Radiation Environments of Outer Planets

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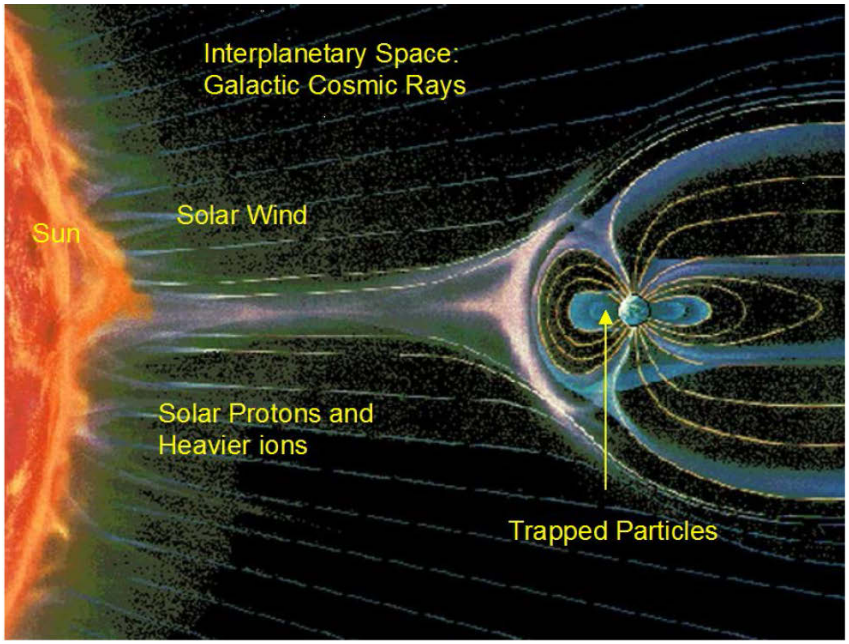
Topics

- Solar wind
- Magnetosphere
- Comparative planetary magnetospheres
- Radiation/plasma environments of giant gas planets:
  - Jupiter
  - Saturn



- Bonus Coverage: Mars – Early results from MSL

Solar Wind

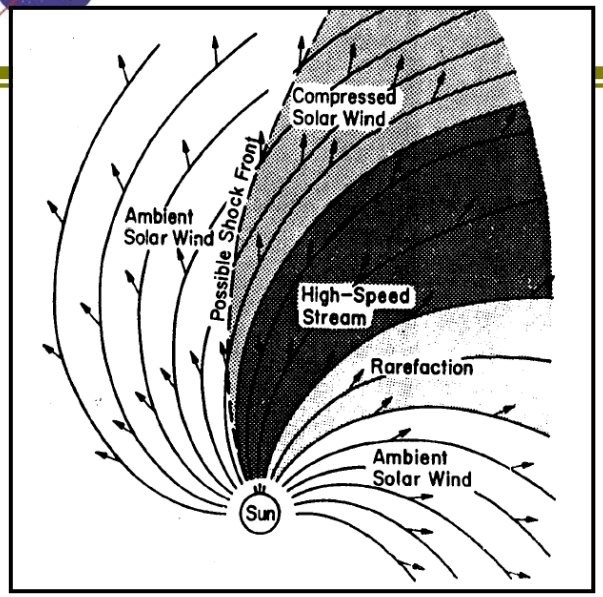
Solar Wind General Characteristics

- The Sun makes itself known throughout much of the Solar System by the influence the solar wind of high-speed charged particles constantly blowing off the Sun. The solar wind may be viewed as an extension of the outer atmosphere of the Sun (the corona) into interplanetary space.

- Stream of charged particles from Sun's corona:
  - Electrons
  - Protons
  - Heavy ions
- Plasma (Equal mixture of positive and negative charged particles)
- Velocity ~300 – 2500 km/s (~400 km/s average)
- Energy ~0.5 – 2.0 keV/nuc

The Solar Wind Environment

Equatorial Plane View

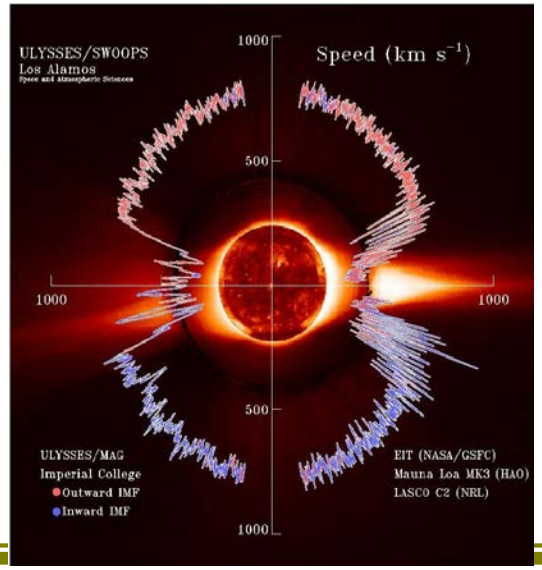


Solar Wind Parameters At 1 AU

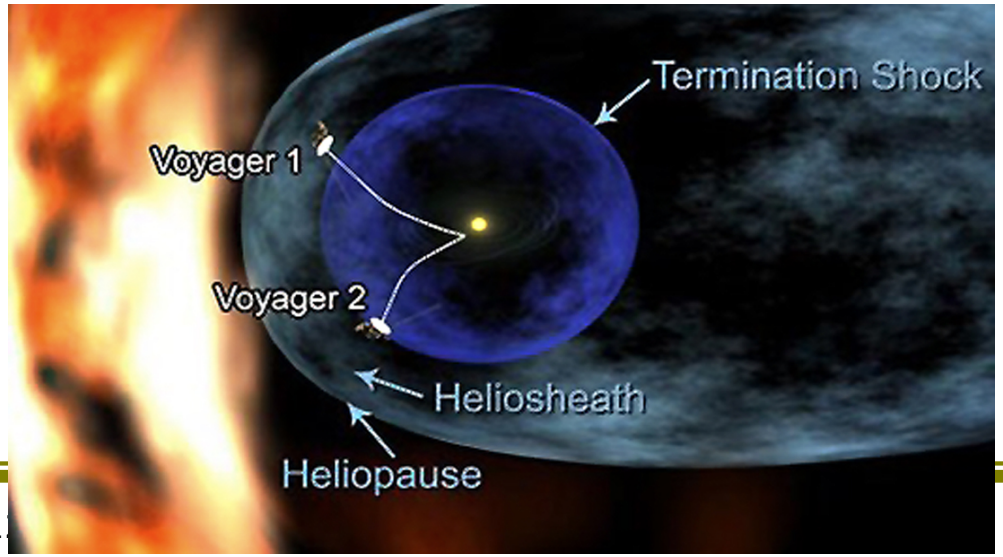
	MIN	MAX	AVG
FLUX (NO#/CM^2-S)	10^8	10^{10}	2-3X10^8
VELOCITY (KM/S)	200	2500	400-500
DENSITY (NO#/CM^3)	0.4	80	5-10
T (eV)	0.5	100	20
T_{max}/T_{avg}	1.0*	2.5	1.4
HELIUM RATIO (N_{He}/N_H)	0.0	0.25	0.05
FLOW DIRECTION	±15° from radial;		~2° East
ALFVEN SPEED (KM/S)	30	150	60
B (γ)	0.25	40	6

*isotropic

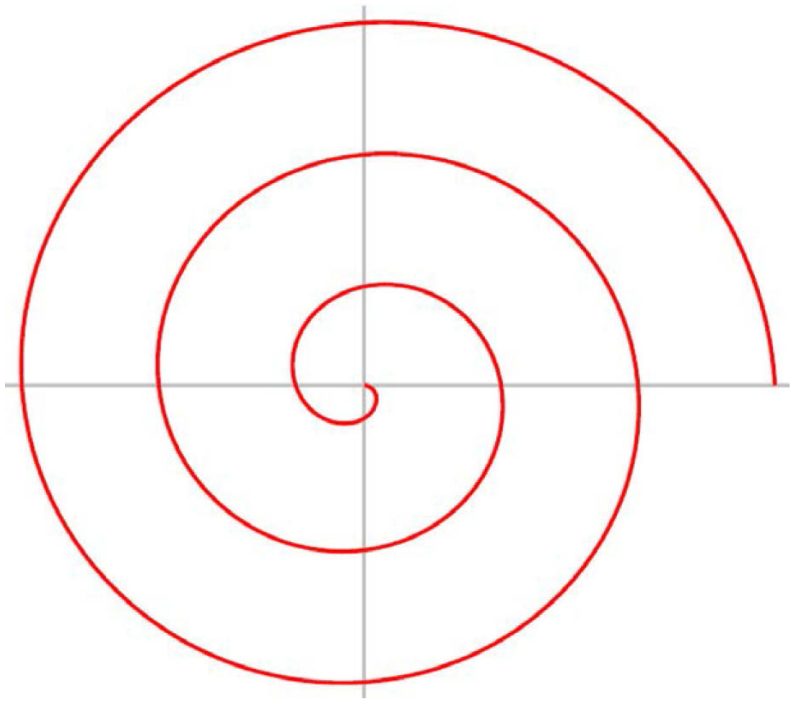
Meridionial View

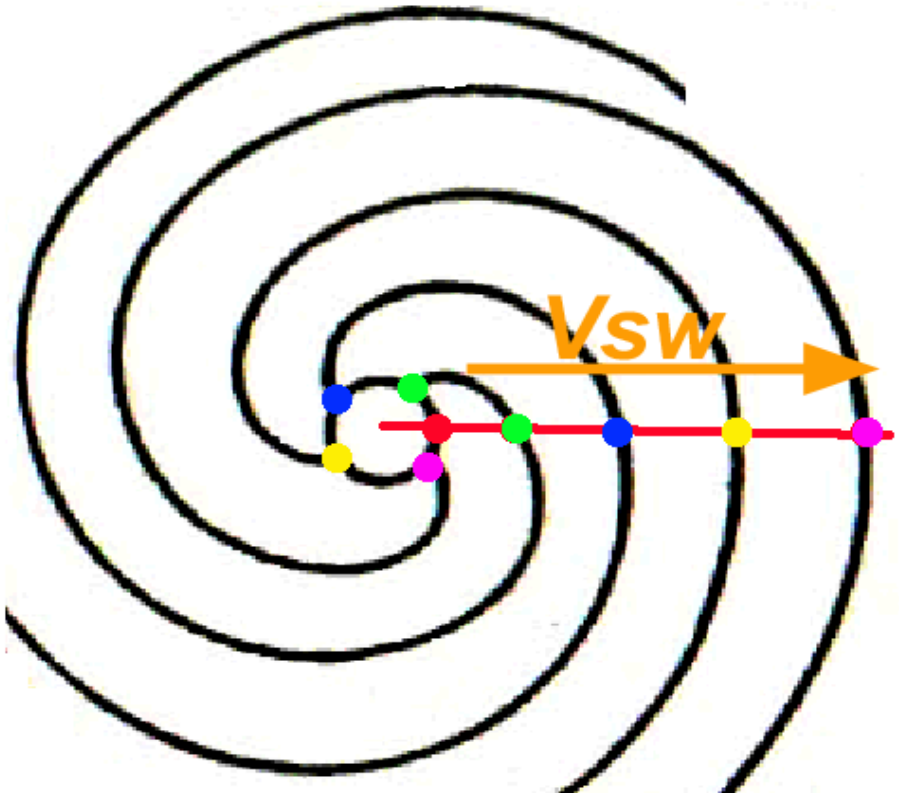


The Solar Heliosphere



The Solar Wind Environment





Archimedean (or Parker) Spiral

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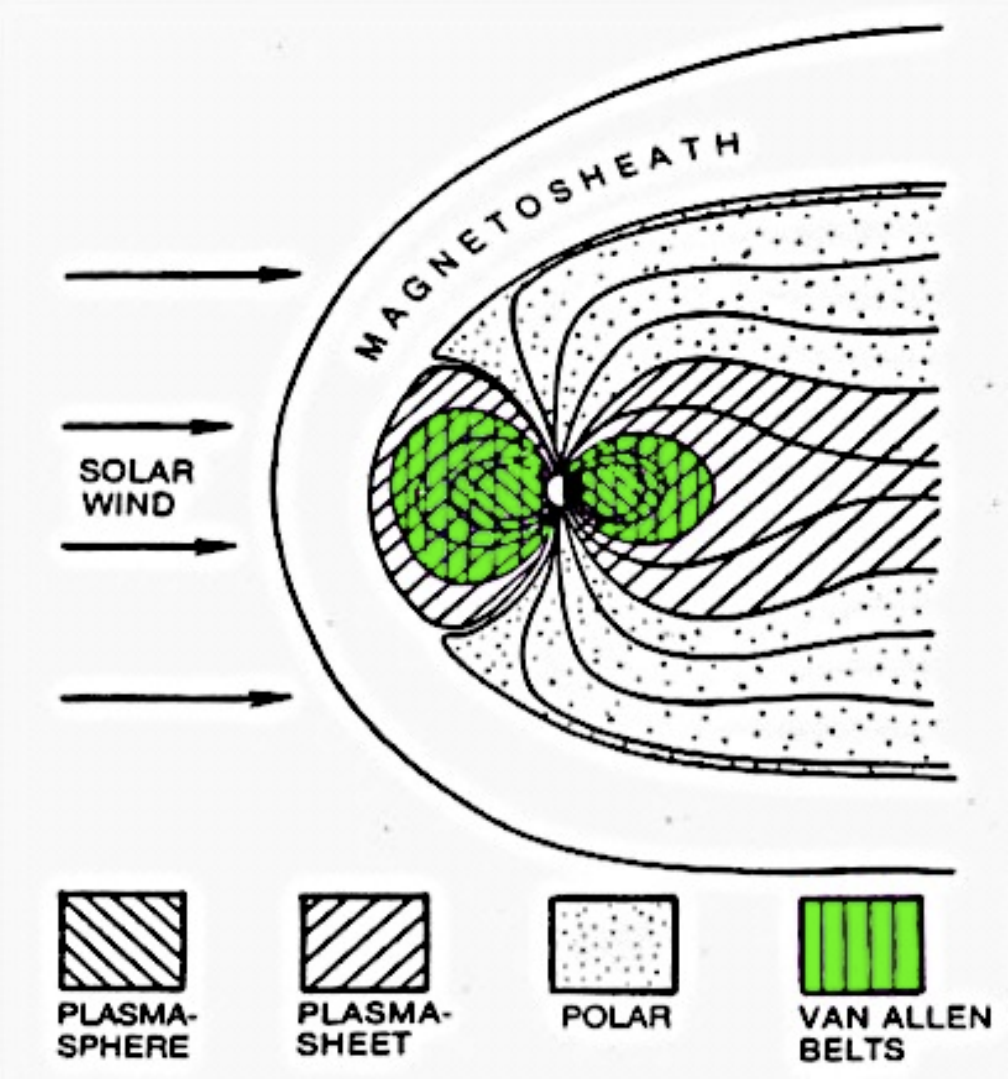
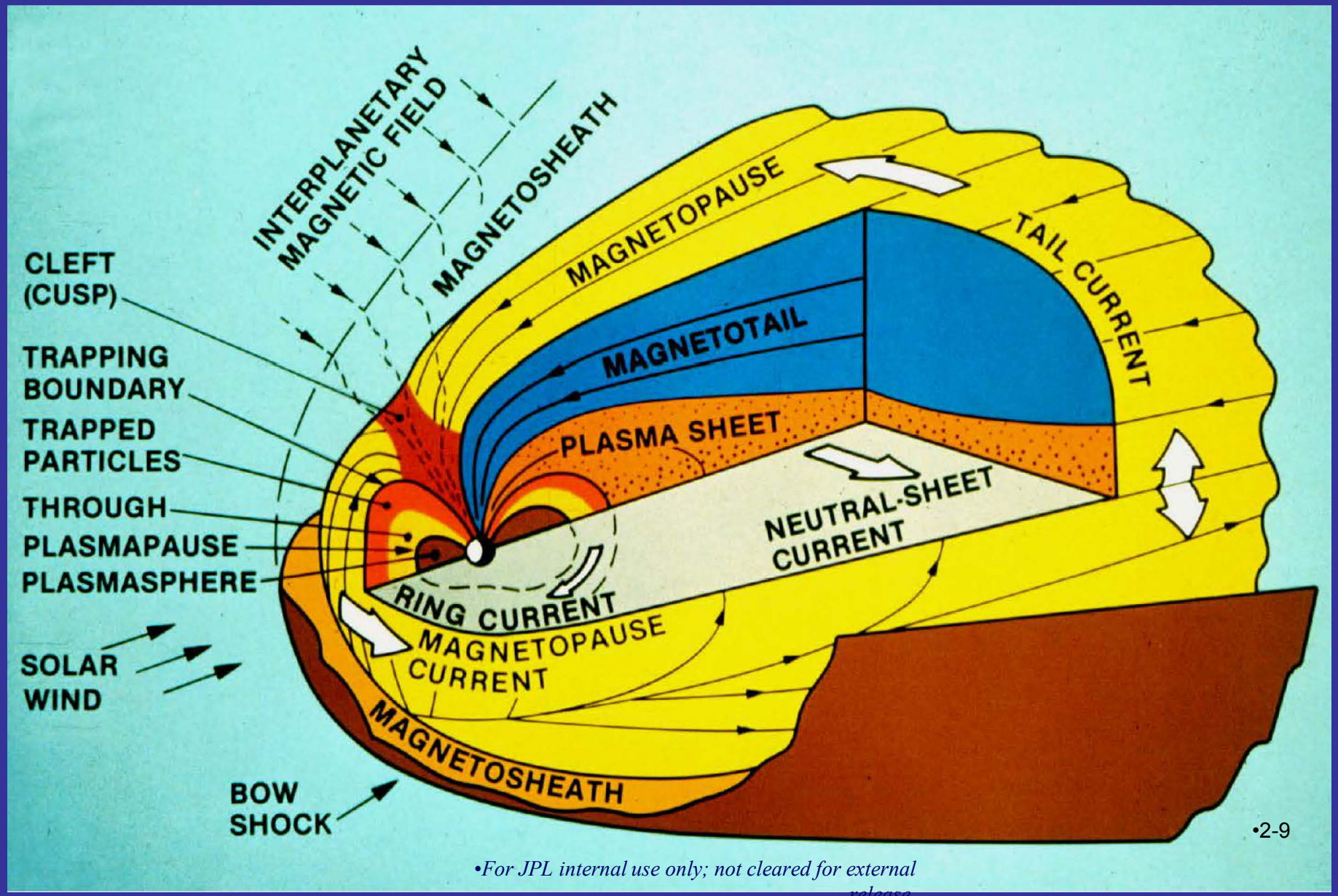
Magnetosphere

Basic Structure of a Magnetosphere



The Earth's Magnetosphere



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Jupiter

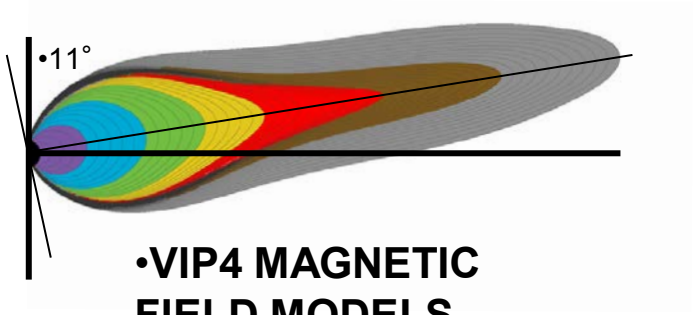
AGENDA

- Jovian magnetosphere
- Status of current models of Jovian radiation environment
  - Jovian magnetosphere overview (magnetic field, plasma torus/disc, aurora)
  - Divine radiation model, GIRE (Galileo Interim Radiation Electron) model update, Inner Belts update for electrons, GIRE2, and JOSE model
  - Statistical variations of electron environment with Rj
  - HIC (Heavy Ion Counter) model of high energy O, S, and C ions
- Europa and Ganymede radiation environments
  - Overview of Europa's and Ganymede's interactions with Jupiter's magnetosphere
  - Radiation at surface of Europa and Ganymede
- Outstanding Jovian radiation environment issues

Jupiter's Magnetosphere

Characteristics	***Earth***	***Jupiter***
Equatorial radius (km)	6.38×10^3	7.14×10^4
Magnetic moment (G-cm^3)	8.1×10^{25}	1.59×10^{30}
Rotation period (hr)	24.0	10.0
Aphelion/perihelion (AU)	1.01/0.98	5.45/4.95

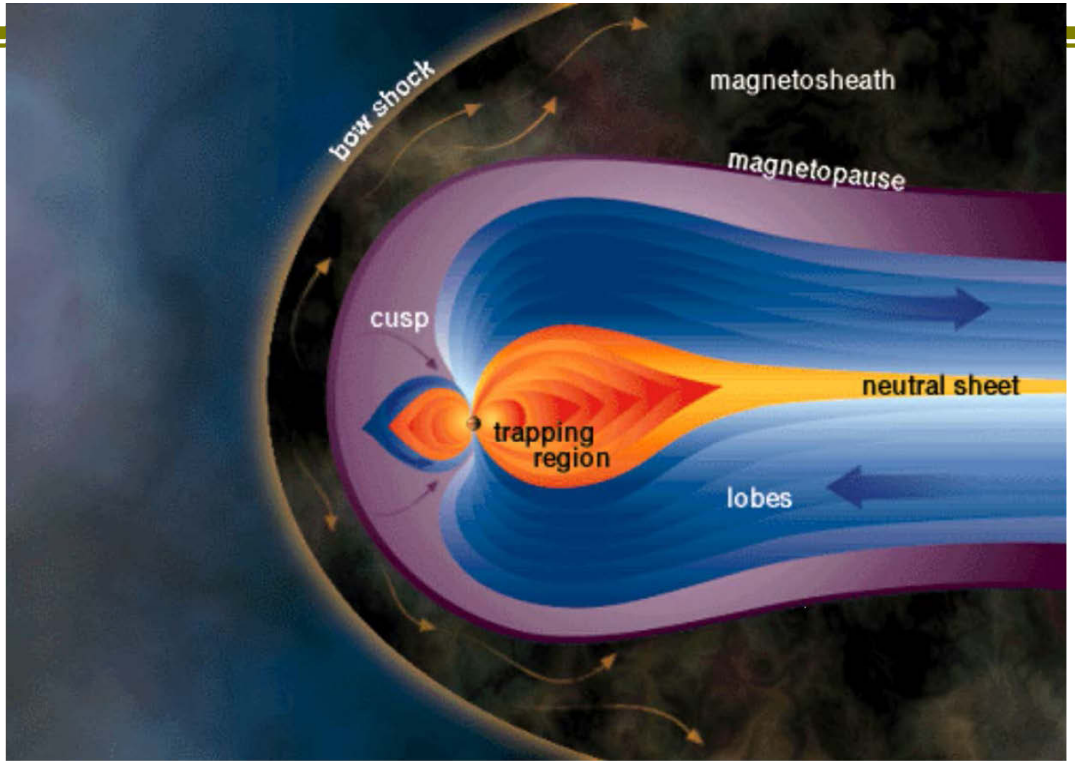
- Jupiter is roughly 10 times the size of the Earth while its magnetic moment is 2×10^4 larger.
- As the magnetic field at the equator is proportional to the magnetic moment divided by the cube of the radial distance, the Jovian magnetic field is proportionally 20 times larger than the Earth's.

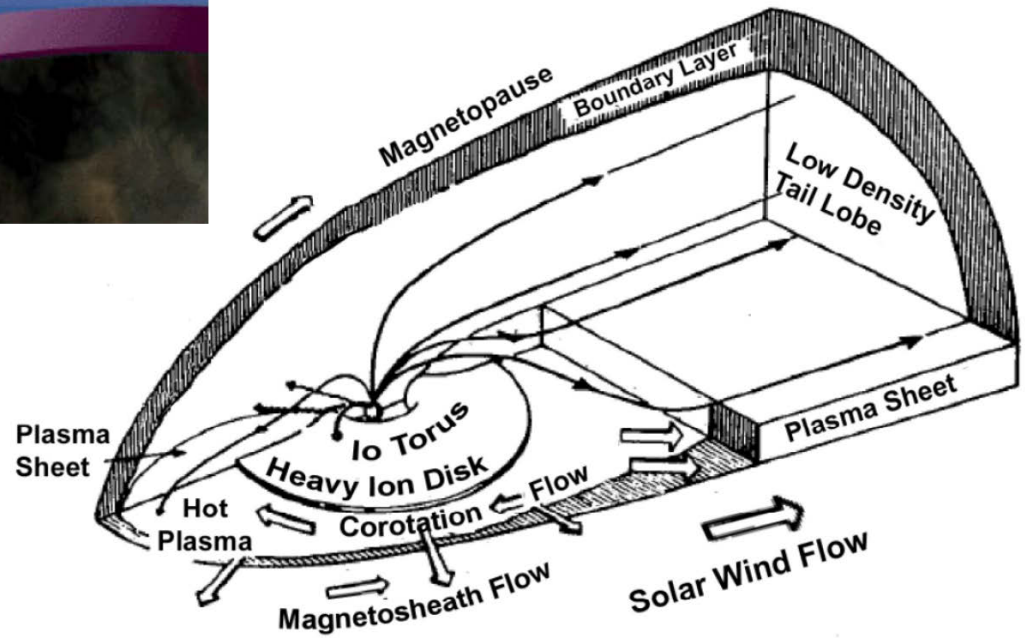


•VIP4 MAGNETIC FIELD MODELS

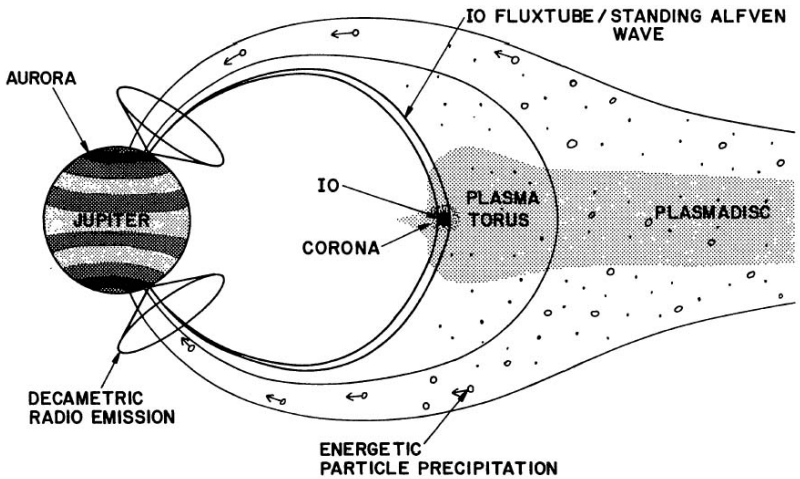
- The energy and flux levels of trapped particles in the Jovian system can be much higher than those at the Earth or in the interplanetary space.

The Jovian Magnetosphere

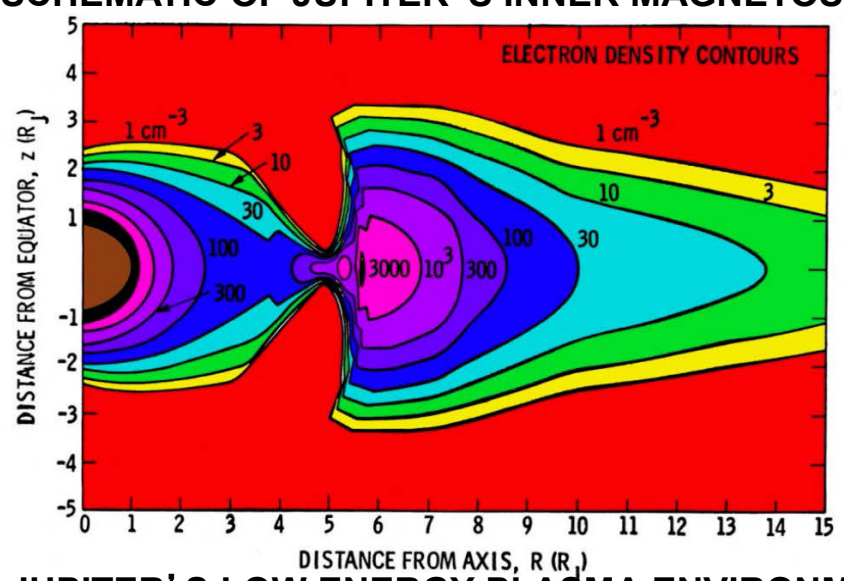




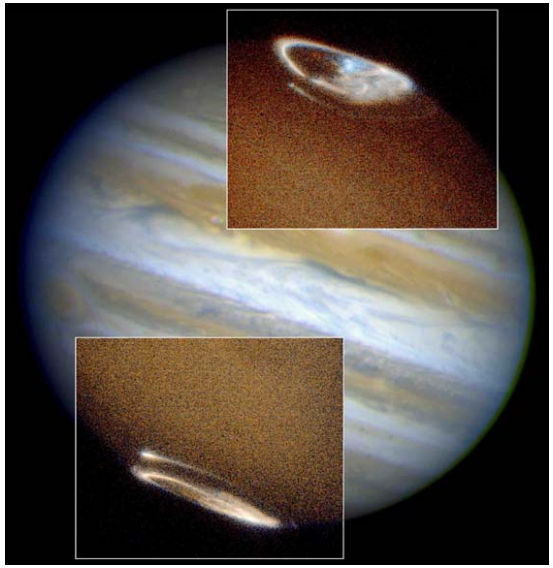
Jupiter's Plasma Environment and Aurora

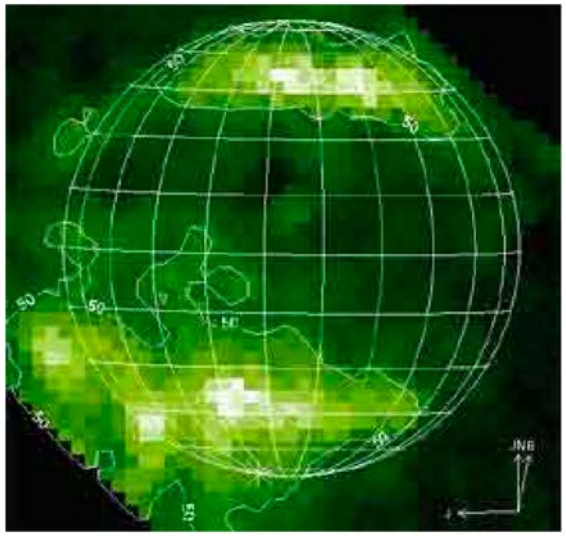


•SCHEMATIC OF JUPITER'S INNER MAGNETOSPHERE



•JUPITER'S LOW ENERGY PLASMA ENVIRONMENT



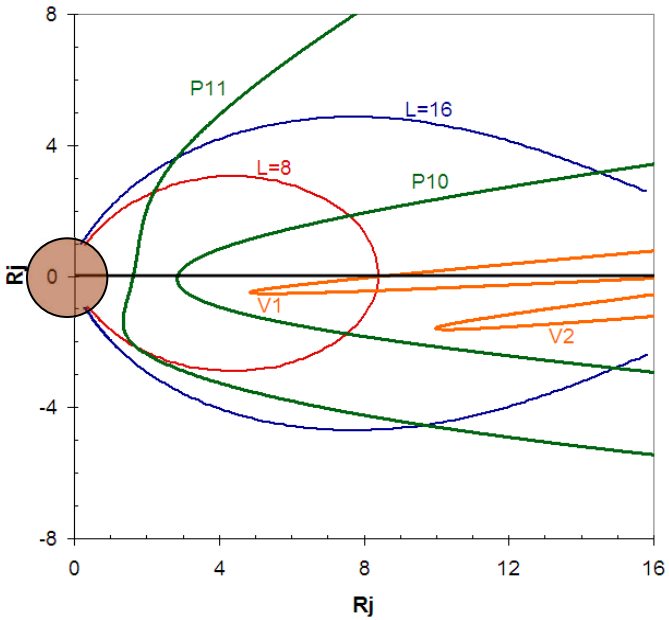


The Jovian Radiation Environment - Models

- Divine Electron and Proton Models
- Galileo Interim Radiation Electron (GIRE) Model
- GIRE2
- Salammbô
- JOSE

The Divine Model

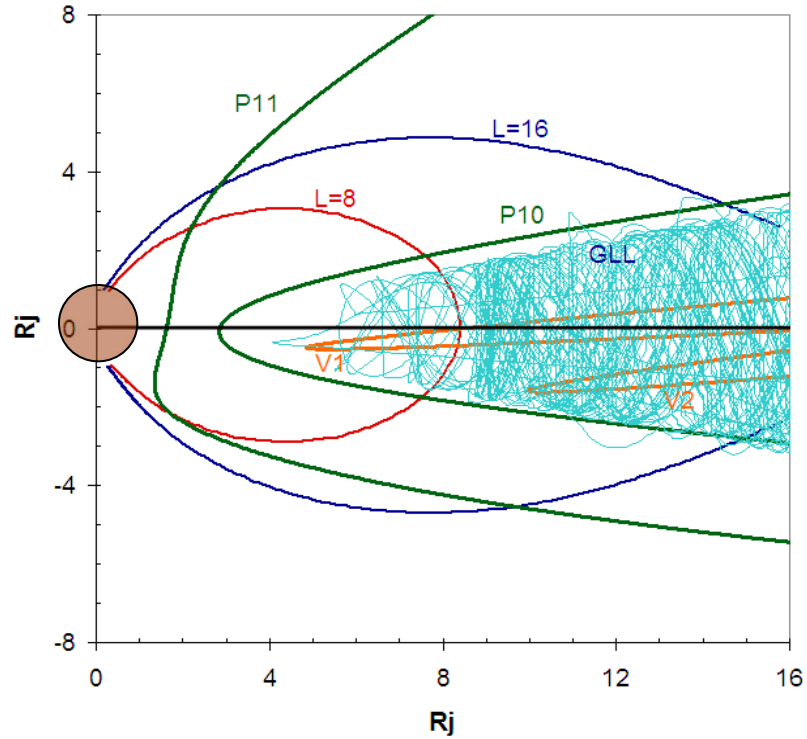
- The Divine model has been the de-facto standard Jupiter radiation model since 1983:
  - It is based on Pioneer and Voyager in-situ data plus Earth-based synchrotron observations
  - It includes models for low energy electrons and ions (~eV to ~10 keV) and high energy trapped electrons and protons (from ~100 keV to >100 MeV)
  - The model can provide radiation environment estimates for a wide spatial range (i.e., 1 < L < 12 for protons; 1 < Rj < 30 for electrons from the equatorial to the pole region) although the model itself was based on the data spatially and temporally limited



•Divine and Garrett, JGR (1983)

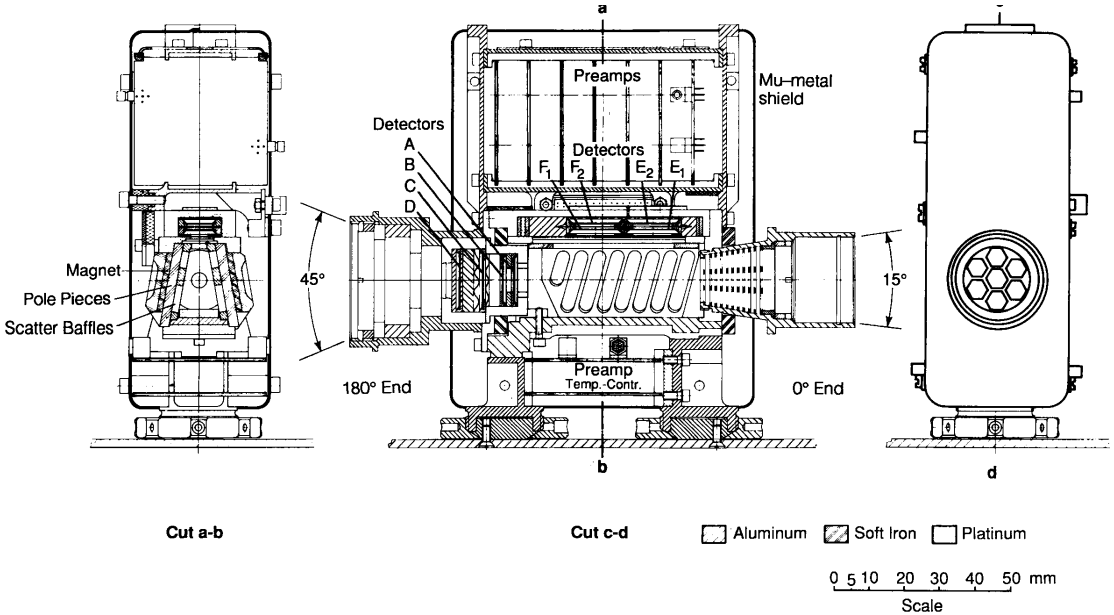
GIRE Update

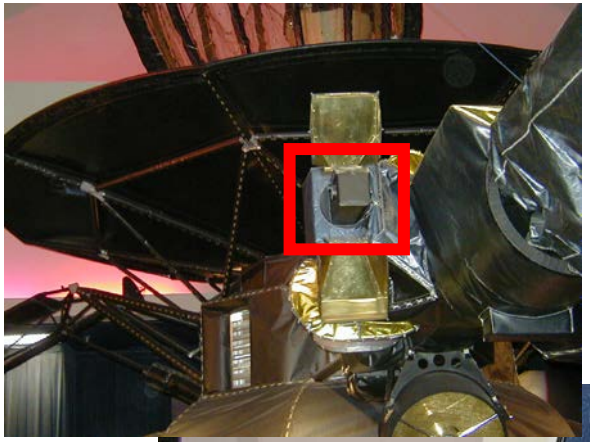
- GIRE is a significant improvement over the Divine's high energy electron model over the range of 8-16 L
- Uses in-situ data from 35 Galileo orbits – based primarily on Energetic Particle Detector data (>1 MeV electron channels)
- Assumes Divine pitch angle distributions
- Covers energy range 0.1 MeV to ~30 MeV

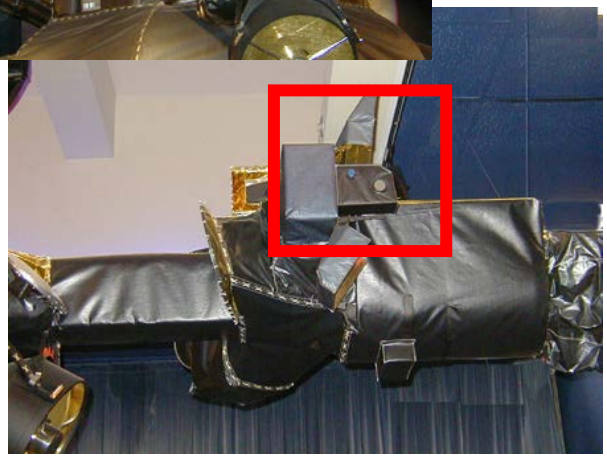


Garrett et al., JPL Publication (2003)
Jun et al., IEEE TNS (2005)

EPD (LEMMS)





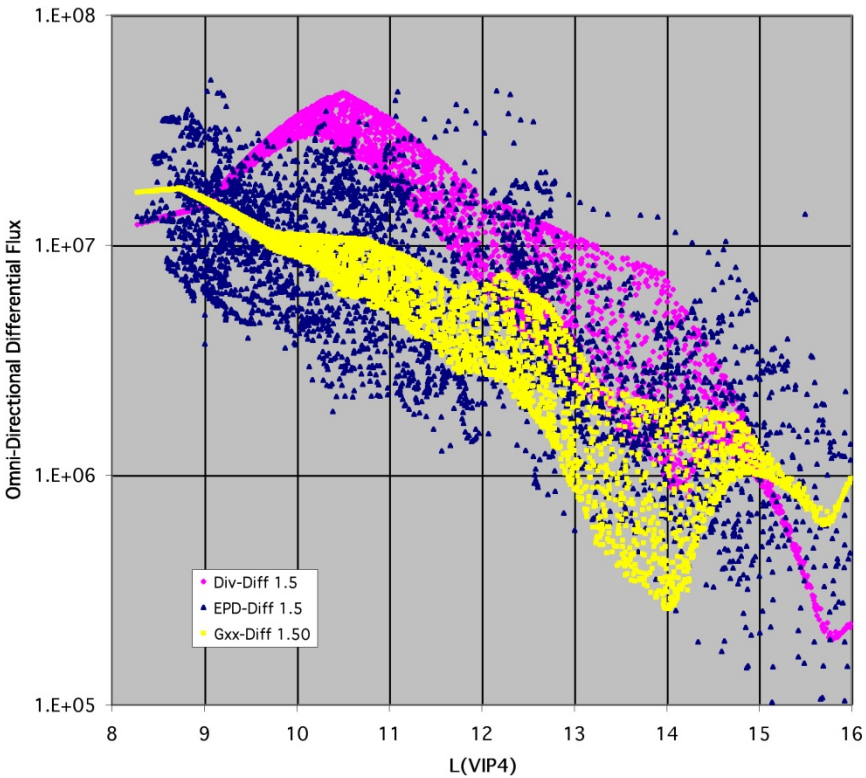


Channel Name	Nominal Energy Range (MeV)
F1	0.174 – 0.304
F2	0.304 – 0.527
F3	0.527 – 0.83
B1	1.5 – 10.5
DC2	>2.0
DC3	>11.0

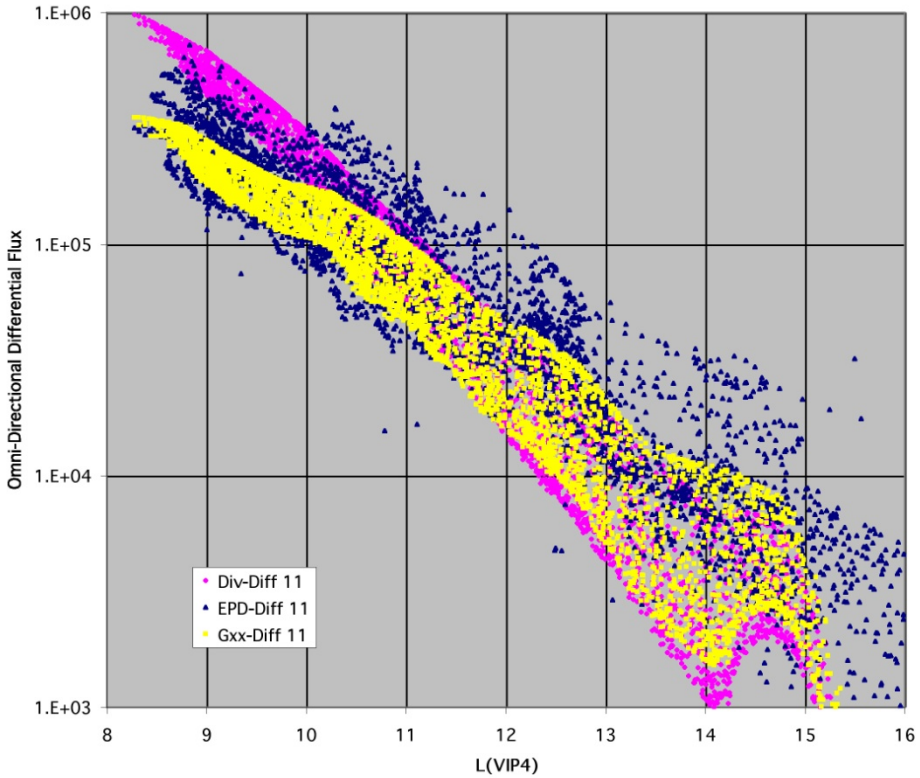
•EPD=CMS+LEMMS

Divine Model, GIRE Model, and EPD Data

Comparisons between observed EPD (blue) fluxes and Divine (pink) and GIRE (yellow) predictions



1.5 MeV ELECTRONS

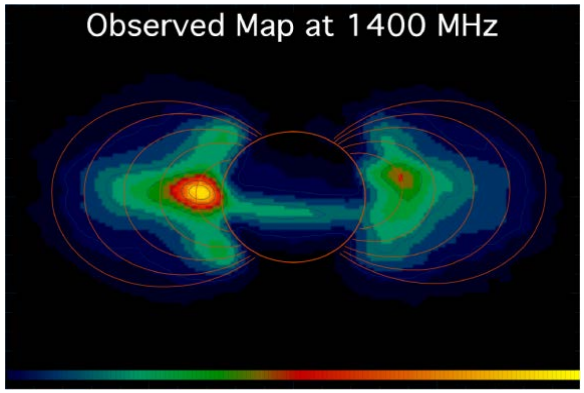


11 MeV ELECTRONS

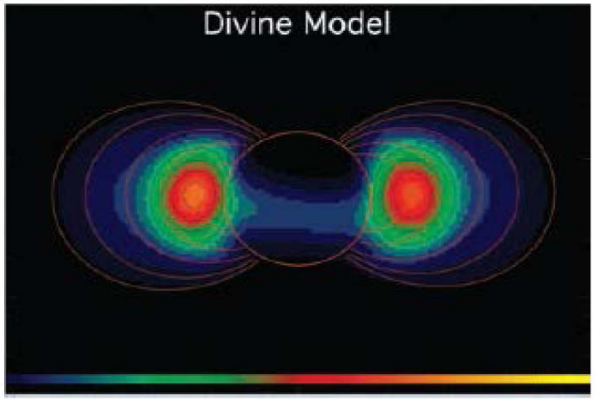
Pink = Divine; Yellow = GIRE; Blue = EPD data

Synchrotron Update

Updated the Divine Model in the L<4 region using Earth-based radio observations

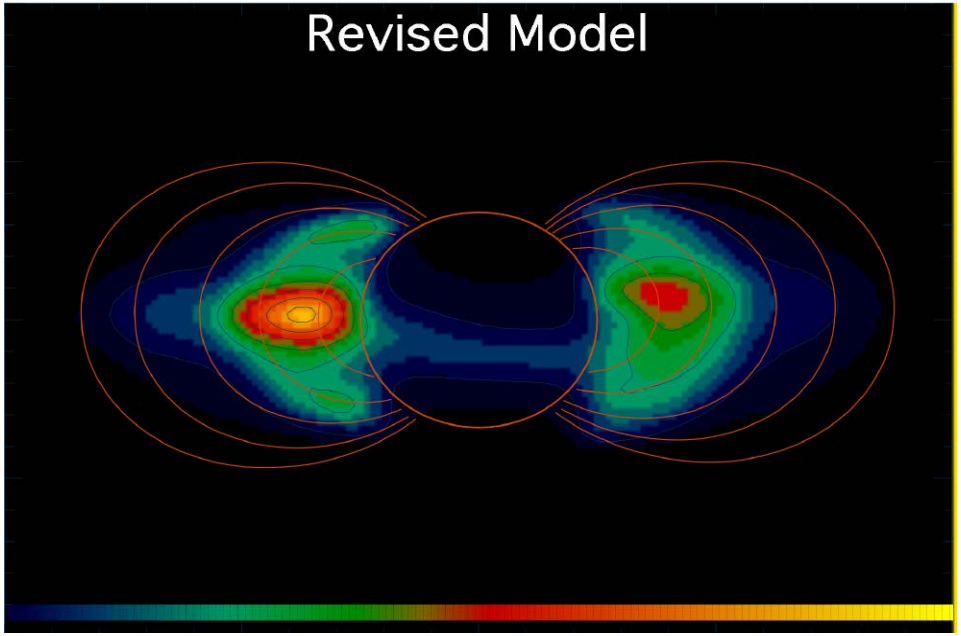


Synchrotron Observations



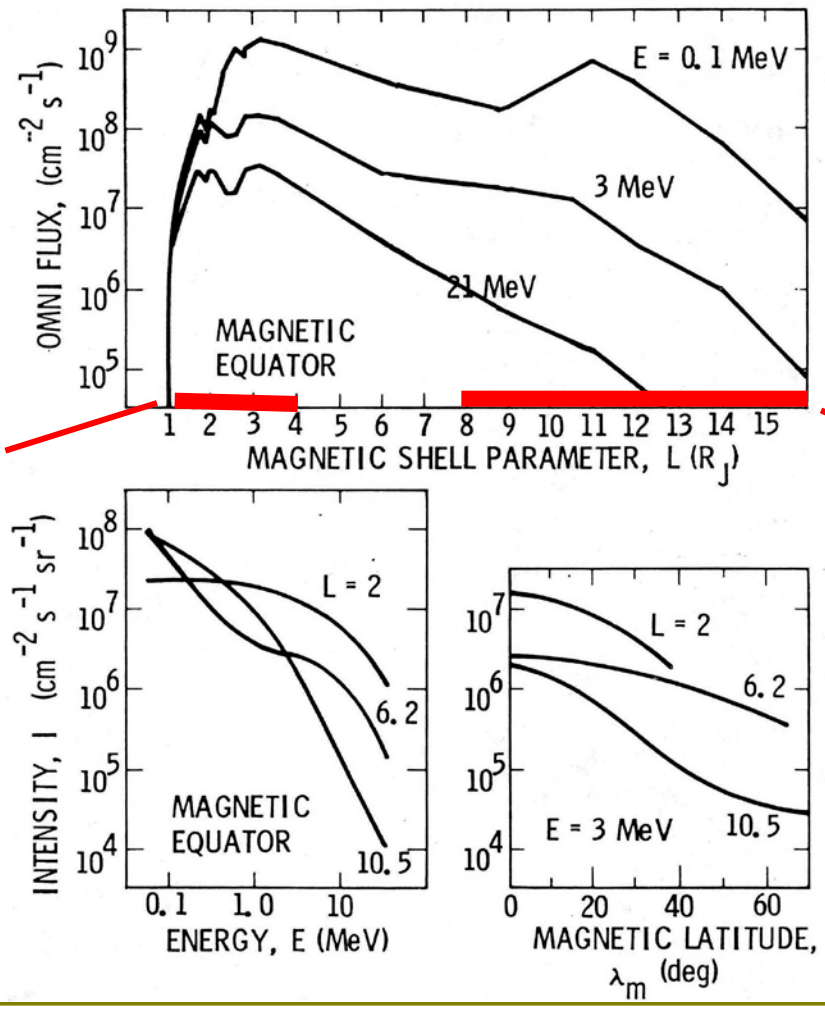
Synchrotron prediction based on the original Divine Model

Synchrotron predictions based on update to Divine Model



Garrett et al., GRL (2005)

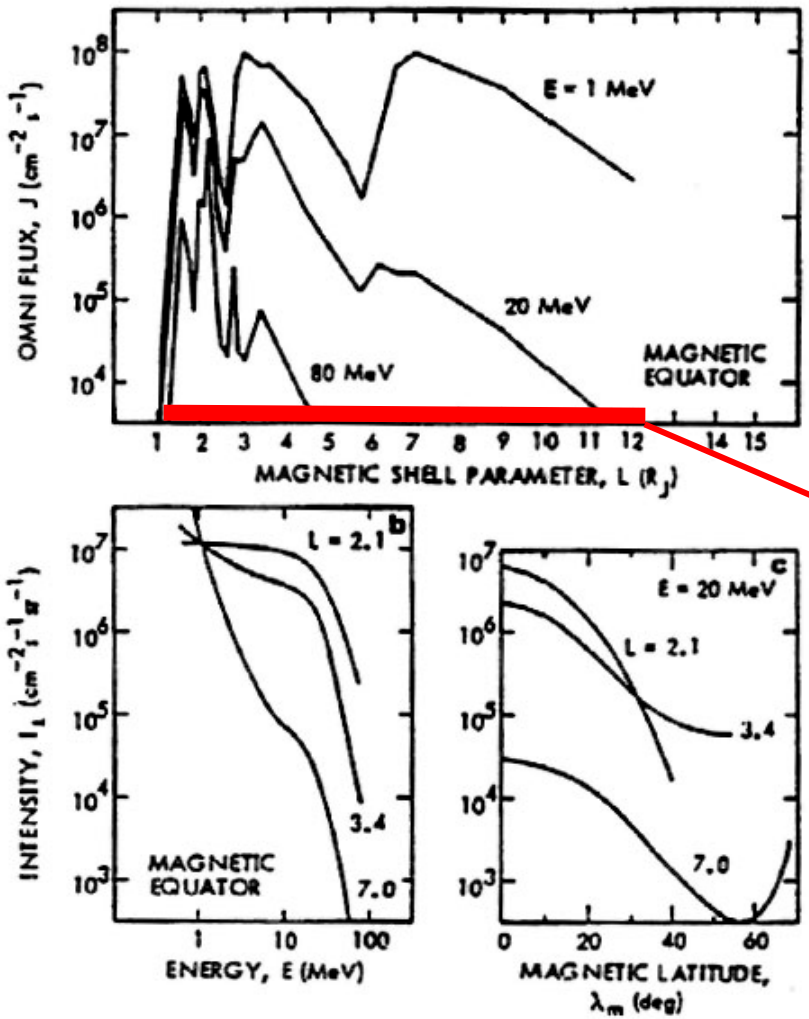
Summary of Spatial Coverage of Electron Models



•***SYNCHROTRON UPDATE***

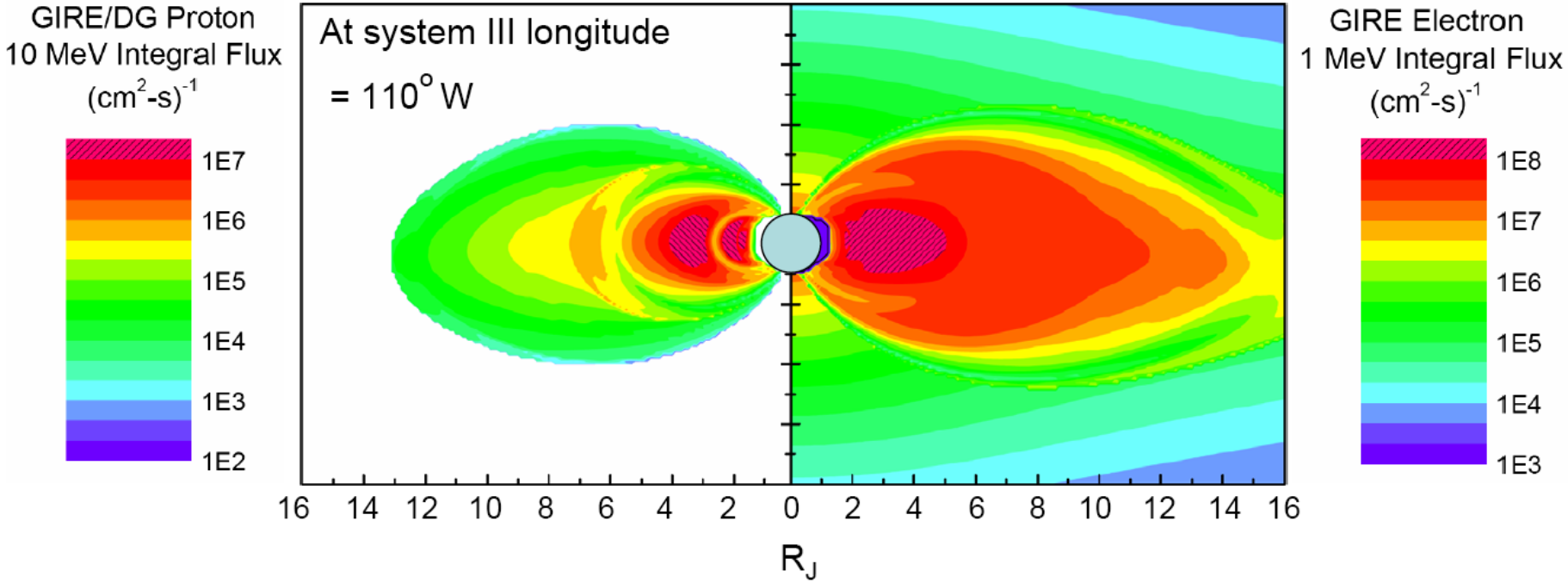
•***GIRE UPDATE***

Summary of Spatial Coverage Proton Model



•*Range of Validity*

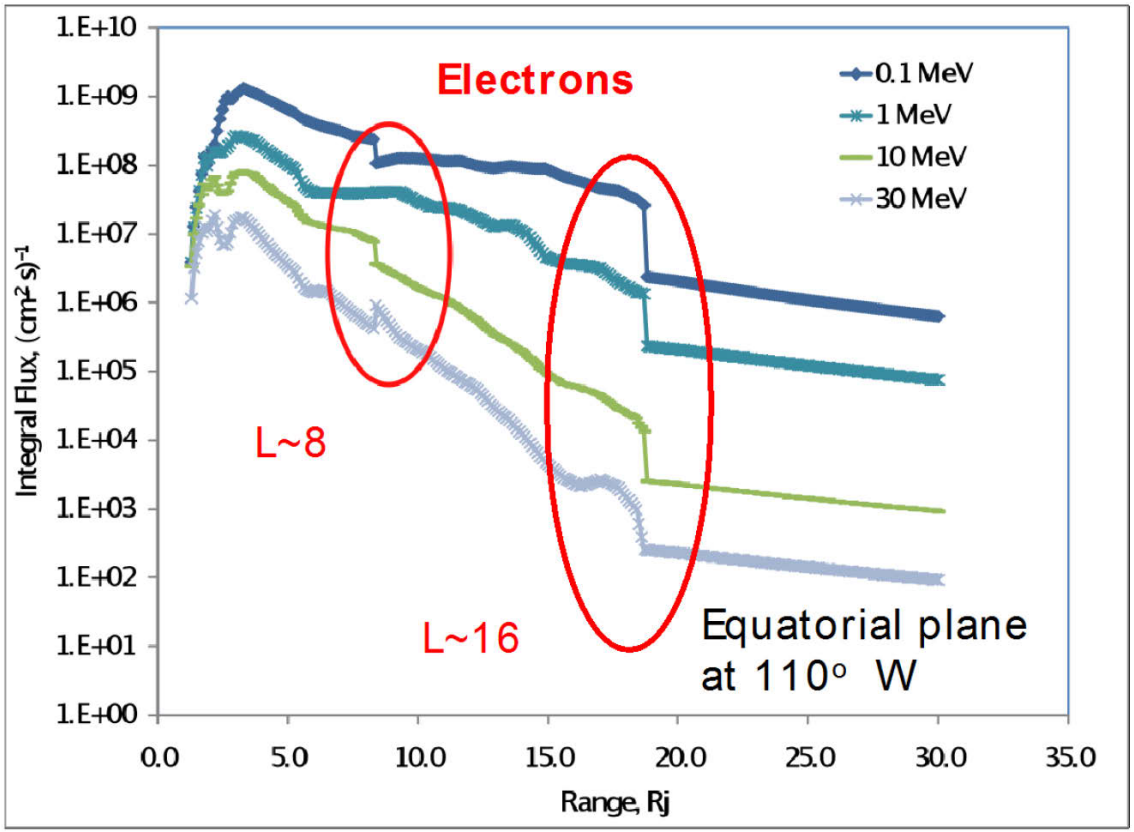
Modeled Jovian Radiation Belt



Contour plots of ≥1 MeV electron and ≥10 MeV proton integral fluxes at Jupiter. Coordinate system used is jovi-centric. Models are based on Divine/GIRE models. Meridian is for System III 110° W.

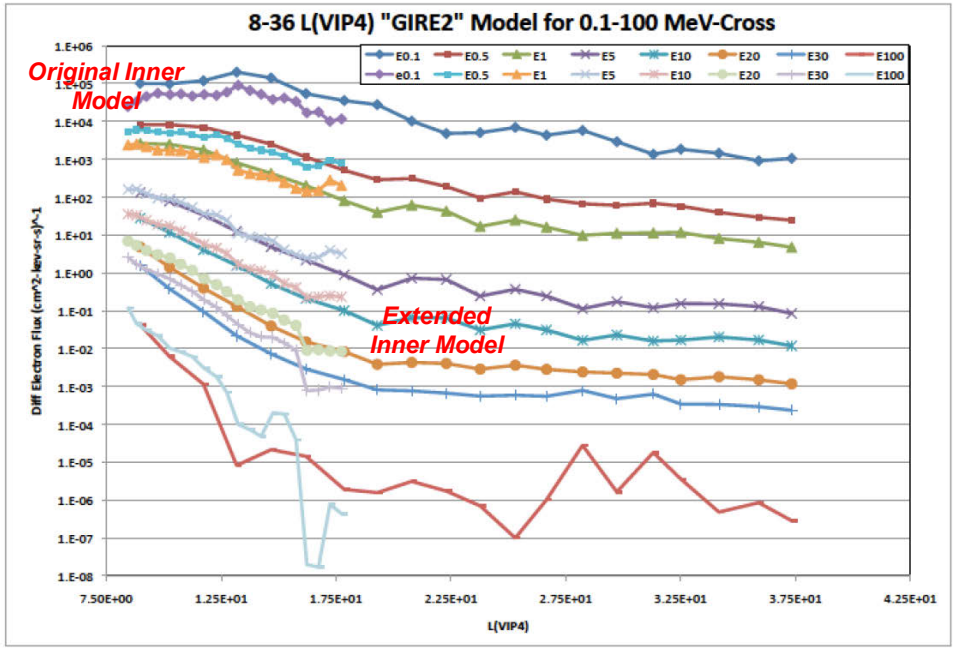
GIRE beyond L<8 and L>16

- The Divine model was not updated for L<8
- The Divine model was not updated beyond L>16

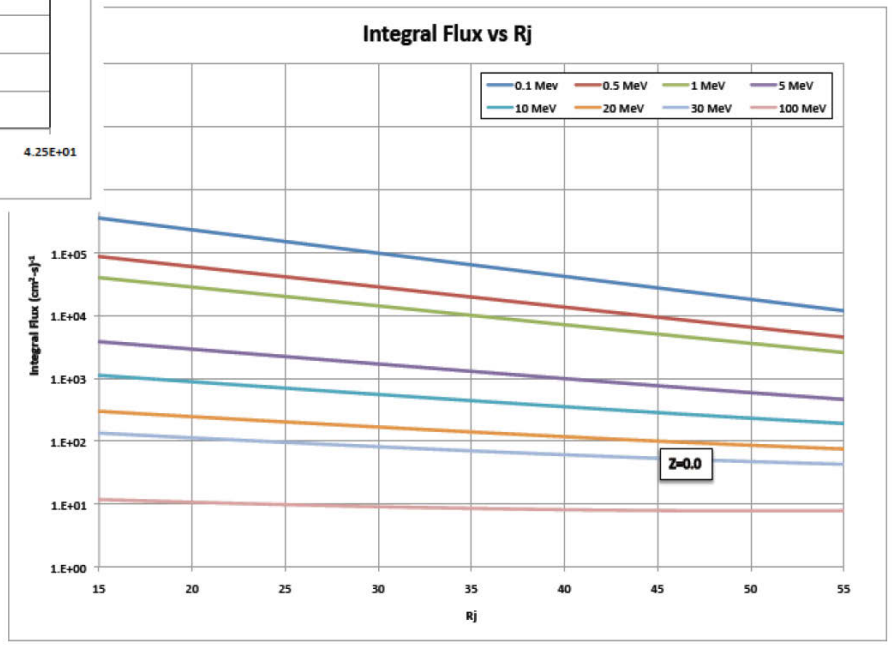


"Discontinuities" resulted from stitching different data sources using different magnetic field models

GIRE2 Development

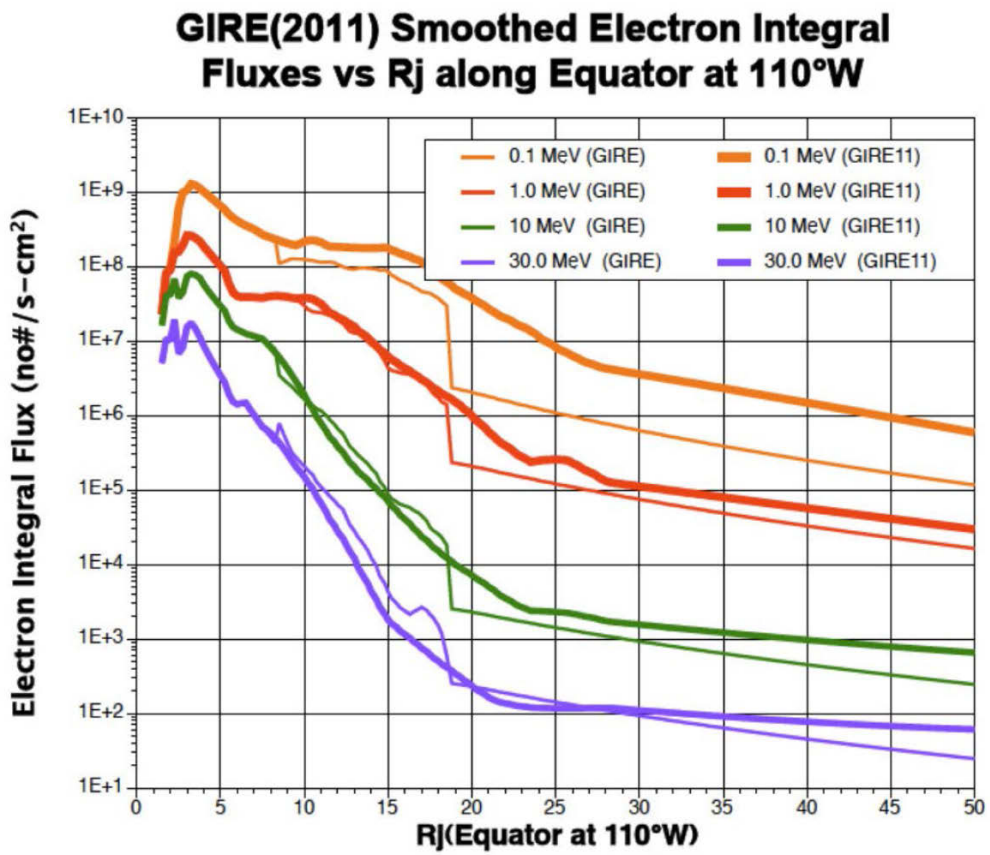


Comparison of original inner GIRE model equatorial electron fluxes with a new version. Based on the VIP4 magnetic field model. Flux varies with L-shell.

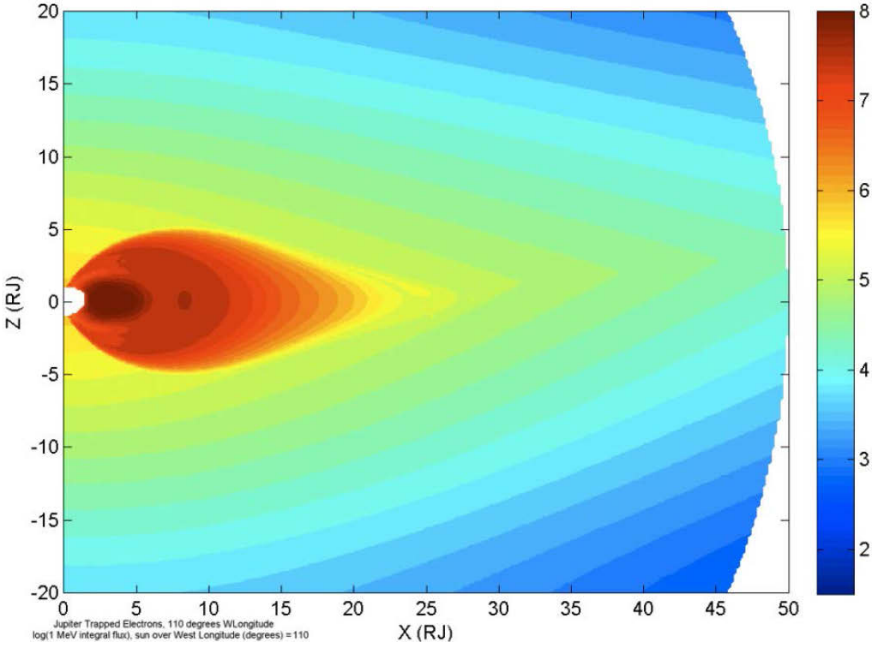


Estimates of the outer, plasma sheet electron fluxes at the equator based on the Khurana magnetic field model. Flux varies with R and Khurana's Z parameter.

GIRE2



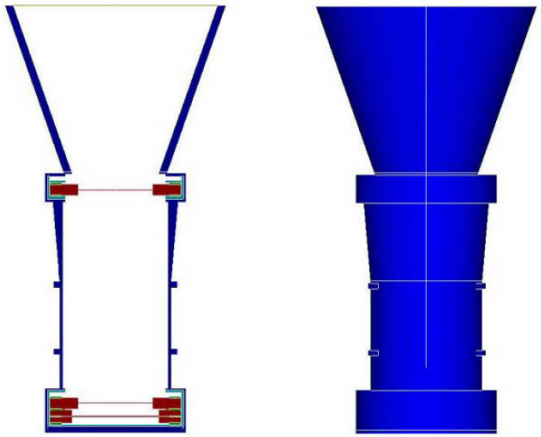
>1 MeV Electron Contour Plot



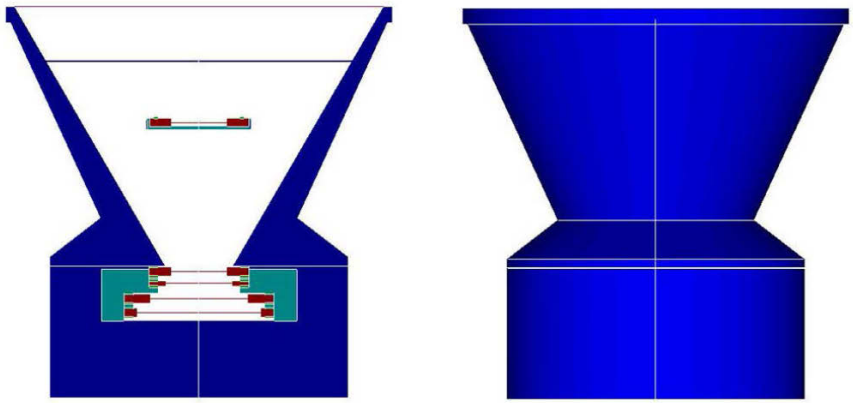
JOSE

- JOvian Specification Environment model developed by ONERA
  - Combination of Divine, GIRE, and Salambo
- Flux prediction for electrons and protons
- Covers to 100Rj
- All relevant in-situ observation data used
  - Electron data based on Galileo/EPD data
- Mean environment model and confidence level model are available
- Implemented in SPENVIS

Heavy Ion Model – Heavy Ion Counter

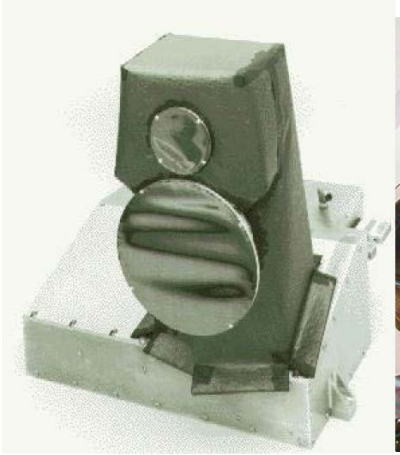


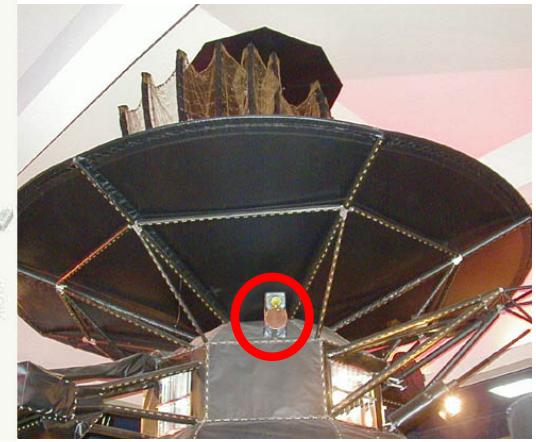
LET B



LET E

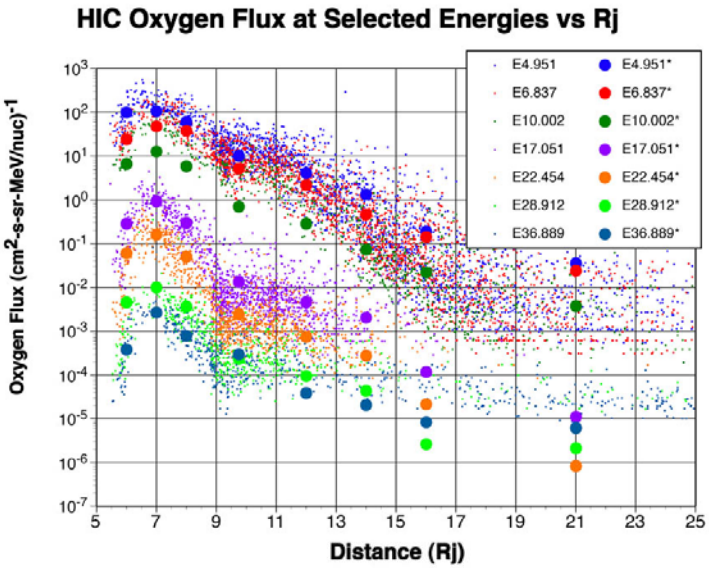
- Two solid-state dE/dx vs energy Low Energy Telescopes (LET B and LET E).
- Measured ~6 to >200 MeV nucl^{-1}, heavy ions from C to Ni.
- Returned data for all but 2 of the 35 orbits of the Jupiter system from 1995 to 2003.

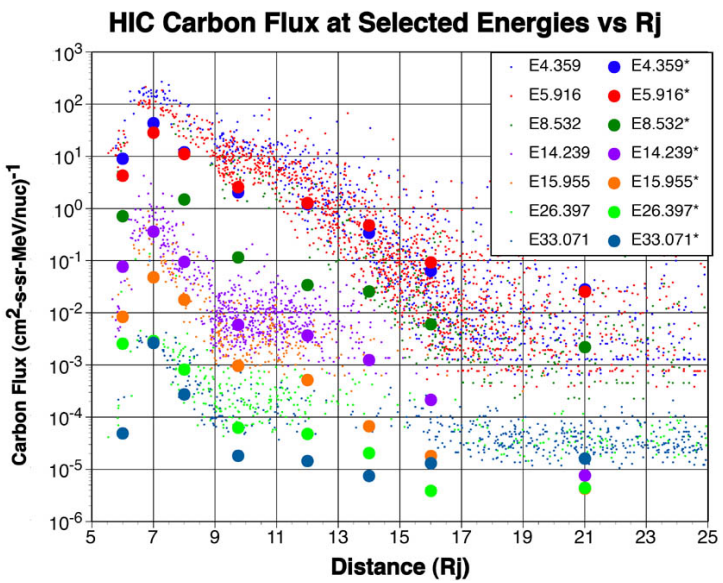


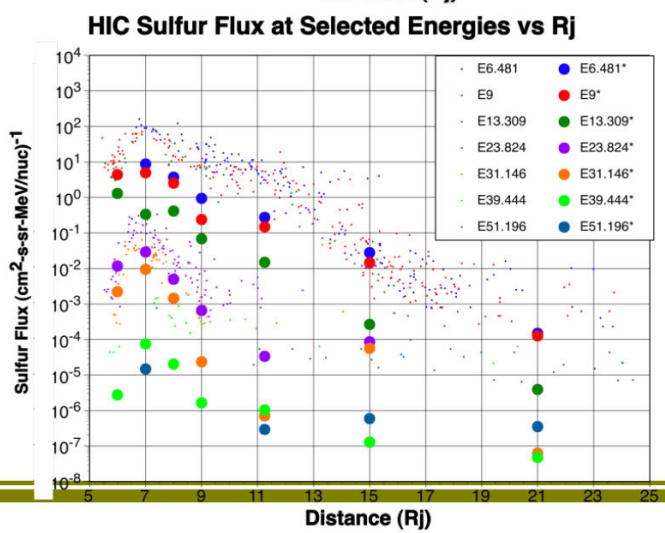


Heavy Ion Counter Observation

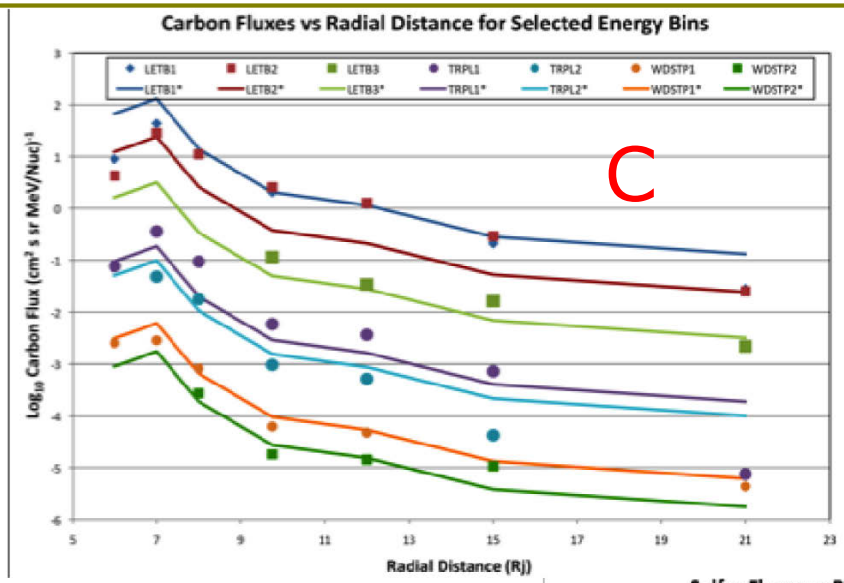
- HIC fluxes at selected energies (small symbols; designated "E4.359", etc.) in units of MeV/nuc vs. radial distance. Also plotted are the averages for selected radial intervals and energies (large symbols; designated "E4.359*", etc.).

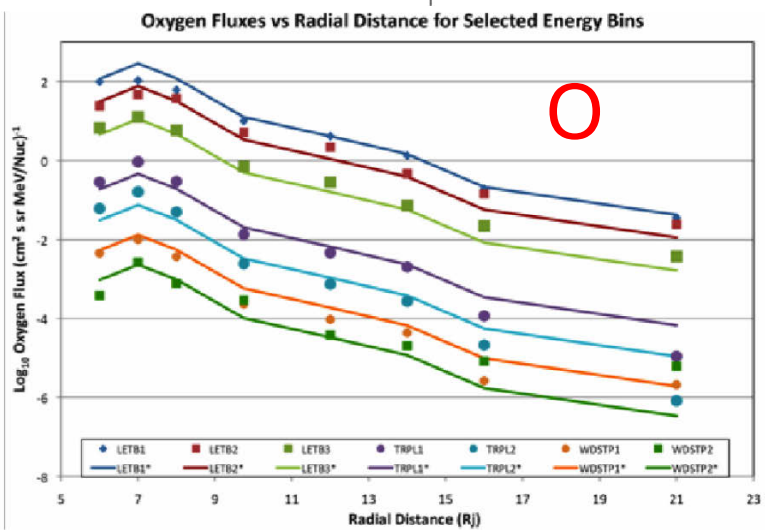


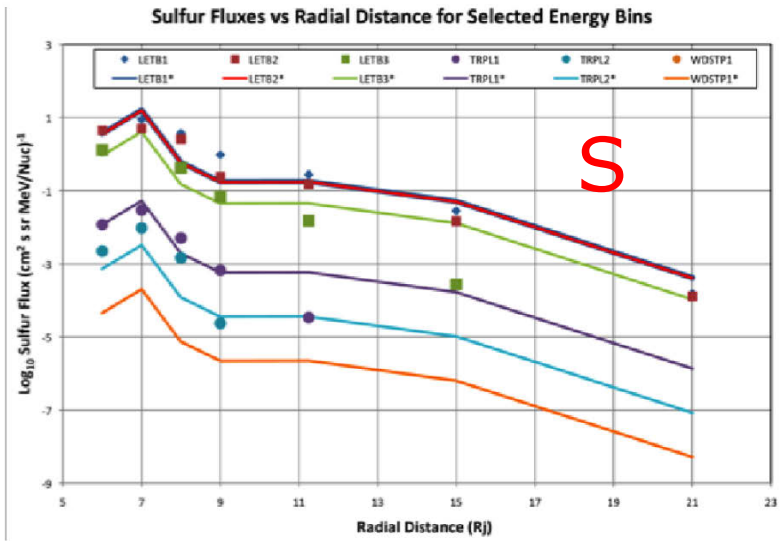




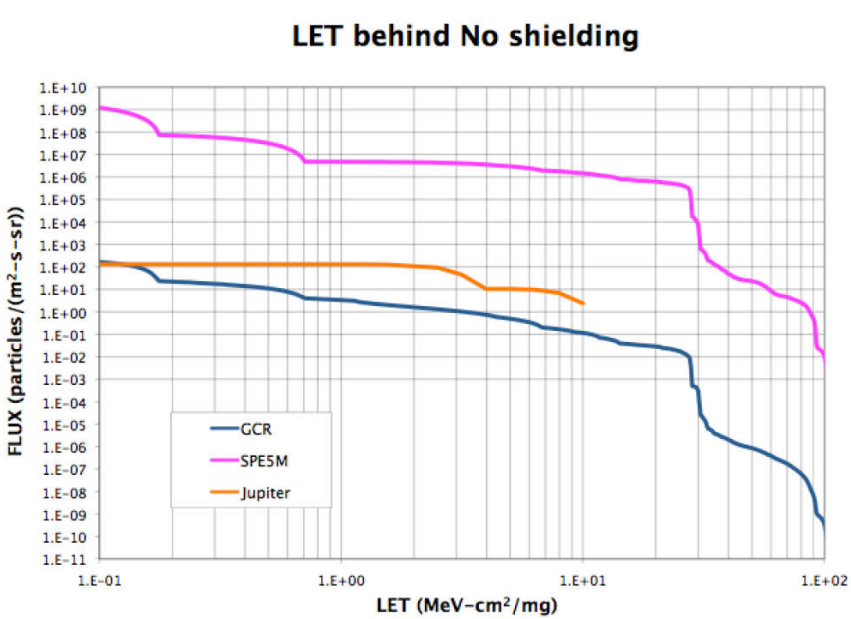
HIC Model Environments

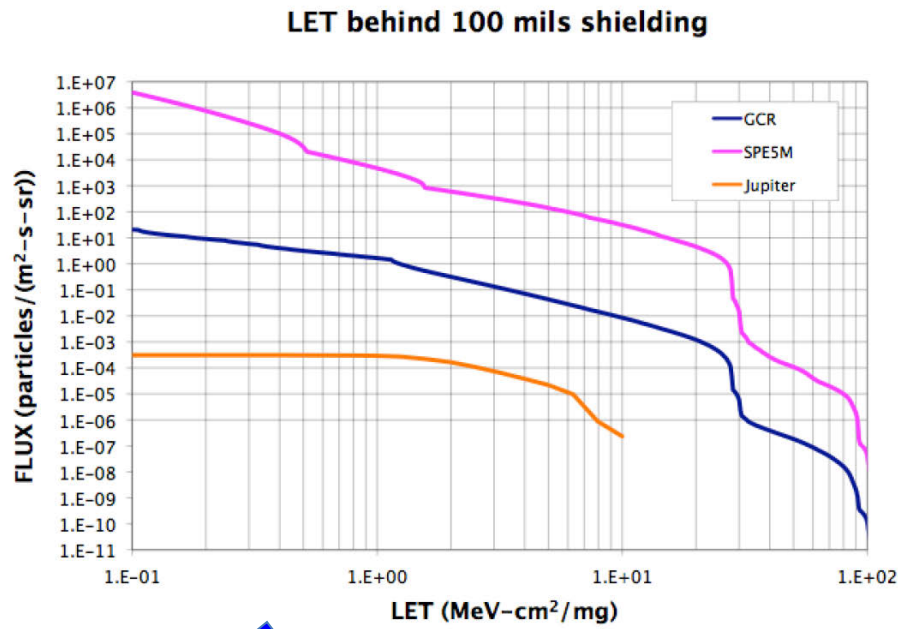






HIC Model Output

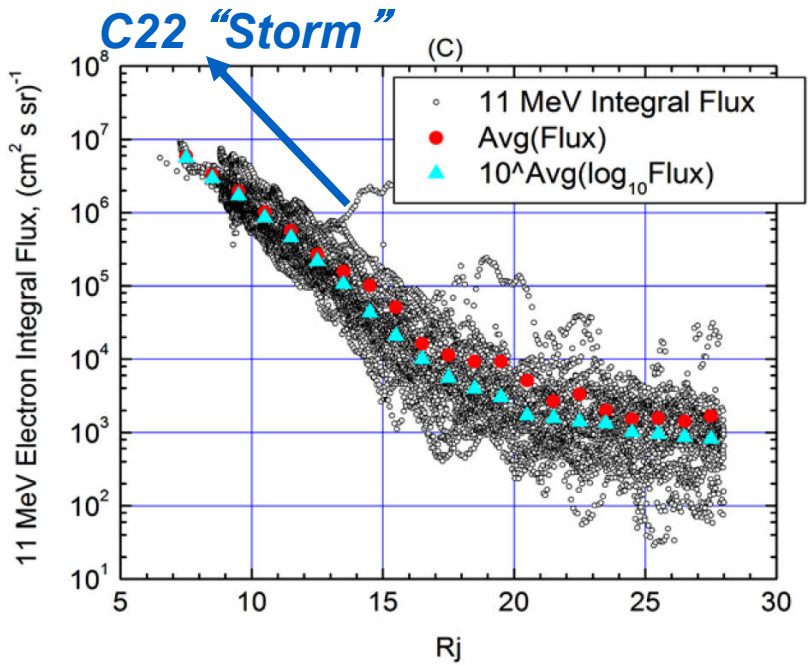




Shielding attenuates the Jovian heavy ion environment to insignificant levels

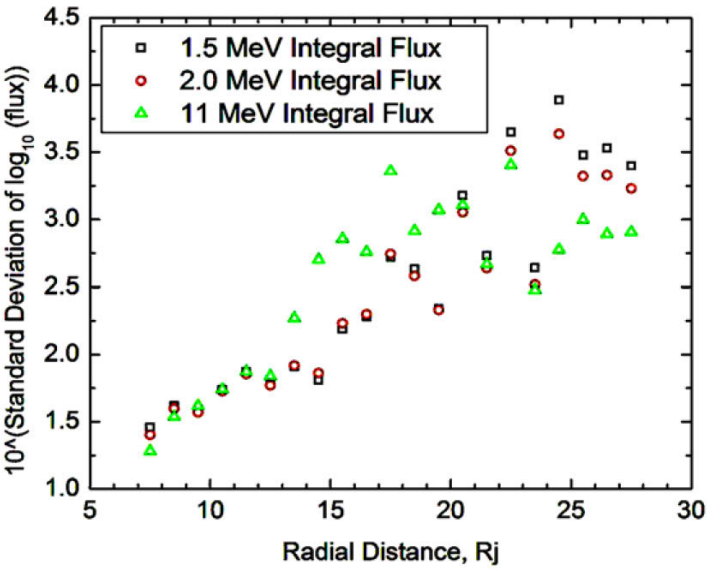
Statistics: Variation of Trapped Electrons

Variations in Energetic Particle Detector Fluxes with distance from Jupiter showing "average" and "storm" variations



- ***Galileo EPD 11 MeV particle fluxes vs radial distance***

Examples of log-normal fits to the Galileo electron fluxes



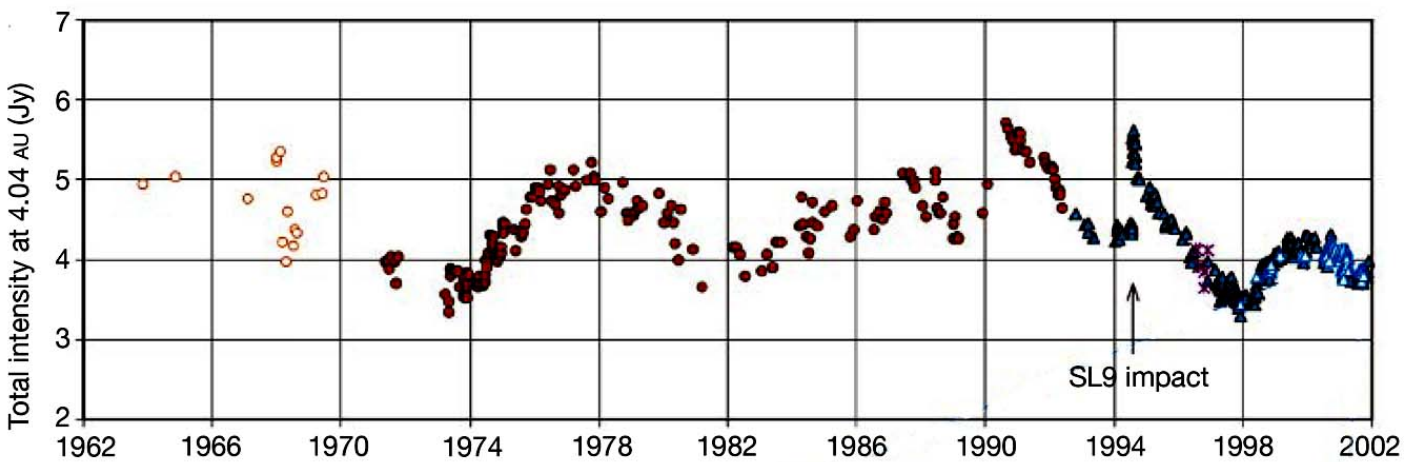
- ***Standard Deviations of Electron Fluxes versus Rj***

Jun et al., Icarus (2005)

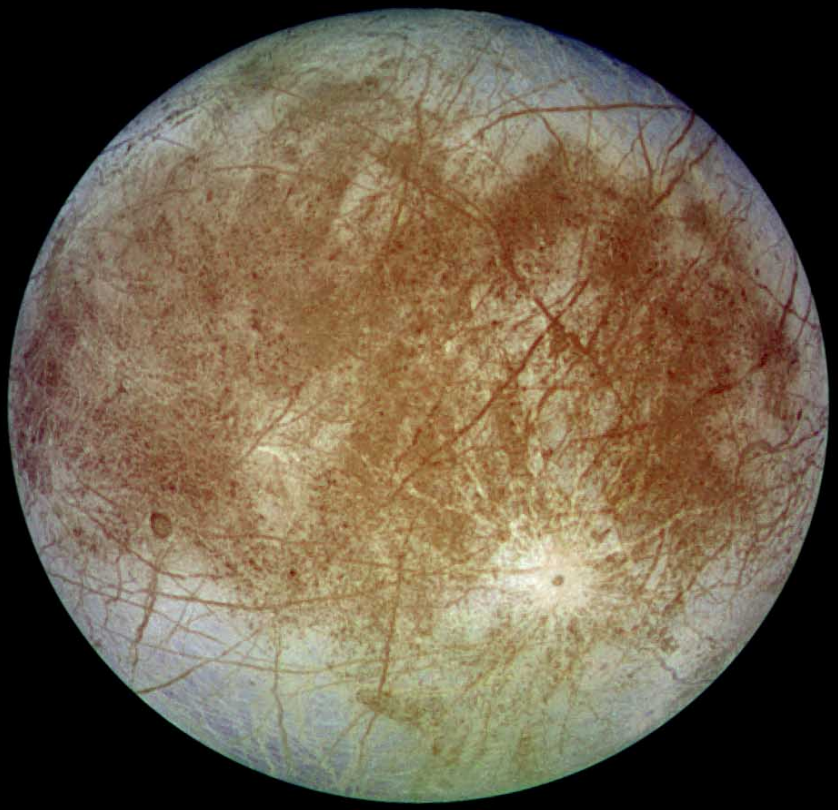
- **"Storm" duration appears to be on the order of hours to days, indicating that the "mean" environment is a good representative of the expected long term exposure**

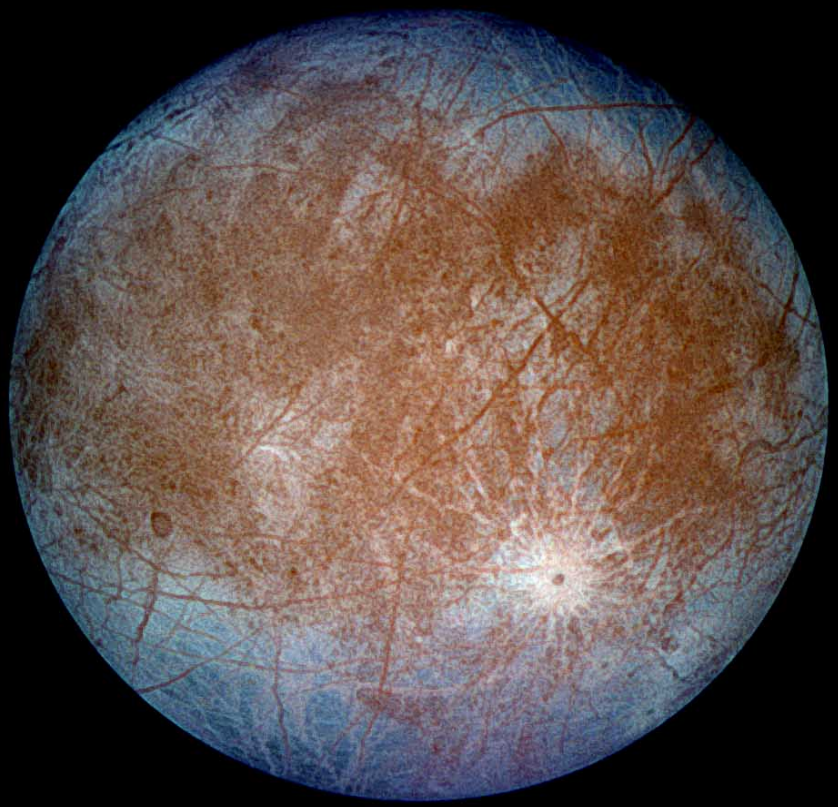
Jovian Radiation Climatology

- QUESTION: How does the jovian environment change on the time scale of years to decades?
  - The "climate", based on the Pioneer (Dec 1973, Dec 1974) and Voyager encounters (Mar 1979, July 1979) versus Galileo (1995-2003), implies variations of ***2-3*** (Divine vs GIRE).
  - The Earth-based Goldstone Apple Valley Radio Telescope (GAVRT) study of the jovian synchrotron radiation shows variations of **~2** in the trapped, relativistic electron populations over 4 decades in inner electron belt (~1.5-2 L).

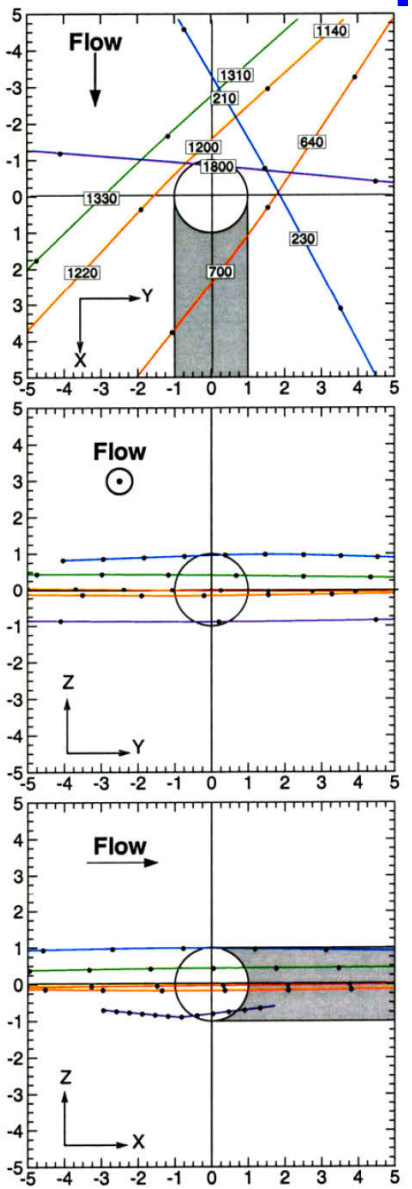


Europa

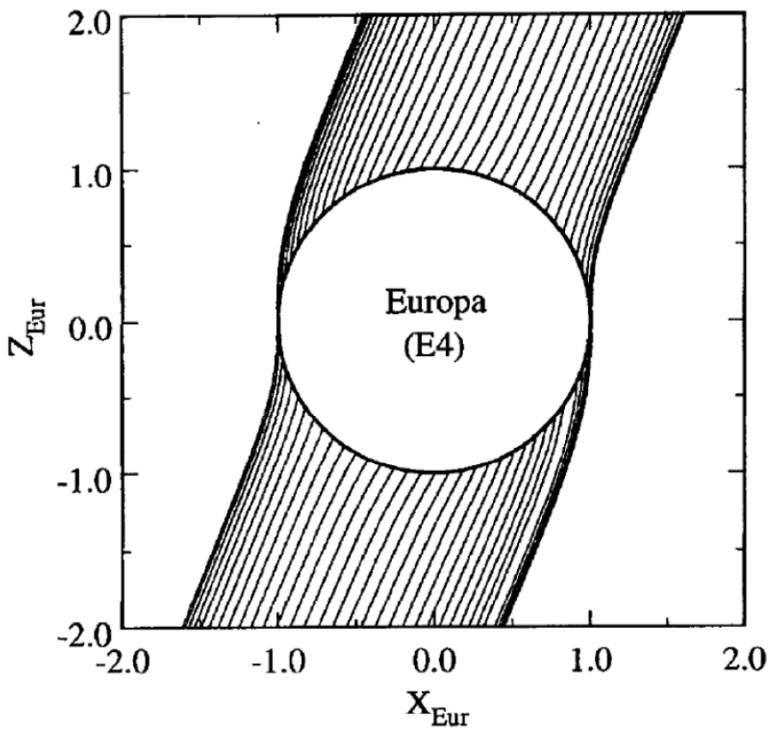




Europa's Magnetic Field Environment

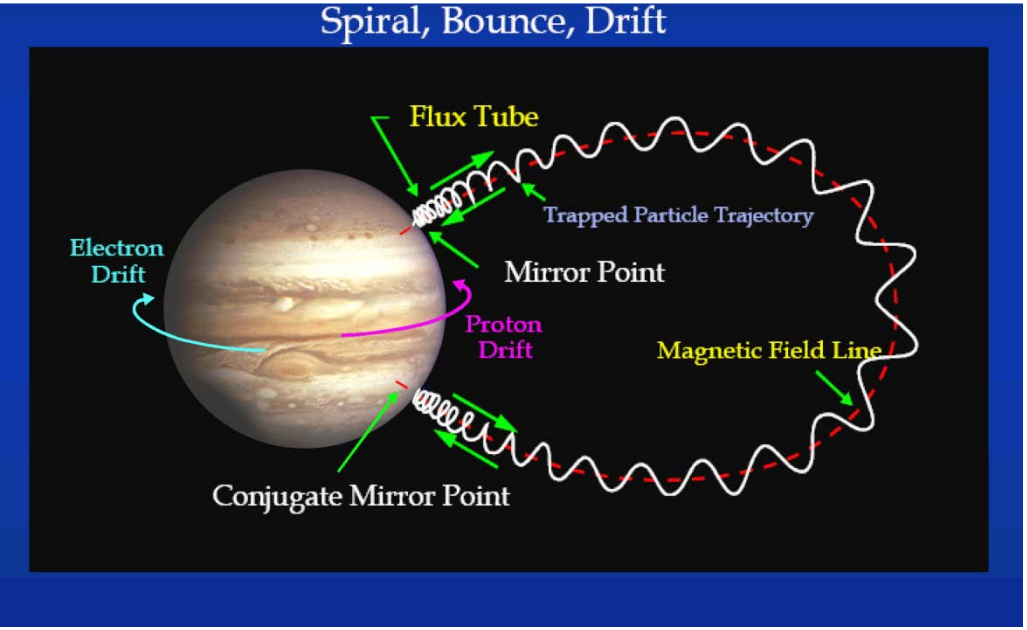


•Europa flybys E4 (red), E12 (orange), E14 (green), E19 (blue), and E26 (purple) by Europa. Cartesian Coordinates: X along flow direction, Y along Europa-Jupiter vector, Z along spin axis.



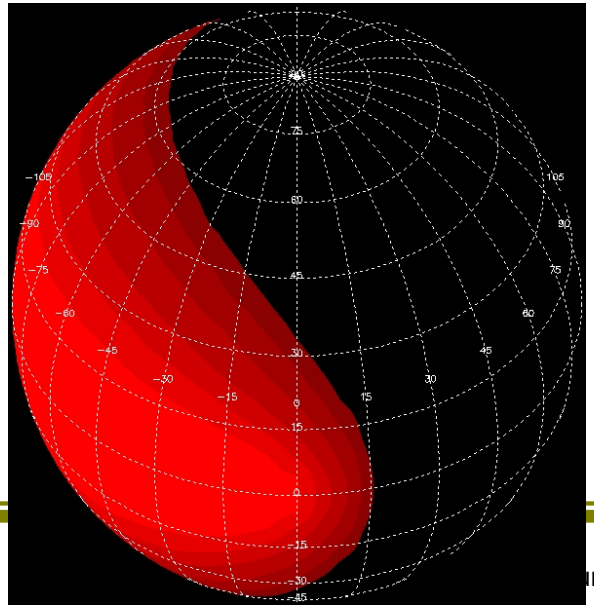
E4 magnetic field line configuration in X_s-Z_s plane from vacuum superposition of external jovian magnetic field (Khurana, 1997) for System III location.

Trapped Particle Motion at Jupiter

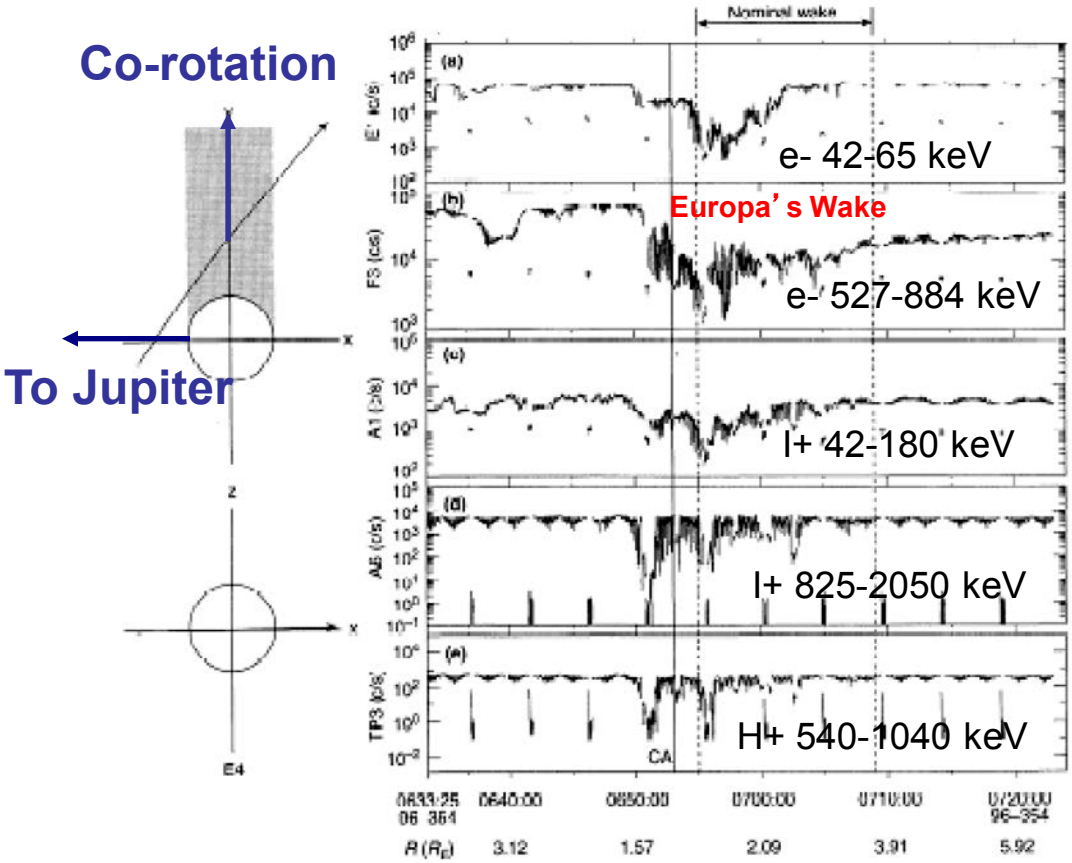


- If the magnetosphere of Jupiter is rigidly co-rotating, plasma flow speed at Europa's orbit (9.5 Rj) is about 118 km/s.
- Europa travels about 14 km/s in its orbit, so that charged particles are overtaking the satellite at all times.

Particles impacting the trailing hemisphere leave regions above poles and leading hemisphere depleted of MeV electron flux (creating wake).



Measurements of Flux Reductions at Europa



EPD observed flux reductions in wake for orbit E4

EPD B1 (1.5-10.5 MeV) Electron Channel

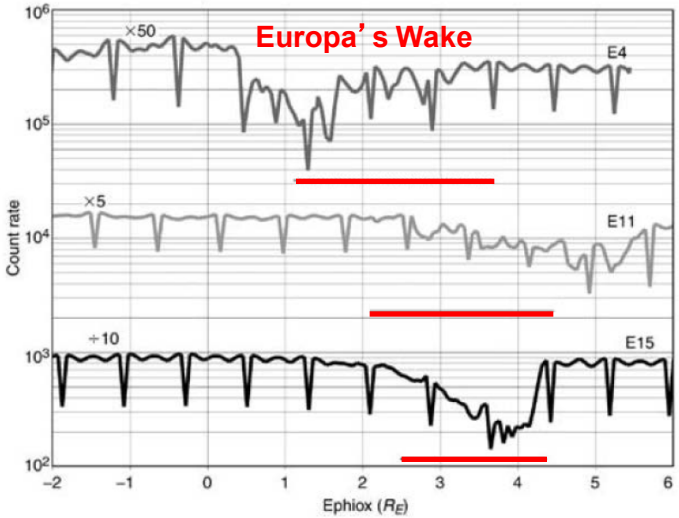
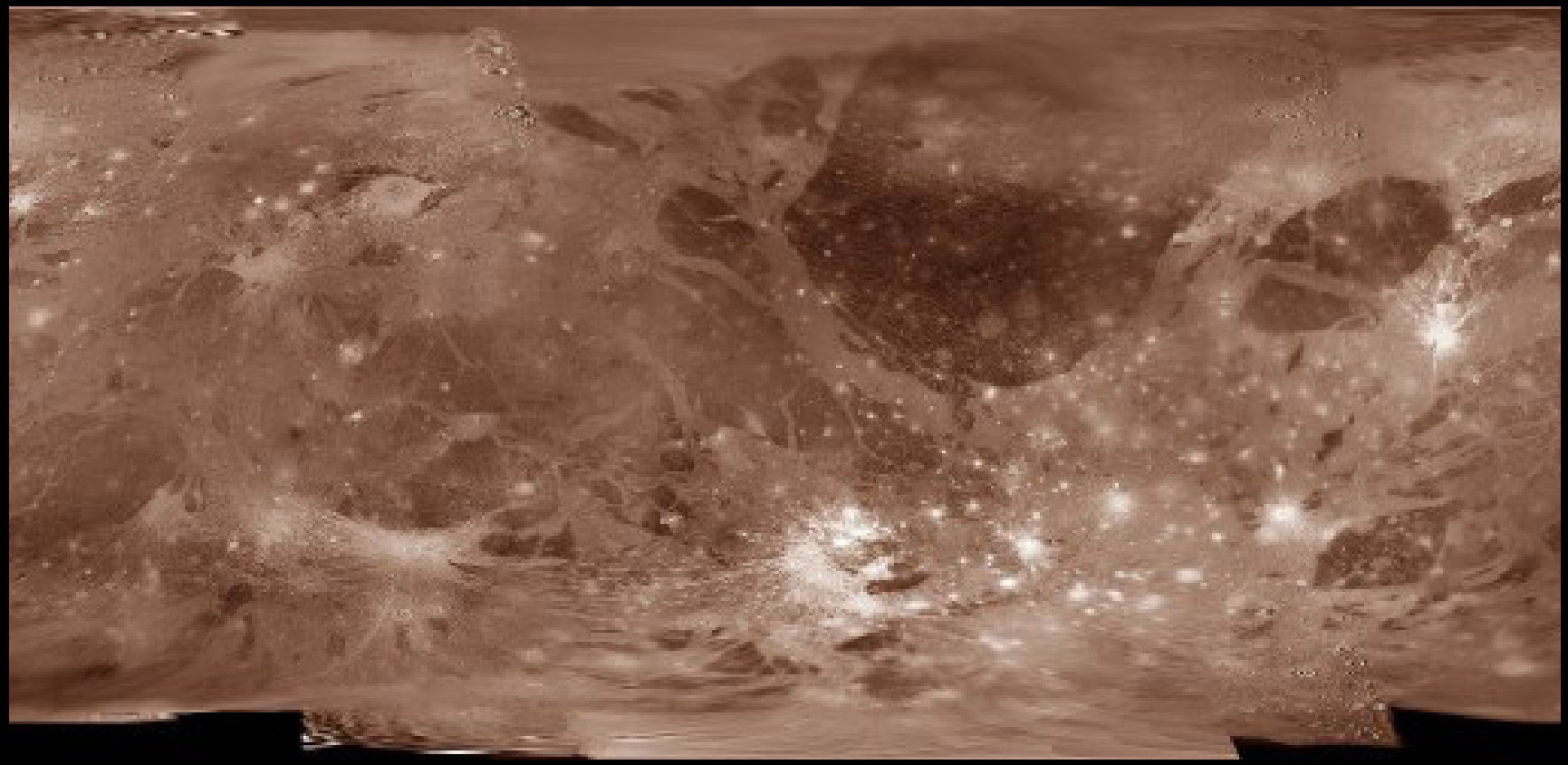


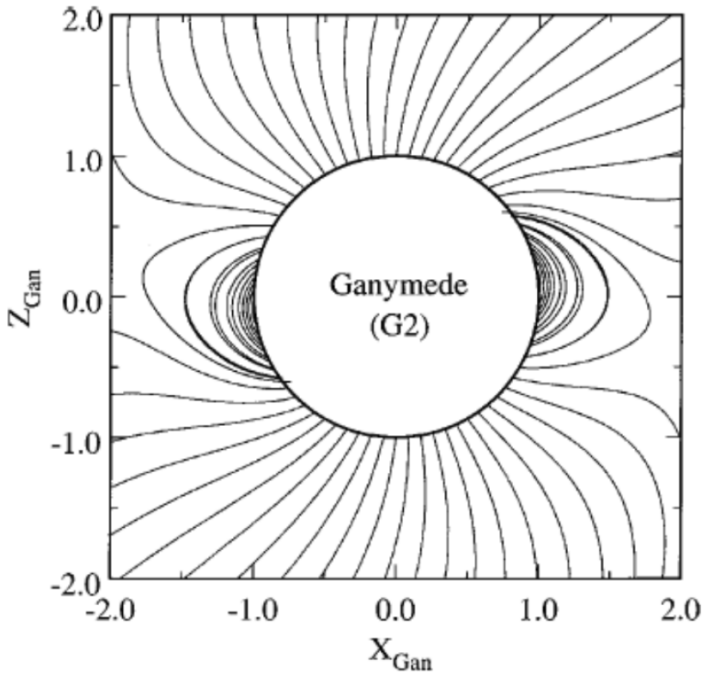
Figure 3. Spin-averaged count rates from the ~1.5–10.5 MeV electron channel on EPD plotted as a function of ephiox, the x-axis of the ephio system. The horizontal lines correspond to the nominal geometric wakes in ephio coordinates.

(Paranicas et al., 2007)

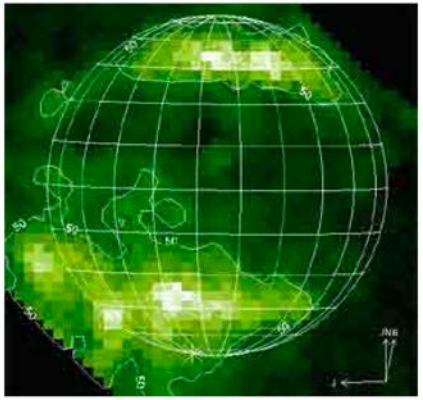
GANYMEDE



Ganymede's Magnetosphere

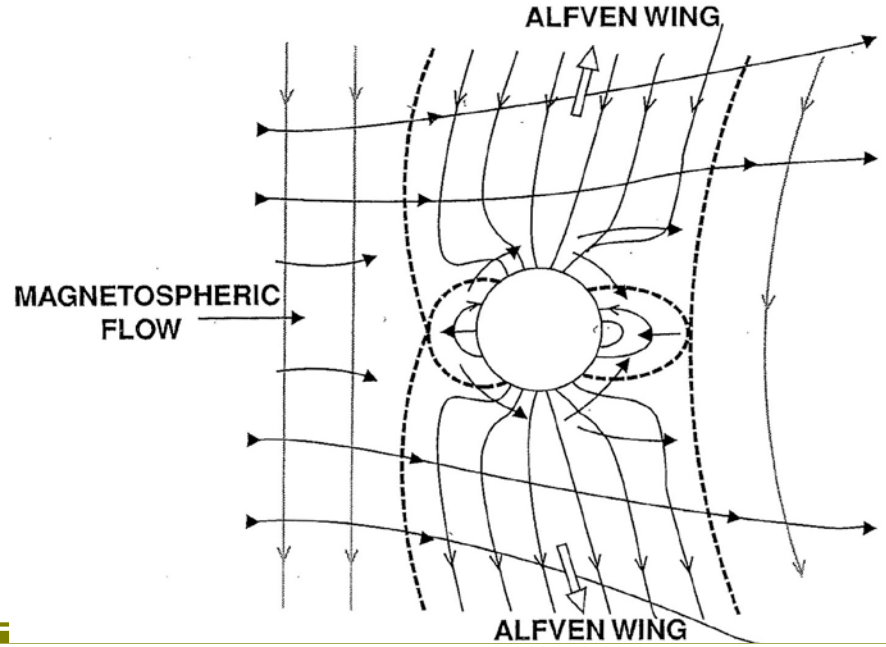


Magnetic field configuration at Ganymede (Cooper et al., Icarus, 2001)

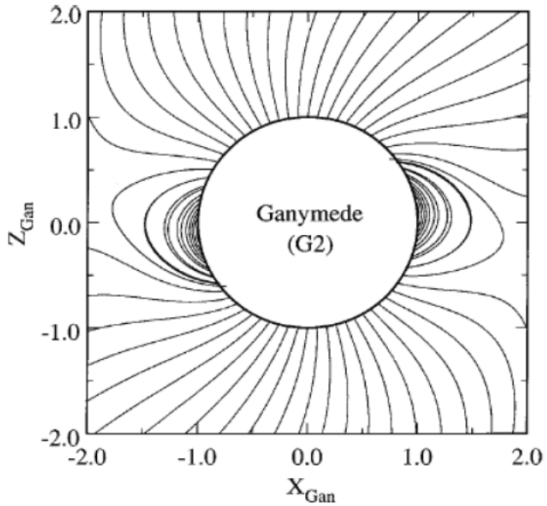


Aurora at Ganymede.

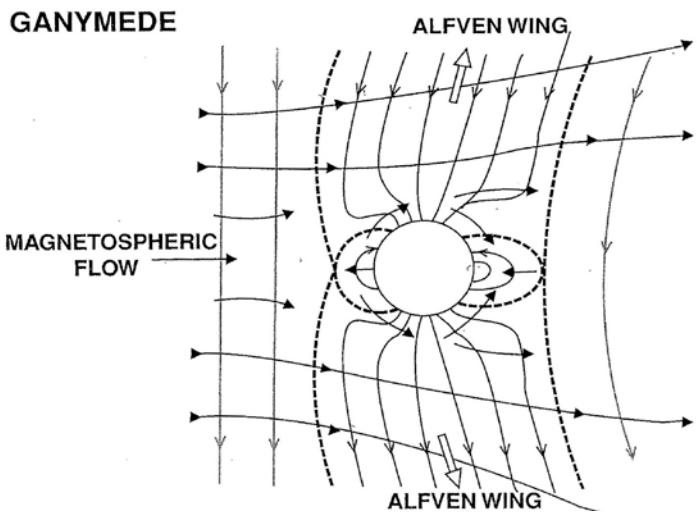
Magnetospheric regions at Ganymede.

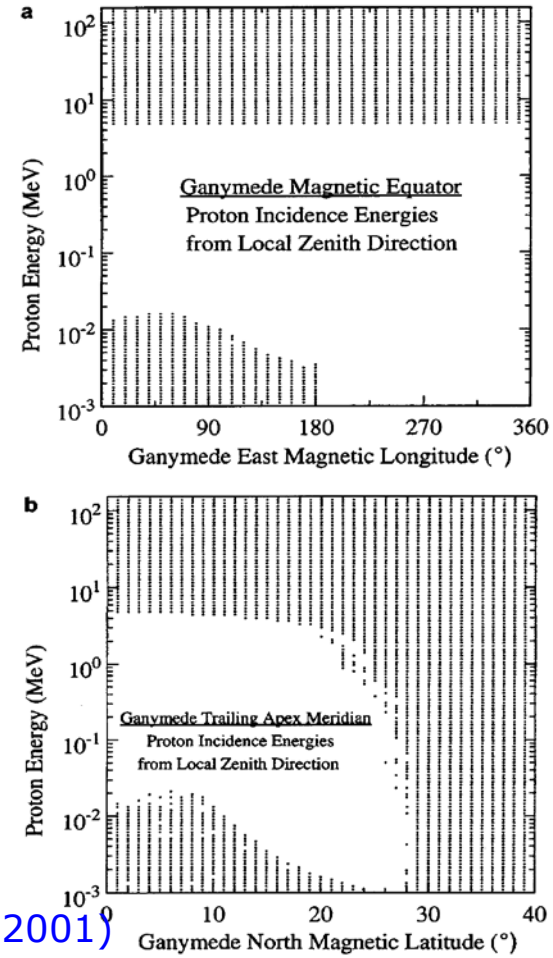


Ganymede's Magnetosphere



Magnetic field configuration at Ganymede





Magnetic (a) east longitude and (b) north latitude for allowed trajectories incident from zenith onto Ganymede's surface.

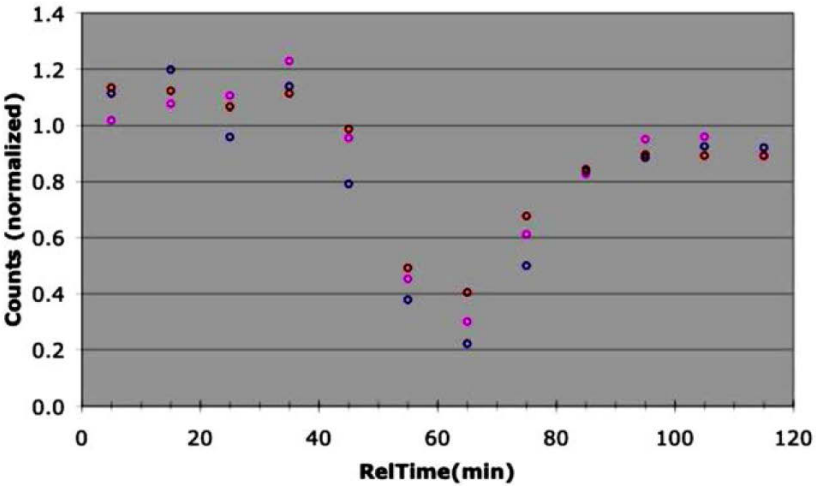
Cooper et al., Icarus (2001)

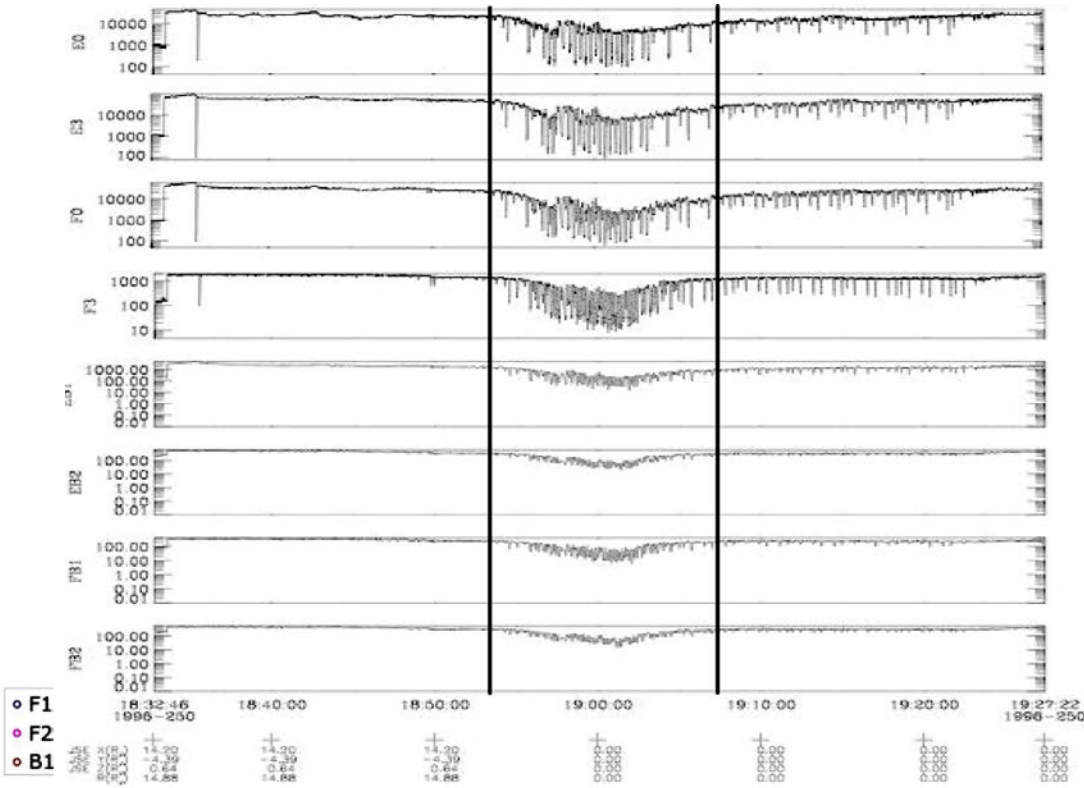
Flux Reductions at Ganymede

Galileo observed reductions in the particle fluxes as at Europa

- **Ganymede Flybys:**
- G1 838.0 km (EPD off)
- ***G2 264.4 km***
- G7 3104.9 km
- G8 1606.2 km
- G28 808.7 km

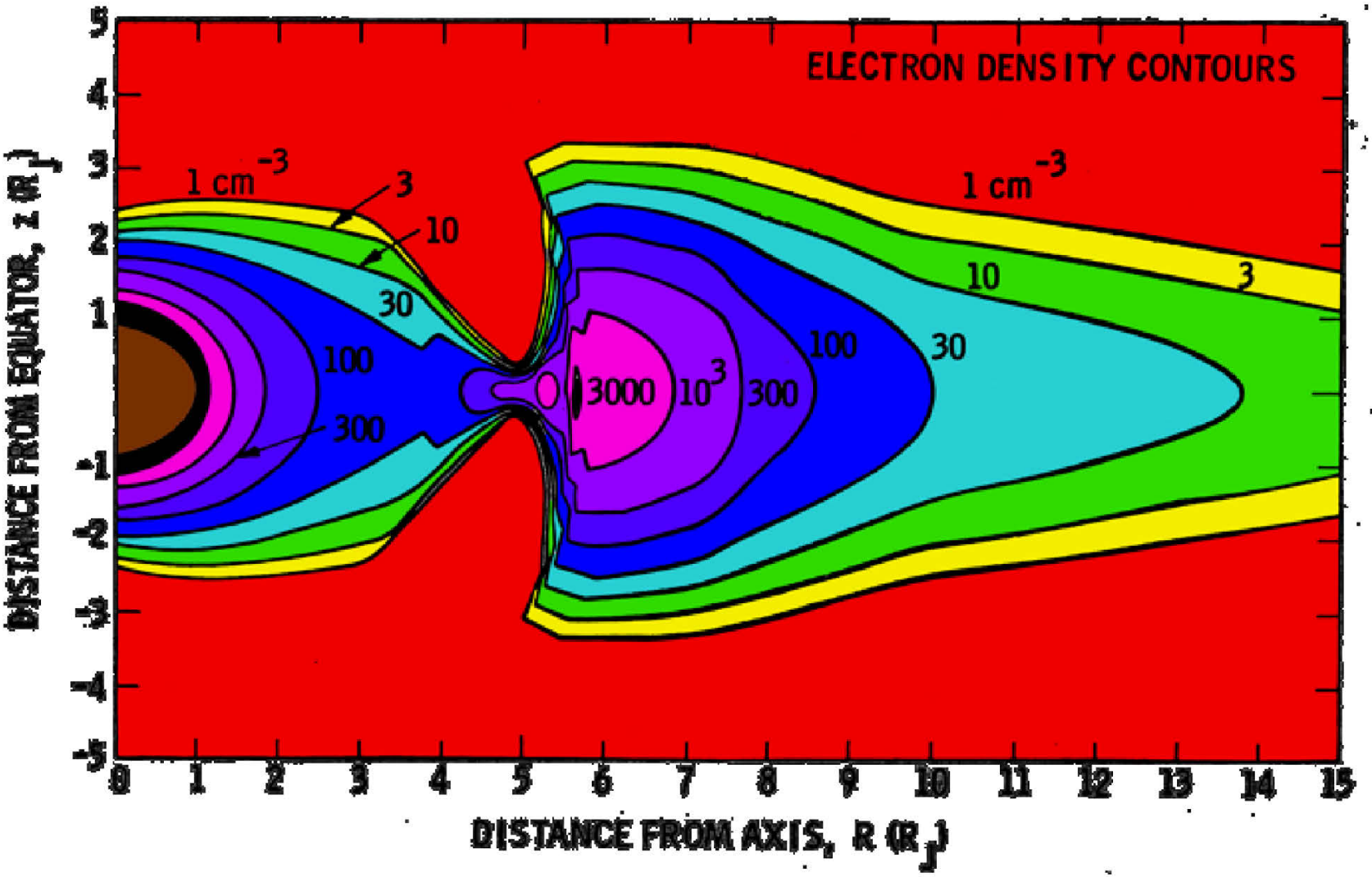
G2 High F1, F2, B1 Electron Fluxes



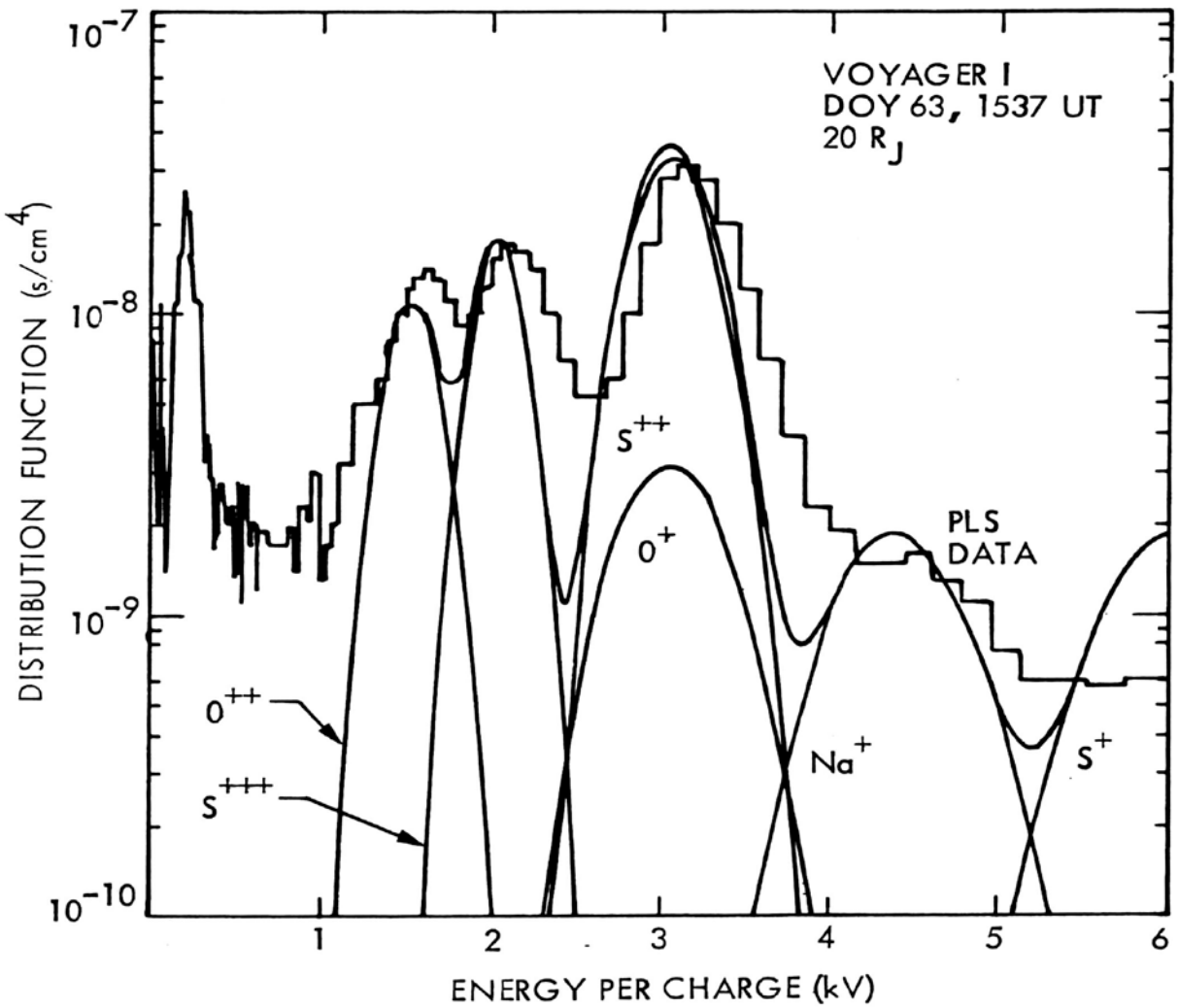


G2 Ganymede encounter EPD low-energy channel counts

Low Energy Electron Plasma Environment



Plasma Distribution

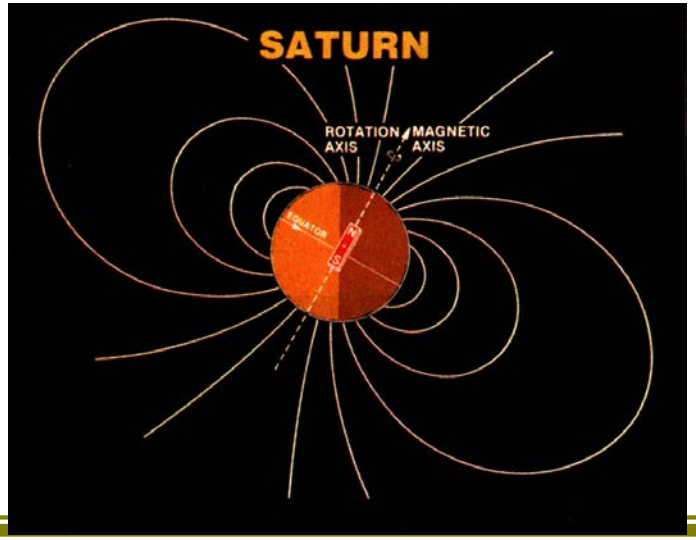


Saturn

Saturn's Magnetosphere

Characteristics	***Earth***	***Jupiter***	***Saturn***
Equatorial radius (km)	6.38×10^3	7.14×10^4	6.03×10^4
Magnetic moment (G-cm^3)	8.1×10^{25}	1.59×10^{30}	4.3×10^{28}
Rotation period (hr)	24.0	10.0	10.6
Aphelion/perihelion (AU)	1.01/0.98	5.45/4.95	15.1/13.5

- Saturn is roughly 10 times the size of the Earth while its magnetic moment is ~500 times larger.
- As the magnetic field at the equator is proportional to the magnetic moment divided by the cube of the radial distance, the Saturn's magnetic field is roughly the same as the Earth's.



Kollman et al., 2011

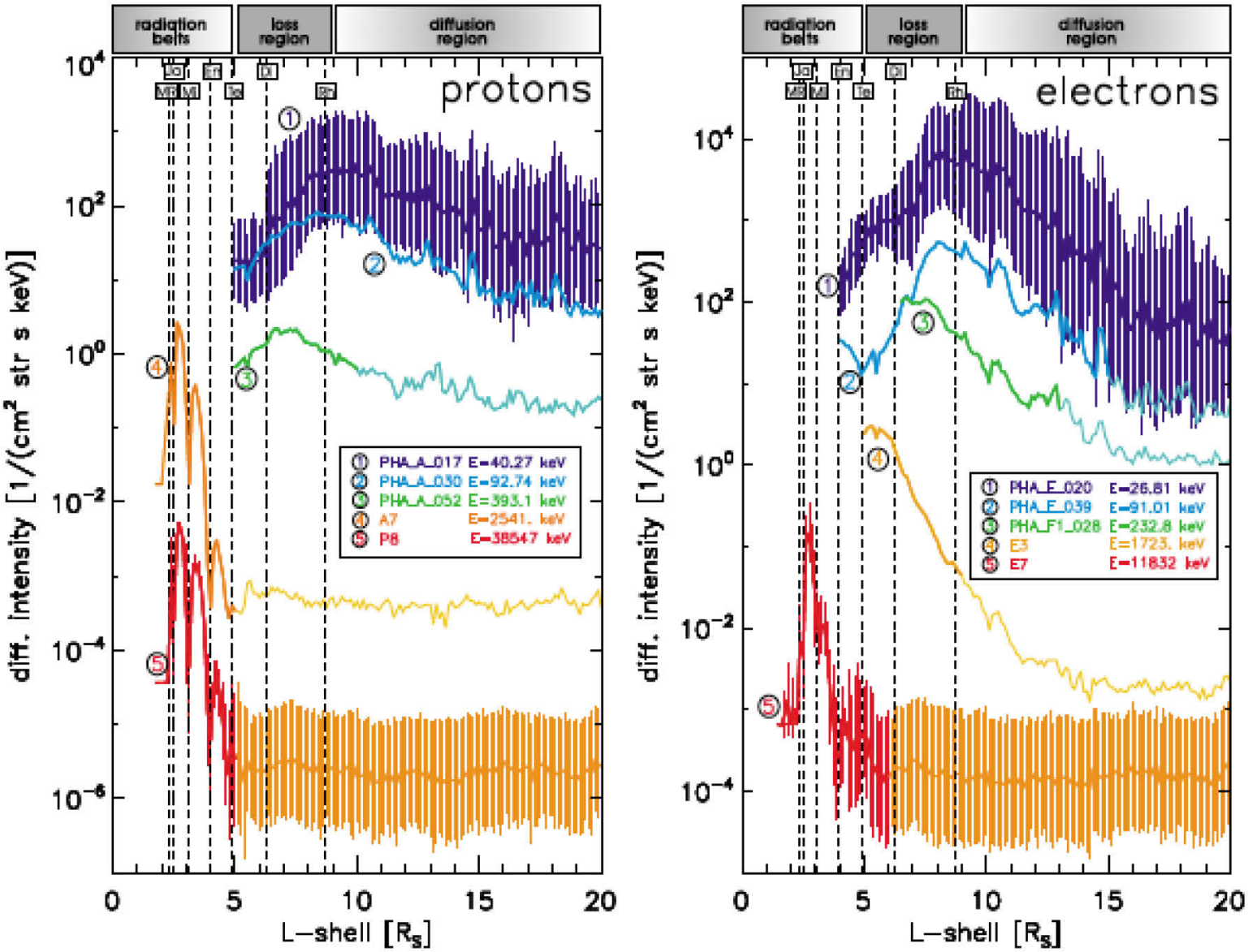


Figure 2. Differential intensities $\bar{j}$ of (left) protons and (right) electrons. The intensities are long-term averages that are derived as described in Figure 1. Error bars show the standard deviation of the averages. A variety of representative LEMMS channels is shown in different colors; their names and

Kollman et al., 2011

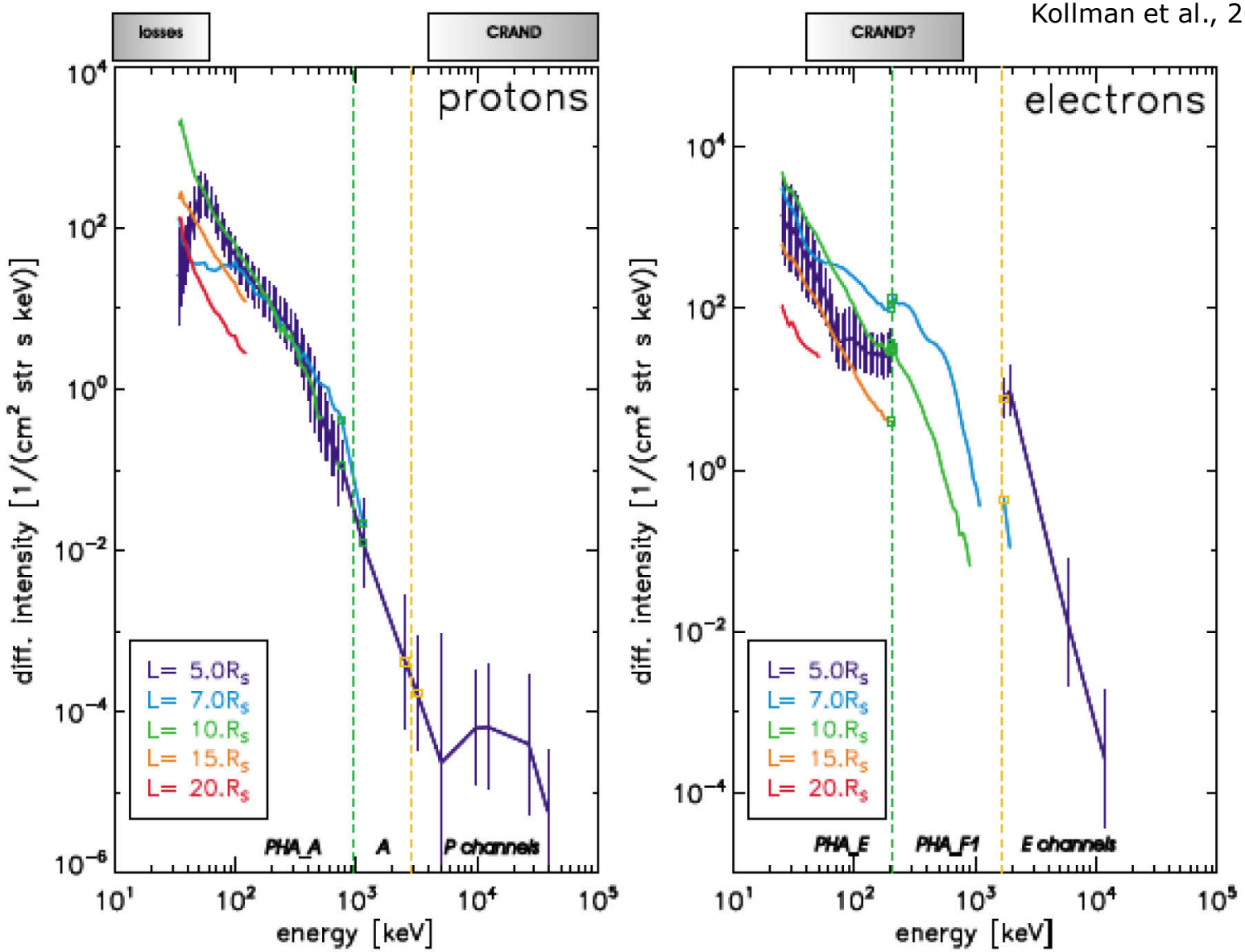
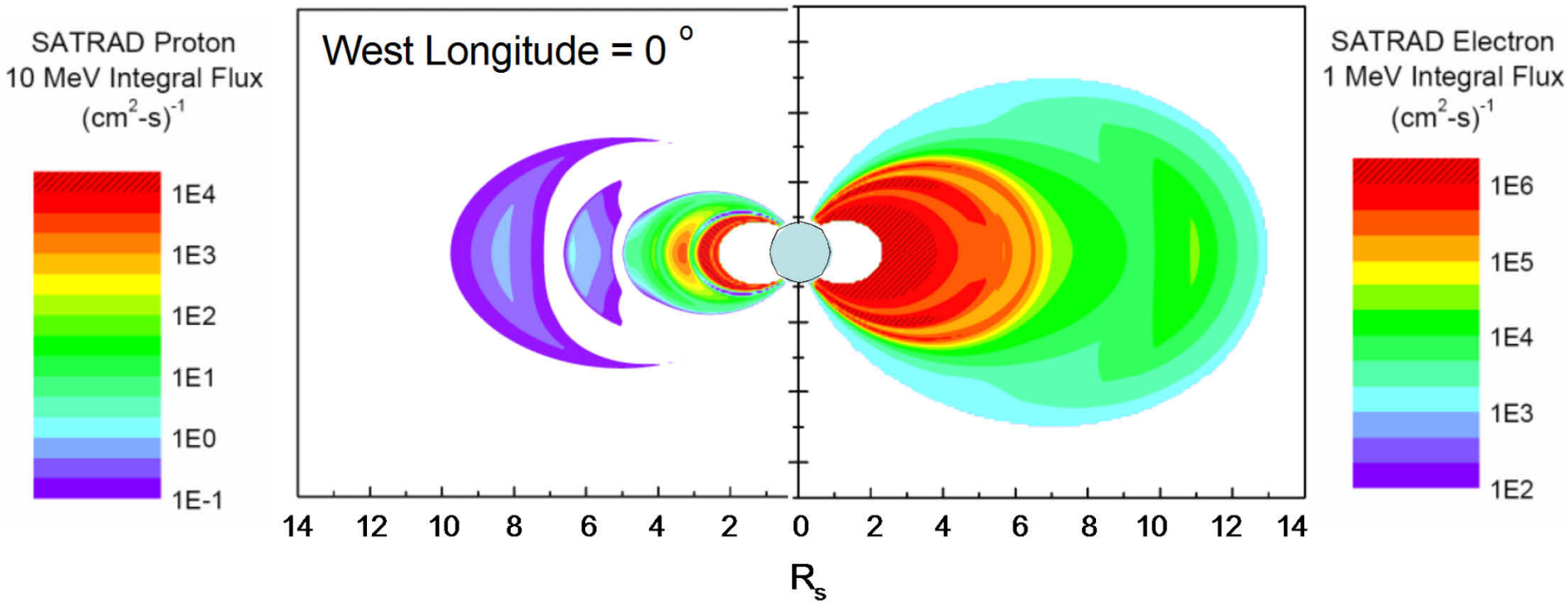


Figure 3. Spectra of long-term averaged differential intensities $\bar{j}$ of (left) protons and (right) electrons with equatorial pitch angle $\alpha_0 = 90° \pm 10°$ for different values of $L \pm 0.5$. Points are given at the mean energies of the respective channels which are defined as the logarithmic average of the energy range. We use several types of channels for this plot that differ in energy range and resolution. Despite ongoing inter-

DIVINE/SATRAD Saturn-Trapped Radiation Models



Contour plots of ≥1 MeV electron and ≥10 MeV proton integral fluxes at Saturn. Coordinate system used is Saturn-centric. Models are based on Divine/SATRAD models. Meridian is for 0° W.

BONUS COVERAGE:
Mars Radiation Environment

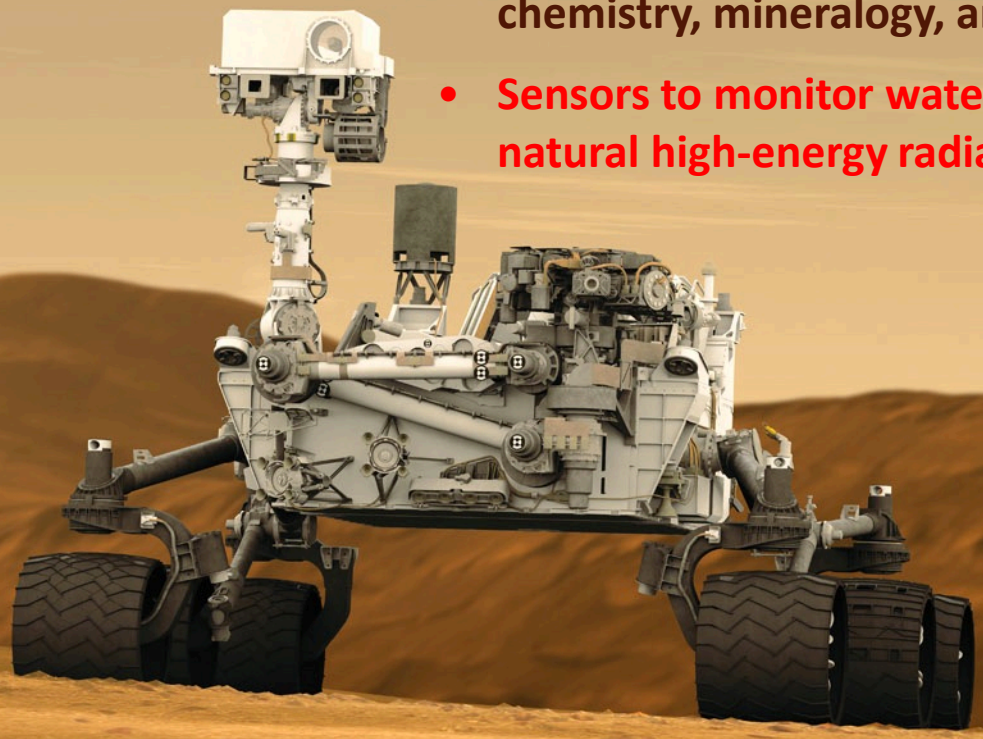
Early Results from the MSL Curiosity Rover

Igor Mitrofanov and the DAN Team
Don Hassler and the RAD Team

Curiosity's Capabilities

- **A Robotic Field Geologist**
- **Long life, ability to traverse many miles over rocky terrain**
- **Landscape and hand-lens imaging**
- **Ability to survey composition of bedrock and regolith**

- **A Mobile Geochemical and Environmental Laboratory**
  - **Ability to acquire and process dozens of rock and soil samples**
  - **Instruments that analyze samples for chemistry, mineralogy, and organics**
  - **Sensors to monitor water, weather, and natural high-energy radiation**



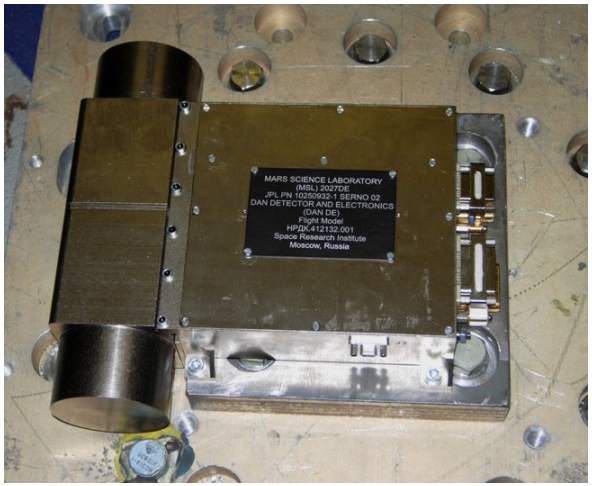
Dynamic Albedo of Neutrons (DAN)

- **Principal Investigator: Igor Mitrofanov**
- **Space Research Institute (IKI), Russia**

- **DAN measures the abundance of H and OH bearing materials (e.g., adsorbed water or hydrated minerals)**

- Active neutron spectroscopy with pulsed 14 MeV neutrons or passive
- Creates profiles along traverses and with depth to 1 m
- Resolves time decay curve and energy spectrum of returned pulse
- Accuracy of 0.1-1% by weight of water (or water-equivalent hydrogen) depending on observation type
- Measures the low-energy background neutrons

- **Thermal & Epithermal Neutron Detectors**

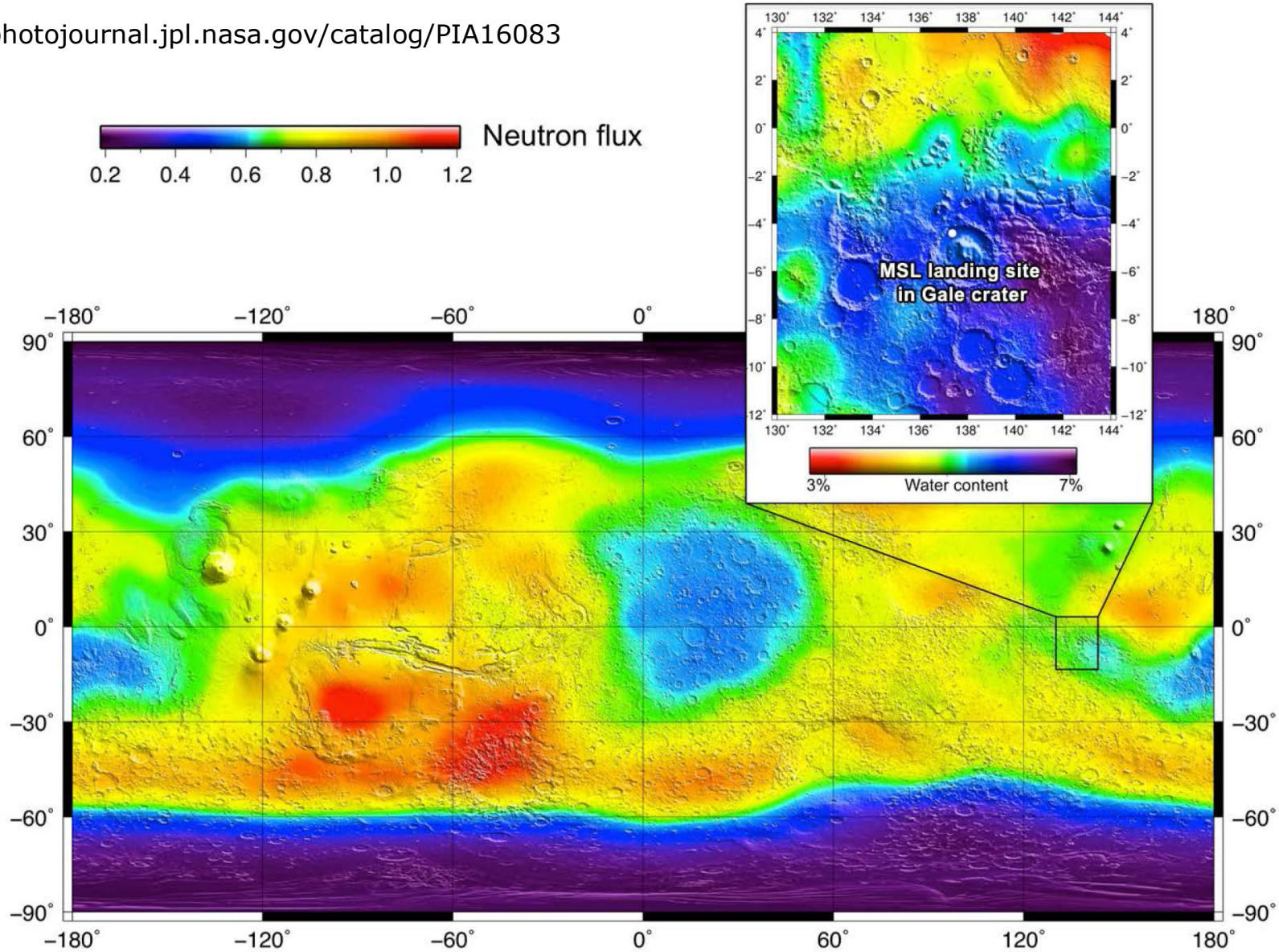


- **Pulsing Neutron Generator**

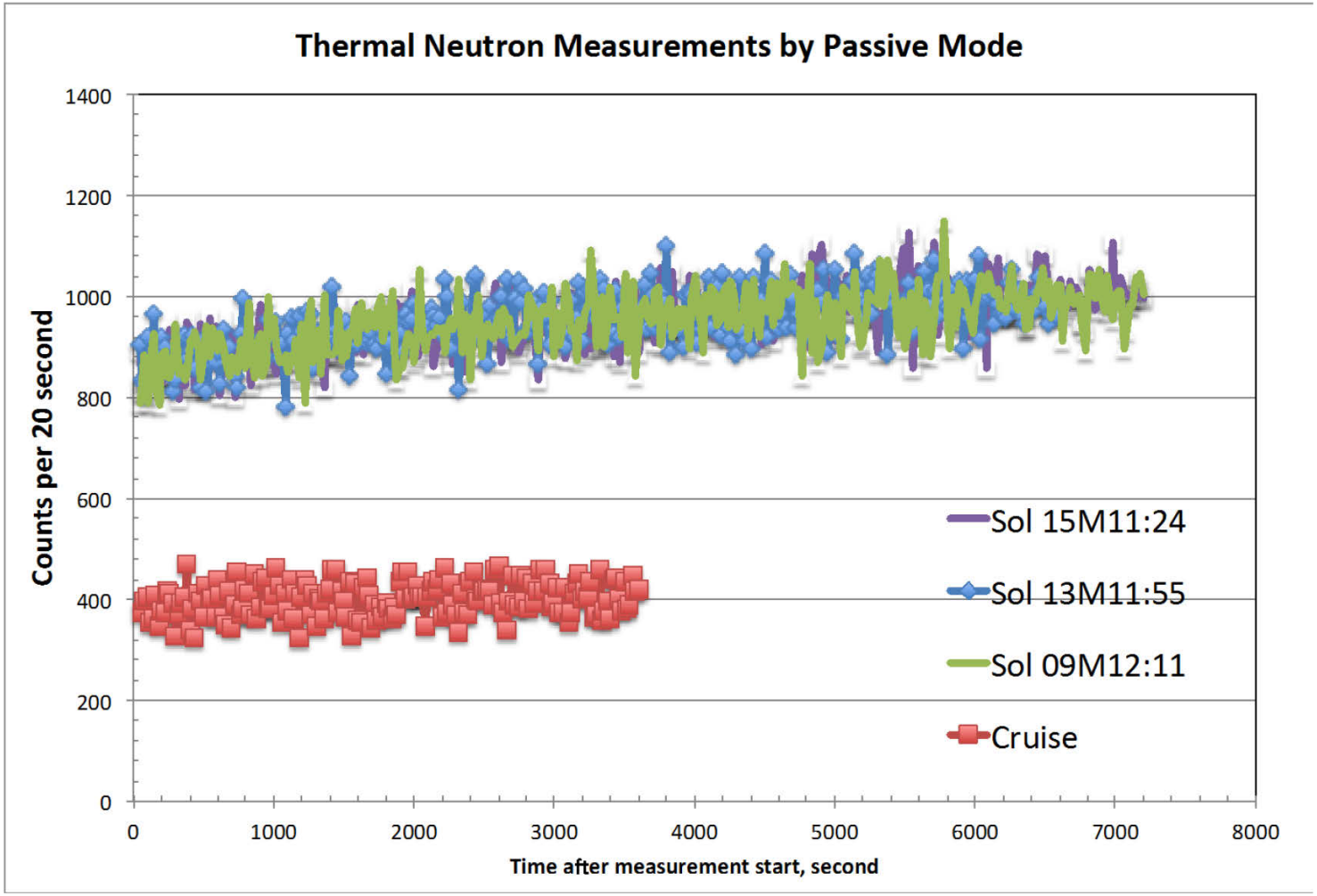
Planetary Radiation Environments

The heritage for investigations with the Dynamic Albedo of Neutrons instrument on NASA's Curiosity rover comes from NASA's Odyssey orbiter. The orbiter has performed global mapping of neutrons, showing varying degrees of hydrogen in the Martian soil as indicated on this chart. The hydrogen is an indicator of the presence of water.

http://photojournal.jpl.nasa.gov/catalog/PIA16083

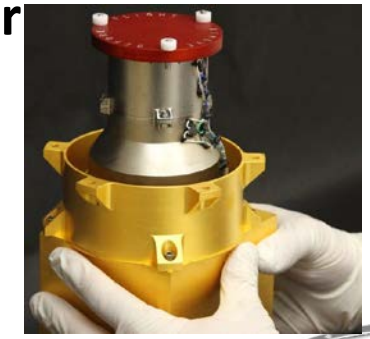


Background Neutrons

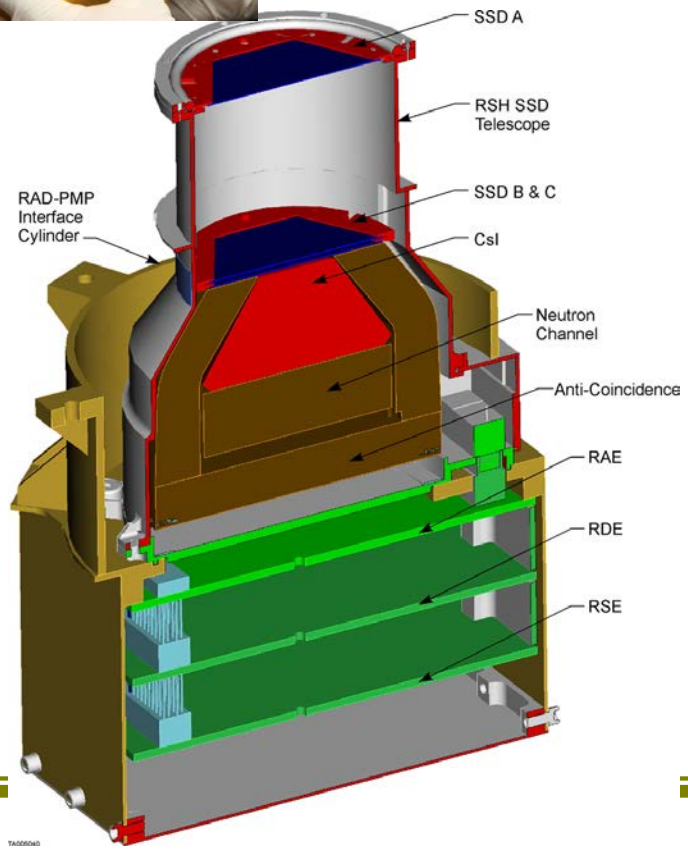


Radiation Assessment Detector (RAD)

- **Principal Investigator: Donald M. Hassler**
- **Southwest Research Institute**



- **RAD characterizes the radiation environment on the surface of Mars**
  - Measures galactic cosmic ray and solar energetic particle radiation, including secondary neutrons and other particles created in the atmosphere and regolith
  - Determines human dose rate, validates transmission/transport codes, assesses hazard to life, studies the chemical and isotopic effects on Mars' surface and atmosphere
  - Solid state detector telescope and CsI calorimeter. Zenith pointed with 65° FOV.
  - Detects energetic charged particles (Z=1-26), neutrons, gamma rays, and electrons



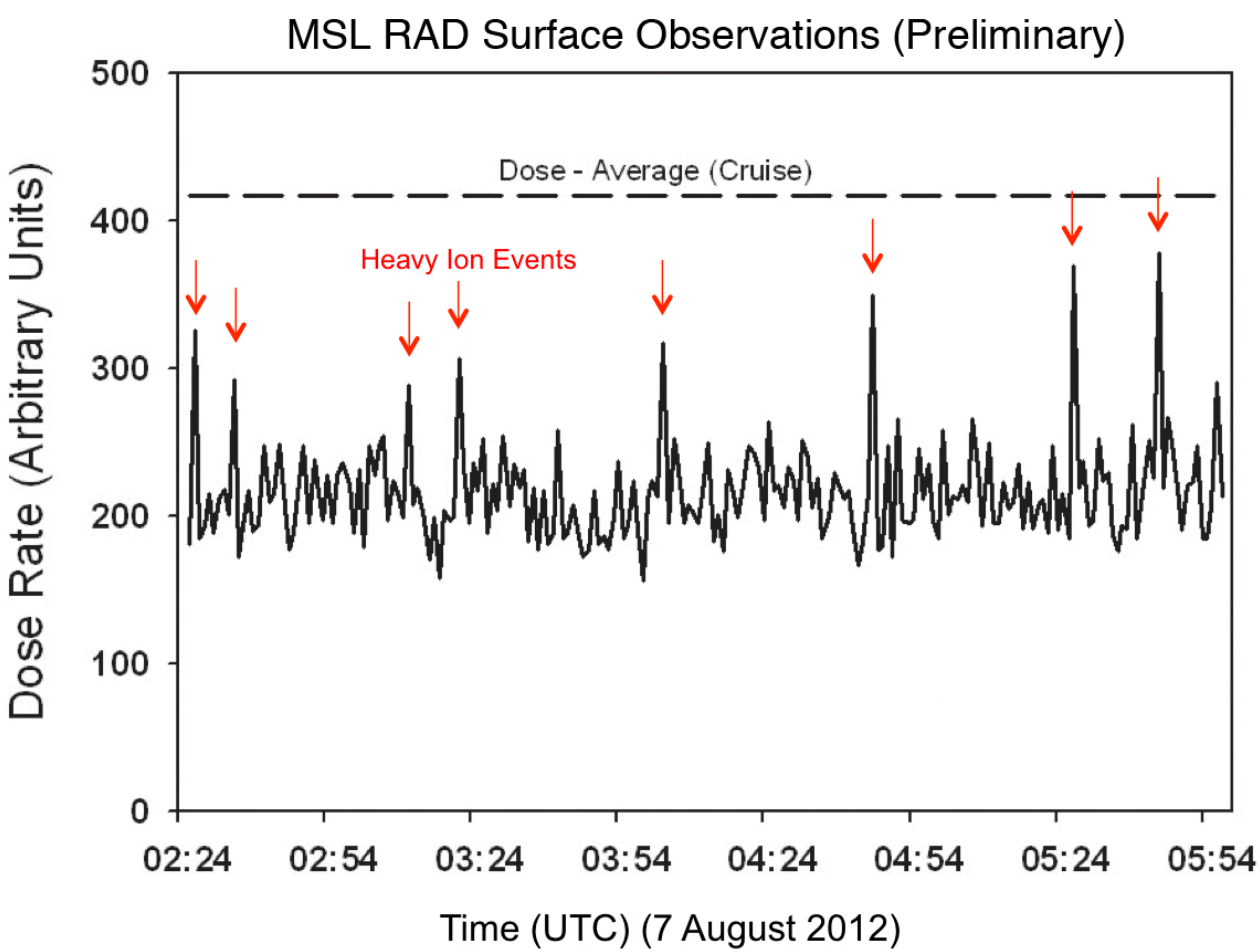
100 Years after the Discovery of Cosmic Rays on Earth…August 7, 1912

- Exactly 100 years after Victor Hess discovered Cosmic Rays from his hydrogen balloon in Eastern Germany…
- …MSL RAD makes the first measurements of the cosmic ray environment on the surface of Mars!

- Credit: Foray (New York Times)

RAD makes the first Radiation Measurements on the Surface of Mars! (August 7, 2012)

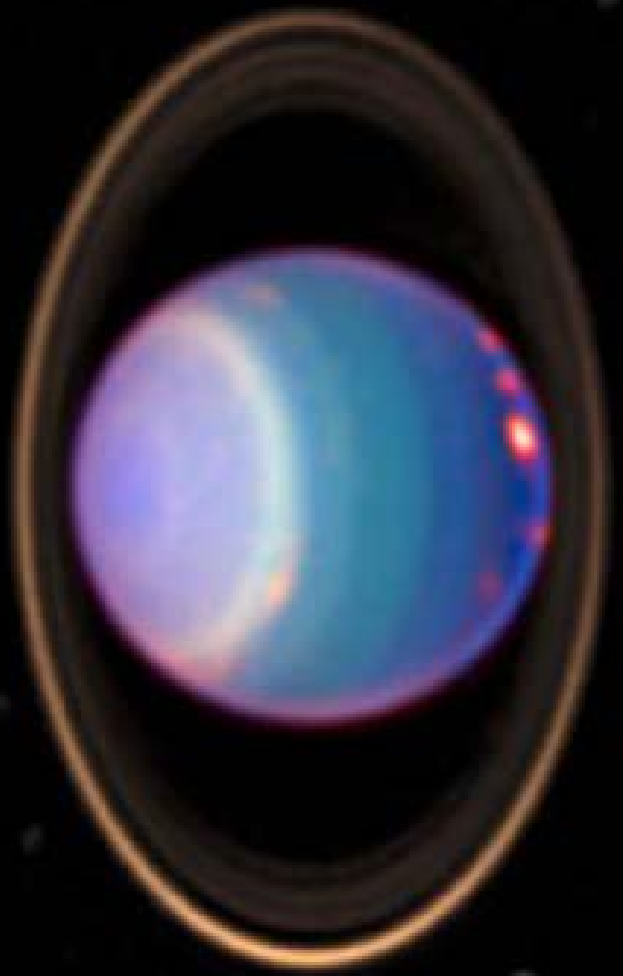
•~3 ½ hrs of RAD observations with 1 obs/min



- Very Quite Solar Activity - no SEP events…
- Several dose corrections have not yet been applied…
  - RTG background
  - Conversion between Silicon & plastic
- Spikes in the measured dose rate are heavy ion events (i.e. Mg, etc.)…
- Accumulating statistics & understanding these "spikes" is what RAD is all about…energy spectra!

BACKUP

Uranus



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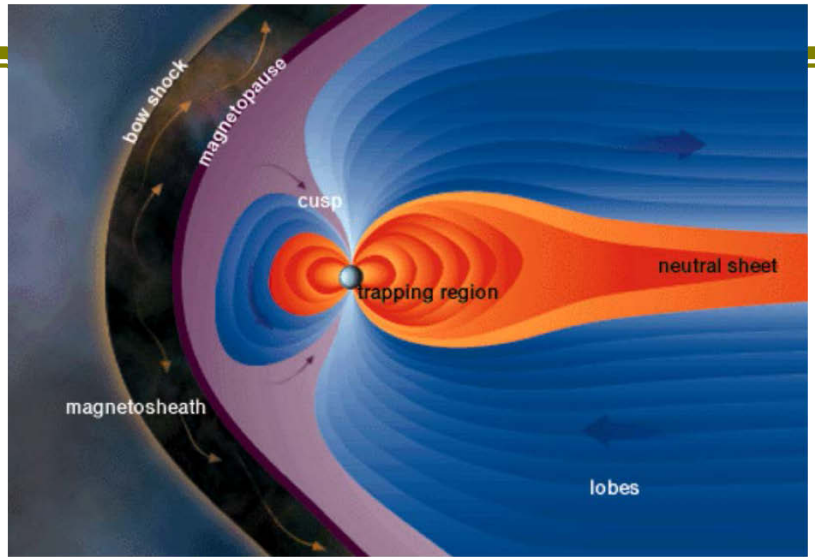
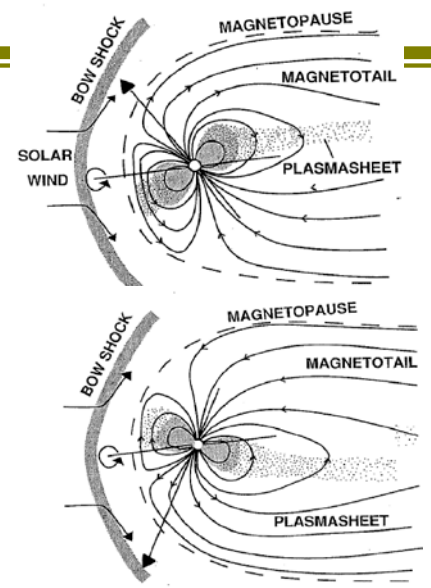
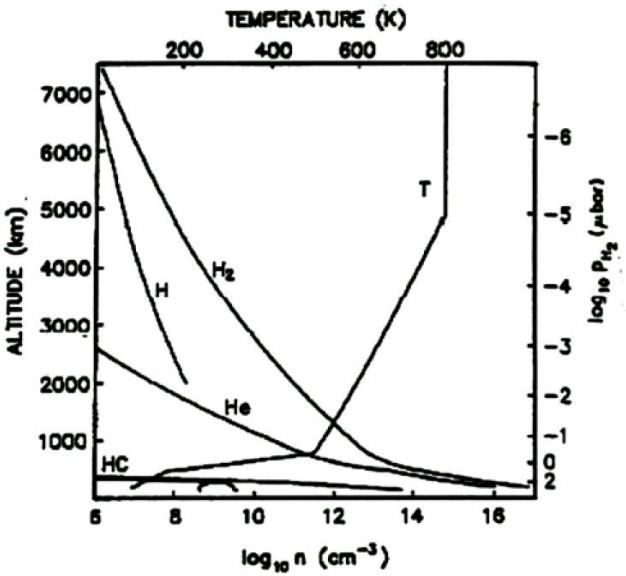
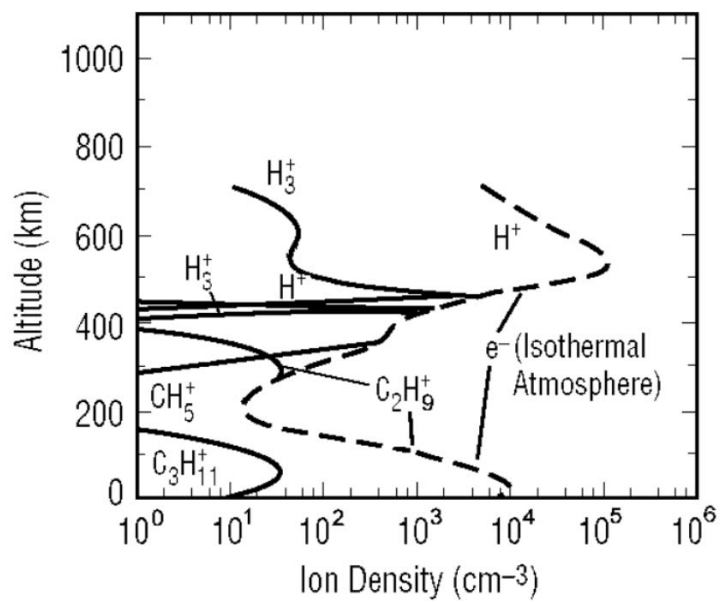
Uranus









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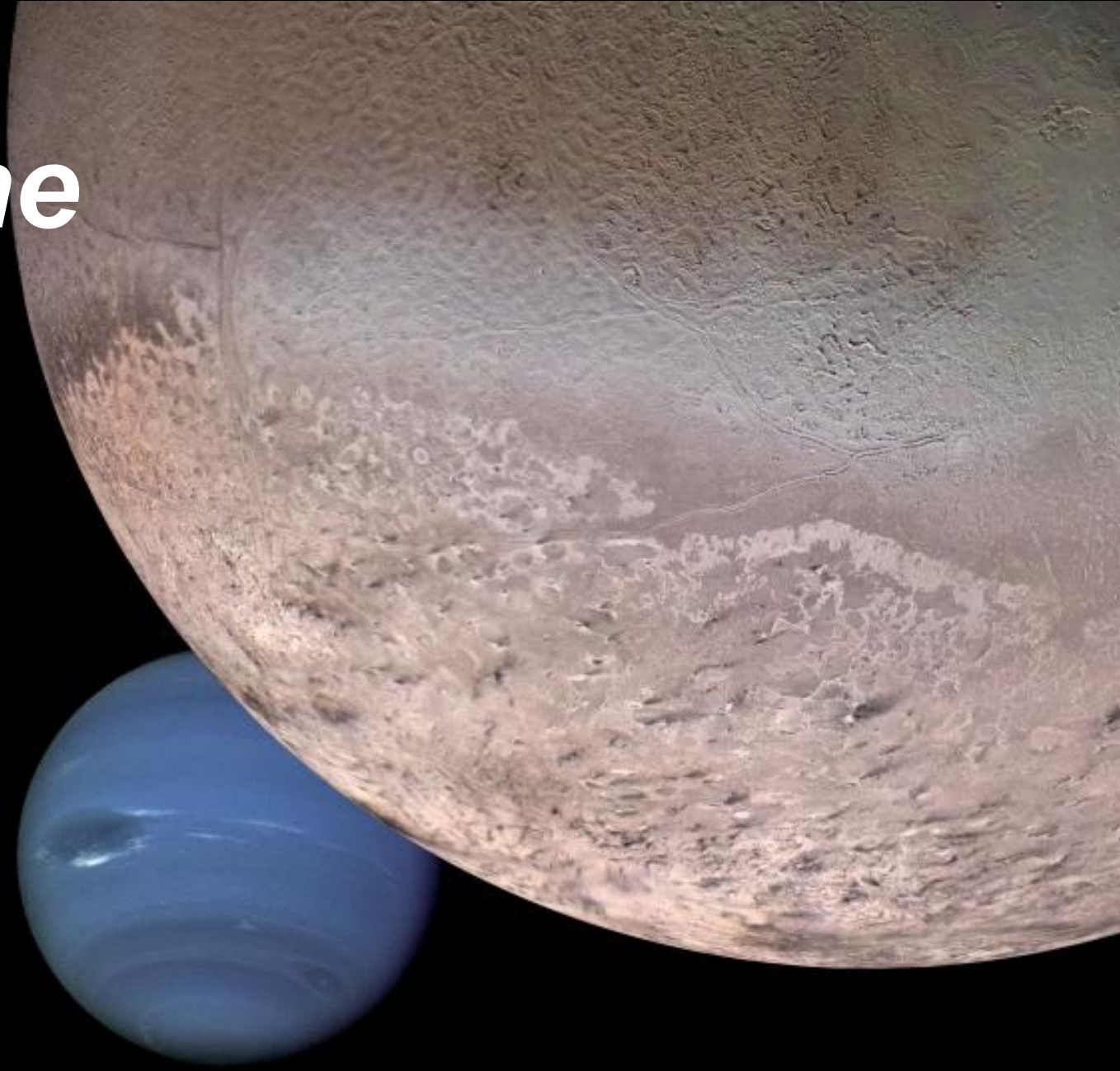
Neptune



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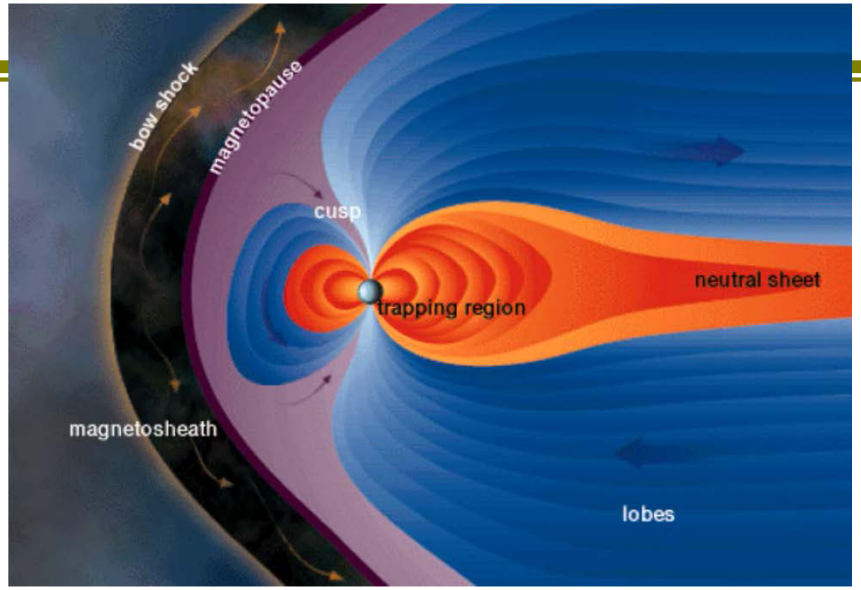
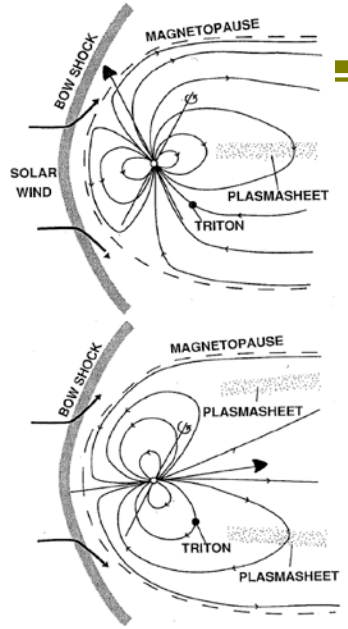
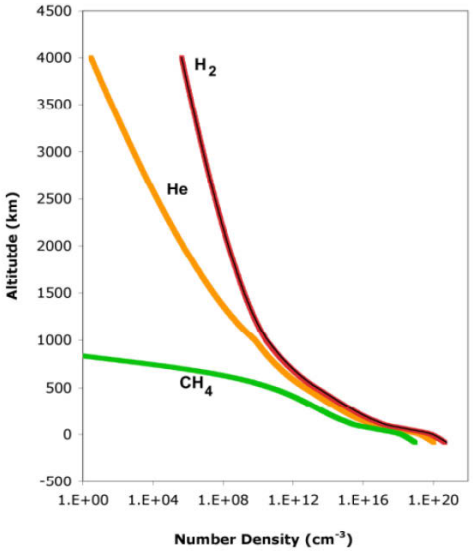
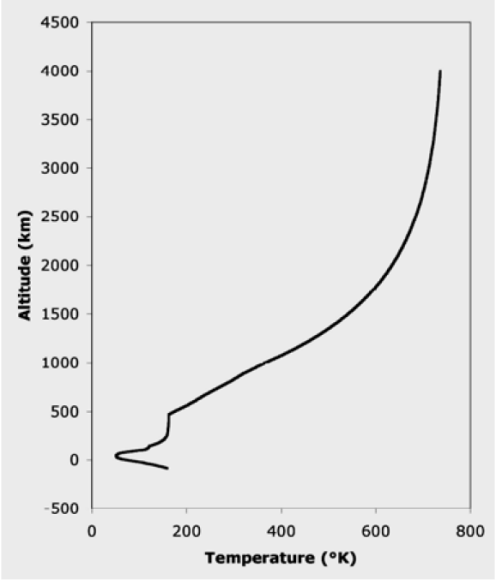
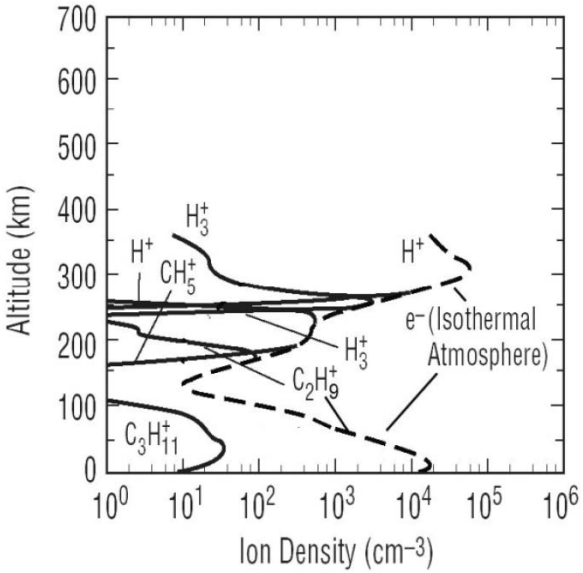
Planetary Radiation Environments











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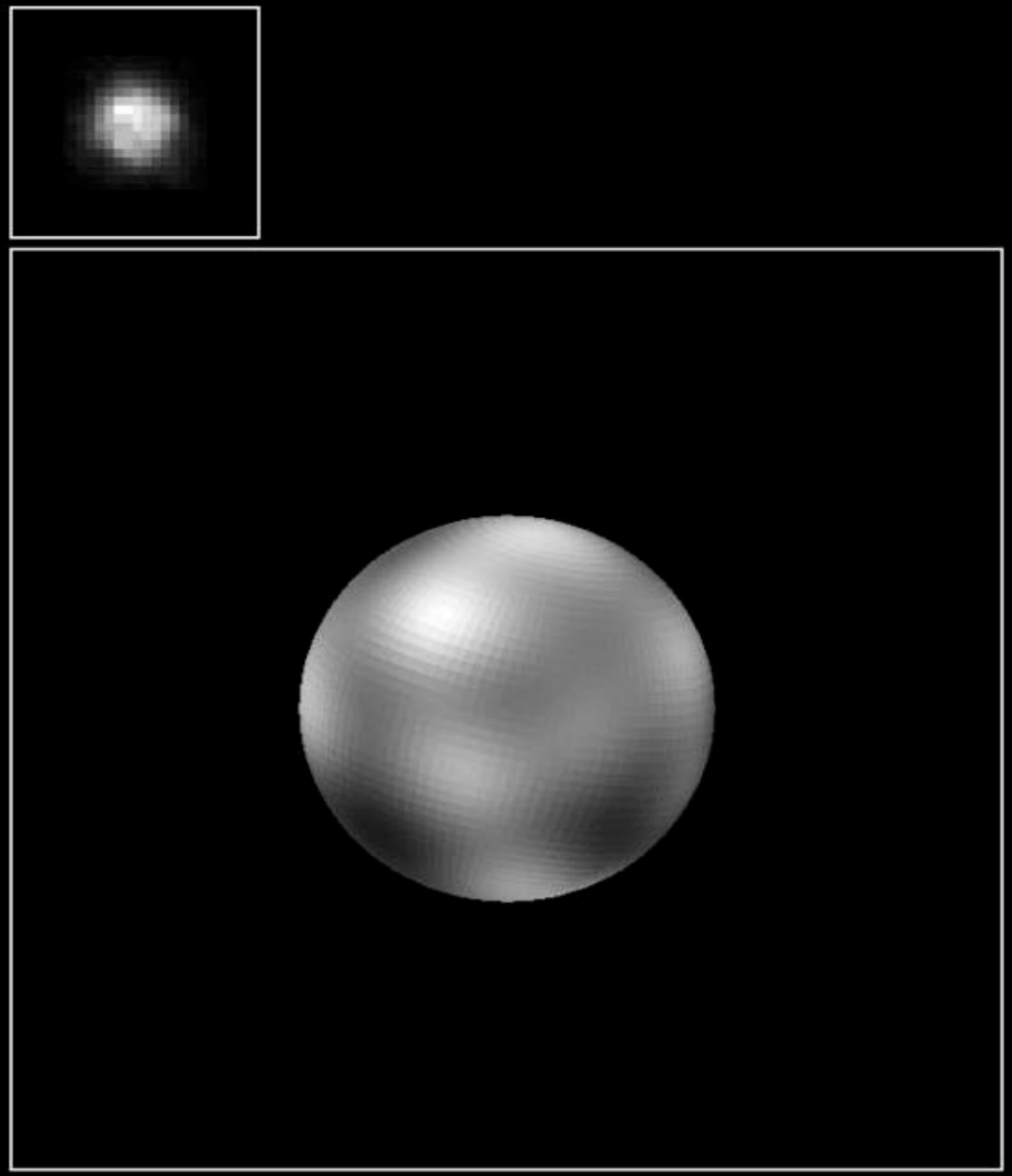
Pluto



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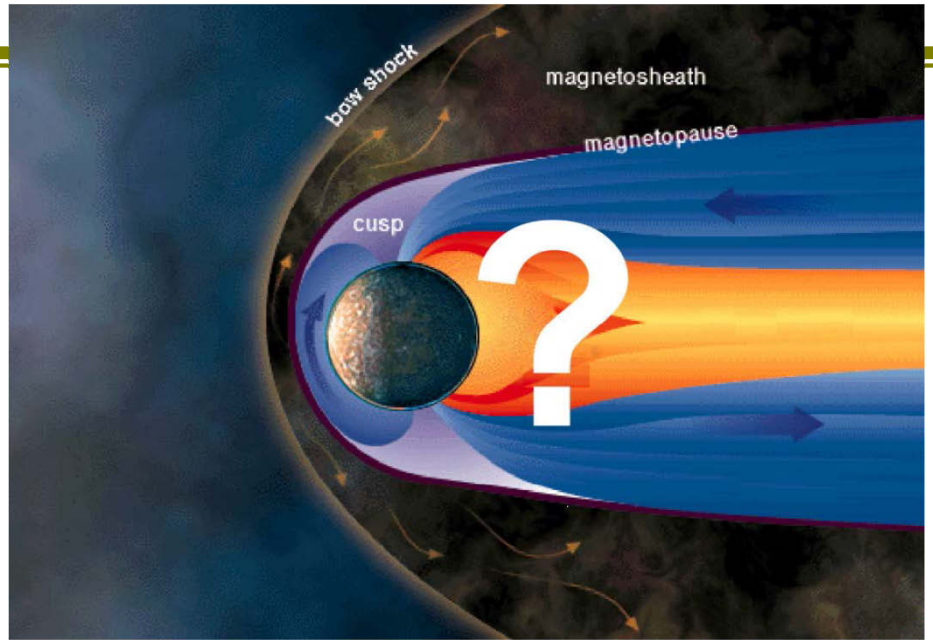
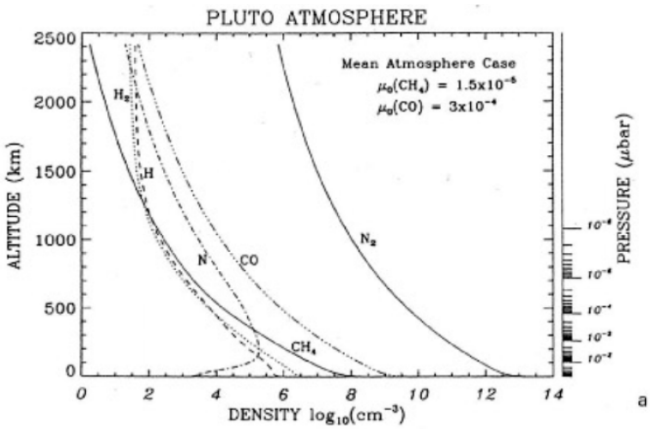
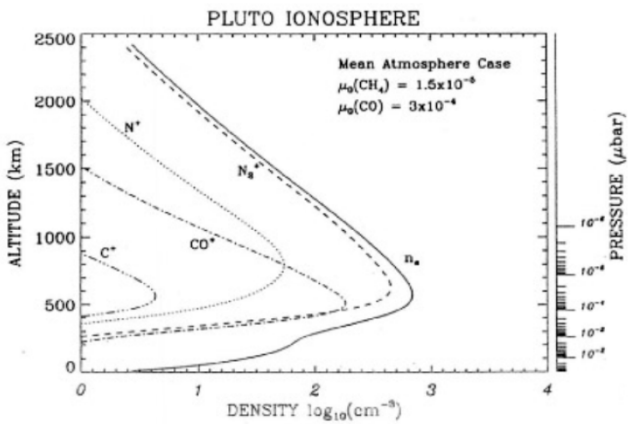
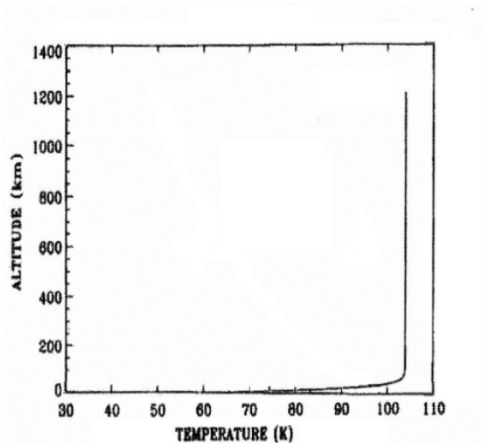
Pluto









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