

Snowmass 2021 - Letter of Interest

The Probe Of Multi-Messenger Astrophysics (POEMMA)

Thematic Areas: (check all that apply /■)

(CF1) Dark Matter: Particle Like

(CF2) Dark Matter: Wavelike

(CF3) Dark Matter: Cosmic Probes

(CF4) Dark Energy and Cosmic Acceleration: The Modern Universe

(CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before

■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities

■ (CF7) Cosmic Probes of Fundamental Physics

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Collaboration: POEMMA

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Abstract: The Probe Of Extreme Multi-Messenger Astrophysics (POEMMA) is designed to identify the sources of Ultra-High-Energy Cosmic Rays (UHECRs) and to observe cosmic neutrinos, both with full-sky coverage. Developed as a NASA Astrophysics Probe-class mission, POEMMA consists of two spacecraft flying in a loose formation at 525 km altitude, 28.5° inclination orbits. Each spacecraft hosts a Schmidt telescope with a large collecting area and wide field of view. A novel focal plane is optimized to observe both the UV fluorescence signal from extensive air showers (EASs) and the beamed optical Cherenkov signals from EASs. In POEMMA-stereo fluorescence mode, POEMMA will measure the spectrum, composition, and full-sky distribution of the UHECRs above 20 EeV with high statistics along with remarkable sensitivity to UHE neutrinos. The spacecraft are designed to quickly re-orient to a POEMMA-limb mode to observe neutrino emission from Target-of-Opportunity (ToO) transient astrophysical sources viewed just below the Earth's limb. In this mode, POEMMA will have unique sensitivity to cosmic ν_τ events above 20 PeV by measuring the upward-moving EASs induced by the decay of the emerging τ leptons following the interactions of ν_τ inside the Earth.

39 POEMMA (Probe Of Extreme Multi-Messenger Astrophysics) is a NASA probe mission designed to ob-
40 serve Ultra-High-Energy Cosmic Rays (UHECRs) and cosmic neutrinos from space¹. With its twin tele-
41 scopes, POEMMA will monitor colossal volumes of the Earth’s atmosphere to detect extensive air showers
42 (EASs) produced by extremely energetic cosmic messengers: UHECRs above 20 EeV (1 EeV $\equiv 10^{18}$ eV)
43 and cosmic neutrinos above 20 PeV (1 PeV $\equiv 10^{15}$ eV) with sensitivity over the entire sky.

44 A POEMMA white paper was submitted to the Astro2020 decadal survey². Given the strong expertise
45 of DOE-led high-energy physics projects, an appropriate DOE contribution to a joint NASA/DOE mission
46 would be the POEMMA hybrid focal surface detectors and electronics.

47 **1 The Observatory**

48 The design of the POEMMA observatory evolved from previous work on the OWL³ and JEM-EUSO⁴
49 designs, the CHANT concept⁵, and the sub-orbital payloads EUSO-SPB1⁶ and EUSO-SPB2⁷. POEMMA
50 is composed of two identical space telescopes that provide significant advantages in terms of exposure and
51 sky coverage to sources of the highest energy particles. Each telescope consists of a wide (45°) field-of-view
52 (FoV) Schmidt optics system with a 4-meter mirror. The focal surface has two complementary capabilities:
53 a fast (1 μ s) ultraviolet camera to observe EAS fluorescence signals and an ultrafast (10 ns) optical camera to
54 detect EAS Cherenkov signals. This hybrid camera is designed to optimize the different science objectives.
55 EASs from UHECRs and cosmic neutrinos are observed from an orbit altitude of 525 km and a wide range
56 of directions in the dark sky.

57 The scientific objectives of POEMMA are achieved by operating the telescopes in two different orien-
58 tation modes: a quasi-nadir stereo fluorescence configuration, for precise UHECR observations (denoted
59 POEMMA-stereo), and a tilted, Earth-limb viewing configuration (denoted POEMMA-limb). In POEMMA-
60 stereo mode, POEMMA is also sensitive to Ultra-High-Energy neutrinos. The POEMMA-limb mode is
61 used to point both telescopes in the direction of astrophysical transient events rising or setting just below the
62 Earth’s limb to detect neutrino emission from astrophysical targets-of-opportunity (ToOs). It also allows for
63 a much greater exposure to UHECRs, albeit with a higher energy threshold.

64 In the POEMMA-stereo configuration, the two wide-angle telescopes, each with several square meters of
65 effective photon collecting area, view a common, immense atmospheric volume corresponding to approx-
66 imately 10^4 gigatons of atmosphere. The POEMMA-stereo mode yields one order of magnitude increase
67 in yearly UHECR exposure compared to that obtainable by ground observatory arrays and two orders of
68 magnitude compared to ground fluorescence observations. In POEMMA-limb mode, POEMMA searches
69 for optical Cherenkov signals of upward-moving EASs generated by tau lepton decays produced by ν_τ inter-
70 actions in the Earth. The terrestrial neutrino target monitored by POEMMA reaches nearly 10^{10} gigatons. In
71 this configuration, an even more extensive volume of the atmosphere is monitored for UHECR fluorescence
72 measurements. Thus, POEMMA uses the Earth and its atmosphere as a gargantuan high-energy physics
73 detector and astrophysics observatory.

74 **2 The Scientific reach**

75 The main scientific goals of POEMMA are to discover the elusive sources of UHECRs with energies above
76 20 EeV and to observe cosmic neutrinos from multi-messenger transients. POEMMA exploits the tremen-
77 dous gains in both UHECR and cosmic neutrino exposures offered by space-based measurements, including
78 full-sky coverage of the celestial sphere.

79 **2.1 Ultra-High-Energy Cosmic-Rays (UHECRs)**

80 The nature of the astrophysical sources of UHECRs and their acceleration mechanism(s) remains a mys-
81 tery⁸⁻¹¹. POEMMA is designed to obtain definitive measurements of the UHECR spectrum, composition,

82 and source locations for $E \gtrsim 20$ EeV, and fulfills the requirements expected from a next-generation in-
 83 strument by the UHECR community¹¹. In both the POEMMA-stereo and POEMMA-limb configurations,
 84 EAS fluorescence signals are observed as video recordings with 1 μ s snapshots. Each POEMMA telescope
 85 records an EAS trace in its focal surface, which defines an observer-EAS plane. In POEMMA-stereo mode,
 86 the intersection of the two observer-EAS planes accurately defines the geometry of the EAS trajectory. Pre-
 87 cise reconstruction of the EAS is achieved for opening angles between these two planes larger than $\sim 5^\circ$.
 88 In POEMMA-limb observations, the EAS trajectory reconstruction is based on monocular reconstruction
 89 where the distance to the EAS in the observer-EAS plane is determined by the evolution in time of the EAS
 90 and a model of the atmosphere.

91 Over its planned 5-year operation, POEMMA will collect a dataset larger than the current statistics of the
 92 Pierre Auger Observatory (Auger) and the Telescope Array (TA) experiment combined¹². With full-sky
 93 coverage, POEMMA will observe the UHECR source distribution over the full celestial sphere, eliminating
 94 the need for cross-calibration between two different experiments with only partial-sky coverage. Together
 95 with primary composition and spectrum measurements well beyond the flux suppression^{13–15}, POEMMA
 96 will be capable of detecting anisotropy at the level of 5σ ¹² for cross-correlation search parameters within the
 97 vicinity of the signal regions for the anisotropy hints reported by TA^{16,17} and Auger¹⁸. Thus, POEMMA will
 98 turn the TA and Auger anisotropy hints (and/or other anisotropy signals yet to be discovered) into significant
 99 detection to finally discover the locations of the UHECR sources.

100 2.2 Cosmic neutrinos

101 POEMMA will also be sensitive to the most energetic cosmic neutrinos, from 20 PeV to the ZeV scale¹⁹,
 102 thus providing an opportunity to make substantial progress in high-energy astrophysics and fundamental
 103 physics²⁰. In the POEMMA-limb configurations, EAS Cherenkov signals from the decay of tau leptons as
 104 they exit the Earth’s surface^{21,22} are observed as video recordings with 10 ns snapshots. Observable tau
 105 lepton decay events for POEMMA are viewed in the directions starting close to the limb of the Earth located
 106 at 67.5° from the nadir for POEMMA’s 525 km altitude.

107 POEMMA will be especially suited for rapid follow-up of ToOs²³ via neutrinos with energies $E_\nu \gtrsim 20$ PeV,
 108 because it will orbit the Earth in a period of 95 mins and will be capable of re-pointing its satellites by 90° in
 109 500 s in its transient tracking mode. In combination, these design features will enable POEMMA to access
 110 nearly the entire dark sky within the time scale of one orbit. POEMMA will also have groundbreaking
 111 sensitivity to neutrinos at energies beyond 100 PeV, reaching the level of modeled neutrino fluences for
 112 nearby sources in many astrophysical scenarios²⁴. Note that POEMMA also has sensitivity to neutrinos
 113 with energies above 20 EeV through fluorescence observations of neutrino induced EASs¹².

114 2.3 Fundamental physics & other science objectives

115 **pp cross section beyond collider energies:** The EASs developing in the atmosphere observed by PO-
 116 EMMA present a fixed-target calorimeter experiment with $E_0 \gtrsim 20$ EeV. This provides a measure of the
 117 inelastic nuclear interactions at an effective center-of-mass energy of $\sqrt{2E_0m_p} \approx 280$ TeV, well above the
 118 current and future²⁵ capabilities of the LHC.

119 **Searches for superheavy dark matter (SHDM):** When SHDM decays into standard model particles, the
 120 final state products are dominated by photons and neutrinos, whose EASs are detectable by POEMMA²⁶.
 121 For neutrinos, both the Cherenkov and fluorescence signals are available yielding outstanding sensitivity for
 122 $E_\nu \gtrsim 20$ PeV to above a ZeV. POEMMA’s photon sensitivity for EAS fluorescence measurements provides
 123 an order of magnitude improvement¹² over the current limits from ground UHECR experiments.

124 **Supplementary science capabilities** of POEMMA include other probes of physics beyond the Standard
 125 Model of particle physics (e.g. violation of Lorentz Invariance²⁷), the study of atmospheric transient lumi-
 126 nous events (TLEs), and the search for meteors and nuclearites²⁸.

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