Initial Results from the Radiation Dosimetry Experiment (RaD-X) Balloon Flight Mission

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• **Research Motivation**
  - Aviation Radiation Health Effects
  - Aviation Radiation Avionic Effects
  - NAIRAS Model Development

• **Cosmic Ray Basics**
  - Sources
  - Energy and Composition
  - Atmospheric Interactions
  - Biological Interactions

• **Dosimetric Quantities**
  - Definitions
  - Range of Values @ Flight Altitude

• **NAIRAS Model**
  - Representative Data Products
  - Variation With Solar Cycle and Geomagnetic Cutoff Rigidity
  - Solar and Geomagnetic Storm Effects

• **RaD-X Science**
  - Motivation (in more detail)
  - Science Goals and Objectives
  - Instrument Selection
The NAIRAS model currently underestimates actual data. This performance is quantified by comparisons with recent DLR-TEPC/Liulin measurements from 2008 [Mertens et al., 2013]

- These results are consistent with the large volume of data reported by Lindborg et al. [2004] and tabulated by the International Commission on Radiation Units and Measurements: ICRU Report 84 [2010]
- The NAIRAS/DLR/ICRU comparisons in publication [Mertens et al., 2013]

Large statistical variations experienced at flight level illustrate the need for RaD-X TOA measurements.

Current NAIRAS model underestimates TEPC flight data by 50%.
NAIRAS Comparisons to Existing Measurements

- NAIRAS comparisons with existing TEPC/Liulin measurements show much larger discrepancies in silicon absorbed dose
  - Suggests larger uncertainty in NAIRAS charged-particle source/transport/interactions
  - TOA measurements characterize charged-particle source (i.e., cosmic ray primaries)

Current NAIRAS model underestimates Liulin charged particle flight data by 70%

<table>
<thead>
<tr>
<th>TEPC dH'(10)/dt</th>
<th>NAIRAS dH'(10)/dt</th>
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<td>Current NAIRAS model underestimates TEPC flight data by 50%</td>
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<tr>
<th>Liulin Dose Rate (Si)</th>
<th>NAIRAS Dose Rate (Si)</th>
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DUS-MRU Flight (02/13/2008)
RaD-X : Radiation Dosimetry Experiment

Science Goals and Objectives
• Improve tools that predict energy deposition characteristics of penetrating cosmic radiation in Earth’s atmosphere
  o Measure radiation dosimetry in upper atmosphere
  o Separate cosmic ray primary contributions
• Identify and characterize low-cost radiation measurement solutions
  o Characterize relationship between solid state radiation instruments and biological response

Mission and Instrument Parameters
• Platform: High-Altitude Balloon
• Launch Site: Fort Sumner, NM (34N, 104W)
• Mission Duration: 20+ hours of science data
• Temporal Sampling: 1-5 minutes
• Launch Date: September 25-26, 2015
• Instruments: (1) TEPC, (2) TID detector, (3) LET spectrometer, and (4) microdosimeter emulator
• All instrument components at TRL 6 or higher

RaD-X Measures Radiobiological Dose and CR Primary Proton and HZE Contributions

Science Team and Partners
NASA Langley
NASA ARC
NASA GSFC/WFF
Prairie View A & M University (PVAMU)
  Center for Radiation Engineering and Science for Space Exploration (CRESSE)
Oklahoma State University
University of Virginia
Space Environment Technologies, Inc.
High-altitude balloon flight (> 20 km) out of Fort Sumner, NM with dosimeter measurements utilized to improve cosmic radiation dose assessment and characterize the energy deposition from CR primaries

- **NAIRAS** underestimates effective body dose by 50% at lower latitudes (≤ 50°), the region of largest model error [Mertens et al., Space Weather, 2013]. Uncertainty must be ≤ 30% for latitudes ≥ 30° for reliable dose assessments [ICRU Report 84, 2010]

- Measurements > 20 km next step needed to understand source of uncertainty and guide model improvement

**GOALS**

1. **Improve tools that predict energy deposition characteristics of penetrating CR in Earth’s atmosphere**
   - Combine different dosimeter measurements and two flight altitudes to assess model uncertainty in CR primaries

2. **Identify and characterize low-cost radiation measurement solutions**
   - Continuous, global measurements for real-time data assimilative modeling
TEPC: Tissue Equivalent Proportional Counter
Far West Technology, Inc.

Liulin LET Spectrometer
Prof. Dachev SRTI-BAS

Total Ionizing Dose (TID) Detector
Teledyne Microelectronic Technologies

RaySure Detector
QinetiQ & Univ. of Surrey, UK
Preparing for Launch at Fort Sumner

Dr. Grunsfeld, NASA SMD Associate Administrator
Dr. Hertz, NASA SMD Astrophysics Division Director
RaD-X PI at Fort Sumner

Waiting for Launch at Fort Sumner
RaD-X Payload Ready for Launch

Payload integrated to balloon gondola

“Big Bill” transporting payload to launch site
RaD-X Launches Sep 25, 2015
Absorbed Dose Rate Measured by TEPC and Liulin

Rad-X Balloon Flight All Instrument Data (No TID) - 09/25/15 to 09/26/15 - Dose Rate

Region B (< 32.5km)
Avg. Altitude: 36.7km
Avg. Pressure: 4.52 hPa
Duration: 6:33:52

Region A (21.0km - 27.0km)
Avg. Altitude: 24.3km
Avg. Pressure: 27.28 hPa
Duration: 8:23:22

Dose Rate Liulin | Averages - Region B: 2.78\micro Gy/hr Region A: 3.36\micro Gy/hr
Dose Rate TEPC | Averages - Region B: 2.73\micro Gy/hr Region A: 3.20\micro Gy/hr
TEPC Measurements of Dose Equivalent and Ambient Dose Equivalent Rates

RaD-X Balloon Flight All Instrument Data - 09/25/15 to 09/26/15 - Ambient Dose Equivalent & Dose Equivalent Rate

- Ambient Dose Equivalent Rate TEPC | Averages - Region B: 11.13 μSv/hr RegionA: 9.08 μSv/hr
- Dose Equivalent Rate TEPC | Averages - Region B: 9.44 μSv/hr RegionA: 7.72 μSv/hr

Region B (> 32.5km)
Avg. Altitude: 34.27 km
Avg. Pressure: 6.44 hPa
Duration: 6:33:52

Region A (21.0km - 27.0km)
Avg. Altitude: 23.78 km
Avg. Pressure: 31.27 hPa
Duration: 8:23:22

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Bulgarian Academy of Sciences
• TEPC Dose Rate Profiles
  – Constructed from +/- 10 minute widow average of measured dose rates
  – Absorbed Dose Rate (Dose) Profile (Top Right)
  – Dose Equivalent (DoseE) Rate (Bottom Right)

• Dose Profile Features
  – Very broad Pfotzer maximum corresponding to the peak in the dose rate

• DoseE Profile Features
  – Key Finding: No Pfotzer maximum in DoseE
  – Lack of low-LET secondary particles above ionization peak is compensated by high-LET albedo neutrons and cosmic ray primary particles
  – Increase in DoseE in Region B due to HZE particles
RaD-X/CSBF Flight Altitudes

RaD-X Payload versus CSBF Altitudes During Balloon Flight

Note: RaD-X/NAIRAS comparisons preliminary until barometric pressure differences resolved
RaD-X / NAIRAS Comparisons

• RaD-X TEPC / NAIRAS Comparisons
  – Dose Equivalent Rate (DoseE):
    o DoseE includes radiobiological weighting of neutrons and other high-LET particles
    o NAIRAS underestimate by less than 10%
  – Absorbed Dose Rate (Dose):
    o Dose insensitive to neutrons
    o NAIRAS underestimate by > 50%

• Trend in NAIRAS Comparisons to the Other Measurements (RaD-X Liulin, ER-2 TEPC, King Air C90 TEPC/Liulin)
  – NAIRAS underestimate measurement data
  – Differences largest near Pfotzer maximum (peak in absorbed dose rate)

• Preliminary Inferences
  – NAIRAS underestimates pion-initiated electromagnetic (π-EM) cascade processes
    o Underestimate charged particle (low-LET) contributions to Dose/DoseE
    o Overestimate neutron (high-LET) contributions to DoseE
  – π-EM backscatter appears to be important (Region A in particular)
  – NAIRAS may underestimate cosmic ray primary protons
• The TEPC Dose-LET spectra show the different particle content in Regions A and B
  – Compare relative contributions from High-LET events
  – High-LET event > 10 keV/um
• Region B: evidence of HZE particles
  – Larger contributions from high-LET events in Region B
• Region A: Cosmic ray primary protons and albedo neutrons
  – High-LET events but much smaller contributions to dose in Region A compared to Region B
• Peak in Region B Dose-LET spectrum interesting and needs further investigation
• RaD-X ConOps design of the two float altitudes (Regions A and B) succeeded in isolating HZE cosmic ray primary particle contributions to dose
## Average Dose: RaD-X + Aircraft

<table>
<thead>
<tr>
<th>Altitude km</th>
<th>Pressure hPa</th>
<th>Platform</th>
<th>Liulin Dose Rate uGy/hr</th>
<th>TEPC Dose Rate uGy/hr</th>
<th>TEPC Dose Equiv uSy/hr</th>
<th>TEPC H*(10) uSy/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>444.9</td>
<td>King Air C90</td>
<td>0.94 ± 0.02</td>
<td>0.90 ± 0.01</td>
<td>2.44 ± 0.11</td>
<td>N/A</td>
</tr>
<tr>
<td>17</td>
<td>92.0</td>
<td>ER-2</td>
<td>N/A</td>
<td>4.63 ± 0.02</td>
<td>8.95 ± 0.22</td>
<td>N/A</td>
</tr>
<tr>
<td>20</td>
<td>85.6</td>
<td>ER-2</td>
<td>N/A</td>
<td>5.00 ± 0.03</td>
<td>10.26 ± 0.34</td>
<td>N/A</td>
</tr>
<tr>
<td>24.3</td>
<td>27.3</td>
<td>RaD-X</td>
<td>3.34 ± 0.03</td>
<td>3.20 ± 0.01</td>
<td>7.70 ± 0.13</td>
<td>9.05 ± 0.15</td>
</tr>
<tr>
<td>36.7</td>
<td>4.5</td>
<td>RaD-X</td>
<td>2.77 ± 0.04</td>
<td>2.73 ± 0.01</td>
<td>9.40 ± 0.17</td>
<td>11.09 ± 0.20</td>
</tr>
</tbody>
</table>
• All instrument flight data recovered and suitable for scientific investigation

• TEPC absorbed dose rate profile shows very broad Pfotzer maximum,

• TEPC dose equivalent profile shows no Pfotzer maximum at all
  – Indicative of high-LET albedo neutrons and cosmic ray primaries

• Assessment of NAIRAS
  – Qualitatively captures the essential features of the atmospheric ionizing radiation field
    o Adequately defined the science objectives and Flight ConOps to achieve science goals
  – Quantitatively, its underestimation of the measurements point to the following deficiencies
    o Inadequate production of $\pi$-EM particles (i.e., the complex region), highlighting the role of backscatter contributions
    o Possibly underestimation of cosmic ray primary protons