Using Space Weather Variability in Evaluating the Environment Design Specifications for NASA's Constellation Program

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Introduction -

- NASA's Constellation program, initiated to fulfill the Vision for Space Exploration, will create a new generation of vehicles for servicing low Earth orbit, the Moon, and beyond.

- Spectral models of solar particle events and trapped radiation belts are necessary for the design requirements of total ionizing radiation dose, single event effects, and spacecraft charging.

- Space radiation and plasma environment specifications for hardware design are necessarily conservative to assure system robustness for a wide range of space environments.
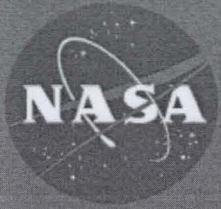
# Establishing design environments as a space weather activity -

- Design environments are required for constructing systems to withstand *"acceptable"* extremes in the space environment
  - What is "acceptable" depends on program risk posture and consequences of risk
    - Lost science (payloads)
    - Denial of service
    - Lost mission
    - Sickness or loss of crew

- "Credible" design environments are based on space environment measurements and models
  - "Credible" is an important concept…the space environments and effects community doesn't simply over design because we don't understand the environment. We design to the level of threat environment a system is required to withstand
  - Space weather monitoring is required for operations in environments more extreme than the design environments
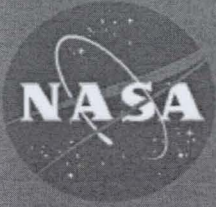
Design Environment - Solar Proton Events

- The SPE environment is the dominant dose driver for all but the lightly shielded components for a Constellation mission

- The SPE design environment is based on ~2x the solar proton environments associated with the October 1989 coronal mass ejection events
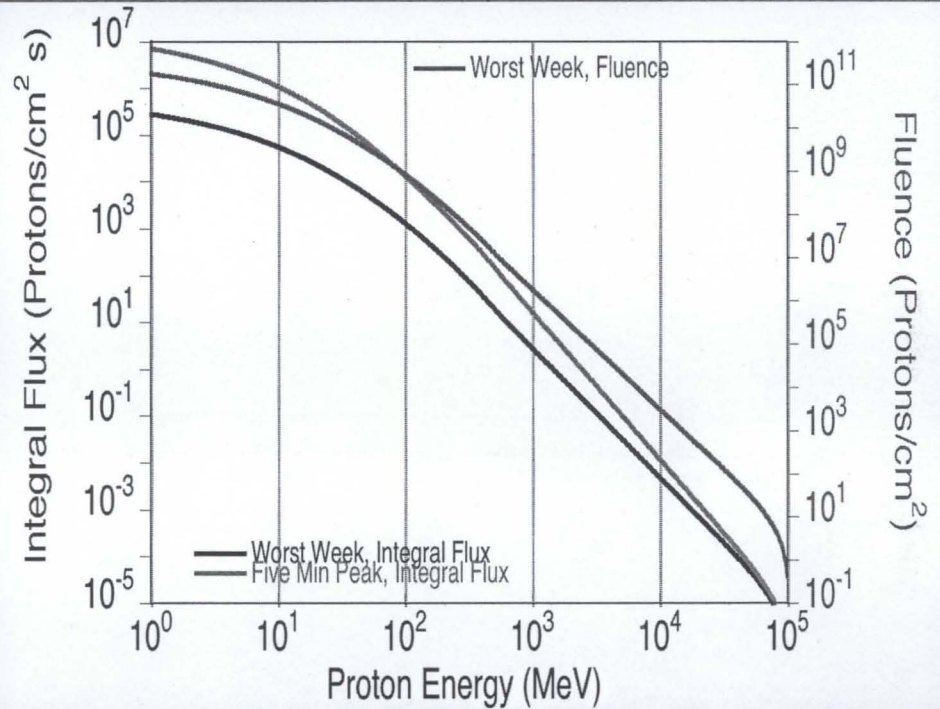
The proton integral flux and the proton fluence (green) as a function of proton energy for the worst week (black) and the worst five minute peak (red)
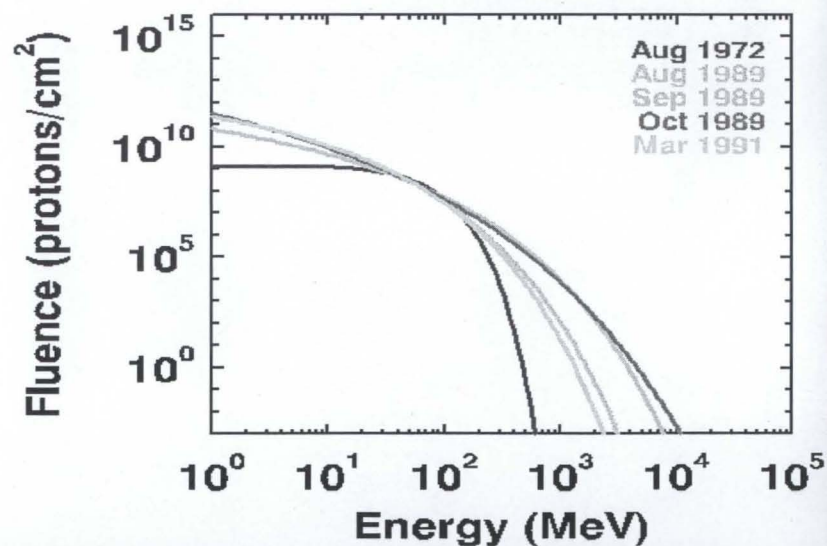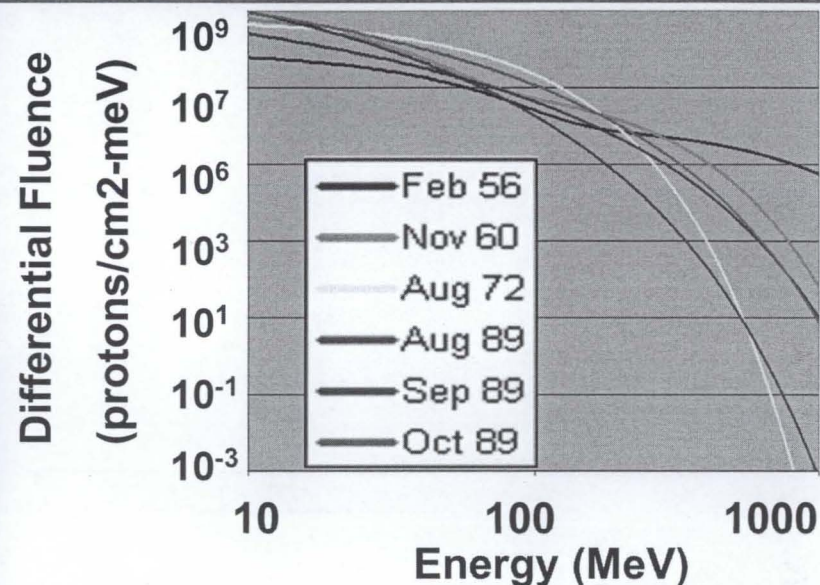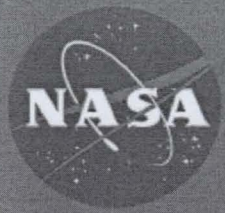
SPE Spectral Variations

Spectral Hardness Comparison for Selected Large SPE Events

(a) Differential fluence spectra for selected events demonstrates both integrated flux and hardness variations for individual events (from Turner, 2005).

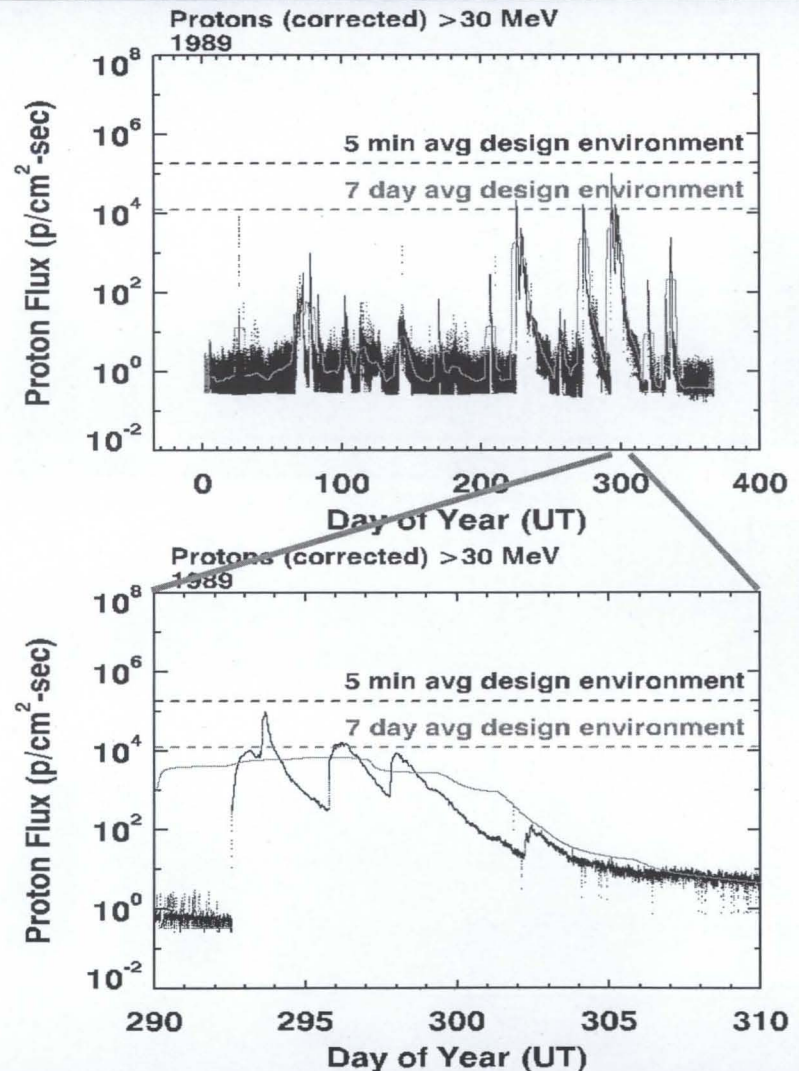(b) Proton fluence normalized to the Carrington event >30 MeV proton fluence [adapted from Townsend et al., 2006].

SPE Design Environment is based on a hard, high flux spectrum exceeded by only a few events:

NASA

- Compare the >30 MeV integral proton flux SPE Design Environment to the measured high flux events in 1989.

- The measured > 30 MeV proton flux from the GOES-7 satellite is given for the complete year of 1989 (top) and for the detail (bottom) for the October 1989 SPE events

- Both 7-day mean and 5-minute peak proton flux design environments exceed the 7-day and 5-min peak averages of the measured flux through the 1989 events

- This comparison demonstrates the conservative nature of the Constellation SPE design environments.

Protons (corrected) >30 MeV
1989

5 min avg design environment

7 day avg design environment

Proton Flux (p/cm²-sec)

Day of Year (UT)

Protons (corrected) >30 MeV
1989

5 min avg design environment

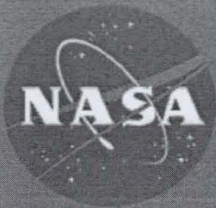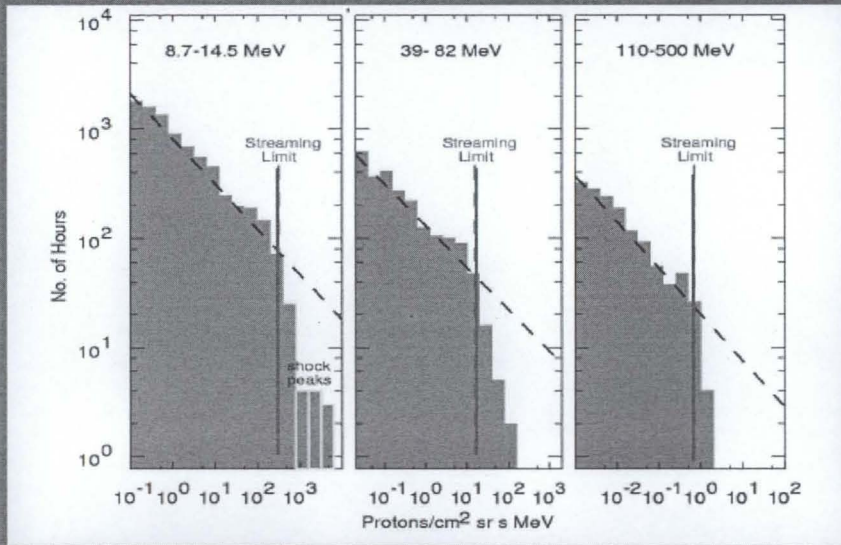7 day avg design environment

Proton Flux (p/cm²-sec)

Day of Year (UT)

Variability - SPE Environment for >100 MeV Protons

• Compare the >100 MeV integral proton flux SPE Design Environment to the measured high flux events in 1989.

• The measured >100 MeV proton flux from the GOES-7 satellite is given for the complete year of 1989 (top) and for the detail (bottom) for the October 1989 SPE events

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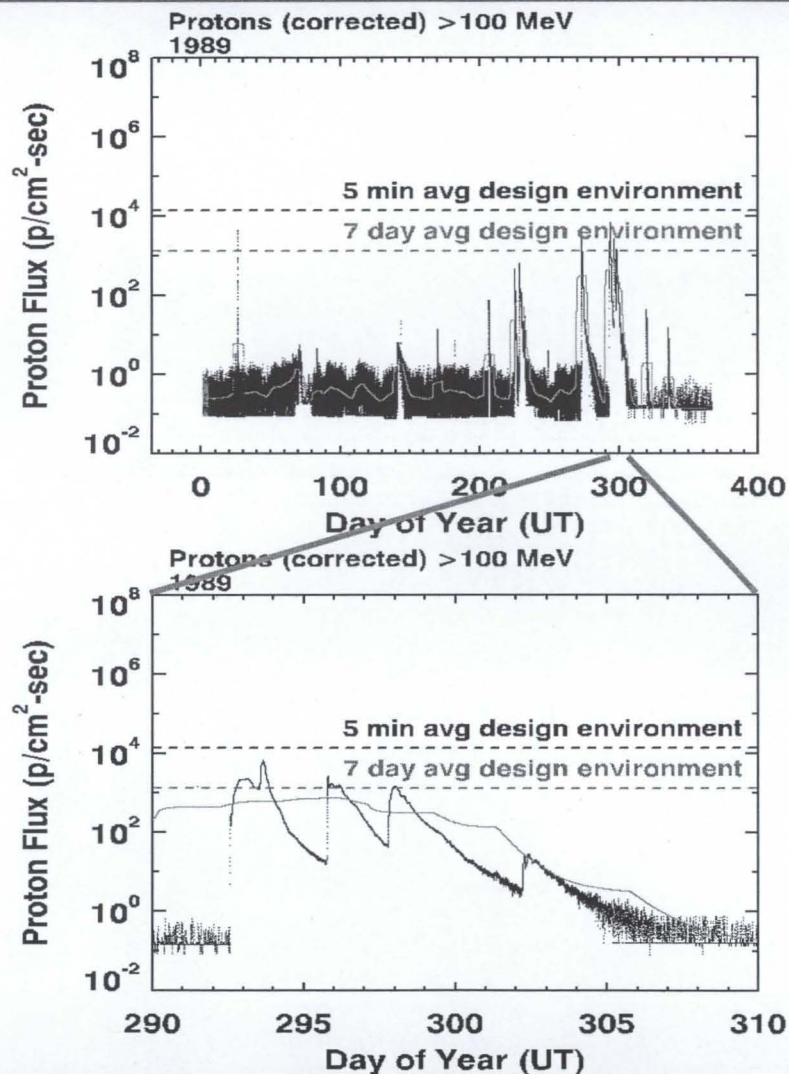
Variability - SPE Streaming Limits

• The Constellation 5-min (red) and 7-day (blue) design environments are compared to the *Reames* [2004] streaming limits (black) for the SPE proton flux. For comparison, the Constellation SPE Design Environment are integrated over the same GOES-7 energy bands used by *Reames*.

• The solar proton flux streaming from shock fronts is limited by wave particle interactions

• This establishes an upper bound for SPE total dose environments in interplanetary space.
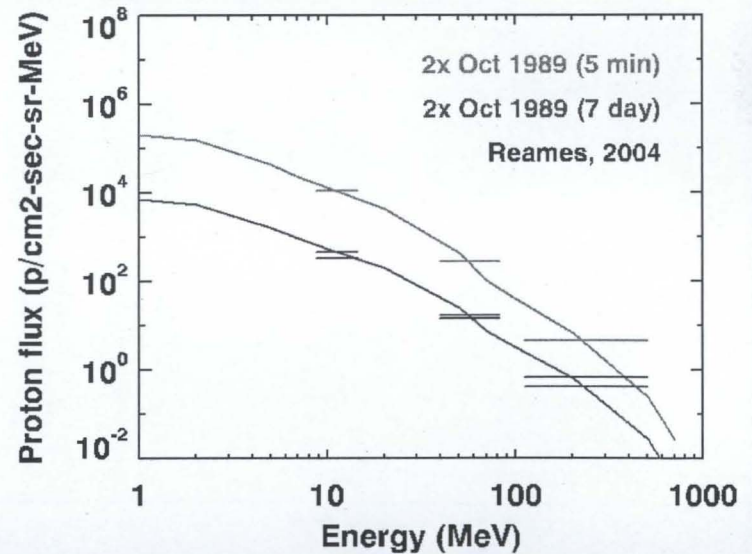
Comparison of Large SPE Event Fluence to SPE Design Environment Fluence

- Constellation worst week environments establish the total ionizing dose for hardware due to solar proton events.

- The design environment is consistent with large proton events recorded during the space age and is within ~2x to ~3x the 1859 Carrington event fluence considered to be the worst case in the past ~400 years [McCracken et al., 2001a,b].

- Large events are credible design environments, $>10^9$ p/cm^2-sr fluences have been observed numerous times in last decade

SPE Event Fluence Comparison

Event MeV)	Flux (Max>30 MeV) (#/cm2-s-sr)	Fluence (>30 MeV) (#/cm2-sr)
1859/09/01	5×10^4 hardware	19×10^9
1960/11/15	-------- spec	9×10^9
1946/07/25	--------	6×10^9
1972/08/04	2×10^4	5×10^9
2000/07/12	--------	4.3×10^9
1989/10/19	--------	4.2×10^9
2001/11/04	--------	3.4×10^9
2003/10/28	4.5×10^3	3.4×10^9
2000/08/00	--------	3.2×10^9
1959/07/14	--------	2.3×10^9
1991/03/22	--------	1.8×10^9
1989/08/12	--------	1.4×10^9
1989/09/29	--------	1.4×10^9

[Sources: Smart and Shea, 2002; Reedy, 2006; Smart et al., 2005]
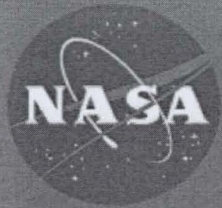
Design Environment -Trapped Radiation

- The radiation belt environment during the earth-moon transit is important for the lightly shielded components

- The Constellation trapped radiation belt design environments are currently based on the AP-8, AE-8 solar maximum models [Sawyer and Vette, 1976; Vette, 1991].

- This spectra is the proton and electron fluence for a single 4 hour transit through the Earth's radiation belts during an Earth-Moon transit.

- The trapped proton and electron fluence dominates the integral fluence at energies less than ~1 MeV while the solar proton contributions dominate the design environments at greater energies
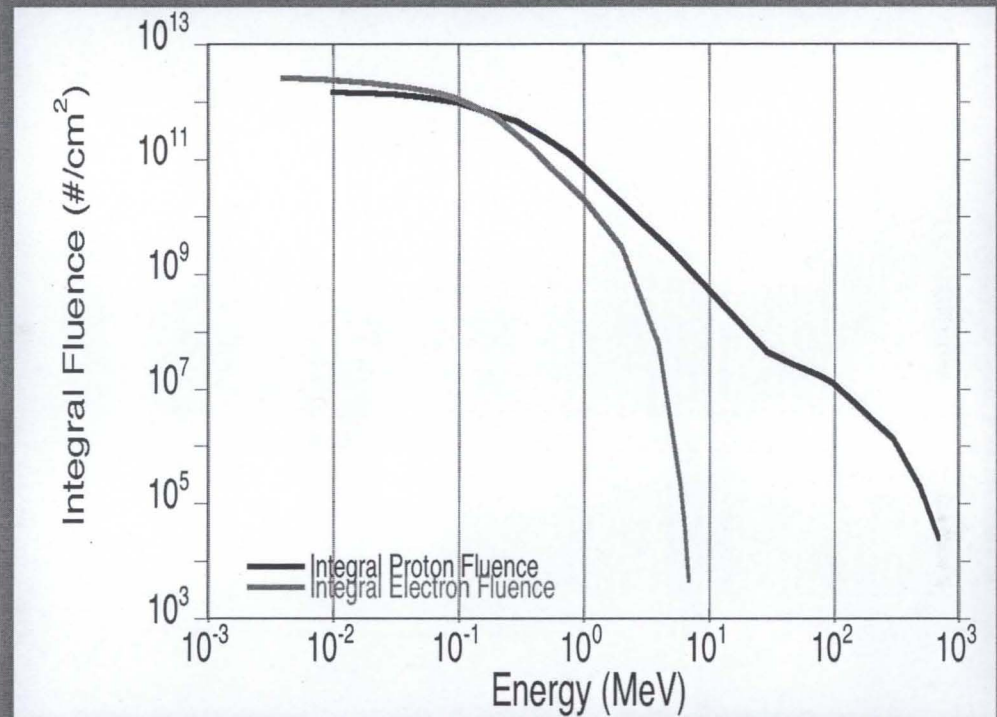

*The integral proton (black) and electron fluence (red) as a function of energy for the worst week*

Variability -Trapped Radiation Environment

• An example of a quiescent radiation belt environment transit example is given by the 3.6 MeV proton flux measured by the Proton Telescope (PROTEL) instrument during Orbit 15 of the Combined Release and Radiation Effects Satellite (CRRES).

• In comparison, the 30.9 MeV measurements from Orbit 615 gives a representative disturbed period following the onset of a strong geomagnetic storm. The new proton belt generated during the March 1991 geomagnetic storm is evident.

• The mean AP-8 Solar Maximum design environment is sufficient for quiescent periods at low energies but the model underestimates the proton flux in the inner belts during disturbed periods at both energies.
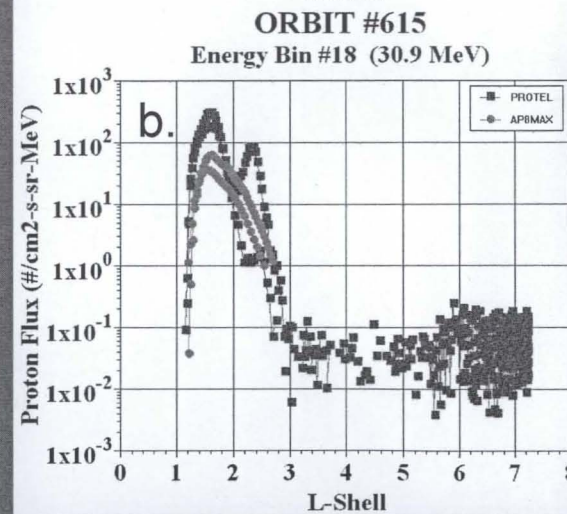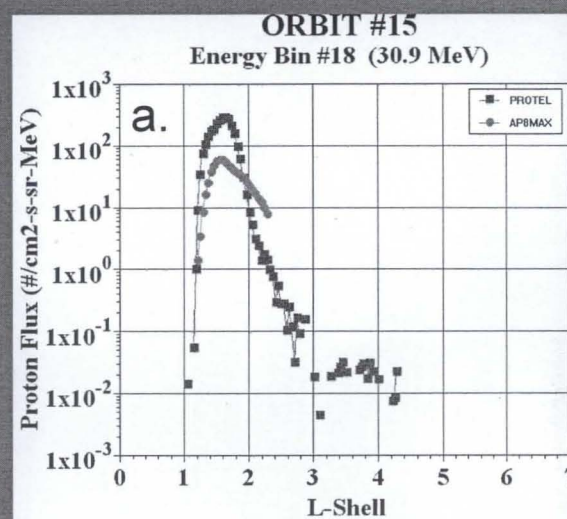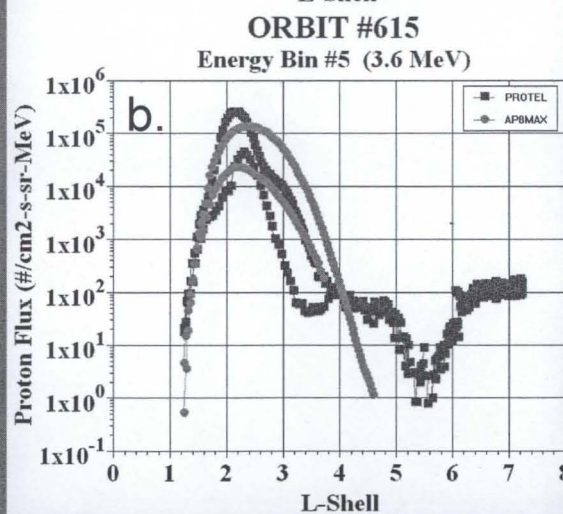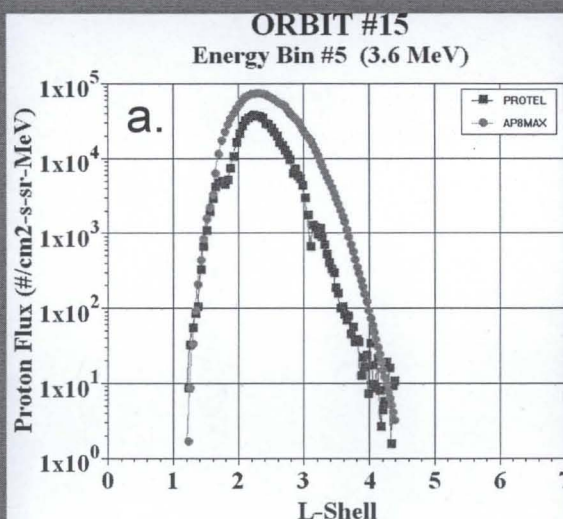

CRRES Proton Telescope measurements (blue) compared to AP-8 Solar Maximum Model Values (red).
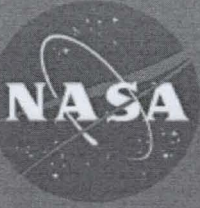
Variability -Trapped Radiation Environment

The quiet Orbit 15 and disturbed Orbit 615 272 keV and 876 keV electron environments exceed the AE-8 Solar Maximum design environments in both of these cases.

While AE-8 may be acceptable as a mean representation of electron flux during the maximum phase of the solar cycle, it is not adequately conservative for use in specifying electron environments for single transits of the Earth's radiation belts.
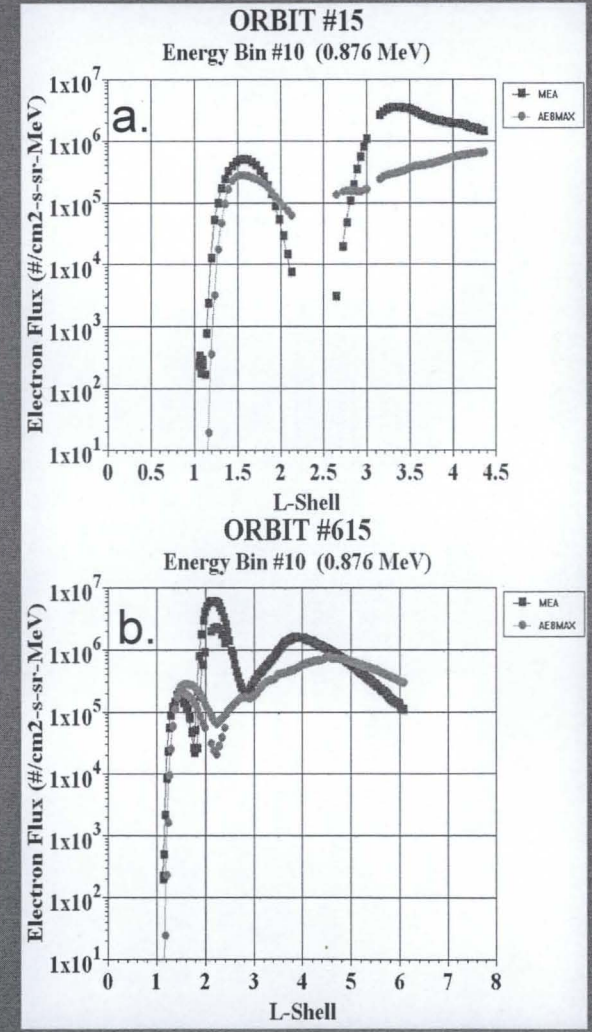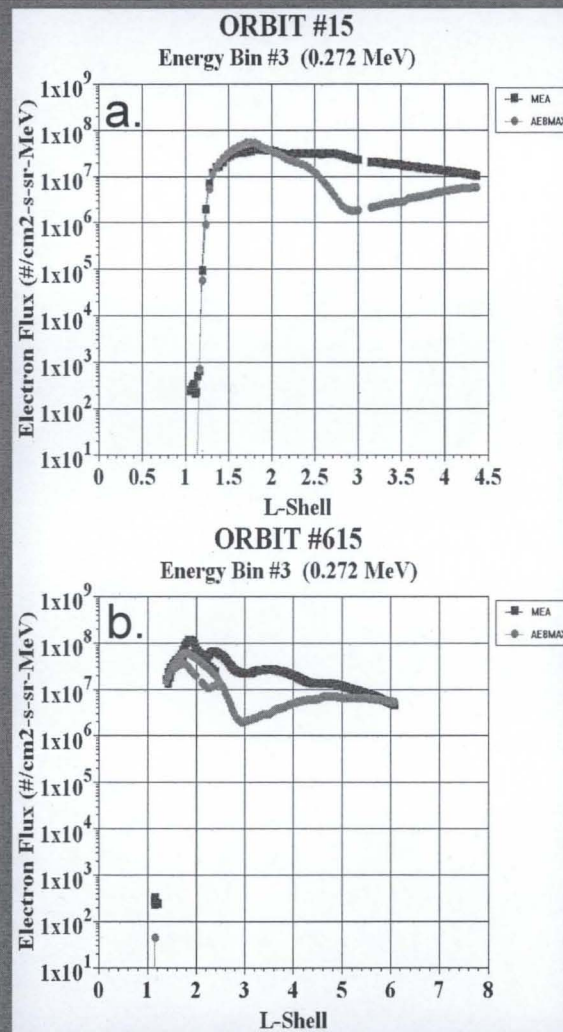
CRRES Magnetic Electron Spectrometer measurements (blue) compared to AE-8 Solar Maximum (red) model values.
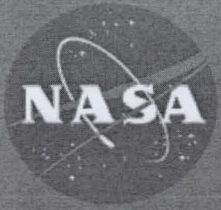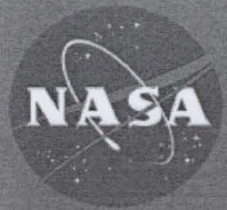
Summary

Solar Particle Event Environment -

• Constellation 7-day SPE environments are based on extreme solar energetic particle event environments which exceed the streaming limits at the lower energies and are on the order of the streaming limits at the highest energies.

• The SPE Design Environment >30 MeV fluence exceeds the >30 MeV fluence observed for most of the large SPE events during the historical space age where in-situ measurements of SPE flux are available and is within a factor of ~2x to ~3x of the large 1859 event fluence that has been inferred from ice core records.

• SPE environments are sufficiently robust for use in designing systems for long term use in environments where dose and dose rate effects are dominated by SPE environments.

Summary

Trapped Radiation Environment -

- Current Constellation trapped radiation environments are derived from AP-8, AE-8 Solar Maximum models which represent the mean environments present during the active phase of the solar cycle.
    - Currently considering options to modify the radiation belt environments to better represent extreme conditions encountered during transit period instead of the mean environments represented by the AP-8/AE-8 solar maximum models.

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• Constellation radiation design environments for hardware have been established to support robust operation in extreme space environments

• Comparison to space weather data demonstrates conservative nature of design environments