeV are observed by the ultraviolet emission from atmospheric fluorescence produced by the EASs generated by these particles as they interact in the atmosphere. A target-of-opportunity program to observe tau neutrinos with energies above 20 PeV involves the observation of Cherenkov emission from upward going EAS produced by tau-lepton decay generated by tau neutrinos that traverse the Earth.

The main questions POEMMA is designed to answer are the origin of ultrahigh-energy cosmic rays (UHECRs) and the origin of astrophysical neutrinos. POEMMA will address these questions by measuring the spectrum, composition, and anisotropies over the full sky of UHECRs with energies above 20 EeV, and observing astrophysical neutrinos above 20 PeV through a target-of-opportunity (ToO) program designed to study neutrino rich multi-messenger electromagnetic and gravitational wave sources. POEMMA will study the physics and astrophysics at energies well above ground-based accelerators, where signatures of new interactions or dark matter may be present (see, e.g., secret neutrino interactions [1, 2], supermassive dark matter [1, 3], and macroscopic dark matter [1, 4]).

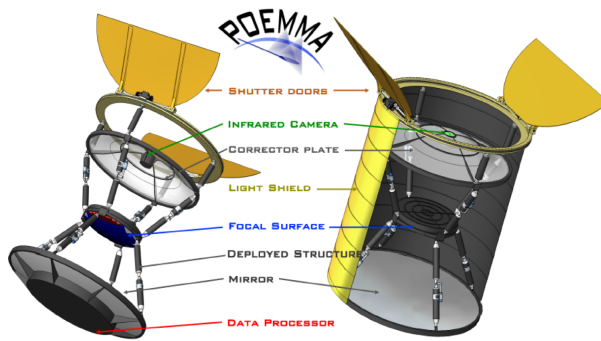


TABLE I: POEMMA Specifications:

Photometer Components			Spacecraft	
Optics	Schmidt	45° full FoV	Slew rate	90° in 8 min
	Primary Mirror	4 m diam.	Pointing Res.	0.1°
	Corrector Lens	3.3 m diam.	Pointing Know.	0.01°
	Focal Surface	1.6 m diam.	Clock synch.	10 nsec
	Pixel Size	3 × 3 mm ²	Data Storage	7 days
	Pixel FoV	0.084°	Communication	S-band
PFC	MAPMT (1μs)	126,720 pixels	Wet Mass	3,450 kg
PCC	SiPM (20 ns)	15,360 pixels	Total Power	880 W
Photometer (One)			Mission (2 Observatories)	
	Mass	1,550 kg	Lifetime	3 year (5 year goal)
	Power	590 W	Orbit	525 km, 28.5° Inc
	Data	< 1 GB/day	Orbit Period	95 min
			Observatory Sep.	~25 - 1000+ km

Each Observatory = Photometer + Spacecraft; POEMMA Mission = 2 Observatories

Figure 2: POEMMA telescopes: The POEMMA observatory comprises of two identical telescopes with a 45 degrees field-of-view (FoV) Schmidt optics provided by a 4-meter mirror, a hybrid focal surface, and a corrector lens designed to reach an optical collection of over 6 m². Figure and table adapted from Ref. [1].

The orbit and optical design of POEMMA enables instantaneous observations of colossal volumes of the atmosphere with projection areas on the ground from 10⁵ km² in Nadir pointing to 10⁷ km² when pointed at the limb of the Earth. The mission involves deploying two telescopes delivered by a dual manifest on an Atlas V to a 525km altitude orbit with 28.5 degree inclination. The orbital period is 95 min and the mission goal is 5 years. Each telescope has a very wide 45 degrees field-of-view (FoV) optics provided by a 4-meter mirror, a hybrid focal surface, and a creative corrector lens that gives an optical collection area of over 6 m². The hybrid focal surface has 126,720 pixels of MAPMTs for fluorescence observations with 1 μs sampling and 15,360 pixels of SiPMs for Cherenkov detection with 20 ns sampling. Both both types of cameras will be flown in 2023 on the Extreme Universe Space Observatory on a Super Pressure Balloon (EUSO-SPB2) [5].

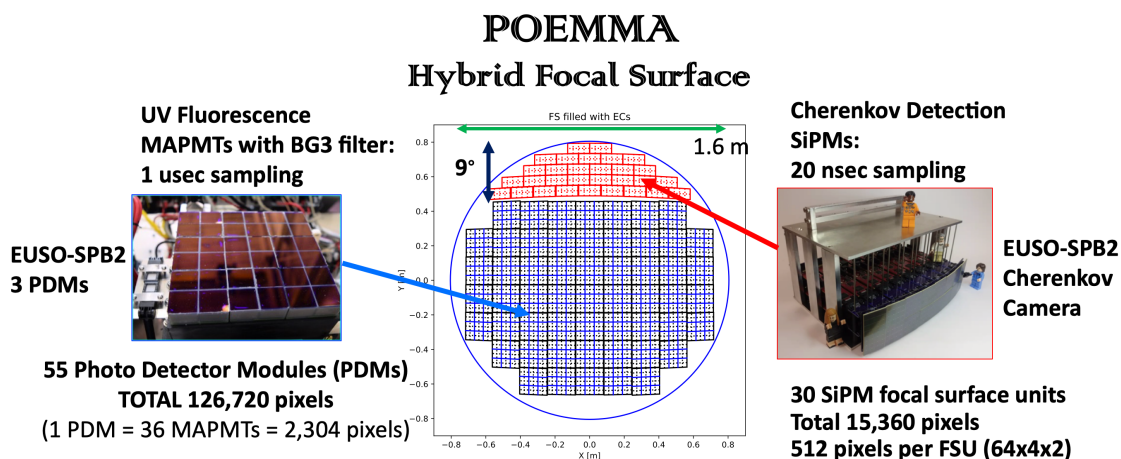


Figure 3: The POEMMA Hybrid Focal Surface was designed with 126,720 pixels of MAPMTs for fluorescence observations with 1 μs sampling and 15,360 pixels of SiPMs for Cherenkov detection with 20 ns sampling. EUSO-SPB2 has both camera types.

POEMMA will reach unprecedented statistics above 20 EeV to study the sources of UHECRs

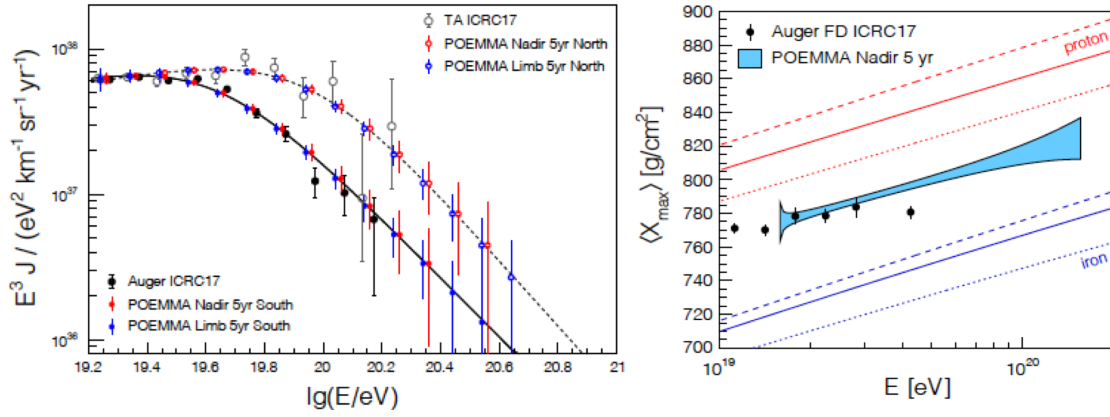


Figure 4: POEMMA UHECR Science: *Left:* Simulated POEMMA spectra compared with Auger 2020 (black dots and solid line) from Ref. [6] and the TA 2019 (black open circles and dotted line) from Ref. [7] for both POEMMA stereo Nadir observations (red) and POEMMA Limb observations (blue). Figure adapted from Ref. [1, 8]. *Right:* Capability of POEMMA to measure $\langle X_{\max} \rangle$ for composition studies at UHEs. The width of the blue band illustrates the expected statistical uncertainties in five years of POEMMA-Stereo (nadir) operations given the number of events per 0.1 in the logarithm of energy, the X_{\max} resolution and efficiency for $\theta < 70^\circ$, and the intrinsic shower-to-shower fluctuations of 40 g/cm^2 . The black dots are fluorescence data from Auger ICRC 2019 [9] and the blue bands are from Ref. [1, 8].

with energy resolution of 17%, angular resolution of about 1 degree, and X_{\max} resolution below 30% all at 100 EeV [8]. This will extend our UHECR observations of spectrum and composition above 100 EeV with a complete sky coverage at energies where anisotropies should become sharper and sources can be identified (see, e.g., [1, 10, 11]).

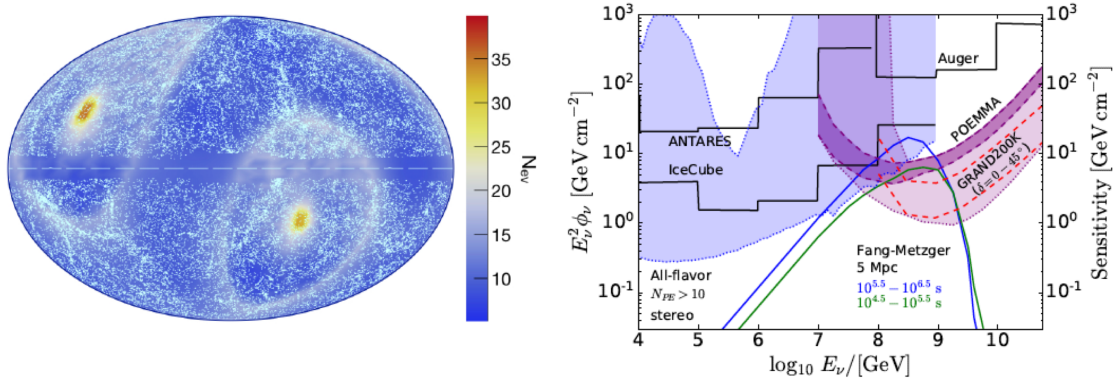


Figure 5: POEMMA Neutrino Science: *Left:* Sky plot of the expected number of neutrino events with POEMMA as a function of galactic coordinates for the Fang and Metzger [12] binary neutron star merger model, placing the source at 10 Mpc Refs. [1, 13]. *Right:* ToO sensitivities to a long burst shown by the magenta band as in Refs. [1, 13]. Also shown are the IceCube all-flavor upper limits (solid histogram) from the GW170817 neutrino search [14]. The red dashed curves represent the projected sensitivity of GRAND200k [15], and models from Fang and Metzger [12] of the all-flavor neutrino fluence produced $10^{5.5} - 10^{6.5} \text{ s}$ and $10^{4.5} - 10^{5.5} \text{ s}$ after a binary neutron star merger event occurring at a distance of 10 Mpc. Figures adapted from [1, 13]

POEMMA will also search for UHE neutrinos with fluorescence and have a ToO program

to observe neutrinos from multi-messenger transient events. POEMMA will observe Cherenkov emission from EAS produced as tau neutrinos cross the Earth and produce tau leptons that decay on their way out of the Earth's surface producing up-going showers [16]. The ToO program will cover tau-neutrino energies above 20 PeV, with full sky coverage, and great sensitivity to many neutrino rich astrophysical transients, such as neutron-star binary coalescence, tidal disruption events, and soft gamma ray bursts [17].

The roadmap to the POEMMA mission starts with previous work for the OWL (Orbiting Wide-field Light-collectors) [18, 19] design, the JEM-EUSO (Joint Experiment Missions for the Extreme Universe Space Observatory) [20] program, the CHANT (CHerenkov Astrophysical Neutrino Telescope) concept [21], and the sub-orbital payloads EUSO-SPB1 (Extreme Universe Space Observatory on a Super Pressure Balloon 1) [22] and EUSO-SPB2 [5]. The OWL designed introduced the stereo vision of two free-flyers with large reflecting optics similar to POEMMA. The JEM-EUSO program developed a number of projects built with the MAPMT cameras like the one proposed for the POEMMA fluorescence system. Currently under construction and scheduled to fly in 2023, EUSO-SPB2 has both a fluorescence telescope pointing Nadir and a Cherenkov telescope pointing towards the limb of the Earth [5, 16, 23]. EUSO-SPB2 will establish both detection techniques for POEMMA. In addition to EUSO-SPB2, the NUSES SmallSat mission is planning to carry the Terzina instrument designed to establish the Cherenkov emission of cosmic rays above the limb [23]. On the ground, the Trinity [24] observatory will also be testing the POEMMA Cherenkov detection technique.

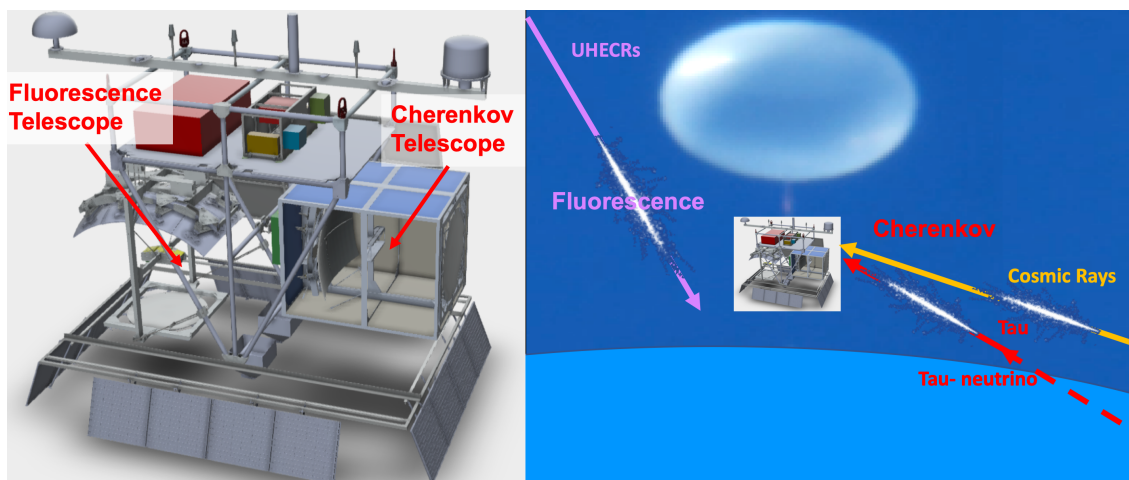


Figure 6: EUSO-SPB2 will test both detection methods of POEMMA. Planned for a 2023 flight, EUSO-SPB2 will observe UHECRs from above with the fluorescence telescope and cosmic rays above the limb with the Cherenkov camera [5].

2. Conclusion

In conclusion, POEMMA will use the Earth's Atmosphere as a gigantic particle observatory to discover the origin of the highest energy cosmic rays ($E > 100$ EeV) [1, 11] and to observe very high energy ($E > 20$ PeV) neutrino emission from astrophysical transient events [1, 17]. These studies

will bring new insight onto the most extremely energetic environments in the present universe enabling the study of new astrophysical and physical phenomena.

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