The Radiation Dosimetry Experiment (RaD-X) Flight Mission: Observations for Improving the Prediction of Cosmic Radiation Health Risk at Aviation Altitudes

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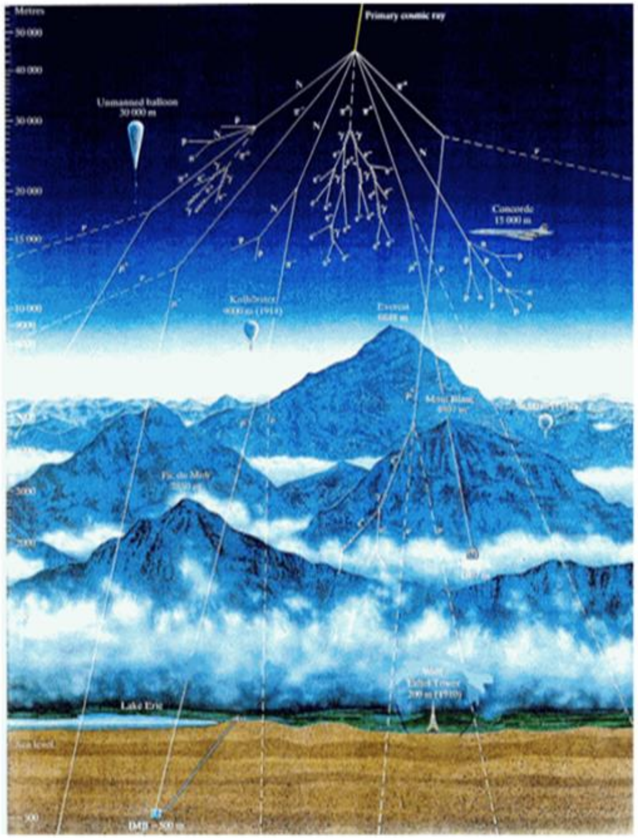
Outline

- **Background and Motivation**
  - Aviation Radiation Health Effects
  - NAIRAS Model Development
- **RaD-X Flight Campaign**
  - Science Goals
  - Instruments
  - Flight Results
- **Summary**

Aviation Radiation Health Effects

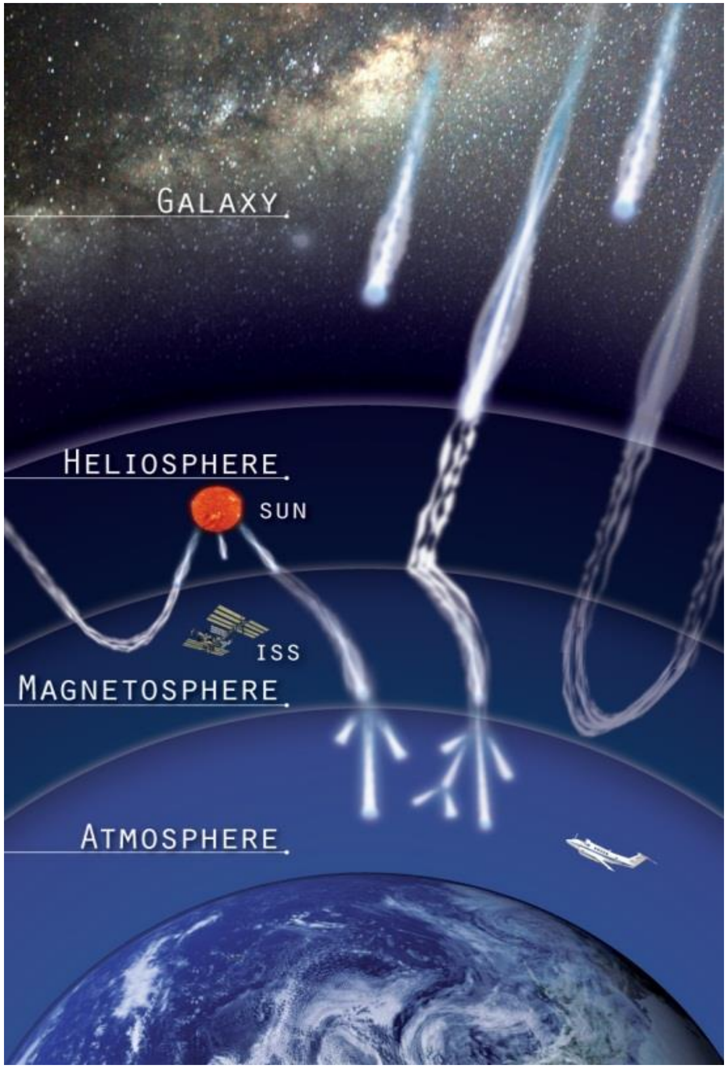
- Cosmic rays **(CR)** are the primary source of ionizing radiation that increases risk of fatal cancer or other adverse health effects to air travelers
- **Commercial aircrews are classified as radiation workers** (ICRP, 1990)
  - Most exposed occupational group (NCRP, 2009)
  - Individual career and storm exposures unquantified and undocumented
- NIOSH pregnant female flight attendant epidemiological studies (Grajewski et al., 2015)
  - **70% increased risk of miscarriage in first trimester due to CR**
- **Maximum public and prenatal exposure easily exceeded** (ICRP recommendations)
  - One high-latitude solar storm event
  - Frequent use of high-latitude routes (~5-10 round-trips)
- Equivalent Flight Exposures
  - **Round-trip international ~ 2 chest x-rays**
  - **100k mile flyer ~ 20 chest x-rays (2 mSv) = 2 x DOE limit**

Cosmic Ray Interactions



NAIRAS Model

- **LaRC's Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) Model**
  - Began model formulation and development in 2004
  - Running in real-time at the LaRC/DAAC since April 2011
- **Distinguishing Features**
  - Real-time physics-based, global model
  - Real-time inclusion of SEP radiation
  - Real-time solar-magnetospheric effects on radiation
  - Real-time meteorological data used

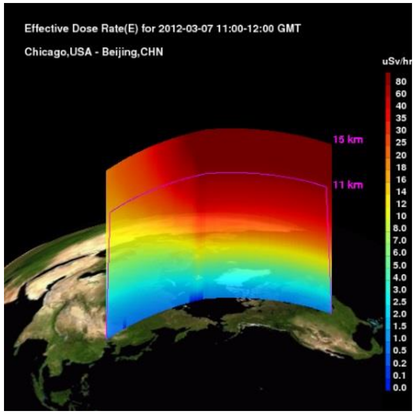


RaD-X : Radiation Dosimetry Experiment

Science Goals

- Provide measurements to characterize dosimetric properties of cosmic ray primaries, which are the ultimate source of aviation radiation exposure
    - Combine measurements from different dosimeters with two float altitudes
- Characterize available low-cost, compact radiation measurement technologies
    - Long-term, continuous, global monitoring of aircraft radiation environment

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



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

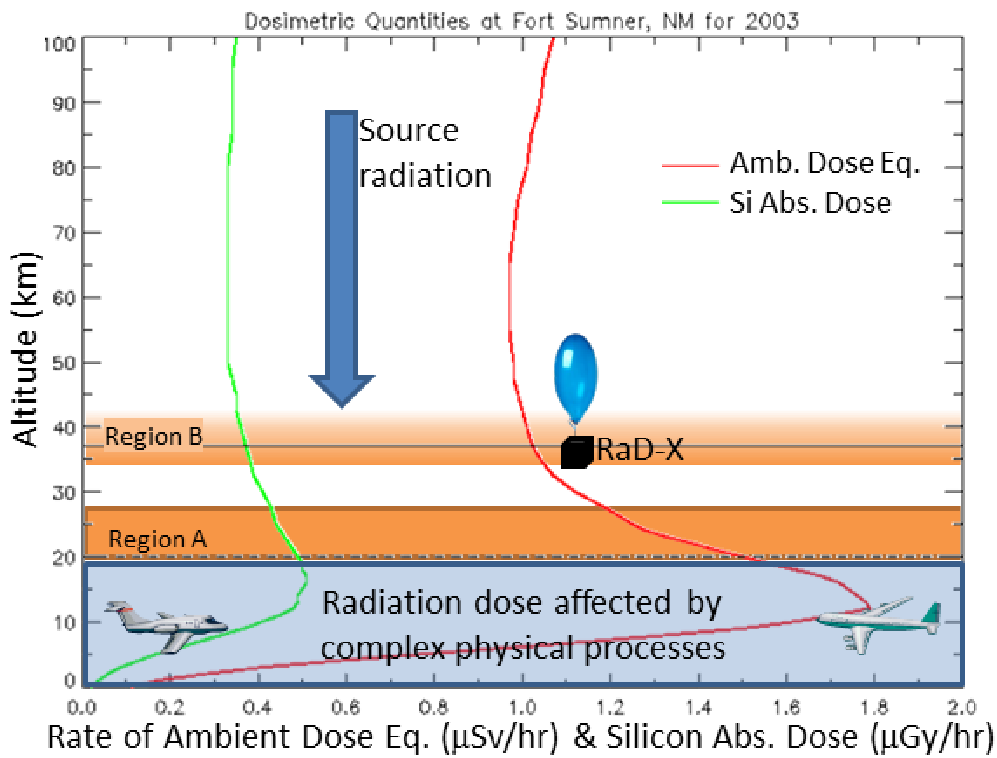
Science Team and Partners

NASA Langley
NASA Ames Research Center
NASA Wallops Flight Facility
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.
German Aerospace Center (DLR)

RaD-X Science Goals

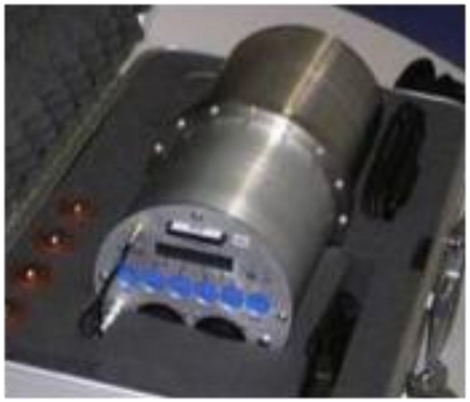
Science Goals

1. **Provide measurements to characterize dosimetric properties of CR primaries**
   - CR primaries ultimate source of aviation radiation exposure
   - Combine different dosimeters and two flight altitudes to achieve goal
2. **Characterize available low-cost, compact radiation measurement technologies**
   - Long-term, continuous monitoring of aircraft radiation environment needed to improve reliability of real-time models



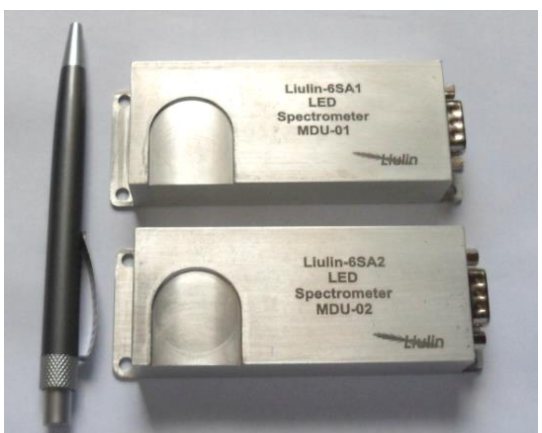
RaD-X Science Instruments

TEPC: Tissue Equivalent Proportional Counter
Far West Technology, Inc.



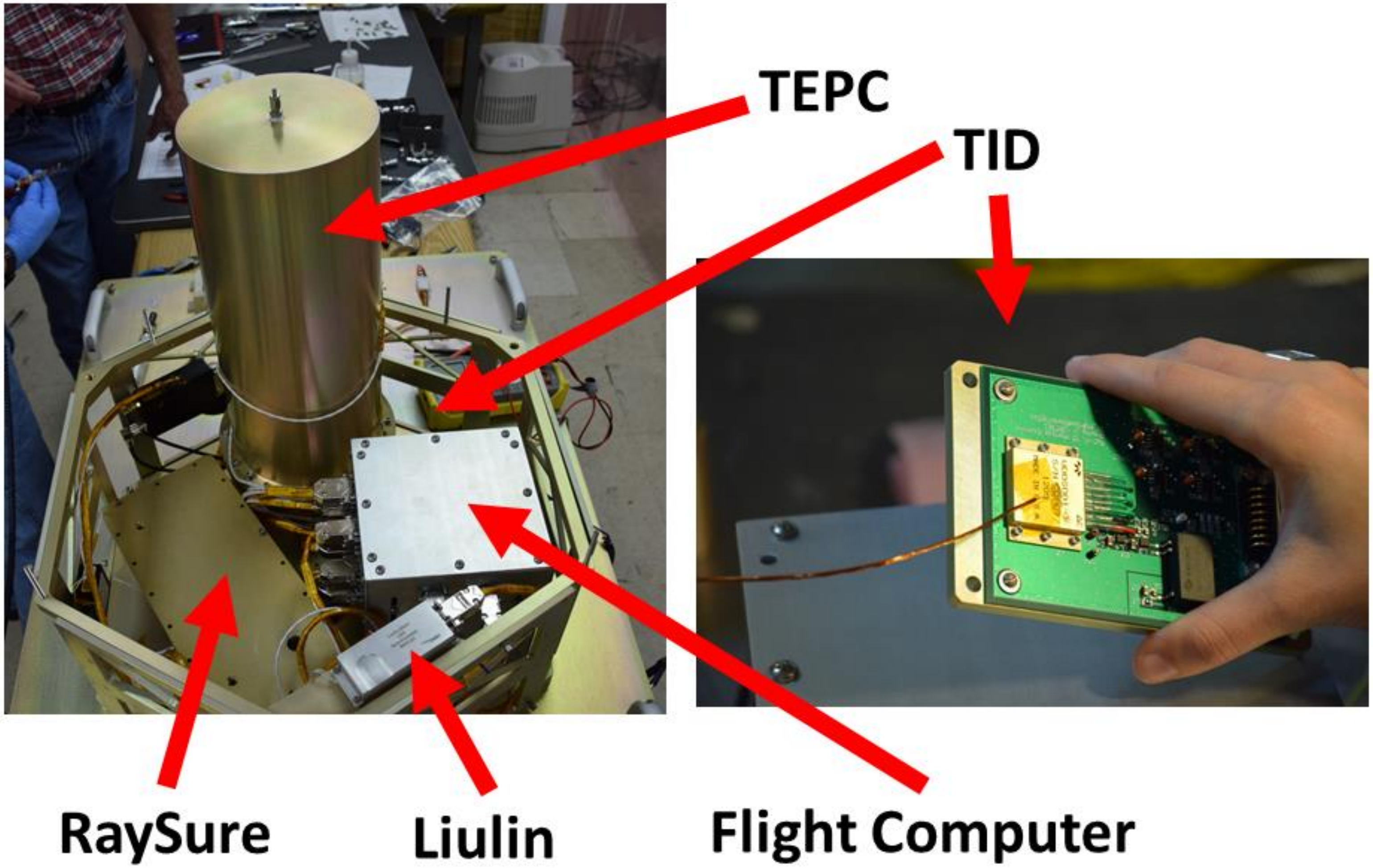
Total Ionizing Dose (TID) Detector
Teledyne Microelectronic Technologies

Liulin LET Spectrometer
Prof. Dachev SRTI-BAS



RaySure Detector
QinetiQ & Univ. of Surrey, UK

RaD-X Payload



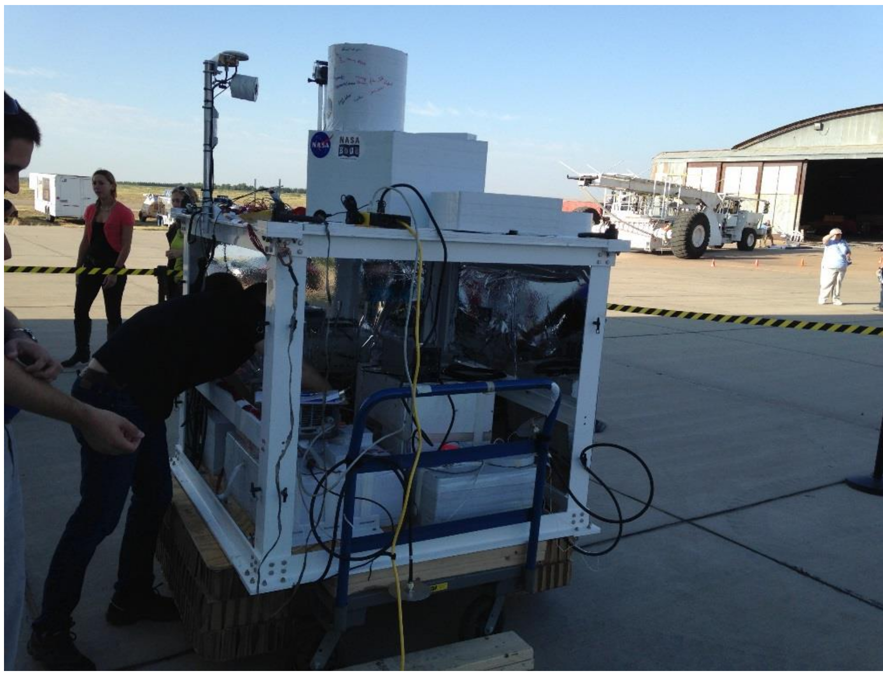
Drs. John Grunsfeld & Paul Hertz

Preparing for Launch at Fort Sumner

Dr. Grunsfeld, NASA SMD Associate Administrator
Dr. Hertz, NASA SMD Astrophysics Division Director

RaD-X Payload Ready for Launch

Payload integrated to balloon gondola



“Big Bill” transporting payload to launch site

RaD-X Launches Sep 25, 2015

RaD-X Balloon in Stratosphere

RaD-X Flight Track

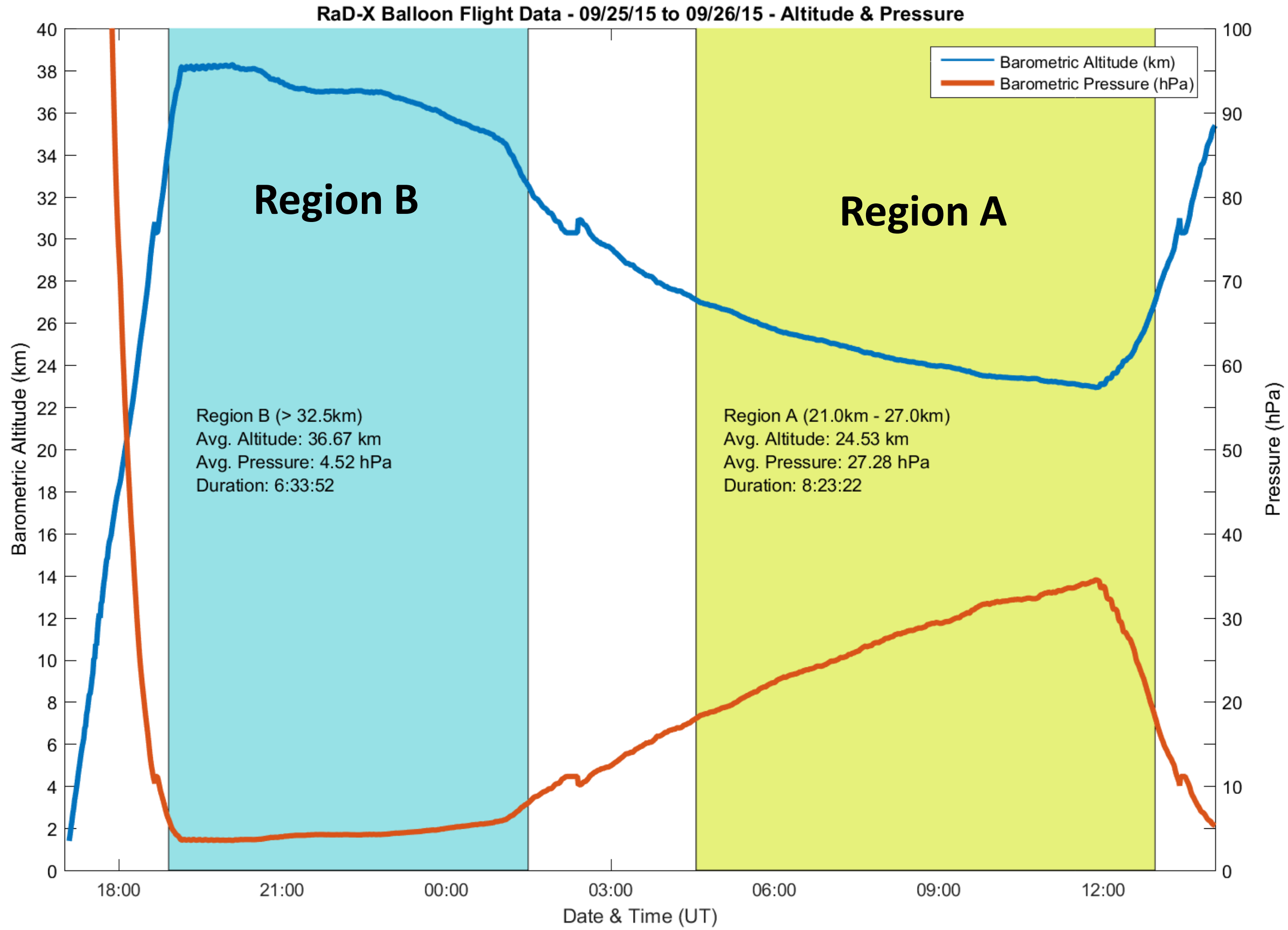
Launch
1:15 PM EDT

Ascent to
Region B

Ballast purged and briefly returned to Region B

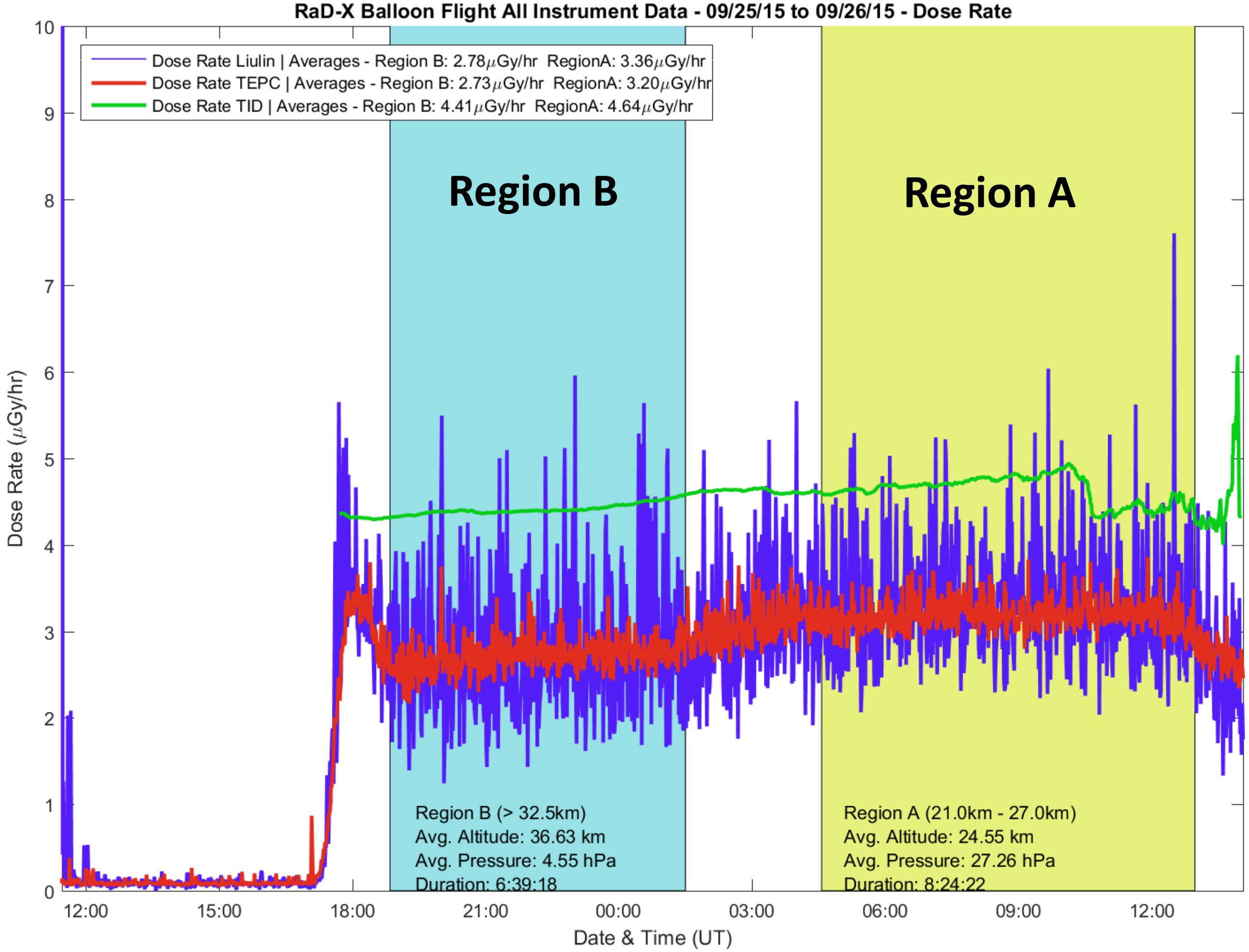
Region B to Region A: No valve-down & No ballast used

RaD-X Flight Pressure-Altitude



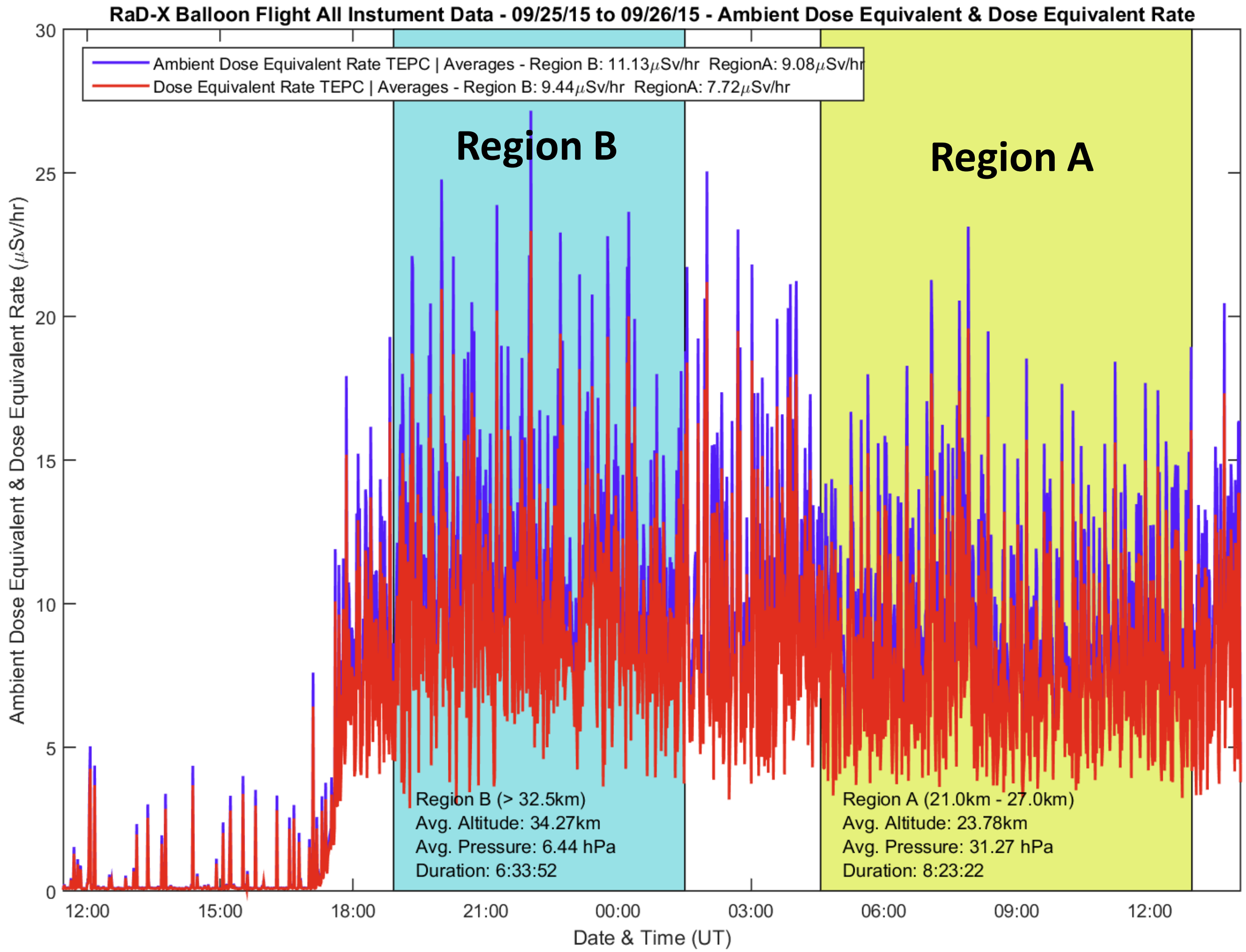
RaD-X Absorbed Dose Rate

Absorbed Dose Rate Measured by TEPC, Liulin and TID



RaD-X Radiobiological Dose Rate

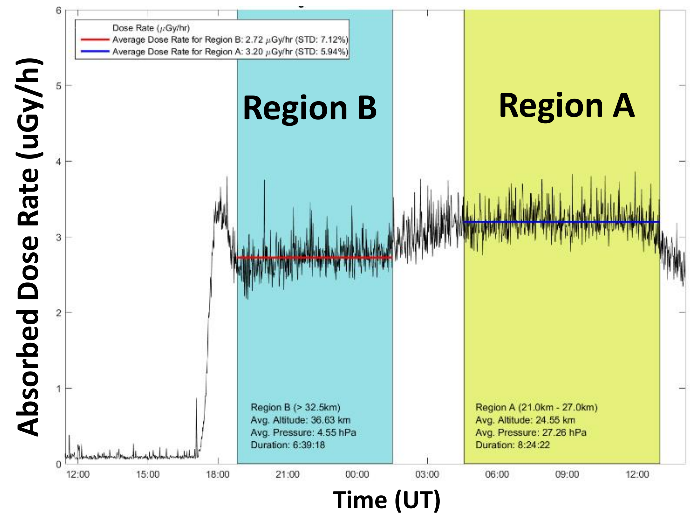
TEPC Measurements of Dose Equivalent and Ambient Dose Equivalent Rates



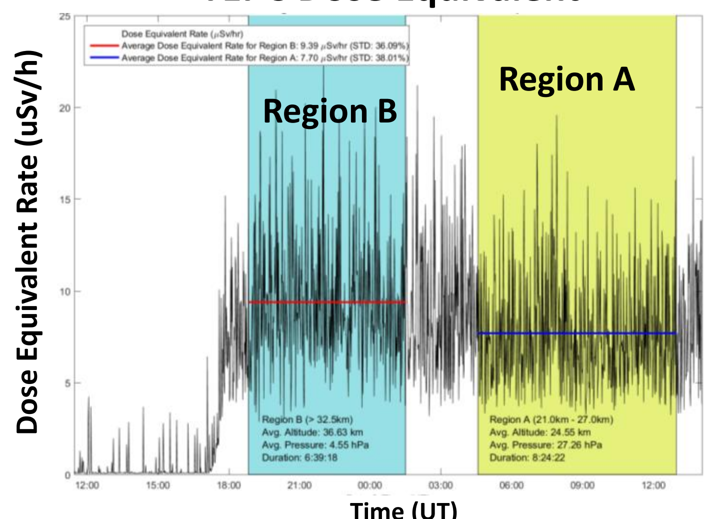
RaD-X / TEPC Dose Rates

- **Absorbed Dose Rates**
  - Average absorbed dose rate is larger in Region A compared to Region B
  - Region A closer to region of Pfotzer maximum
    - Protons dominant source of cosmic ray primary contributions
    - Secondary particle production is near maximum
- **Dose Equivalent Rate**
  - Average dose equivalent rate is larger in Region B compared to Region A
  - High-LET energy deposition events assigned a larger relative weight in computing dose equivalent rate
  - Higher dose equivalent in Region B consistent with presence of heavy-ion cosmic ray primaries

TEPC Absorbed Dose

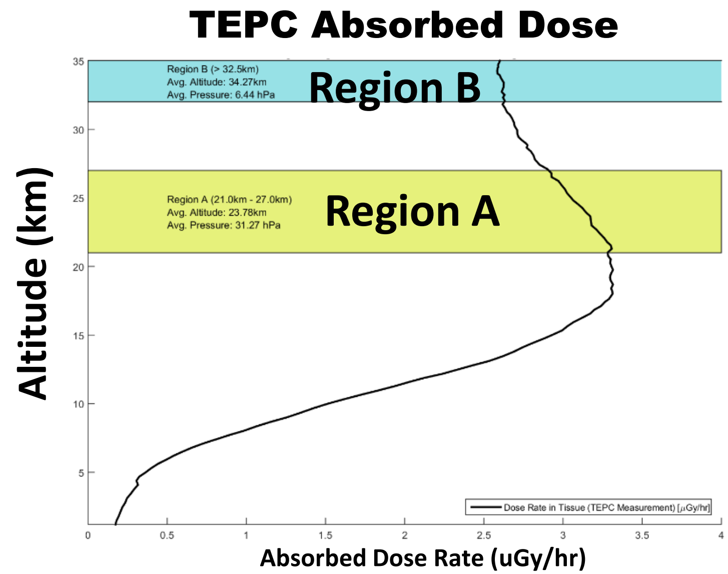


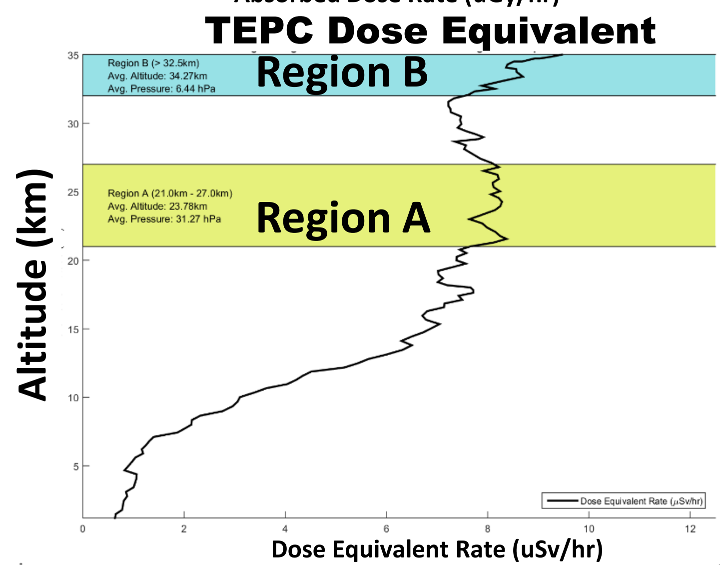
TEPC Dose Equivalent



RaD-X TEPC Dose Rate Profiles

- **Absence of Pfotzer Maximum in Dose Equivalent**
  - No peak in dose equivalent rate as altitude increases (Pfotzer maximum)
  - Complex mixture of high-LET and low-LET radiations, originating from both cosmic ray primaries and secondaries
  - This feature not reproduced in all models, particularly those that don't include heavy-ion cosmic ray primaries in the transport physics
- **Increase in Dose Equivalent with Altitude above 32 km**
  - Dose equivalent rate increase with altitude above 32 km, which is found to be statistically significant
  - Increase in dose equivalent rate with altitude due to increase in high-LET radiations, which is consistent with presence of heavy-ion cosmic ray primaries

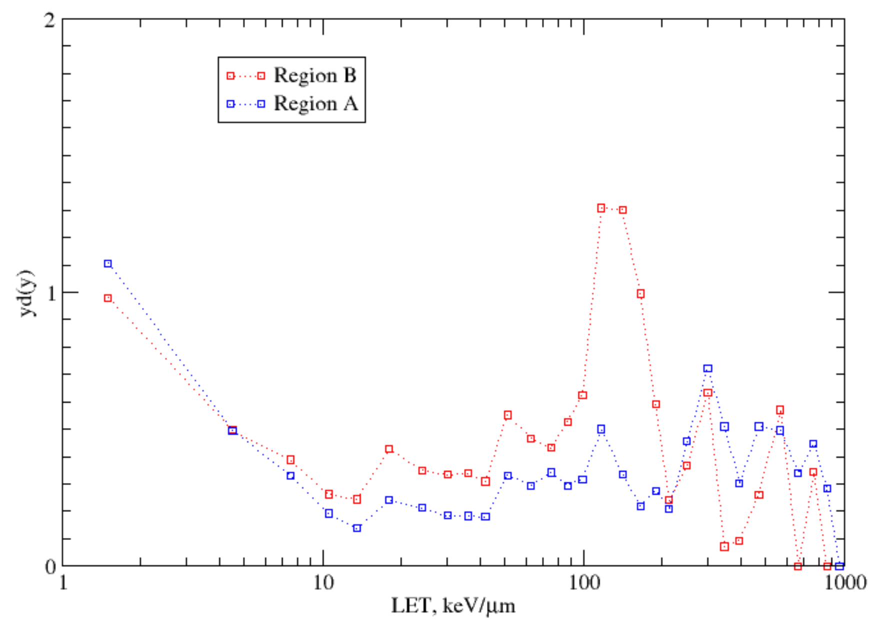




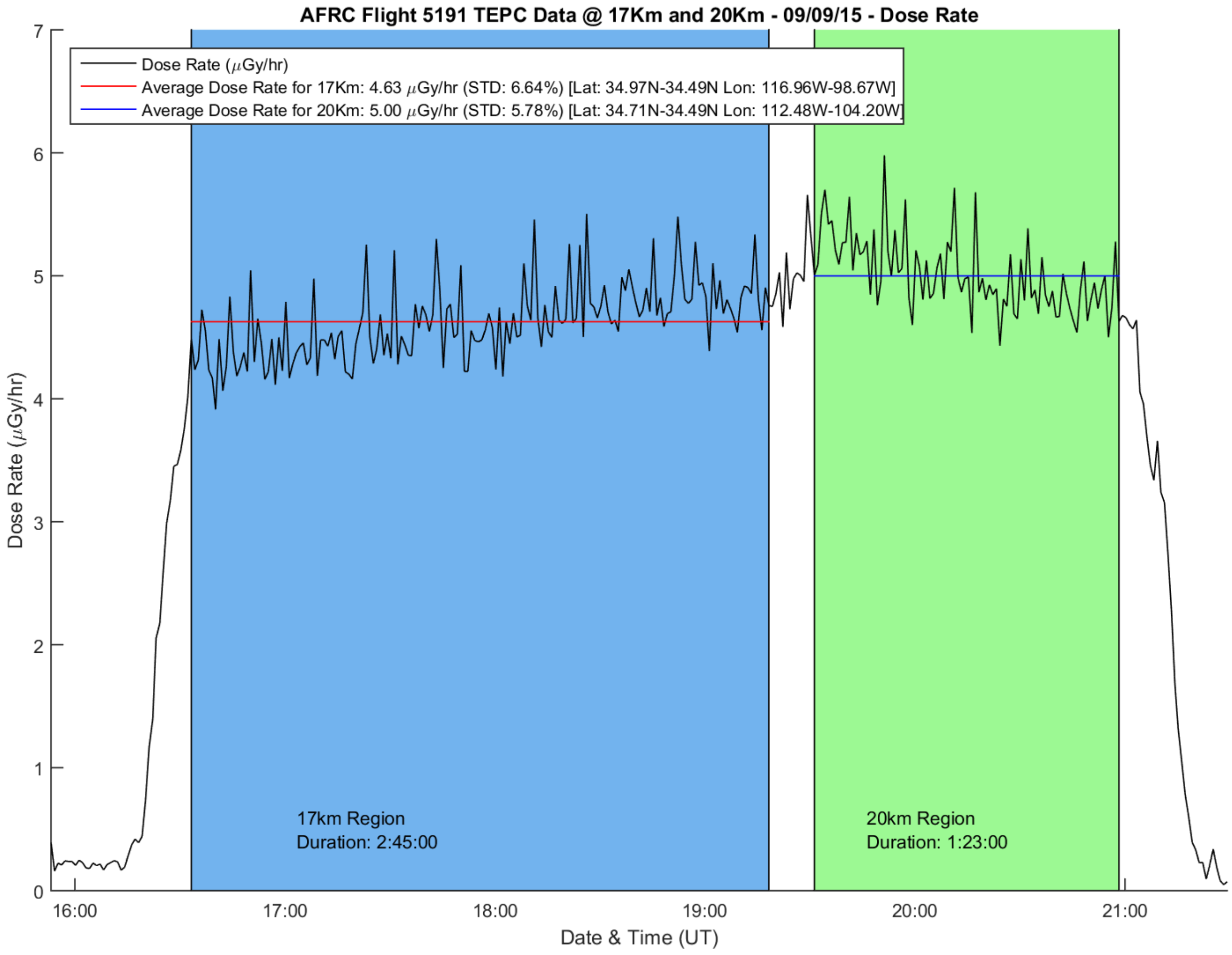
RaD-X TEPC Lineal Dose Spectra

- **TEPC lineal dose distribution** shows very different energy deposition characteristics in Regions A and B
  - Greater contributions to absorbed dose in Region B from LET > 4-5 keV/um
  - Significant peak in Region B lineal dose distribution at roughly 150 keV/um
- **Peaks in lineal dose distribution for LET > 100 keV/um**
  - Peaks are in close alignment with *edge points* of main target fragments of the A-150 tissue-equivalent plastic
  - *Proton*, *carbon* and *nitrogen edge points* are at roughly 144 keV/um, 677 keV/um and 752 keV/um, respectively
  - *Alpha edge point* from (α,n) reaction is located at roughly 263 keV/um
- **Enhanced peak in Region B lineal dose distribution at ~ 150 keV/um**
  - **Enhancement in high-LET protons**
  - **Heavy-ion primaries are a potential source of enhanced high-LET protons through collisional interactions with A-150 plastic**
    - **Target fragments: recoil protons**
    - **Heavy-ion projective fragments**

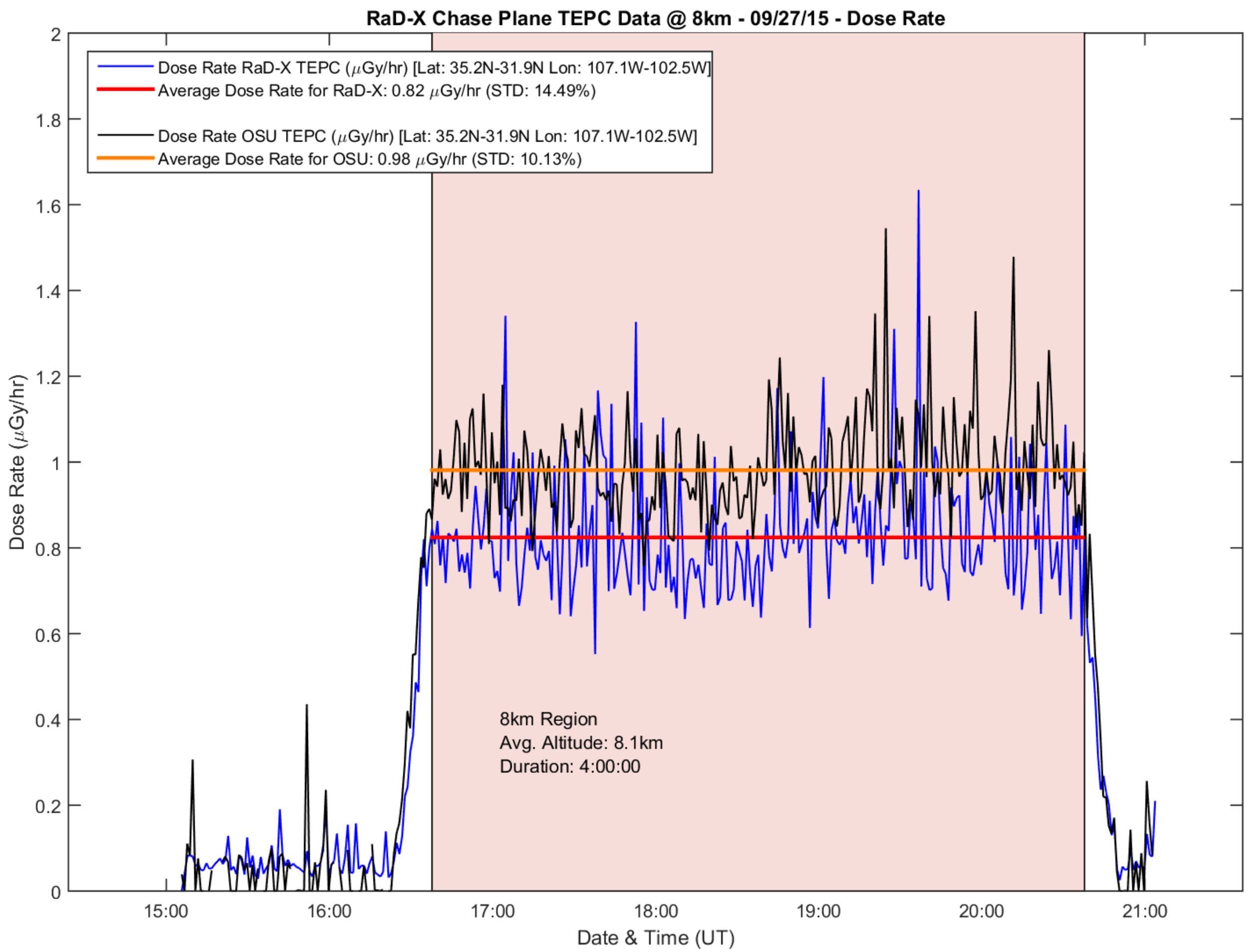
RaD-X TEPC Lineal Dose Distribution



NASA/AFSC ER-2 TEPC Dose



CSBF/Chase TEPC Dose



Average Dose: RaD-X + Aircraft

Altitude km	Pressure hPa	Platform	Liulin	TEPC	TEPC	TEPC	TEPC
			Dose Rate uGy/hr	Dose Rate uGy/hr	Dose Equiv uSy/hr	<Q> (unitless)	H*(10) uSy/hr
8	444.9	CSBF	0.94 ± 0.02	0.90 ± 0.01	2.44 ± 0.11	2.60 ± 0.13	N/A
17	92.0	ER-2	N/A	4.63 ± 0.02	8.95 ± 0.22	1.93 ± 0.04	N/A
20	85.6	ER-2	N/A	5.00 ± 0.03	10.26 ± 0.34	2.03 ± 0.06	N/A
24.6	27.3	RaD-X	3.34 ± 0.03	3.20 ± 0.01	7.70 ± 0.13	2.37 ± 0.04	9.05 ± 0.15
36.6	4.5	RaD-X	2.77 ± 0.04	2.73 ± 0.01	9.40 ± 0.17	3.40 ± 0.05	11.09 ± 0.20

RaD-X Flight Campaign Summary

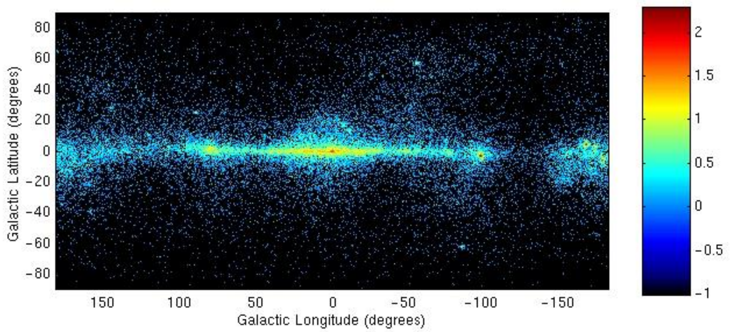
- Dosimetric measurements at 5 strategic altitudes important for interrogating the physics of cosmic radiation transport in the atmosphere
  - Measurements from the low-end of commercial aircraft altitudes, to regions near the Pfotzer maximum, to high altitude where cosmic ray primaries are present
- TEPC dose equivalent profile shows an absence of the Pfotzer maximum
  - Indicative of complex mixture of low-LET and high-LET radiations from cosmic ray primaries and secondaries
- Large systematic bias introduced into calculated TID dose rates due to large voltage noise superimposed on TID power supply line
  - *Mitigation approach*: calculate average absorbed dose rate in Regions A and B based on accumulated dose in these regions
  - *Result*: Agree with Liulin to within 5%
- Next Steps
  - Investigate a more rigorous removal of large voltage noise imposed on TID output pins
  - Detailed comparisons between RaD-X flight data and NAIRAS model

Backup Slides

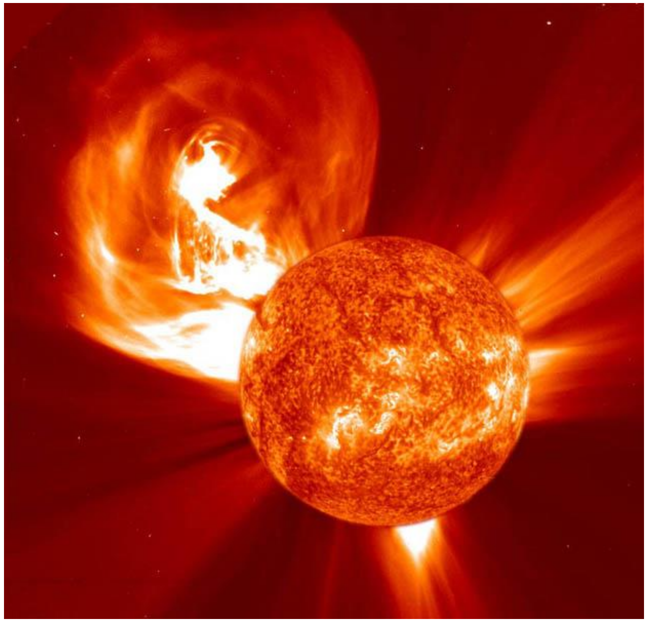
Sources of Cosmic Rays

- **Galactic Cosmic Rays (GCR)**
  - Originate from outside the solar system
  - Best explanation: supernova remnants + interstellar shock acceleration
- **Solar Cosmic Rays, or Solar Energetic Particles (SEP)**
  - Originate from solar flares and shock-associated coronal mass ejections (CMEs)
  - Interplanetary shock acceleration

Milky Way Galaxy



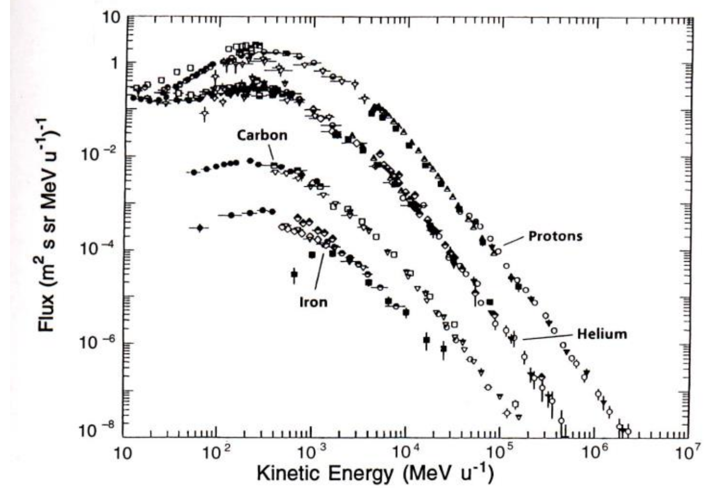
Sun



Cosmic Ray Composition and Energy

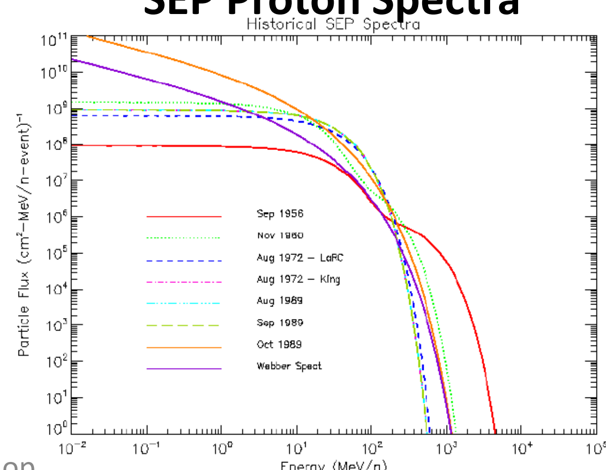
- **GCR (Galactic Cosmic Ray)**
  - **98% nuclei, 2% e-/e+**
  - **Nuclear component**
    - 87% Hydrogen (protons)
    - 12% Helium (alpha)
    - 1% heavy nuclei
  - **Particle Spectra (relative to SEP)**
    - High energy component; few particles
    - High-energy > moderately influenced by Earth's magnetic field

GCR Particle Spectra

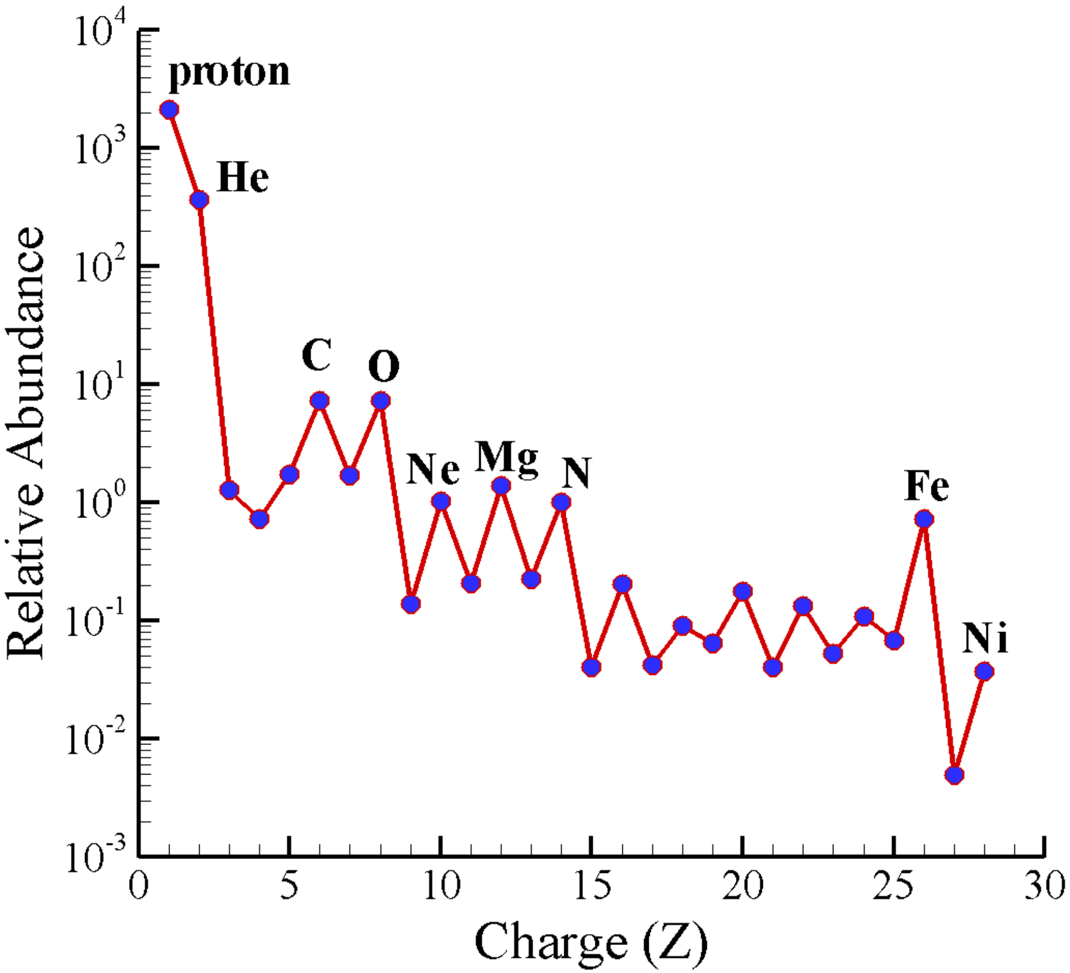


- **SEP (Solar Energetic Particles)**
  - **Protons, alphas, and electrons**
  - **Particle Spectra (relative to GCR)**
    - Low-Medium energy component; many particles
    - Low-mid energy > significantly influence by Earth's magnetic field

SEP Proton Spectra



GCR Compositions



Relative abundance of elements in the 1977 solar minimum GCR environment, normalized to neon

Dosimetric Quantities

Absorbed Dose

$D_j(\mathbf{x})$: Energy deposited in a target medium (e.g., tissue, silicon) by the radiation field of particle j

Unit: Gray (Gy) = Joules per kilogram

Equivalent Dose in Tissue

Unit: Sievert (Sv) = Joules per kilogram x radiation weighting factor

$$H_{j,T} = w_j D_{j,T}$$

$D_{j,T}$ ← Absorbed dose from particle j averaged over the tissue volume

w_j ← Radiation weighting factor (radiobiological effectiveness)

Dosimetric Quantities

Effective Dose

Unit: Sievert (Sv) = Joules per kilogram x radiation weighting factor x tissue weighting factor

$$E = \sum_T \sum_j w_T H_{j,T}$$

Tissue weighting factor

Effective dose is full-body averaged dose proportional to the total biological detriment

All ICRP recommended radiation exposure limits are expressed in terms of effective dose

Dosimetric Quantities

Dose Equivalent in Tissue

Unit: Sievert (Sv) = Joules per kilogram x radiation quality factor

$$H_{j,T}(\mathbf{x}) = \int_L Q(L) D_{j,T}(\mathbf{x}, L)\, dL$$

LET: Linear energy transfer (keV/μm)

LET-dependent quality Factor Q(L)

Absorbed dose LET-spectrum from particle j at point **x** in tissue

Ambient Dose Equivalent

Unit: Sievert (Sv)

$$H^*(10) = \sum_j H^*_{j,T}(10)$$

Dose equivalent produced by an expanded and aligned field at 10-mm depth along the radius of a 300-mm diameter spherical tissue phantom

Operational proxy for effective (body) dose

Dosimetric Quantities: Summary

Radiation Protection Applications

- **Effective Dose (Sv) - Calculated**
  - Total body detriment from exposure
  - ICRP limits and recommendations
  - Primary NAIRAS output provided to stakeholders
- **Ambient Dose Equivalent (Sv) – Measured/Calculated**
  - ICRU/ICRP operational proxy for effective dose
  - Can be observed by combining a calibration factor with TEPC measurements of LET-spectra (D(L)) in tissue equivalent material

Other Useful Measurement Observables

- **Absorbed Dose in Silicon**
  - Can provide information on the ionizing radiation field
  - Seek to develop empirical relationship to ambient dose equivalent
- **Silicon LET-spectra**
  - Separate groups of particles in the ionizing radiation field

Aircraft Radiation Exposure: Typical Dose Values

- **Unit of radiation dose related to health risk = Sievert (Sv)**
  - Chest x-ray = 0.1 millisievert (mSv)
  - Instant death > 3 Sv
- **ICRP recommended limits**
  - Public annual limit < 1 mSv
  - Prenatal limit < 1 mSv total; < 0.5 mSv any month
  - Radiation worker annual limit < 20 mSv
    - ❑ Pilots are classified as radiation workers
- **Typical passenger exposure**
  - One round-trip international = 0.2 mSv (2 chest x-rays)
  - 100k mile flyer = 2 mSv (20 chest x-rays)
- **Solar storm exposures at high-latitude**
  - January 2005 = 1 mSv
  - February 1956 = 5 mSv
  - Carrington 1859 = 20 mSv (average)

Geomagnetic Cutoff Rigidity

$$\frac{d\mathbf{p}}{dt} = \frac{Ze}{c}\mathbf{v} \times \mathbf{B}$$ ← **Lorentz-Force**

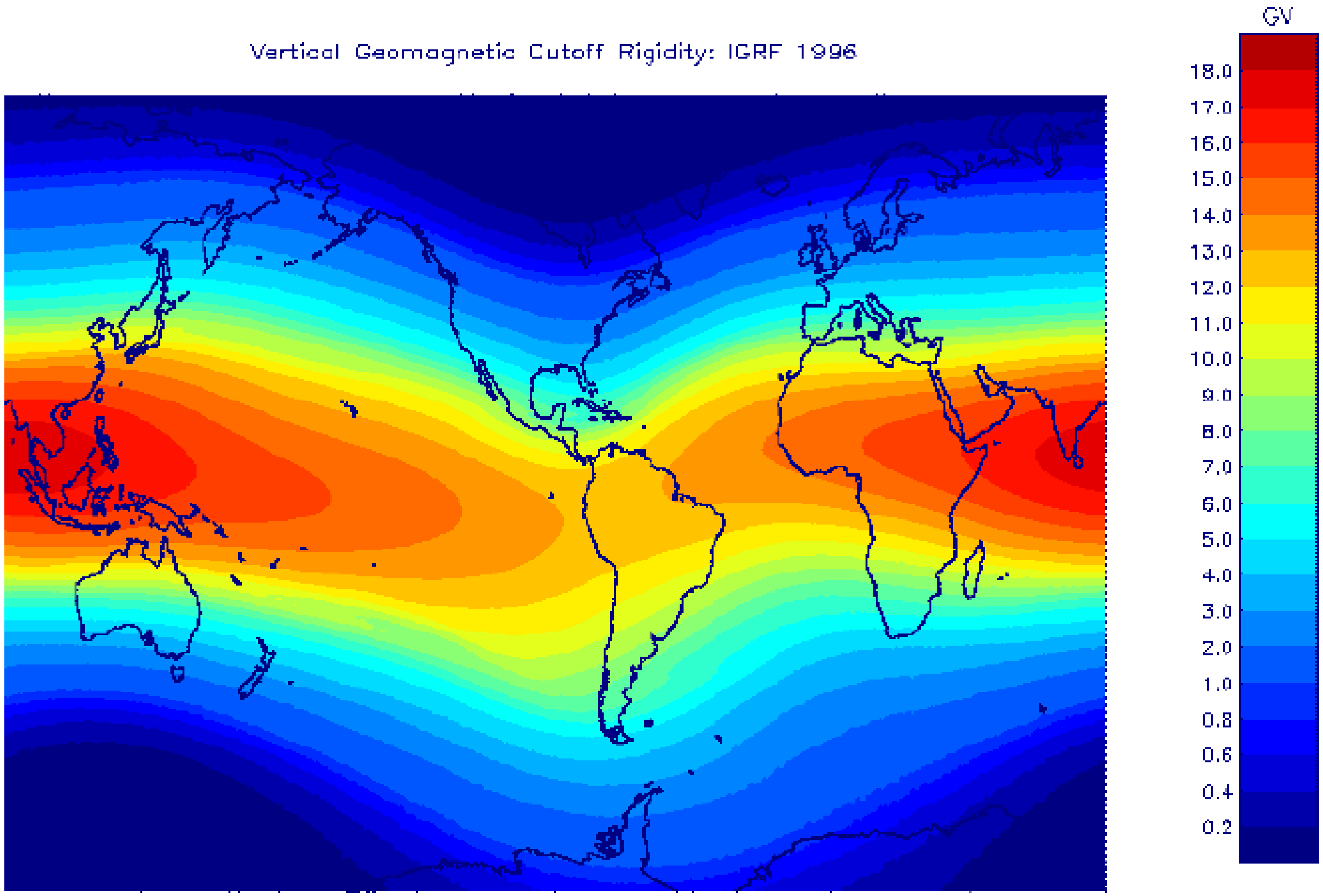
$$\frac{R}{B}\frac{d\hat{\mathbf{v}}}{ds} = \hat{\mathbf{v}} \times \hat{\mathbf{B}}$$ ← **For given B-field, particles with same rigidity follow identical trajectories**

$$R \equiv \frac{pc}{Ze}$$ ← **Rigidity**

Minimum Access Energy

$$E = \left[\sqrt{R_c^{\,2}\left(Z/A \cdot \mathrm{amu} \cdot c^2\right)^2 + 1} - 1\right] \cdot \mathrm{amu} \cdot c^2$$

Geomagnetic Cutoff Rigidity

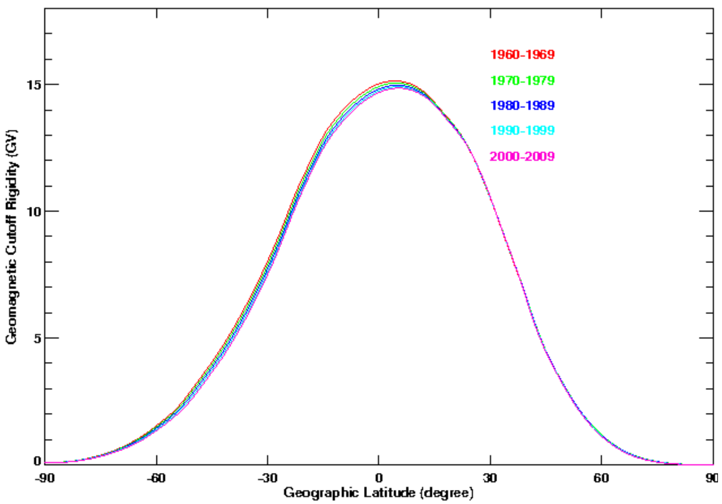


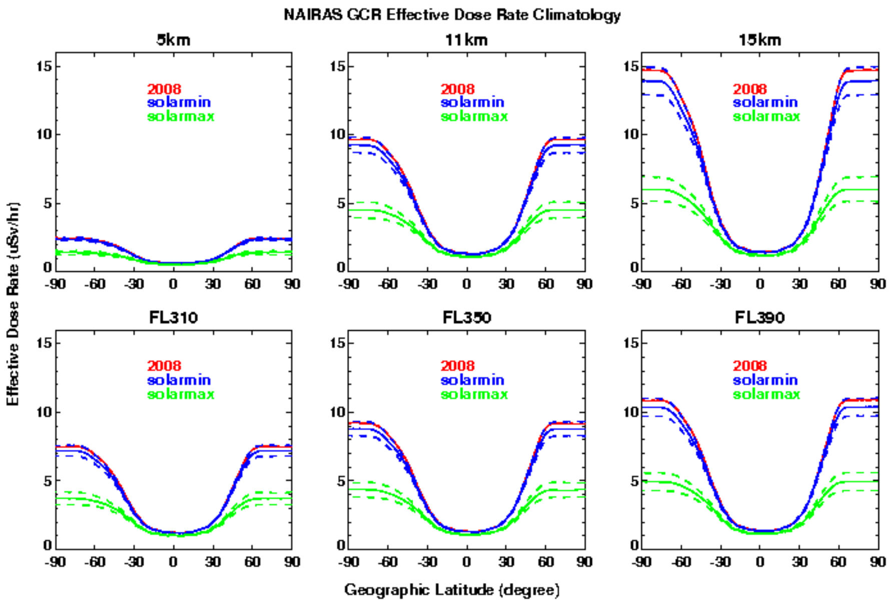
Global grid of quiescent vertical geomagnetic cutoff rigidities (GV) calculated from charged particle trajectory simulations using the IGRF model for the 1996 epoch (solar cycle 23 minimum).

Solar Cycle and Cutoff Effects

Effective dose rate vs Latitude

Cutoff Rigidity vs Latitude

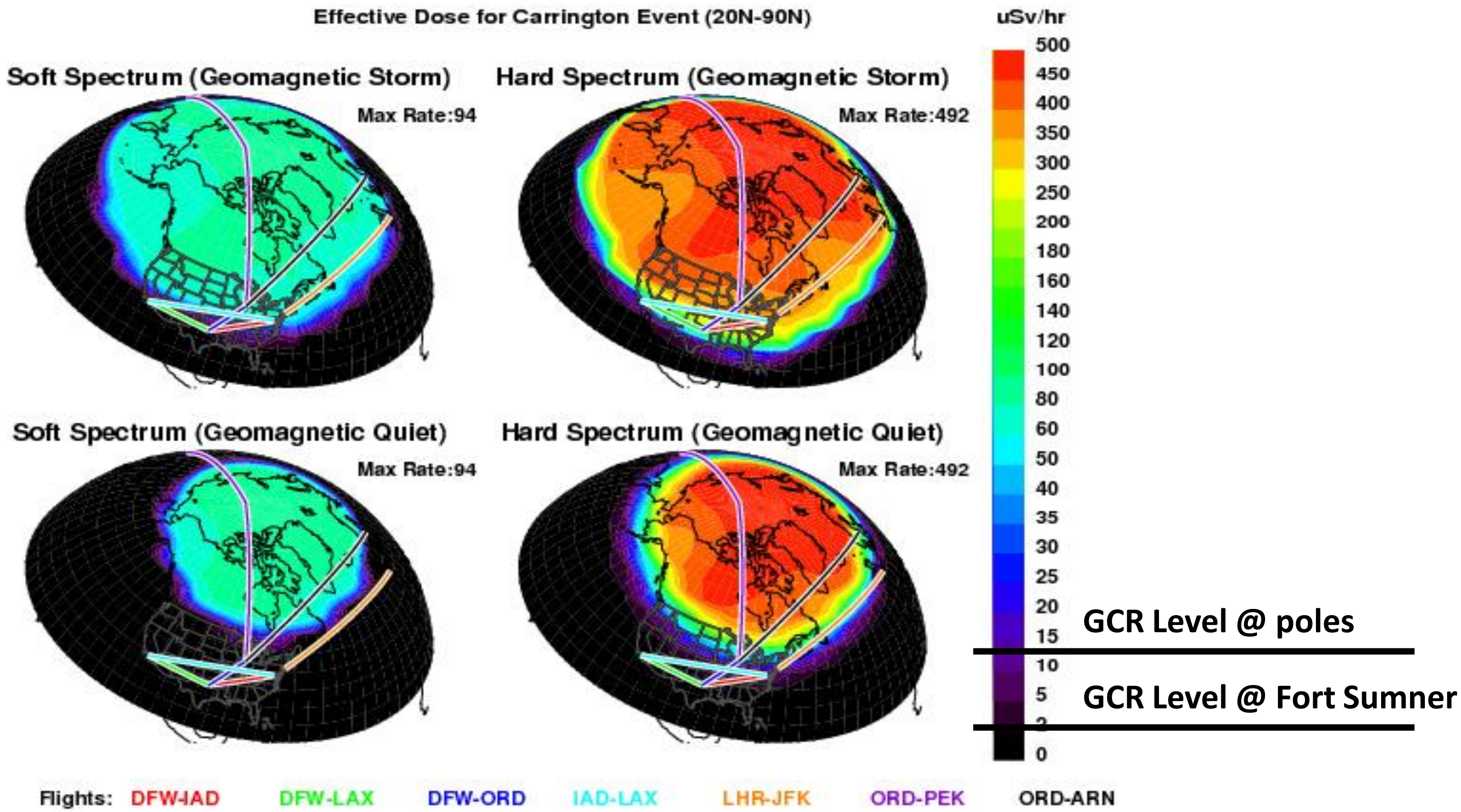




Cutoff Effect: Dose increase toward poles

Solar Cycle Effect: Smax = DoseMin & Smin = DoseMax

SEP and Geomagnetic Storm Effects

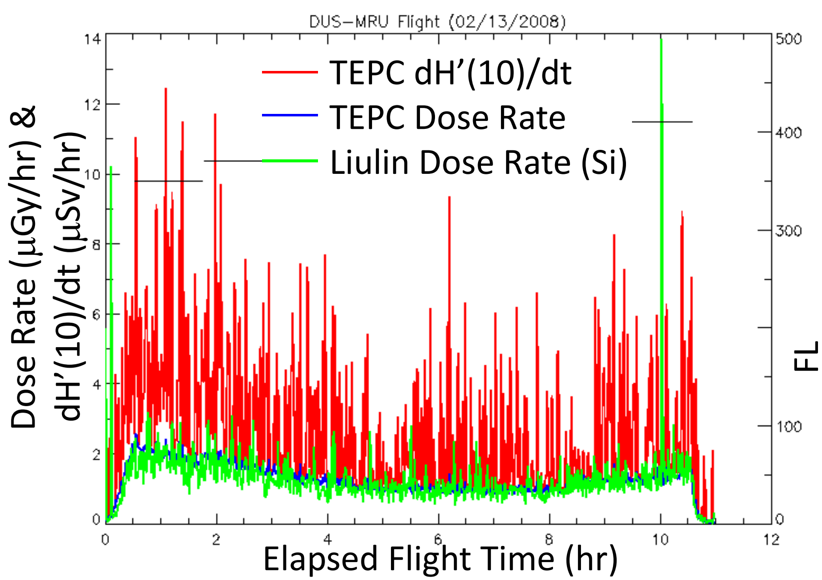


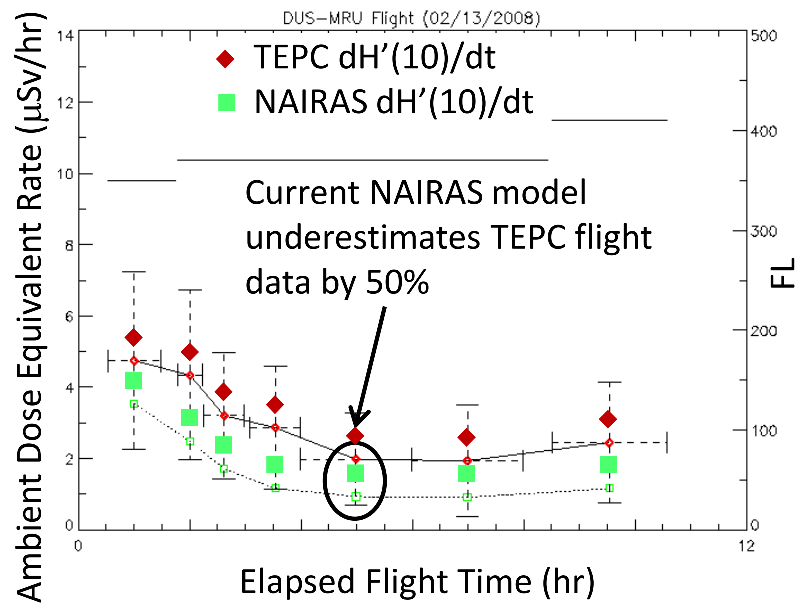
SEP Effect: Enhanced dose in polar regions

Geomagnetic Effects: SEP dose expanded to lower latitudes

NAIRAS Comparisons to Aircraft Dose

The NAIRAS model currently underestimates measurement data.
This performance is quantified by comparisons with recent DLR-TEPC/Liulin measurements from 2008 and comparisons with data tabulated by the International Commission of Radiation Units and Measurements (ICRU) [*Mertens et al.,* 2013]





Mertens, et al. (2013), *Space Weather, 11, 1-33*, doi:10.1002/swe.20100