A NASA Probe-class mission to perform transformational measurements of UHECRs and Cosmic Neutrinos.

John Krizmanic
CRESST/NASA/GSFC/UMBC
for the POEMMA Collaboration

MAPMT arrays for EAS fluorescence light detection

SiPM arrays for Cherenkov light detection from upward $\nu_e$ induced EAS
Outline

1. Scientific and Experimental Motivation
2. POEMMA & Mission Description.
3. POEMMA UHECR & UHE Neutrino Performance via air fluorescence measurements.
4. POEMMA VHE Neutrino Performance via optical Cherenkov measurements.
5. SiPM discussion regarding space-based optical Cherenkov measurements.
6. SiPM discussion regarding space-based air fluorescence measurements.
7. Summary

Stereo Viewing of UHECRs $E \gtrsim 20$ EeV via Fluorescence: 10’s of µsec timescale

Upward $\tau$-lepton EAS $E \gtrsim 20$ PeV via Cherenkov: ~10 nsec timescale
POEMMA Study Collaboration

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JAPAN: RIKEN: Marco Casolino
GERMANY: KIT: Michael Unger; ESO: F. Oikonomou

40+ scientists from 21+ institutions (US + 6)
OWL, JEM-EUSO, Auger, TA, Veritas, CTA, Fermi, Theory
POEMMA: Science Goals

POEMMA Science goals:

primary

- **Discover the origin of Ultra-High Energy Cosmic Rays**
  - Measure Spectrum, composition, Sky Distribution at Highest Energies ($E_{CR} > 20$ EeV)
  - Requires very good angular, energy, and $X_{\text{max}}$ resolutions: stereo fluorescence
  - Allows for high sensitivity UHE neutrino measurements

- **Observe Neutrinos from Transient Astrophysical Events**
  - Measure Cherenkov light from upward-moving EAS from $\tau$-leptons source by $\nu_\tau$ interactions in the Earth ($E_\nu > 20$ PeV)
  - Requires tilted-mode of operation to view limb of the Earth & ~10 ns timing
  - Allows for tilted UHECR air fluorescence operation, higher GF but degraded resolutions

secondary

- study **fundamental physics** with the most energetic cosmic particles: CRs and Neutrinos
- search for super-Heavy Dark Matter
- study Atmospheric Transient Events, survey Meteor Population
UHECR Status

Origin: UHECRs still unknown

Giant ground Observatories: Auger & TA
- sources are extragalactic: Auger dipole > 8 EeV
- spectral features – discrepancies E > 50 EeV
- interesting Composition trends – unknown E > 50 EeV
- source anisotropy Hints E > 50 EeV

\[ E^{2.6} \rho(E) \sim 10^{-2} \, \text{m}^2 \text{s}^{-1} \text{sr}^{-1} \, \text{GeV}^{-1} \]

\[ \sqrt{E} \rho(E) (\text{GeV}^{-1} \, \text{m}^2 \, \text{s}^{-1} \, \text{sr}^{-1}) \]

Galactic

Super Galactic

arXiv:1709.07321
POEMMA: UHECR Exposure History
### POEMMA: Instruments

#### TABLE I: POEMMA Specifications:

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Optics</strong></td>
<td></td>
</tr>
<tr>
<td>Schmidt</td>
<td>45° full FoV</td>
</tr>
<tr>
<td>Primary Mirror</td>
<td>4 m diam.</td>
</tr>
<tr>
<td>Corrector Lens</td>
<td>3.3 m diam.</td>
</tr>
<tr>
<td>Focal Surface</td>
<td>1.6 m diam.</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>3 x 3 mm²</td>
</tr>
<tr>
<td>Pixel FoV</td>
<td>0.084°</td>
</tr>
<tr>
<td><strong>PFC</strong></td>
<td></td>
</tr>
<tr>
<td>MAPMT</td>
<td>126,720 pixels</td>
</tr>
<tr>
<td>SiPM (20 ns)</td>
<td>15,360 pixels</td>
</tr>
<tr>
<td><strong>Photometer</strong></td>
<td></td>
</tr>
<tr>
<td>One</td>
<td>1,550 kg</td>
</tr>
<tr>
<td>Power (w/cont)</td>
<td>700 W</td>
</tr>
<tr>
<td>Data</td>
<td>&lt; 1 GB/day</td>
</tr>
<tr>
<td><strong>Spacecraft</strong></td>
<td></td>
</tr>
<tr>
<td>Slew rate</td>
<td>90° in 8 min</td>
</tr>
<tr>
<td>Pointing Res.</td>
<td>0.1°</td>
</tr>
<tr>
<td>Pointing Know.</td>
<td>0.01°</td>
</tr>
<tr>
<td>Clock synch.</td>
<td>10 μsec</td>
</tr>
<tr>
<td>Data Storage</td>
<td>7 days</td>
</tr>
<tr>
<td>Communication</td>
<td>5-band</td>
</tr>
<tr>
<td>Wet Mass</td>
<td>3,450 kg</td>
</tr>
<tr>
<td>Power (w/cont)</td>
<td>550 W</td>
</tr>
<tr>
<td>Mission</td>
<td>(2 Observatories)</td>
</tr>
<tr>
<td>Lifetime</td>
<td>3 year (5 year goal)</td>
</tr>
<tr>
<td>Orbit</td>
<td>525 km, 28.5° Inc</td>
</tr>
<tr>
<td>Orbit Period</td>
<td>95 min</td>
</tr>
<tr>
<td>Observatory Sep.</td>
<td>~25 - 1000+ km</td>
</tr>
</tbody>
</table>

Each Observatory = Photometer + Spacecraft; POEMMA Mission = 2 Observatories
POEMMA: Schmidt Telescope details

Two 4 meter F/0.64 Schmidt telescopes: 45° FoV

- Primary Mirror: 4 meter diameter
- Corrector Lens: 3.3 meter diameter
- Focal Surface: 1.6 meter diameter
- Optical Area_{EFF}: \(~6\) to \(2\) m²

Hybrid focal surface (MAPMTs and SiPM)

3 mm linear pixel size: 0.084° FoV
POEMMA: Hybrid Focal Plane

UV Fluorescence Detection using MAPMTs with BG3 filter (300 – 500 nm) developed by JEM-EUSO: 1 usec sampling

Cherenkov Detection with SiPMs (300 – 1000 nm): 20 nsec sampling

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

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

UV Fluorescence Detection using MAPMT with BG3 filter (300 – 500 nm) developed by JEM-EUSO: 1 usec sampling

Cherenkov Detection with SiPMs (300 – 1000 nm):
20 nsec sampling

Elementary Cell (EC)
SiPM (8x8)

MC results:
$\theta_c \lesssim 2.5^\circ \rightarrow \lesssim 20$ ns
0.084° FoV$_{pix}$ puts signal into single pixel

55 Photo Detector Modules (PDMs) = 126,720 pixels
1 PDM = 36 MAPMTs = 2,304 pixels
POEMMA: Mission (Class B)

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: 1250 W (w/contig)
Data: < 1 GB/day
Data Storage: 7 days
Communication: S-band
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 Stereo UHECR mode and limb-viewing neutrino mode

**Quasi-nadir UHECR Stereo UHECR mode**

Sat 2

Sat 1

UHECR observation in stereo (Fluorescence)

**Tilted limb-viewing neutrino mode**

Sat 2

Sat 1

Above Limb observation
Earth skimming neutrinos
SAT 1 & SAT2 (Cherenkov)

UHECR observation in stereo (Fluorescence)

Satellite Separation ~300 km
Larger SatSep maximizes GF
Lower SatSep minimizes $E_{\text{Thres}}$

Measurements occur during dark, quasi-moon less nights:
Fluorescence Duty Cycle: 11%
Cherenkov Duty Cycle: 20%

Satellite Separation ~30 km
When both in Cherenkov light pool can use time coincidence to reduce PE threshold in light of air glow background.
significant increase in exposure

Uniform sky coverage to guarantee the discovery of UHECR sources

Spectrum, Composition, Anisotropy $E_{\text{CR}} \geq 50$ EeV

Very good energy ($< 20\%$), angular ($\lesssim 1.2^\circ$), and composition ($\sigma_{X_{\text{max}}} \approx 30$ g/cm$^2$) resolutions
Effectively comes for free in stereo UHECR mode:
POEMMA’s excellent angular resolution allows for efficiently selecting neutrino events started ≥ 2000 g/cm² atmospheric column depth.
POEMMA Tau Neutrino Detection: see PhysRevD.100.063010

High-Energy Astrophysical Events generates neutrinos ($\nu_e, \nu_\mu$) and 3 neutrino flavors reach Earth via neutrino oscillations.

POEMMA designed to observe neutrinos with $E > 20$ PeV through Cherenkov signal of EASs from Earth-emerging tau decays.
ToO Neutrino Sensitivity: see arXiv:1906.07209

IceCube, ANTARES, Auger Limits for binary neutrino star merger GW170817

One orbit sky exposure assuming slewing to source position

<table>
<thead>
<tr>
<th>Source Class</th>
<th>Short Burst</th>
<th>Long Burst</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of GS</td>
<td>No. of GS</td>
</tr>
<tr>
<td>TDEs</td>
<td>1.12 × 10^3</td>
<td>0.77</td>
</tr>
<tr>
<td>TDEs</td>
<td>2.23 × 10^4</td>
<td>1.44 × 10^3</td>
</tr>
<tr>
<td>TDEs</td>
<td>NA*</td>
<td>1.07 × 10^3</td>
</tr>
<tr>
<td>Blazar Flares</td>
<td>NA*</td>
<td>1.91 × 10^3</td>
</tr>
<tr>
<td>GRB Reverse Shock (SM)</td>
<td>9.88 × 10^4</td>
<td>0.69</td>
</tr>
<tr>
<td>GRB Reverse Shock (wind)</td>
<td>2.65 × 10^4</td>
<td>141.75</td>
</tr>
<tr>
<td>BH-BH merger</td>
<td>6.94 × 10^4</td>
<td>47.84</td>
</tr>
<tr>
<td>HLH-LH merger</td>
<td>3.48 × 10^4</td>
<td>2.4 × 10^4</td>
</tr>
<tr>
<td>NS-NS merger</td>
<td>6.88 × 10^4</td>
<td>24.75</td>
</tr>
<tr>
<td>WD-WDS merger</td>
<td>20.06</td>
<td>0</td>
</tr>
<tr>
<td>Newborn-born Crab-like pulsars (p)</td>
<td>1.56 × 10^4</td>
<td>1.07 × 10^{-5}</td>
</tr>
<tr>
<td>Newborn-born magnetars (p)</td>
<td>2.1 × 10^4</td>
<td>0.13</td>
</tr>
<tr>
<td>Newborn-born magnetars (Fe)</td>
<td>4.07 × 10^4</td>
<td>0.26</td>
</tr>
</tbody>
</table>

**Bold:** > 20% Prob of an event in 5 years
POEMMA: upward $\tau$-lepton EAS Cherenkov considerations

$\Delta \alpha$ $\beta_E(33 \text{ km})$ $\beta_E(525 \text{ km})$ $\beta_E(1000 \text{ km})$
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

$\tau$-lepton Yield Calc:
- PREM Earth Model
- Kotera2010 mixed UHECR composition cosmogenic $\nu$ flux
POEMMA: upward $\tau$-lepton EAS Cherenkov spectrum variability

Atmospheric optical attenuation:
- Rayleigh Scattering
- Aerosols (scale height $\sim 1$ km)
- Ozone (decimates signal $\lesssim 300$ nm)
Air Glow Background in Cherenkov Band

### Cumulative SUM: Night-sky airglow spectrum, VLT/UVES (Hanuschik, 2003; Cosby, 2006)

<table>
<thead>
<tr>
<th>Wavelength interval (nm)</th>
<th>Intensity [photons m$^{-2}$ 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>

### Work by Simon Mackovjak

**Viewing at angles away from nadir views more optical depth of air glow layer.**

-x6 for viewing limb from 500 km

### Requirement for < 1e-2 background events per year leads to high PE thresholds

- 10 PE (dual Cher measurement)
- 20 PE (single Cher measurement)

**314 nm – 900 nm**

Use to calculate effective PDE (for SiPM): $<\text{PDE}> = 0.1$

- 12,090 photons/m$^2$/sr/ns
- 314 nm – 1000 nm
- ~25,000 photons/m$^2$/sr/ns
- 314 nm – 500 nm
- 570 photons/m$^2$/sr/ns
SiPMs now have high PDE in Fluorescence Band but ...

Nitrogen Fluorescence:
- λ band from < 300 nm → > 1000 nm
- Dominated by lines around 337.1, 357.7, 391.4 nm
- QE/PDE needs to be optimal in this band
- Use filter (usually BG3) to constrain wavelength band to reduce background from air glow
- Issue with this filter with transmission above 700 nm
POEMMA will open two new Cosmic Windows:

- Space-based measurements provides order of magnitudes improved sensitivity
- UHECRs (> 20 EeV), to identify the source(s) of these extreme energy messengers
- Neutrinos from astrophysical Transients (> 20 PeV), and high sensitivity to UHE neutrinos (> 20 EeV)

Neutrino $\tau$-lepton induced Cherenkov signals span $300 \text{ nm} \leq \lambda \leq 1000 \text{ nm}:

- Wide spectral range of SiPM’s and nsec time response critical in the detection
- PE signal range: 10 PE to 10,000+
- Advances in PDE improvements helpful
- Large air glow background leads to high PE thresholds (for triggering and analysis)

UHECR and UHE neutrino measurements may benefit for PDE improvement in fluorescence band

- Huge air glow background and wide SiPM spectral requires additional constraints on UV filter
  - If leads to significant reduction if effective PDE, science affected via increased UHECR and UHE neutrino EAS energy thresholds

However, benefits do exist:

- Lower mass for SiPMs vs PMTs, SiPMs do not require high voltage
- Leads to mass savings ... in Space MASS = COST!
POEMMA: Diffuse neutrino flux 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)
- \( \nu_e : \nu_\mu : \nu_\tau = 1:1:1 \)
POEMMA: Neutrino mode example configuration

Neutrinos

UHECRs

9°

total

7° from
limb

Neutrinos

Calcs & plots by F. Sarazin

Altitude: 525 km
Field of view: 45°
Above limb angle: 2.0°
Pointing (on-orbit): 47.0°
Pointing (off-orbit): 88.5°
Max distance: 1000 km
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 ± 0.3°, 159.62 ± 0.7°</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 ± 0.3°, 61.41 ± 0.7°</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.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>34</td>
<td>-27.4</td>
<td>62.6</td>
<td>26.8</td>
</tr>
<tr>
<td>34</td>
<td>-35</td>
<td>55</td>
<td>34.6</td>
</tr>
</tbody>
</table>

POEMMA can tilt to view 9° × 30° ‘spot’
But these events may be bright enough
to be seen in the UV fluorescence
detector with ~1 usec coincidence.

\[ \theta_{\text{CONE}} \approx 1.0 \text{ deg} \]
\[ \omega \approx 1.0 \times 10^{-3} \text{ sr} \]

\[ \theta_{\text{EFF}} \approx 4.5 \text{ deg} \]
\[ \omega \approx 2.0 \times 10^{-2} \text{ sr} \]

\( \gamma \tau \approx 60 \text{ km} \)
for 1.2 EeV

POEMMA
signal size
\(~6000 \text{ PEs in cone}\)

GF’s similar (~200 km² sr): 2 events/70 days (ANITA 1-3) -> ~2 events per year for POEMMA