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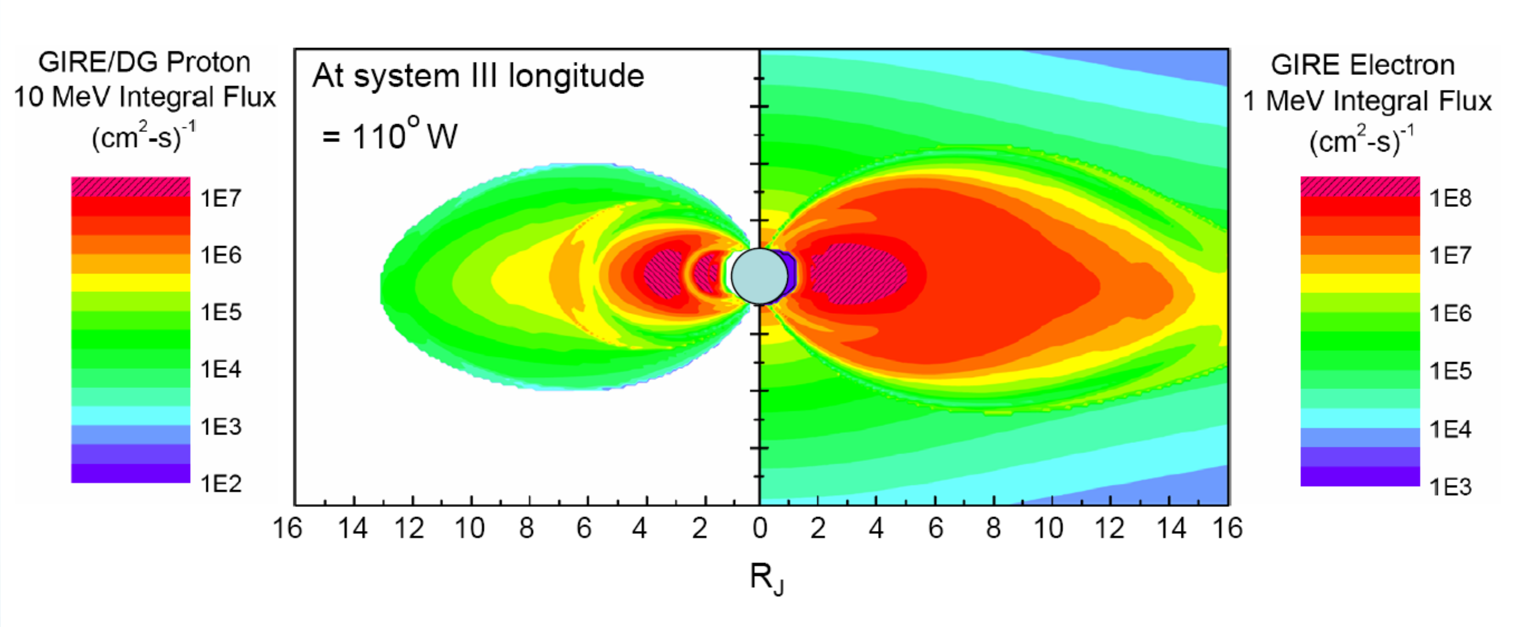
Radiation Effects on Satellites—A JPL Perspective



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Radiation Effects on Satellites—A JPL Perspective

- **AGENDA**
  - ***Overview of Space Weather and Radiation Effects on JPL Missions***
  - ***Examples of Radiation Effects on JPL Mission Ops***
  - ***Summary***

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Overview of Space Weather and Radiation Effects on JPL Missions

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JPL Interplanetary Missions

- The Deep Space Network and its Space Flight Operations Facility are responsible for communications with spacecraft beyond Earth orbit. The DSN communicates primarily at S-band and X-band and is beginning to support higher frequency, Ka-Band:

	Transmit:	Receive:
S-Band	2110-2120 MHz	2290-2300 MHz
X-Band	7145-7190 MHz	8400-8450 MHz
Ka-Band	34200-34700 Mhz	31800-32300 MHz

SFOF

- The DSN is responsible for around the clock control and data receipt for 30 active missions:

DSN

CURRENT DSN OPERATIONAL SPACECRAFT

ACE	Geotail	NExT (STARDUST)
Cassini	Hayabusa (MUSC)	ROSETTA
CHANDRA (XRO)	INTEGRAL	SOHO
Chandrayaan-1	Mars Express (MEX)	Spitzer Space Telescope
CLUSTER II (A)	Mars Odyssey	STEREO Ahead & Behind
CLUSTER II (B)	MER 1	Venus Express (VEX)
CLUSTER II (C)	MER 2	Voyager 1 (VIM)
CLUSTER II (D)	MESSENGER	Voyager 2 (VIM)
DAWN	MRO	WIND
EPOXI (Deep Impact)	New Horizon	WMAP
MSL	Juno	Grail

JPL Terrestrial Missions

- **JPL Division 88 (Earth Science Missions) is responsible for the following Earth missions and instruments:**
  - Atmospheric Infrared Sounder (AIRS)
  - Advanced Spaceborne Thermal Emission and Reflection (ASTER)
  - Multi-Angle Imaging Spectroradiometer (MISR)
  - Microwave Limb Sounder (MLS)
  - Tropospheric Emission Spectrometer (TES)
  - Active Cavity Radiometer Irradiance Monitor (ACRIM) Satellite
  - Cloudsat
  - Gravity Recovery and Climate Experiment (GRACE) Satellite
  - Jason-1/2 Satellites
  - Quikscat

Space Weather Effects on JPL Ops

- **Space Weather Effects on Communications**
  - JPL operates primarily at S-band and X-band and is beginning to support higher frequency Ka-Band to avoid Earth weather and ionospheric scintillation.
  - Solar wind density and planetary ionospheres affect signal propagation (the effects are used to evaluate planetary ionospheres)
- **Space Weather Effects on Spacecraft Performance/Anomalous Behavior**
  - *Cumulative Radiation Effects (TID, DDD)*
  - *SEE: Single Event Upsets, Latch-up, Single Event Transients, etc.*
  - Surface Charging/Wake Effects (Solar Wind, Aurora, Geosynchronous Orbit)
  - *Internal Charging (Radiation Belts)*
  - Power Loss (Plasmas)
  - VxB Electric Fields
  - Surface Degradation/Erosion (Oxygen Erosion, Ion Sputtering, Comet Dust)
  - Space Debris/Micrometeoroid Impacts (e.g., Meteor Streams, Dust Rings, etc.)
  - "Exotic Environments": Glow, Lightning (Venus, Jupiter), Io Volcanoes, Titan Seas, Dust (Mars, Moon), etc.

Examples of Radiation Effects on JPL Mission Ops

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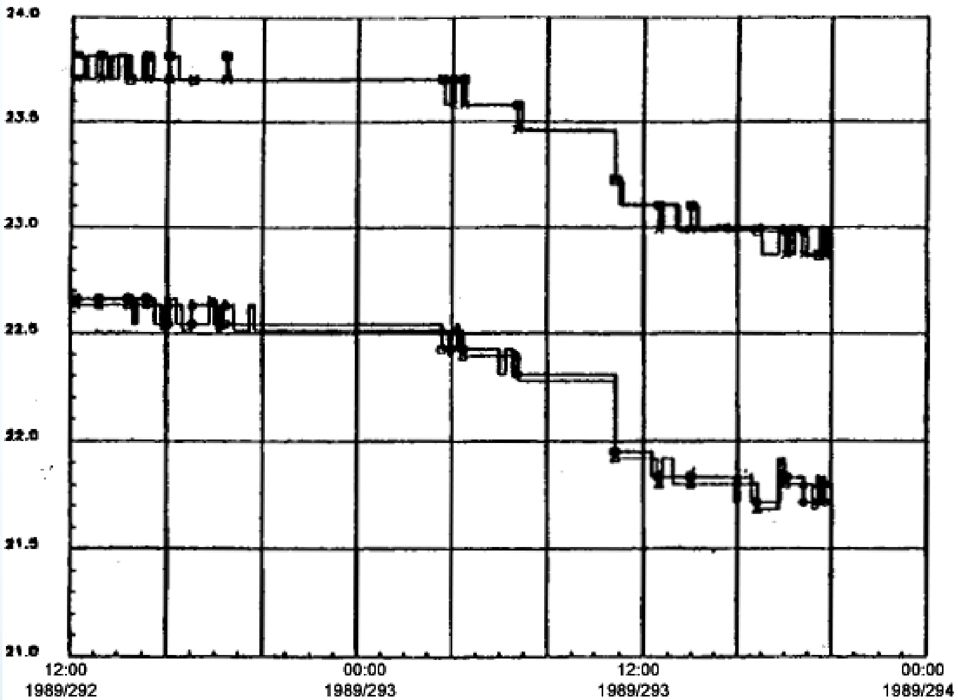
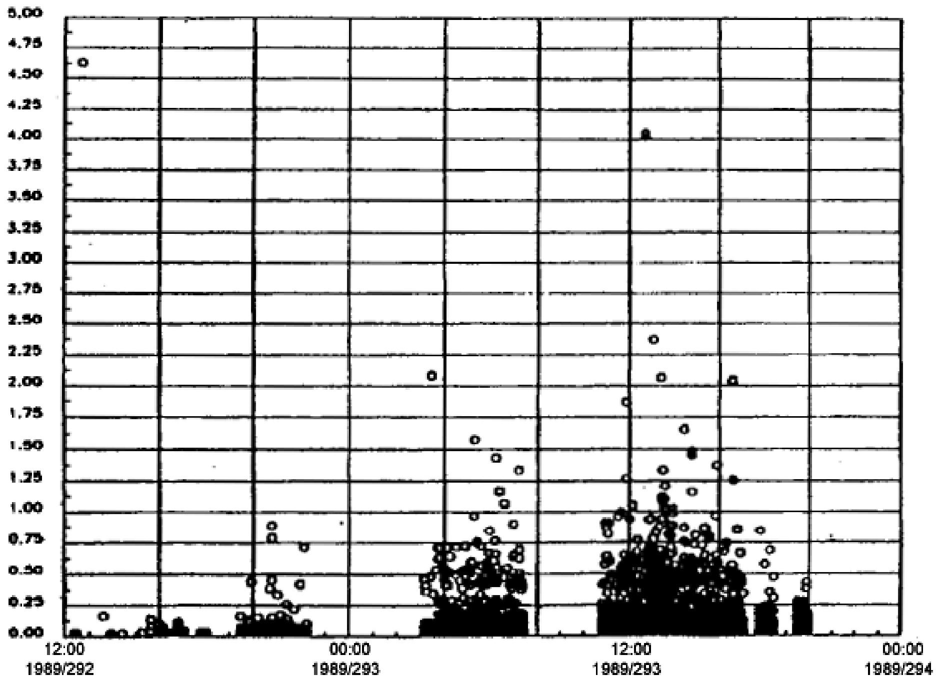
1989 Solar Proton Event Effects on Venus Magellan Mission

SOLAR ARRAY CURRENT



STAR SCANNER VOLTAGE



Lessons Learned: Need SPE forecast to prepare for operational impacts (e.g., loss of power and attitude control)

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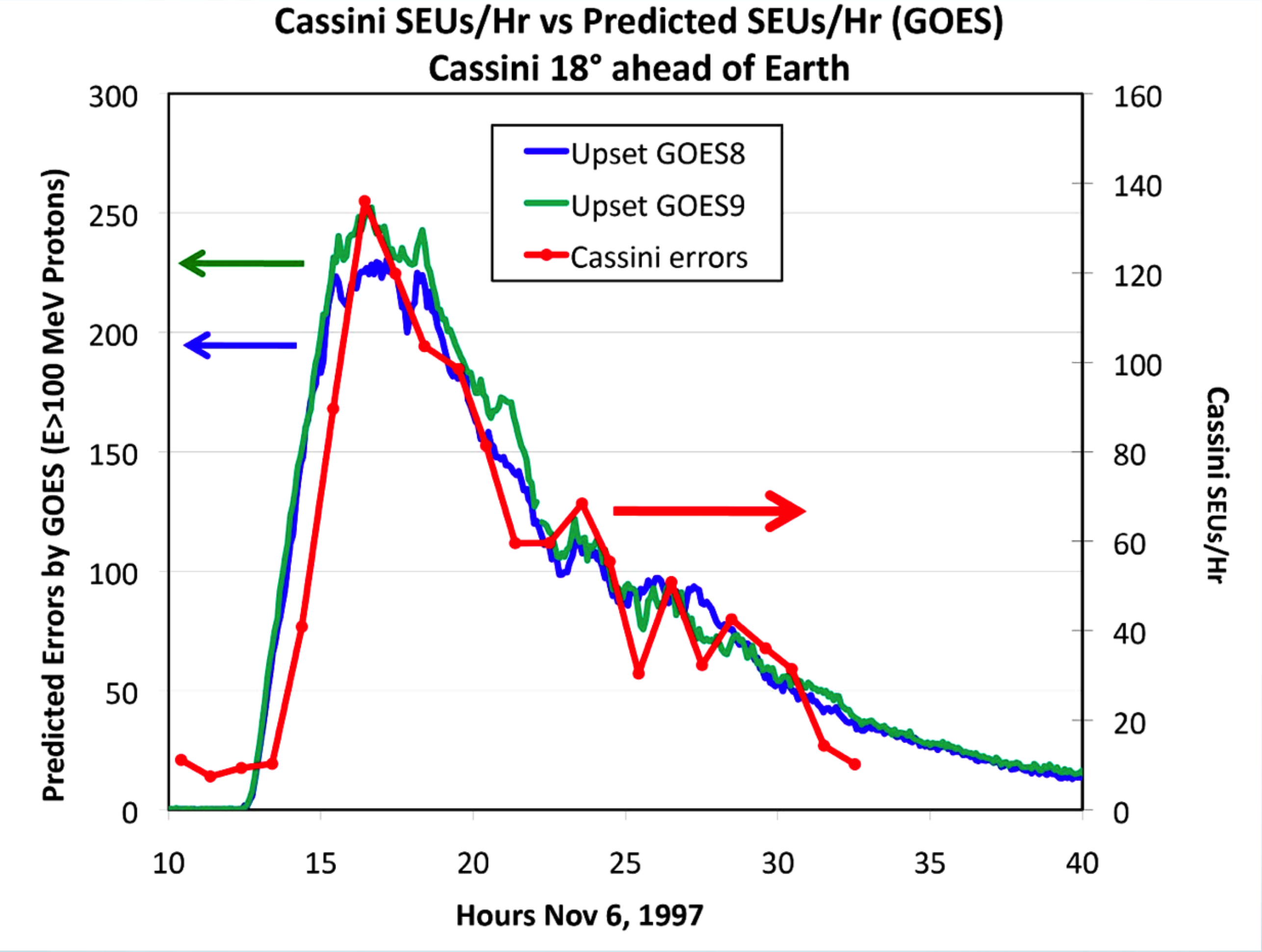
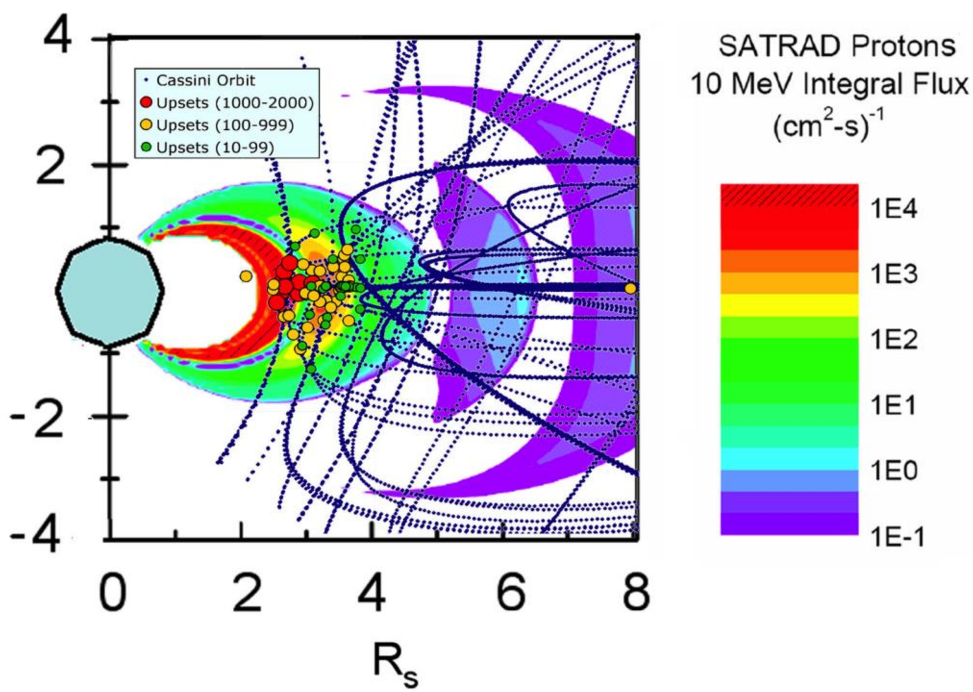
Solar Proton Event (SPE) Effects on Cassini



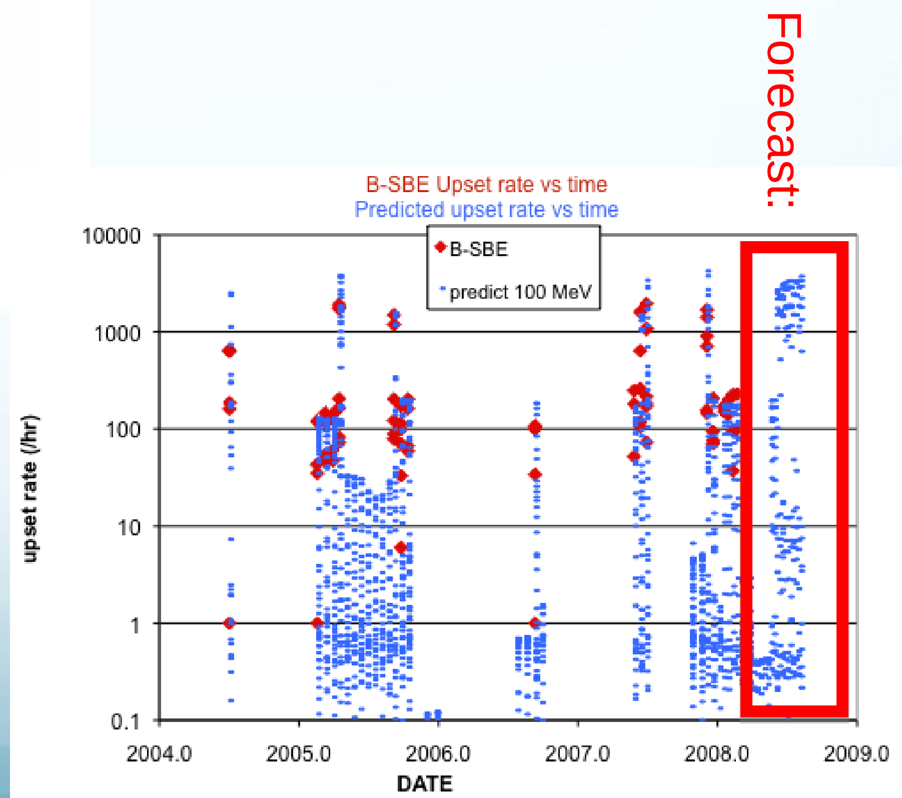
Lessons Learned: Real Time SPE Observations can Predict Effects on Ops (Cassini Solid State Recorder Upsets)

Trapped Proton Effects on Cassini



Upsets along Cassini orbital traces overlaid on SATRAD >10 MeV proton flux predictions

Observed (through mid-2008) vs predicted (SATRAD >100 MeV proton fluxes) hourly upsets



Lessons Learned: Radiation belt models can predict upsets and drive Ops planning even at Saturn!

Space Weather Effects on JPL Ops During the 2003 Halloween Storms

Oct 23: Genesis at L1 entered safe mode. Normal operations resumed on Nov. 3

Oct 24: Midori-2 Polar satellite failed (Spacecraft charging…)

Stardust comet mission went into safe mode; recovered.

Oct 28: ACE lost plasma observations.

Mars Odyssey entered Safe mode

Oct 29: During download Mars Odyssey had a memory error

MARIE instrument powered off (has NOT recovered)

Oct 30: Both MER entered "Sun Idle" mode due to excessive star tracker events

Two UV experiments on GALEX had excess charge so high voltages turned off.

Nov. 6 Mars Odyssey spacecraft commanded out of Safe mode; operations nominal.

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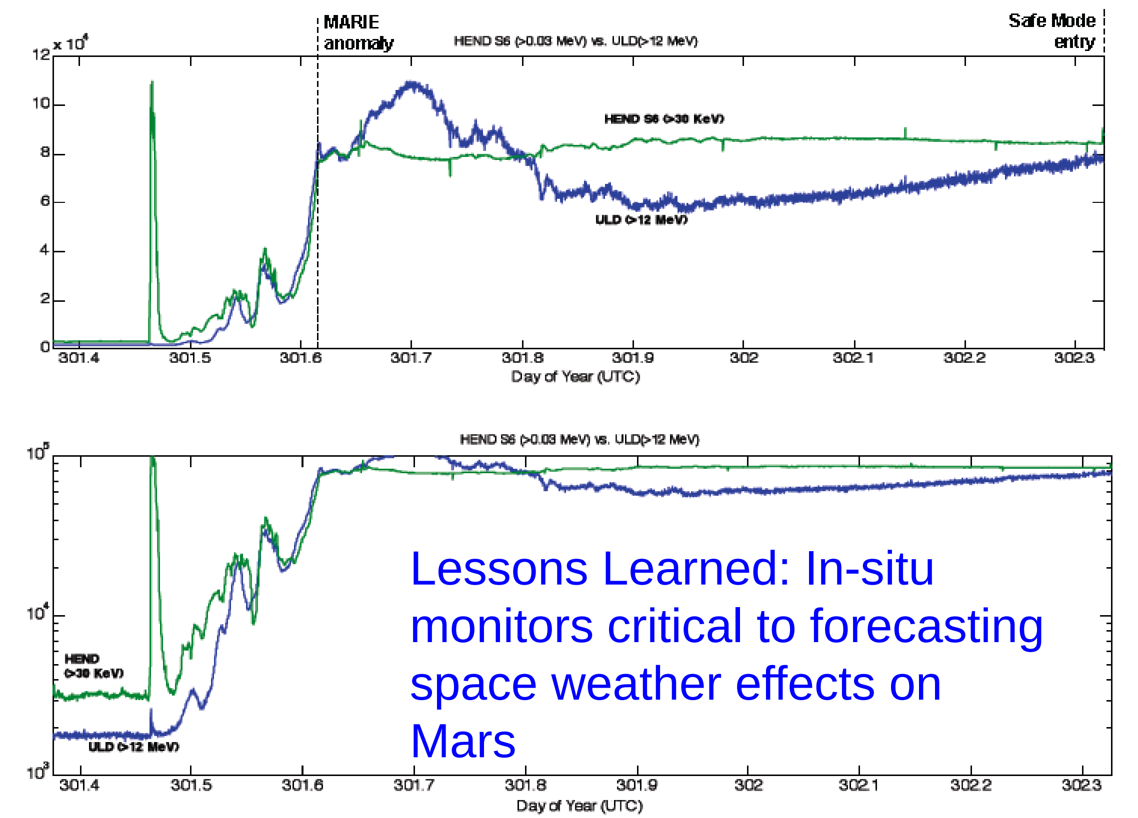
Space Weather Effects on Ops At Mars

Mars Odyssey High Energy Neutron Detector

Safe mode entry Oct. 28-29, 2003 (linear & log scales)



Lessons Learned: In-situ monitors critical to forecasting space weather effects on Mars

Oct 28: Mars Odyssey entered Safe mode

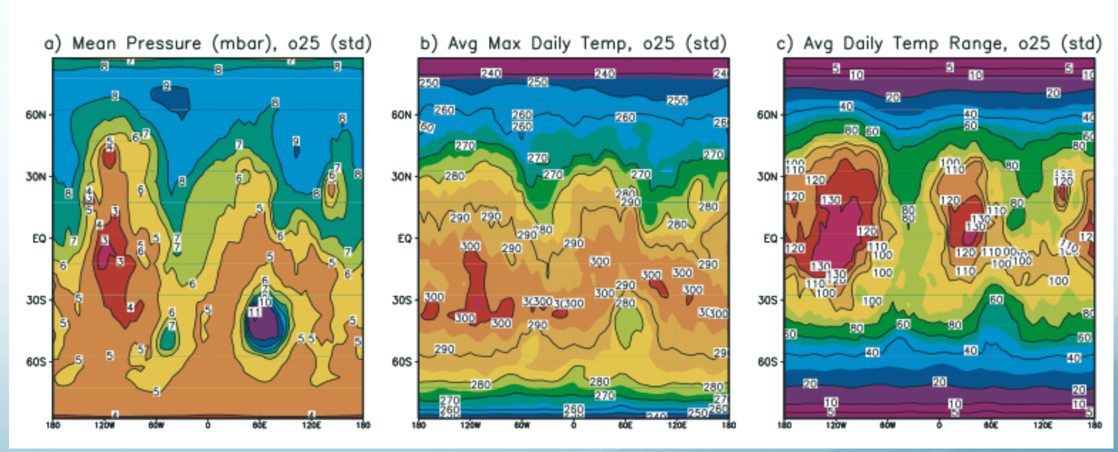
Oct 29: During download Mars Odyssey had a memory error

MARIE instrument powered off (has NOT recovered)

Space Weather Effects at Mars Surface

SEUs visible in MER PanCams on Martian surface

Lessons Learned: Multiple models may be required to forecast space weather



Martian GCM

To forecast SEU effects, need to propagate high energy SPE H, He, C, O, Si, Fe ions and GCR through the Martian atmosphere and then through sensitive systems

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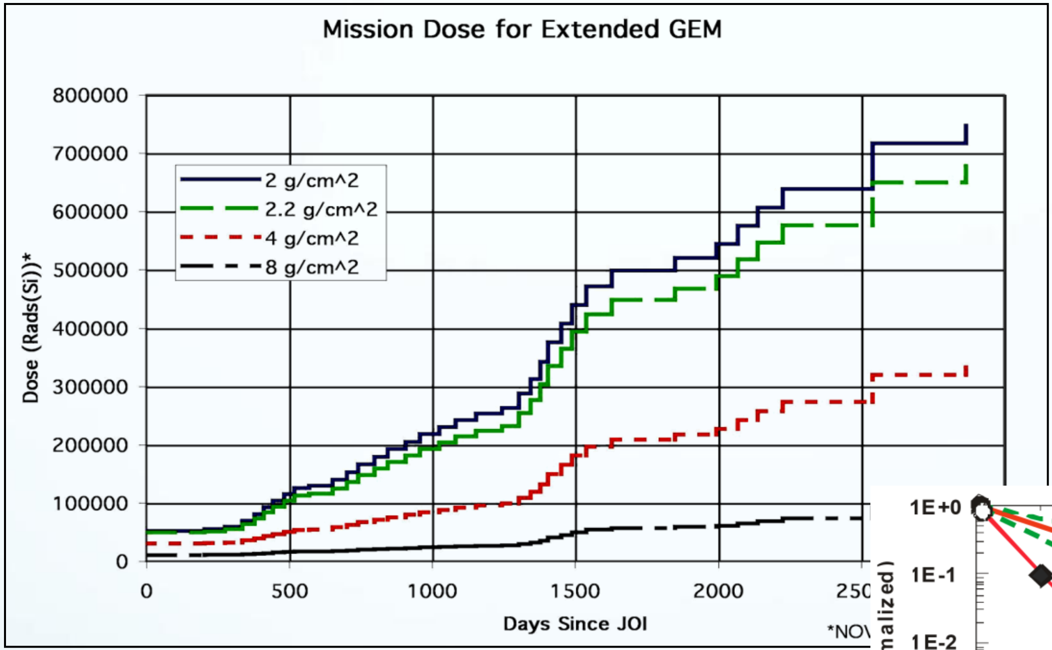
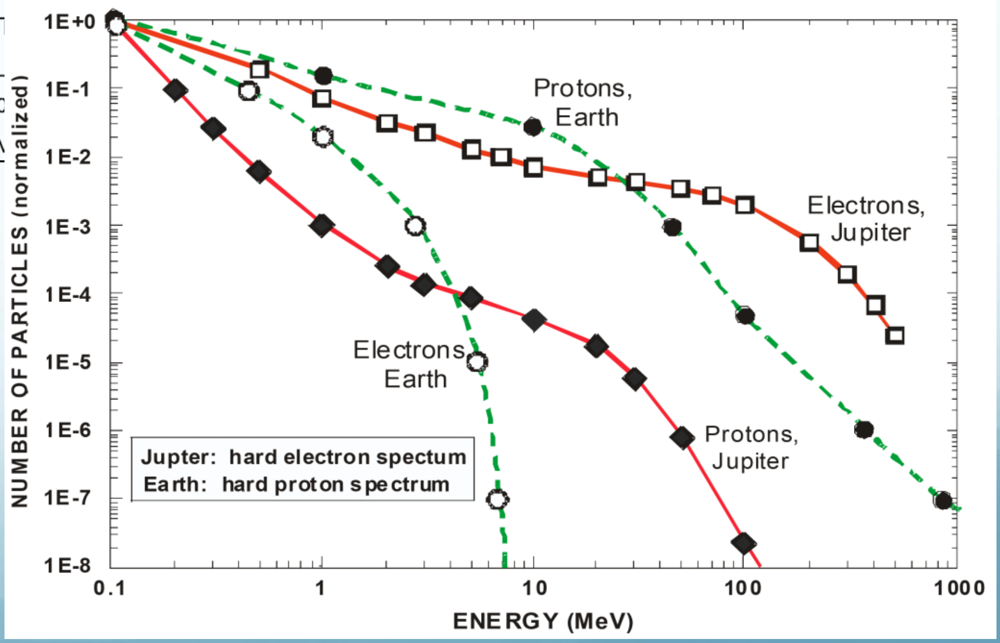
Jovian Mission Doses

Galileo Mission Dose Estimates



Jovian vs Terrestrial Radiation Spectra



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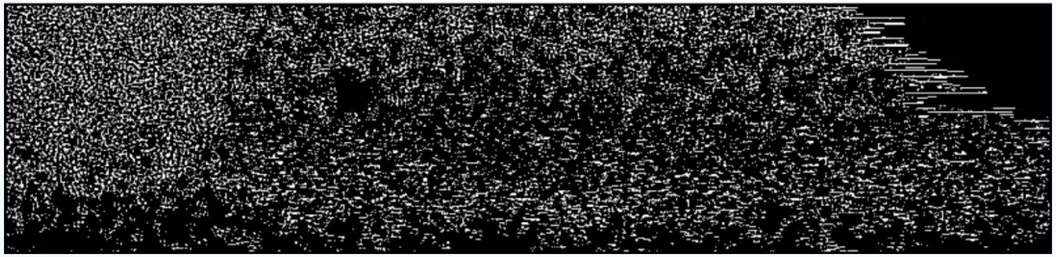
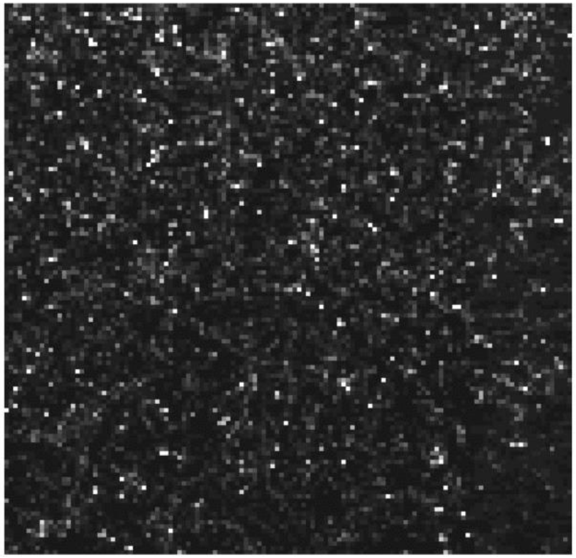
Example of Galileo SEU trails near Europa





CCD IONIZATION TRAILS:

- **Radiation exposure 1.7 s for bottom; 7.5 s for top. Pixels are 15x15x10 um.**
- **Top is raw image stretched to show hits.**
- **Second is difference between raw image and median filtered image to emphasize hits.**
- **CCD protected by 1 cm of tantalum. Hits are probably from secondaries generated in tantalum.**
- **Taken ~10,000 km from Europa (white spot in first picture).**
- **Last picture is blow up to show upsets.**

Courtesy Alan Delamere, Ball Aerospace, Ken Klaasen, JPL

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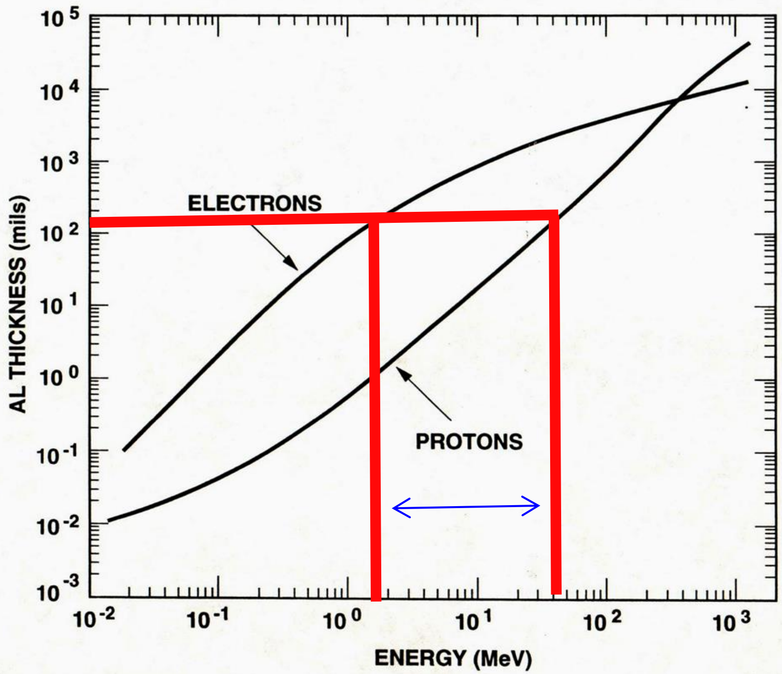
Internal Electrostatic Discharge— Attack of the Killer Electrons…

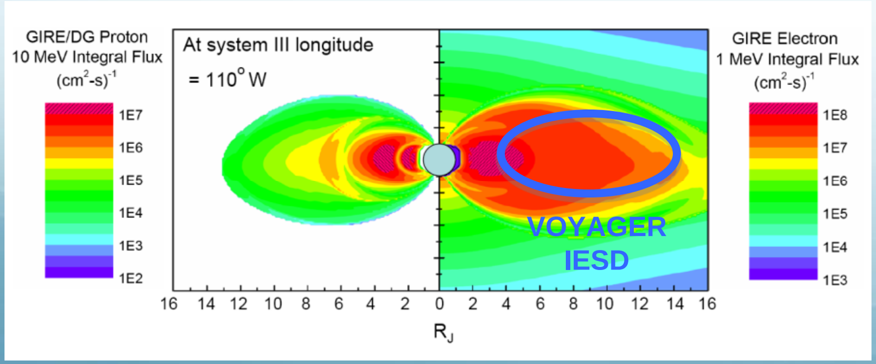
CHARGED PARTICLE INTERACTIONS

PROTON/ELECTRON ENERGY vs PENETRATION DEPTH FOR AL

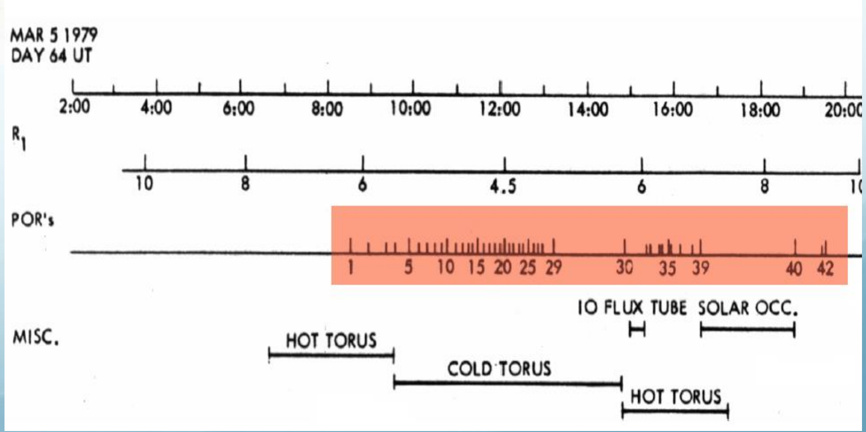


DISCHARGES IN DIELECTRICS

Lichtenberg Pattern



Occurrence Frequency Of Voyager 1 PORs



42 IESD Events on Voyager 1!!!

Summary

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Summary

- **WHAT ARE THE PRIMARY SPACE WEATHER/RADIATION CONCERNS FOR JPL MISSIONS?**
  - SPACE RADIATION EFFECTS HAVE IMPACTED JPL MISSION OPS AND ARE POTENTIALLY EXPENSIVE PROBLEMS
  - THERE ARE STILL UNKNOWN EFFECTS OF SPACE WEATHER ON SPACE OPS
  - PROPER DESIGN AND FORE-KNOWLEDGE (CLIMATOLOGY AND REAL TIME FORECAST) CAN LIMIT IMPACT OF RADIATION ON OPS
- **WHAT CAN WE DO?**
  - DESIGN: EVALUATE THE MISSION AND OPS PLANS USING AN INTEGRATED APPROACH THAT INCLUDES RADIATION EFFECTS
  - BUILD: REQUIRE ADEQUATE TESTING (RECOMMEND ENGINEERING TEST MODEL!) IN THE RELEVANT SPACE WEATHER AND RADIATION CONDITIONS UNDER REALISTIC OPS
  - LAUNCH: DEFINE SPACE RADIATION LAUNCH CRITERIA FOR JPL MISSIONS
  - FLIGHT: DURING FLIGHT, EVALUATE EFFECTIVENESS OF RADIAITON FORECASTS AND MITIGATION METHODOLOGIES ON OPS
  - POST FLIGHT: USE OPS EXPERIENCE TO UPDATE RADIATION MODELS AND DESIGN TECHNIQUES

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