Compact Full-Field Ion Detector System for CubeSat Science beyond LEO

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Outline

• GRC Technology Research & Development
  – Technology Challenges and Solutions

• Application Concept System
  – Objectives
  – Design
  – R&D Timeline

• Background: State of the Art
  – Detector Systems in Flight
  – Advantages of WBG Detectors
  – CFIDS Technology Challenges

• CFIDS Application for Deep Space CubeSats
  – Space Radiation Environment in Deep Space
  – Planetary Effects of Space Radiation
  – Lunar Science Opportunity

• Summary
  – Acknowledgements
GRC Advanced Radiation Detector Technology Research and Development

• GRC Expertise and Facilities in:
  – Harsh Environment Thin Films
  – SiC Devices & Harsh Environment Packaging
  – Micro-Optics
  – Space-Based Instrumentation

• These strengths are combined into an in-house Radiation Instrumentation Research effort

MISSE 7 SiC JFET & Ceramic Packaging (arrow) on a Rad-Hard Electronics Board for ISS flight

In-House Microsystems Fabrication

Thin Film Characterization

AEVA SiC Radiation Detector
Technology Challenges and Solutions

- Goal is to develop a radiation detector system to fly on small satellite platforms (such as CubeSats) to reduce cost, development time of missions.
  - Design point: 1U CubeSat volume, mass for detector system (10 cm x 10 cm x 10 cm, 1 kg)

- CubeSats currently flown LEO applications, but future is in Deep Space.
  - High radiation particle influx from multiple directions (spherical $4\pi$ solid angle)

- Current radiation detector technologies need temperature compensation.
  - CubeSat platform size, power limits instrumentation systems.
  - More complex systems require new technology.

- Solution is the development of new robust, low power, thermally stable solid state radiation detector technology for omni-directional measurements in a compact space radiation detector system.
  - Wide band gap semiconductors, micro-optics technologies.
Application Concept: Compact Full-Field Ion Detector System (CFIDS)

- Mapping of heavy ions > 100 MeV/amu
  - Integrated system with solid-state Cherenkov detector and large area detectors in surrounding wedges
- High radiation flux rates for 10+ year missions
  - Precision rad-hard, thermally stable wide band gap detectors used
- Low noise, multi-directional measurements at single locations
  - Compact, spherical detector system

**Space radiation detector with spherical geometry**

- Technology covered by U.S. Patents 7,872,750 (January 18, 2011) and 8,159,669 (April 17, 2012)
Application Concept: Compact Full-Field Ion Detector System (CFIDS)

- CFIDS comprised of a spherical Cherenkov detector surrounded by stacked LET detectors with absorbers, Trigger and Veto detectors
GRC Advanced Radiation Detector Technology
R&D Timeline

  - Study of SiC radiation detectors
  - Demonstration of dosimeter based on SiC diode detector element
- OCT/STMD Center Innovation Fund (three 10-week efforts)
  - Design and fabrication of Proof-of-Concept ZnO Detector for UV Cherenkov light detection (2011, 2012) (patent pend.)
  - Low-Power Scintillator-Diode Detector study (2013)
### Background: Sampling of Space Radiation Detector Systems in Flight

<table>
<thead>
<tr>
<th>Detector System</th>
<th>Originator</th>
<th>Platform/Date</th>
<th>Detectors</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>IVCPDS/EVCPDS/MARIE</td>
<td>JSC (SwRI is current keeper of this heritage)</td>
<td>ISS/2000 Mars Odyssey/2002</td>
<td>Si, 1mm thick, 1x1 cm square anode</td>
<td>Low-to-Mid energy ions: LET, trigger</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Si, 300μm thick, 24x24 array of 1 mm² diodes</td>
<td>Low-to-Mid energy ions: LET, position tracking</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Si(Li), 5 mm thick, 2.5 mm dia.</td>
<td>Mid-to-High energy ions (low LET)</td>
</tr>
<tr>
<td></td>
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<td>5 cm dia. PMT w/ 1 cm thick glass disk Cherenkov Detector</td>
<td>High energy ions (200-500 MeV/amu)</td>
</tr>
<tr>
<td>CRaTER</td>
<td>BU/MIT/SwRI</td>
<td>LRO/2005</td>
<td>Pairs of 140μm and 1mm thick Si detectors 35mm diameter</td>
<td>Sort heavy ions from zenith, compare from surface (bi-directional)</td>
</tr>
<tr>
<td>RAD</td>
<td>SwRI/JPL</td>
<td>Curiosity/2011</td>
<td>Si detectors; avalanche photodiodes w/ CsI, “Bicron” 432 scintillators</td>
<td>General dose measurement: Neutron, gamma, proton, alpha</td>
</tr>
<tr>
<td>PEPSSI/JEDI</td>
<td>APL</td>
<td>New Horizons/2006 JUNO/2011</td>
<td>Segmented TOF detector w/ solid state detectors and multichannel plates</td>
<td>&lt; 1 MeV ions, electrons; 10 years for development to flight (TRL 3 to 6)</td>
</tr>
</tbody>
</table>
Background: State of the Art (SOA)

- **Cherenkov Detectors**: UV-sensitive photomultiplier tubes (PMTs) on a UV-transparent radiator material
  - PMT Size: 5 cm dia., 10-12 cm long, 180 cm³ (without radiator)
  - Power: 1000 V, 5 nA dark current

- **LET Detectors**: Surface-effect detectors made from diodes (Si PIN) or lithium-drifted silicon (Si(Li))
  - Si PIN Size: 1 mm² to 1 cm² active area
  - Si(Li) Size: 30 cm² x 5 mm thick active volume
  - Power: 100-300 V, 5 nA (PIN) to 5 µA (Si(Li)) dark current
  - Performance: operates 0°C – 60°C, 100°C typical Li drifting temperature; dark current temperature sensitive

- **Scintillator Trigger/Veto Detectors**: Bulk scintillator (<50°C) on either photomultiplier tubes (PMTs) or avalanche photodiode arrays (APDs; i.e. silicon photomultipliers):
  - APD Size: 9 mm² active area (arrays)
  - Power: 30 V, >5 nA dark current, >0.150 µW
  - Performance: operates -20°C – 40°C; temperature sensitivity of dark current requires active temperature compensation

- **Wide band gap (WBG) detectors** promise to be lower power, more robust
## Advantages of WBG Detectors: Lower Power and More Robust

<table>
<thead>
<tr>
<th>Detector</th>
<th>Active Area</th>
<th>Mass</th>
<th>Volume</th>
<th>Voltage</th>
<th>Dark Current</th>
<th>Minimum Power Draw</th>
<th>Maximum Signal to Noise</th>
<th>Maximum Operating Temperature</th>
<th>Temperature Sensitivity of Dark Current</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cherenkov</strong> Detector:</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>SOA: PMT</td>
<td>20 cm²</td>
<td>170 g</td>
<td>180 cm³</td>
<td>1000 V</td>
<td>5 nA</td>
<td>5 μW</td>
<td>4x10⁴</td>
<td>50°C</td>
<td>0.2%/°C</td>
</tr>
<tr>
<td>Proposed: ZnO</td>
<td>2 mm²</td>
<td>11 g</td>
<td>0.80 cm³</td>
<td>10 V</td>
<td>5 nA</td>
<td>0.05 μW</td>
<td>4x10⁴</td>
<td>125°C</td>
<td>0.05%/°C</td>
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<tr>
<td><strong>LET:</strong></td>
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</tr>
<tr>
<td>SOA: Si PIN</td>
<td>1 cm²</td>
<td>0.5 g</td>
<td>185 mm³</td>
<td>100 V</td>
<td>5 nA</td>
<td>0.5 μW</td>
<td>1x10⁵</td>
<td>60°C</td>
<td>20%/°C</td>
</tr>
<tr>
<td>SOA: Si(Li)</td>
<td>30 cm²</td>
<td>35 g</td>
<td>15 cm³</td>
<td>300 V</td>
<td>5 μA</td>
<td>1.5 mW</td>
<td>2x10⁴</td>
<td>60°C</td>
<td>30%/°C</td>
</tr>
<tr>
<td>Proposed: SiC</td>
<td>1 cm²</td>
<td>0.3 g</td>
<td>90 mm³</td>
<td>5 V</td>
<td>50 pA</td>
<td>0.250 nW</td>
<td>2x10⁵</td>
<td>120°C</td>
<td>0.1%/°C</td>
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<tr>
<td><strong>Scintillator Trigger/Veto:</strong></td>
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<tr>
<td>SOA: PMT</td>
<td>20 cm²</td>
<td>170 g</td>
<td>180 cm³</td>
<td>1000 V</td>
<td>5 nA</td>
<td>5 μW</td>
<td>4x10⁴</td>
<td>50°C</td>
<td>0.2%/°C</td>
</tr>
<tr>
<td>SOA: APD</td>
<td>9 mm²</td>
<td>3 g</td>
<td>200 mm³</td>
<td>30 V</td>
<td>5 nA</td>
<td>0.15 μW</td>
<td>8x10⁴</td>
<td>85°C</td>
<td>30%/°C</td>
</tr>
<tr>
<td>Proposed: GaP</td>
<td>4.8 mm²</td>
<td>5 g</td>
<td>170 mm³</td>
<td>5 V</td>
<td>20 pA</td>
<td>0.1 nW</td>
<td>4x10⁵</td>
<td>125°C</td>
<td>0.5%/°C</td>
</tr>
</tbody>
</table>
## CFIDS Technology Challenges

<table>
<thead>
<tr>
<th>Component</th>
<th>Technology Challenge</th>
<th>Approach</th>
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</thead>
<tbody>
<tr>
<td>Fast Cherenkov Detector</td>
<td>ZnO UV detector packaging</td>
<td>GRC Harsh Environment Packaging expertise; Examine SiC diode back-up</td>
</tr>
<tr>
<td>Trigger/Veto Scintillator Counters</td>
<td>GaP photodiodes with fiber scintillators</td>
<td>Compare COTS to custom packaging</td>
</tr>
<tr>
<td>Large Area WGB LET Detectors</td>
<td>SiC Diode array</td>
<td>GRC Harsh Environment Packaging expertise; Examine single-crystal option</td>
</tr>
<tr>
<td>Signal Conditioning Electronics</td>
<td>Space available</td>
<td>GRC Space Electronics expertise</td>
</tr>
<tr>
<td>Detector Integration</td>
<td>Mass limit</td>
<td>More reliance on lower density metals (Al, Ti); Higher fidelity models</td>
</tr>
</tbody>
</table>
CFIDS Application for Deep Space CubeSats

- Detector assembly design point of 1U volume (10x10x10 cm³)
- Signal conditioning electronics an additional ½U volume
  - Charge Integration, ADC, Power Regulation, Data Formatting
  - Dependent on CubeSat bus Command and Data Handling (C&DH)
- Easily adaptable to 3U, 6U layouts for operation beyond LEO
- Allows new possibilities for unique Deep Space Science on a CubeSat platform
Space Radiation Environment in Deep Space

- Outside the Magnetosphere, the space environment contains a variety of sources of radiation that affects spacecraft as well as planets, moons and asteroids:

  - **Solar Wind**
    - Stream of H\(^+\), He\(^+\) from Sun
    - ~1 keV/u peak
    - ~3x10\(^8\) particles/cm\(^2\)/sec @ 1 AU

  - **Coronal Mass Ejections (CMEs)**
    - Pulses of H\(^+\), He\(^+\)
    - ~30 keV/u peak
    - ~1x10\(^9\) particles/cm\(^2\)/sec @ 1 AU

  - **Solar Particle Events (SPE)**
    - Pulses of H\(^+\), He\(^+\)
    - ~100 MeV/u peak
    - ~3x10\(^4\) particles/cm\(^2\)/sec @ 1 AU

  - **Galactic Cosmic Radiation (GCR)**
    - Stream of H\(^+\) to Fe\(^+\) (Z=1→26)
    - ~300 MeV/u broad peak
    - ~0.1/u\(^2\) particles/cm\(^2\)/sec
Planetary Effects of Space Radiation

• Dynamic changes in planetary magnetospheres
  – Higher the flux, mass and energy, the more penetrating the radiation through the magnetic field to the planetary body
  – CMEs biggest affect on magnetospheres, but even GCR is not minor (4%-8%)
  – Penetrating radiation will modify planetary surfaces and atmospheres

• In Earth atmosphere, heavy GCR ions linked to
  – Aerosol production
  – Unstable isotope production as well as ozone depletion
  – Lightning triggers
  – Lower-troposphere cloudiness and long-term climate change

• Elsewhere, GCR ions linked to
  – Neutron generation in Martian atmosphere
  – Space weathering of moons, asteroids and spacecraft surfaces

• Direct measurements in-situ lacking…. Models abound
Lunar Science Opportunity

- Moon has no substantial magnetic field or atmosphere
- High Z, high energy (HZE) GCR ions have enough energy to significantly change composition, disrupt molecular structure, cause loss of molecular hydrogen, and cause chemical reactions, including the polymerization of organics, and potentially be linked to formation Fe$^0$-rich coatings on silicate grains
- These processes are implicated, though not yet directly measured, for many rocky or icy bodies with meager to no atmospheres lacking magnetospheres
- Direct measurements in-situ either in orbit or on the lunar surface will identify specific processes and quantify the effects

*Metri sunt necesse Malum*

“Measurements are necessary evils”
Summary

• NASA GRC is leveraging expertise in harsh environment thin films, SiC devices & harsh environment packaging, micro-optics, and space-based instrumentation to advance radiation detector technology

• Application of wide band gap semiconductors as radiation detectors holds the promise of improved low-power, robust detectors for CFIDS

• CFIDS radiation instrumentation system in a Deep Space CubeSat will allow in-situ studies of HZE GCR interactions in lunar environments
Acknowledgements

• Elizabeth McQuaid and Nicholas Varaljay (GRC)
  – ZnO UV detector fabrication

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  – SiC dosimeter diode detector fabrication

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  – General semiconductor and shielding studies for space radiation protection

• Dr. Ben Malphrus (Morehead State University)
  – CubeSat architecture and development

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