POEMMA
Probe of Extreme Multi-Messenger Astrophysics:
CRs and Neutrinos

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CRESST/NASA/GSFC/UMBC
for the POEMMA Collaboration
Outline

1. Introduction/Overview of study.
2. Instrument description.
5. Initial tau neutrino sensitivity calculations and results.
6. Closing remarks.
NASA Solicitation NNH16ZDA001N-APROBES (Scope of Program):

Announced: 19-Feb-16   Due Date: 15-Nov-16   Selection: 17-Mar-17

NASA has started preparations for the 2020 Astronomy and Astrophysics Decadal Survey (http://science.nasa.gov/astrophysics/2020-decadal-survey-planning/). One of the tasks of the 2020 Decadal Survey Committee will be to recommend a portfolio of astrophysics missions. The Decadal Survey Committee may choose to recommend a portfolio of missions containing a mix of prioritized large- and medium-size mission concepts, or even a program of competed medium-size missions. NASA and the community are interested in providing appropriate input to the 2020 Decadal Survey regarding medium-size mission concepts, also referred to as Astrophysics Probe concepts.

To this end, NASA is soliciting proposals to conduct mission concept studies for Astrophysics Probe missions. Following peer review of the proposed mission concept studies, NASA will select a small number of proposals for 1.5 year (18 month) funded studies. Results of the selected studies will be provided by NASA as input to the 2020 Decadal Survey.

Astrophysics Probes are envisioned to have a total lifecycle (NASA Phases A through E) cost between that of a MIDEX mission (~$400M) and ~$1B. Proposals for concept studies may envision missions that include contributions from other agencies (national or international), industry, and universities.

Should NASA choose to develop a mission that flows from any selected mission concept study, the responsibility for that mission will be assigned by NASA; there is no expectation that the mission concept study team or participating organization.

Specific instructions for a NASA Class B mission definition, eg launch date, costing, ...
Funded instrument definition, eg IDL, and mission definition, eg MDL, studies
FINAL REPORT IN PREPARATION
POEMMA: study collaboration

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NASA/MSFC: Mark J. Christl (Deputy PI), Roy M. Young, Peter Bertone, Jeff Apple, Gary Thornton, Brent Knight, Kurt Dietz, Mohammad Sabra
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Colorado School of Mines: Lawrence Wiencke, Frederic Sarazin
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Georgia Institute of Technology: A. Nepomuk Otte
Space Sciences Laboratory, University of California, Berkeley: Eleanor Judd
University of Iowa: Mary Hall Reno
Jet Propulsion Laboratory: Insoo Jun, L. M. Martinez-Sierra
Vanderbilt University: Steven E Csorna
APC Univerite de Paris 7: Etienne Parizot, Guillaume Prevot
Universita di Torino: Mario Edoardo Bertaina, Francesco Fenu, Kenji Shinozaki
University of Geneva: Andrii Neronov
Gran Sasso Science Institute: Roberto Aloisio

Scientists from 16+ institutions from
OWL, JEM-EUSO, Auger, TA, Veritas, CTA, Fermi, Theory
POEMMA: Heritage

Based on OWL 2002 study, JEM-EUSO, EUSO balloon experience, and CHANT proposal

OWL 2002 design

EUSO: Extreme Universe Space Observatory

EUSO-Balloon
EUSO@TA
Mini-EUSO

TUS, KLYPVE-EUSO

CHANT

EUSO-SPB1

EUSO-SPB2

Cherenkov from Astrophysical Neutrinos Telescope

MASS:*Maximum*
Energy*Auger*(Air)*
Shower*Satellite*
******Italian*Mission
POEMMA: UHECR and Neutrino Observation Modes

Stereo mode air fluorescence UHECR observation:
- Achieve significant increase in exposure via space-based observations (x10 arrays; x100 fluorescence) with full-sky coverage
- Achieve good angular and energy resolution
- Achieve sufficient $X_{\text{MAX}}$ resolution to perform UHECR composition measurements
- UHE $\nu$ interactions in atmosphere, deeper in atmosphere (if sufficient flux)

Limb-viewing mode air fluorescence UHECRs:
- Achieve significant increase in exposure via space-based observations with full-sky coverage, but at higher energy scales
- Good energy resolution, angular resolution suffers
- $X_{\text{MAX}}$ resolution degraded as well and low event statistics, if no post-GZK recovery

Limb-viewing mode Cherenkov upward tau-lepton EAS:
- Use Earth as $\nu_\tau$ converter
- View near Earth limb for good HE acceptance
- Beamed Cherenkov signal allows for energy threshold ~ few 10 PeV.
- Target-of-Opportunity mode if receive a transient alert
POEMMA: Exposure History
POEMMA: Instruments

Two 4 meter F/0.64 Schmidt telescopes: 45° FoV
Hybrid focal surface (MAPMTs and SiPM)
3 mm linear pixel size: 0.084° FoV

Instrument Mass: 1,550 kg
Primary Mirror: 4 meter diameter
Corrector Lens: 3.3 meter diameter
Focal Surface: 1.6 meter diameter
Optical Area_{EFF}: ~6 to 2 m²
Instrument Power: 590 W
Science Data: ~1 GB/day
POEMMA: Optics Details

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3 mm linear pixel size: 0.084° FoV

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POEMMA: Hybrid Focal Plane

UV Fluorescence Detection using MAPMTs with BG3 filter: developed by JEM-EUSO: 1 usec sampling

Cherenkov Detection with SiPMs: 20 nsec sampling

55 Photo Detector Modules (PDMs)= 126,720 pixels
1 PDM = 36 MAPMTs = 2,304 pixels

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1 PDM = 36 MAPMTs = 2,304 pixels

Elementary Cell (EC)

30 SiPM focal surface units
Total 15,360 pixels
512 pixels per FSU (64x4x2)
Si-Diode for LEO radiation backgrounds rejection

9°
POEMMA: Hybrid Focal Wavelength & Timing Response

UV Fluorescence Detection using MAPMTs with BG3 filter: developed by JEM-EUSO: 1 usec sampling

Cherenkov Detection with SiPMs: 20 nsec sampling

Elementary Cell (EC) SiPM (8x8)

Prelim MC results: \( \theta_c \lesssim 2.5^\circ \)

Calc by D. Bergman
POEMMA: Mission

Mission Lifetime: 3 years (5 year goal)
Orbits: 525 km, 28.5° Inc
Orbit Period: 95 min
Satellite Separation: ~25 km – 1000+ km
Satellite Position: 1 m (knowledge)
Pointing Resolution: 0.1°
Pointing Knowledge: 0.01°
Slew Rate: 8 min for 90°
Satellite Wet Mass: 3860 kg
Power: 2030 W
Data: 1 GB/day
Data Storage: 7 days
Communication: S-band (X-band if needed)
Clock synch (timing): 10 nsec

Operations:
- Each satellite collects data autonomously
- Coincidences analyzed on the ground
- View the Earth at near-moonless nights, charge in day and telemeter data to ground
- ToO Mode: dedicated com uplink to re-orient satellites if desired
POEMMA: UHECR and Neutrino Sky Coverage

UHECR Stereo Mode

Neutrino Mode: SiPM part of focal plane

Calcs & plots by K. Shinozaki

Calcs & plots by C. Guépin & F. Sarazin

Paper in preparation
POEMMA: Preliminary Stereo UHECR Performance

POEMMA Parameterized Optics implemented in updated OWL simulation:
- 3 mm pixels, uniform layout
- uBiAlkali PMT QE: \( \lambda \) dependence w/~40% at peak
- Int time 1 usec
- 90% factor to account for SiPM area
- 500 photons/nsec/m²/sr background used to set MC trigger threshold: < 1 kHz focal plane rate (matches well to ESAF results for nadir pointing)
- Trigger requires same trigger in each satellite
- Duty cycle 10%
Small 0.084° coupled with small RMS spot size allows to use geometric reconstruction:
- plane opening angle > 3°
- track length > 4 pixels
- Leads to excellent angular resolution
- Leads to 80+% acceptance of triggered events

Further work needed to determine energy and $X_{\text{MAX}}$ resolution via full event reconstruction:
- $E_{\text{RES}}$ at least as good from monocular reconstruction: $\lesssim$ 20%
- $X_{\text{MAX}}$ resolution not dominated by PE statistics above ~ 50 EeV
POEMMA: Neutrino mode example configuration

Calcs & plots by F. Sarazin

Altitude: 525 km
Sat. separation: 30 km
Field of view: 45°
Above limb angle: 2.0°
Pointing (on-orbit): 47.0°
Pointing (off-orbit): 88.5°
Max distance: 1000 km

9° total

7° from limb
POEMMA: Preliminary Monocular UHECR performance

POEMMA Parameterized Optics implemented in ESAF (JEM-EUSO simulation and analysis code)
- JEM-EUSO layout of focal plane
- JEM-EUSO PMT QE 27%
- GTU time 2.5 usec
- 500 photons/nsec/m²/sr air glow background
- Duty cycle 14.4%

Monocular Performance ≤ ν Mode UHECR
- Annual exposure ≥ 10⁵ km² sr above 10²⁰ eV
- Energy resolution: 20 – 25%
- Angular Resolution: several degrees (anticipated to improve once GTU = 1 usec)
- X_max resolution: ~100 g/cm²
POEMMA: Air Glow Background in Cherenkov Band

<table>
<thead>
<tr>
<th>Wavelength interval [nm]</th>
<th>Intensity [photons m² sr⁻¹ ns⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>314 - 500</td>
<td>570</td>
</tr>
<tr>
<td>314 - 700</td>
<td>2020</td>
</tr>
<tr>
<td>500 - 700</td>
<td>1450</td>
</tr>
<tr>
<td>500 - 800</td>
<td>5030</td>
</tr>
<tr>
<td>500 - 900</td>
<td>12090</td>
</tr>
</tbody>
</table>

314 nm – 900 nm
Use to calculate effective PDE (for SiPM): <PDE> = 0.1
12,090 photons/m²/sr/ns vs 570 photons/m²/sr/ns (λ < 500 nm)

Viewing at angles away from nadir views more optical depth of air glow layer.
x6 for viewing limb from 500 km

Work by Simon Mackovjak
POEMMA: upward tau EAS Cherenkov simulations

Baseline Simulation: \( \nu_\tau \rightarrow \tau \rightarrow \text{EAS} \rightarrow \text{Cherenkov} \rightarrow \text{atmosphere} \rightarrow \text{detector} \)

- Work by M. Hall Reno, T. Venters, and J. Krizmanic
- New tau yield calculations by M. Reno
- Parameterized EAS with Hillas-based Cherenkov generation
- Static atmosphere with aerosol, ozone, and molecular absorption
- Two different implementations
- Assumptions: \( E_{\text{EAS}} = 0.5 \ E_\tau \); Ignore muon channel (for now)
- Cherenkov light strength and angle as a function of \( \beta_E \) and EAS altitude (\( \leq 20 \) km)
- POEMMA Instrument Model: \( A_{\text{EFF}} = 2.5 \ \text{m}^2 \); \( <\text{PDE}> = 0.2 \) for signal

\[
\begin{array}{|c|c|c|c|}
\hline
\Delta \alpha & \beta_E(33 \text{ km}) & \beta_E(525 \text{ km}) & \beta_E(1000 \text{ km}) \\
\hline
1 & 3.6 & 7.0 & 8.2 \\
2 & 5.2 & 10.0 & 11.7 \\
3 & 6.6 & 12.3 & 14.5 \\
4 & 7.9 & 14.4 & 16.9 \\
5 & 9.1 & 16.2 & 19.0 \\
6 & 10.3 & 18.0 & 21.0 \\
7 & 11.4 & 19.6 & 22.8 \\
8 & 12.6 & 21.2 & 24.6 \\
\hline
\end{array}
\]

PREM Earth Model

Flux1, BDHM

Paper in preparation
POEMMA: preliminary neutrino sensitivity

All flavor Sensitivity Limit:
- 5 year
- 20% duty cycle
- 10 PE threshold with time coincidence to reduce air glow background ‘false positives’
- 2.44 events/decade (90% CL)
- 17% hit for ignoring μ channel
- Viewing to 7° away from Limb (or to ~20° Earth Emergence Angle)

References:
- IceCube (2018): arXiv:1807.01820, Fig 6
- ANITA: arXiv:1803.02719, Fig 6
- ARIANNA: arXiv:1410.7352, Fig 6
- ARA-37: arXiv:1105.2854, Fig 29
- GRAND10k: arXiv:1708.05128, Fig 1
POEMMA: preliminary neutrino sensitivity

All flavor Sensitivity Limit:
- 5 year
- 20% duty cycle
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- 2.44 events/decade (90% CL)
- 17% hit for ignoring $\mu$ channel
- Viewing to 7° away from Limb (or to ~20° Earth Emergence Angle)

Thanks to Ke Fang for the source models: see arXiv: 1708.05128, Fig 3
UFA: arXiv:1505.02153, Figs 5 & 12
POEMMA: preliminary tau neutrino aperture (Earth Skimming)

- Viewing to 7° away from Limb (or to ~20° Earth Emergence Angle)
POEMMA: anomalous ANITA upward EAS

arXiv:1803.05088v1

TABLE I: ANITA-I,-III anomalous upward air showers.

<table>
<thead>
<tr>
<th>event, flight</th>
<th>date, time</th>
<th>Lat., Lon.</th>
<th>Altitude</th>
<th>Ice depth</th>
<th>El., Az.</th>
<th>RA, Dec</th>
<th>$E_{shower}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3985267, ANITA-I</td>
<td>2006-12-28:00:33:20UTC</td>
<td>-82.6559, 17.2842</td>
<td>2.56 km</td>
<td>3.53 km</td>
<td>$-27.4 \pm 0.3^\circ, 159.62 \pm 0.7^\circ$</td>
<td>282.14064, +20.33043</td>
<td>0.6 ± 0.4 EeV</td>
</tr>
<tr>
<td>15717147, ANITA-III</td>
<td>2014-12-20:08:33:22.5UTC</td>
<td>-81.39856, 129.01626</td>
<td>2.75 km</td>
<td>3.22 km</td>
<td>$-35.0 \pm 0.3^\circ, 61.41 \pm 0.7^\circ$</td>
<td>50.78203, +38.65498</td>
<td>0.56±0.3 EeV</td>
</tr>
</tbody>
</table>

1 Latitude, Longitude of the estimated ground position of the event.
2 Sky coordinates projected from event arrival angles at ANITA.
3 For upward shower initiation at or near ice surface.

POEMMA can tilt to view $9^\circ \times 30^\circ$ ‘spot’

But these events may be bright enough to be seen in the UV fluorescence detector with $\sim1$ usec coincidence.

$\theta_{CONE} = 1.0 \text{ deg}$
$\omega \approx 1.e-3 \text{ sr}$

POEMMA
signal size
$\sim6000$ PEs in cone

$t$-lepton
$\gamma ct \sim 60 \text{ km}$
for 1.2 EeV

GF’s similar ($\sim200 \text{ km}^2 \text{ sr}$): 2 events/70 days (ANITA 1-3) -> $\sim2$ events per year for POEMMA
POEMMA: Summary

- POEMMA was funded for a NASA Astrophysics Probe Study and we have completed an instrument and mission design within Study constraints with the goal of maximizing the UHECR and Earth-skimming tau neutrino performance.

- Initial simulation results yield:
  - UHECR Stereo performance with all-sky coverage:
    - 5 Year exposure: $5 \times 10^5 (1.5 \times 10^6)$ km$^2$ sr yr at 40 (100) EeV
    - Angular resolution: $\lesssim 1^\circ$ for $E_{\text{CR}} \geq 40$ EeV
    - Energy resolution: $\sim 20\%$
    - $X_{\text{MAX}}$ resolution: $\sim 20$ g/cm$^2$ above 40 EeV (PE statistics term); work in progress
  - UHECR tilted performance:
    - 5 Year exposure: $5 \times 10^5 (1.5 \times 10^6)$ km$^2$ sr yr at 40 (100) EeV; $2 \times 10^6$ km$^2$ sr yr at 130 EeV
    - Angular resolution: $\lesssim 5^\circ$ for $E_{\text{CR}} \geq 100$ EeV (zenith angle dependent), work in progress
    - Energy resolution: $\sim 20-25\%$
    - $X_{\text{MAX}}$ resolution: $\sim 100$ g/cm$^2$
  - Earth-skimming tau neutrino differential sensitivity ($E^2 \, dN/dE$ [GEV cm$^{-2}$ sr$^{-1}$ s$^{-1}$]):
    - $10^{-6}$ at 25 PeV with minimum of $10^{-7}$ at 300 PeV [5 year, 90% CL]
    - Expanding azimuthal energy range to 360$^\circ$ increases sensitivity by 12
  - Target-of-Opportunity mode for neutrino observations allows for transient follow up observations (if in available celestial sky): model with $10^4$ sec to peak $\nu$ flux presented at this conference.
  - ANITA anomalous events would be very bright in POEMMA
- POEMMA simulations will continue to better quantify performance for the final report.
- This work is in support of NASA hoping to define a new, Probe Class of mission; input to decadal review, (hopefully) recommendation for Probe Class; agency enactment; then (hopefully) AO for actual mission in 2020’s
- Thus there is an opportunity to improve performance such as focused technology development, especially in large scale optics: UV measurements with 1 km spatial resolution from 1000 km distance is $10^4$ away from the diffraction limit.

- **Neutrino Simulation work will continue via a recently selected NASA APRA proposal:**
  - Goal to develop *robust* end-to-end neutrino simulation package for space-based and sub-orbital experiments: focus on upward $\tau$-lepton from Earth **optical Cherenkov and radio signals** (at first), e.g. put in tau decay fractions to form composite EAS, muonic EAS, variable atmosphere and other atmospheric effects, determine backgrounds, etc.
  - 3 year proposal: target is to release package to the community early in the third year.

- See paper by R. dos Anjos et al. (arXiv:1810.04251) which has evaluated impact of POEMMA UHECR measurement capability on understanding UHECR composition.
**POEMMA**

**Nadir for UHECR:**
Radius 200-400 km

**Limb for Neutrinos:**
Radius 2.6-3.7 $10^3$ km

**TOO mode for neutrino follow up of special events**