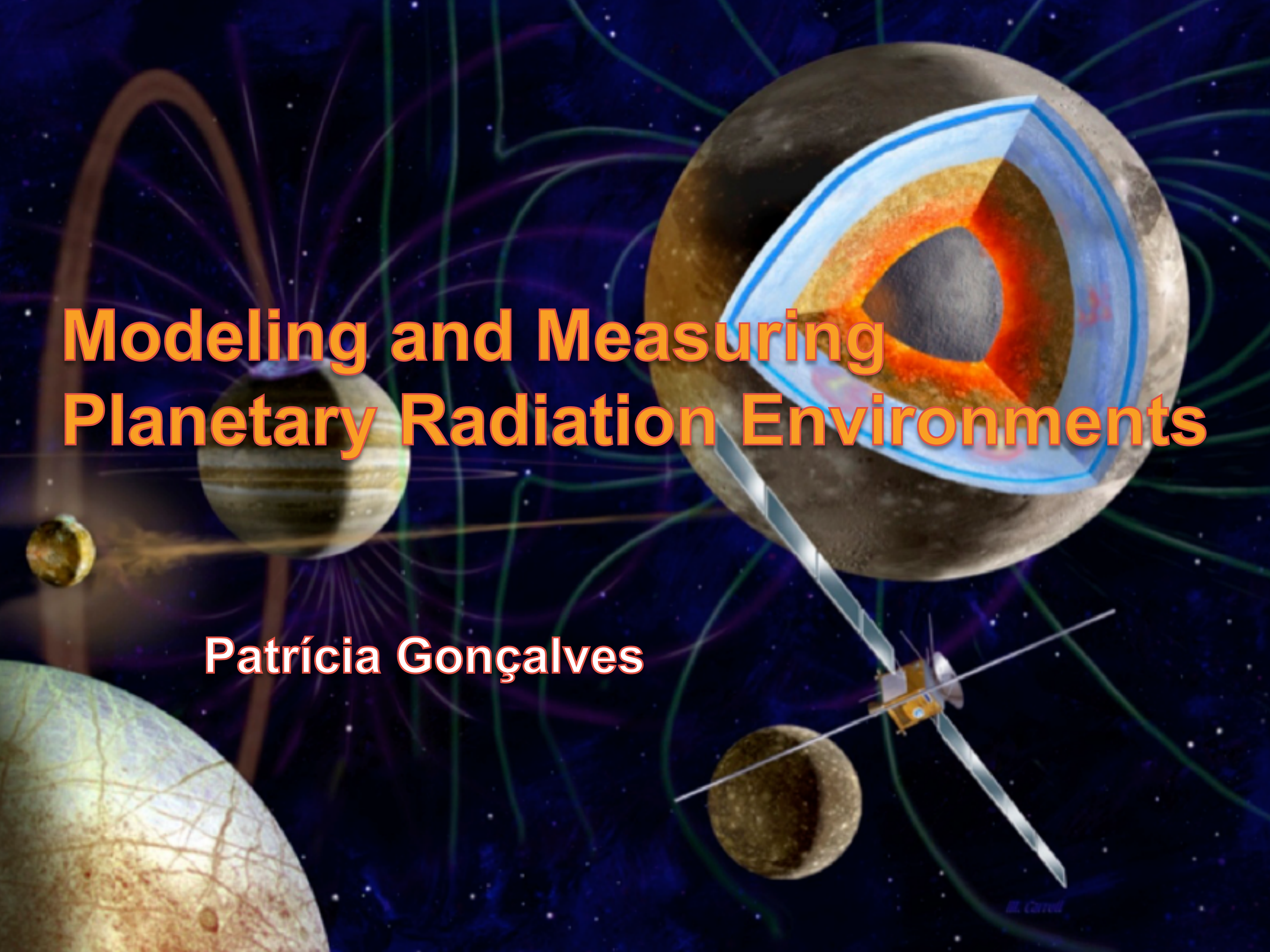


Modeling and Measuring Planetary Radiation Environments

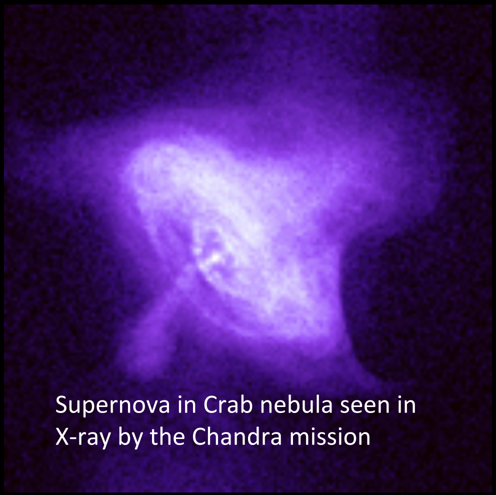
Patrícia Gonçalves

Radiation Environment in the Solar System

Galactic Cosmic Rays

low flux but highly penetrating

p I^{n+}



Supernova in Crab nebula seen in X-ray by the Chandra mission

Solar Particle Events

sporadic, intense & dangerous

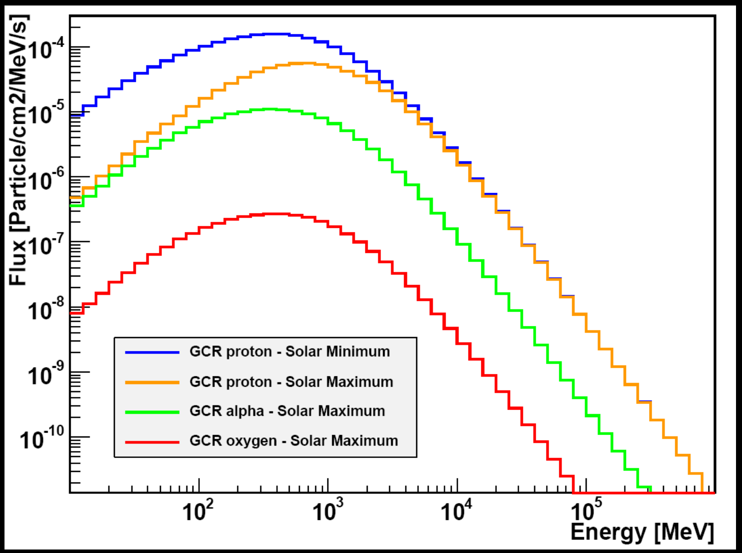
e^- p I^{n+}

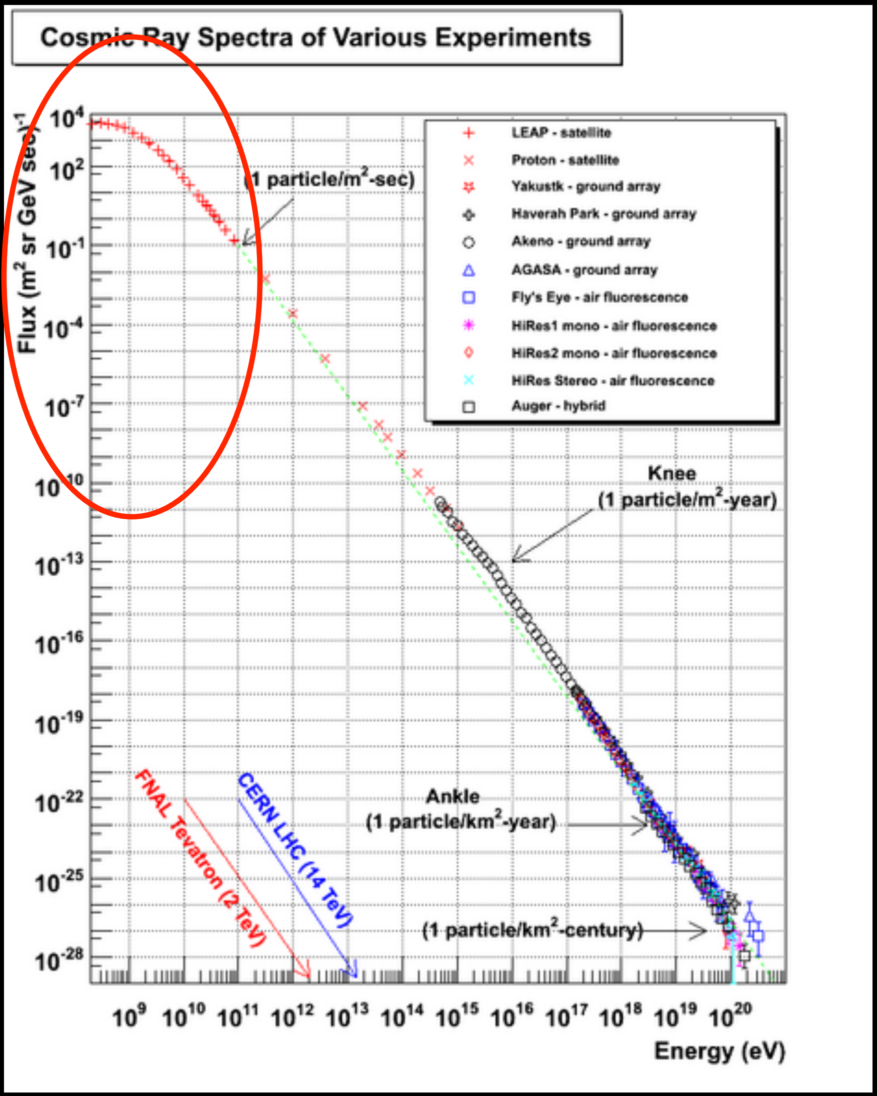
Radiation Belts

high radiation dose

e^- p

“Galactic” Cosmic Rays (GCR)





Low flux but highly penetrant

- Protons and nuclei: energy spectra peak at ~1 GeV/n
- Solar cycle modulated flux : inversely proportional to the Sun’s activity
- E < 1 GeV/n: highly affected by solar activity

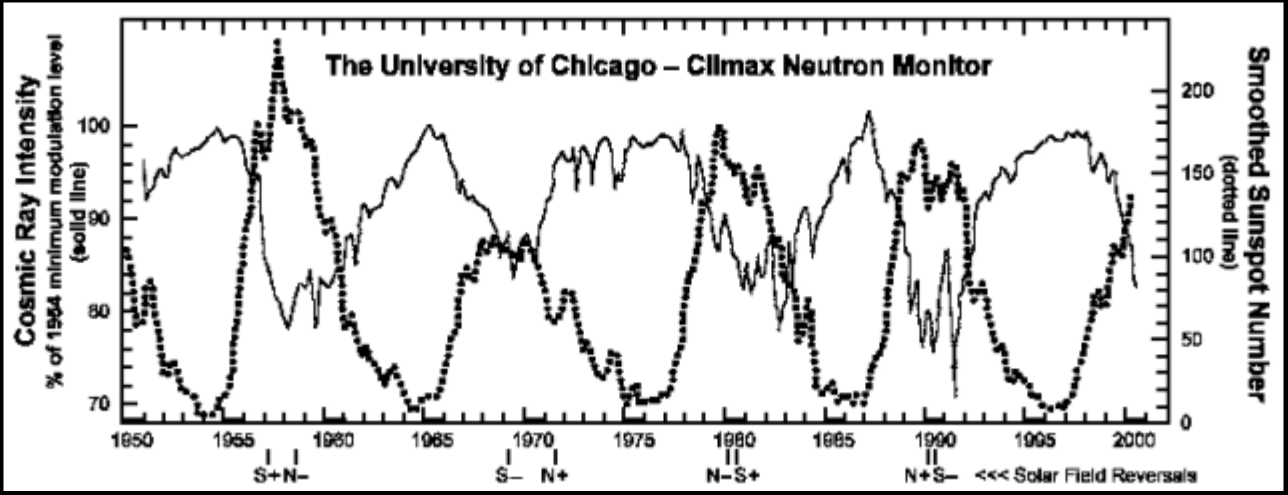
GCG and Solar cycle

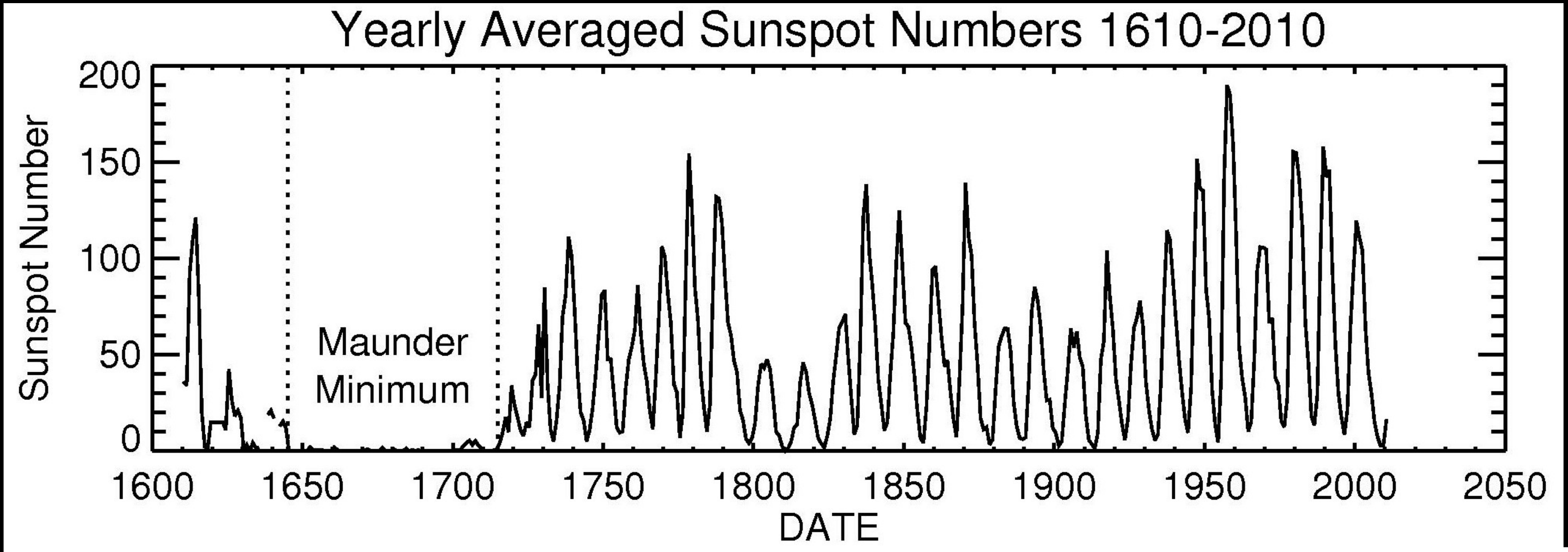
Modulation with solar activity

11 year solar cycle

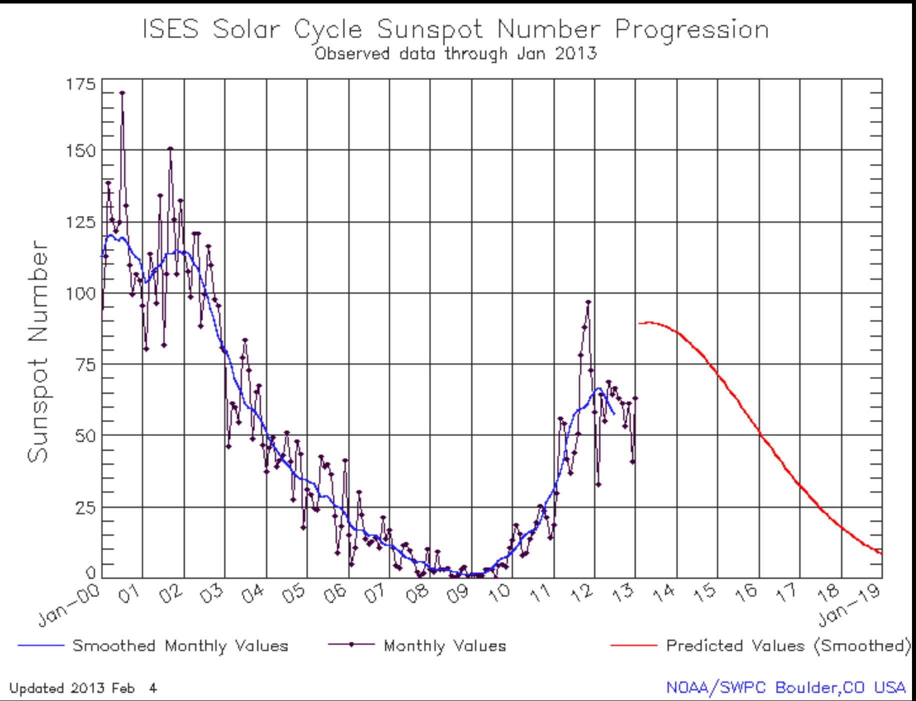
Maximum:
solar storms and SEP

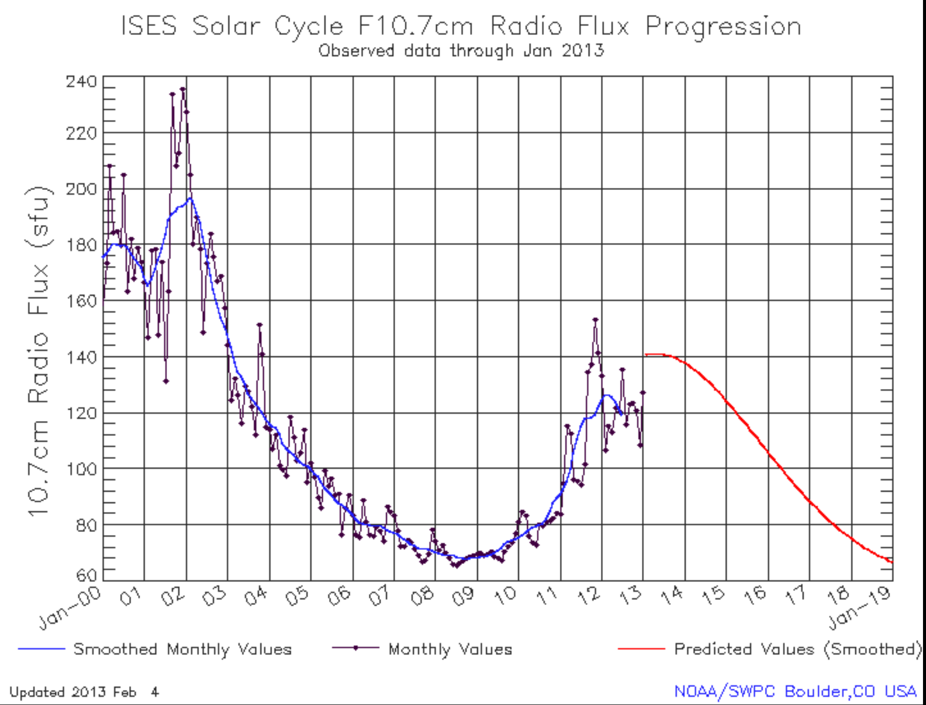
Minimum:
more GCR





Solar cycle 24

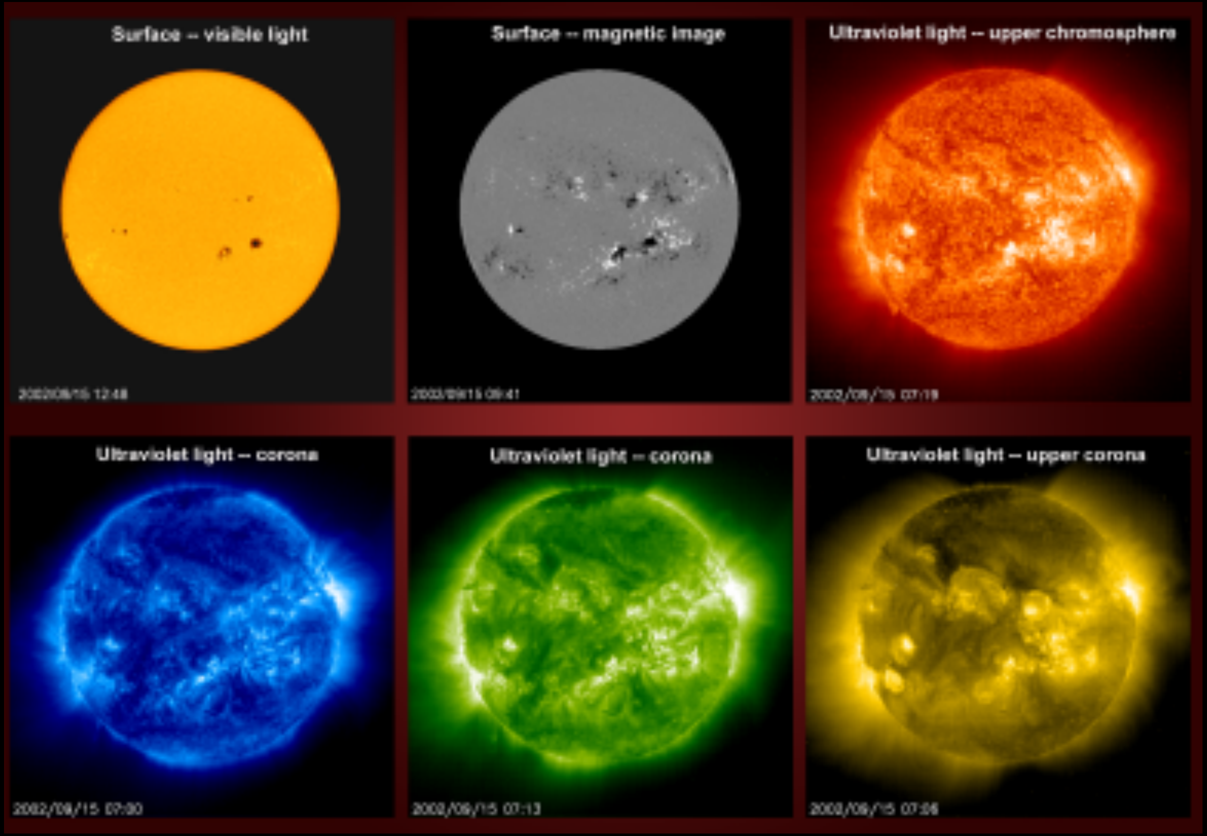


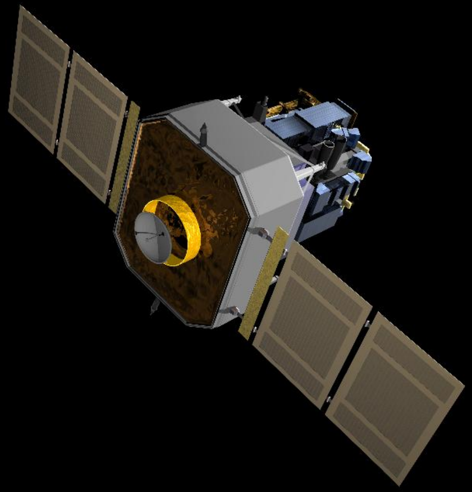


The Sun

SOHO : Solar and Heliospheric Observatory

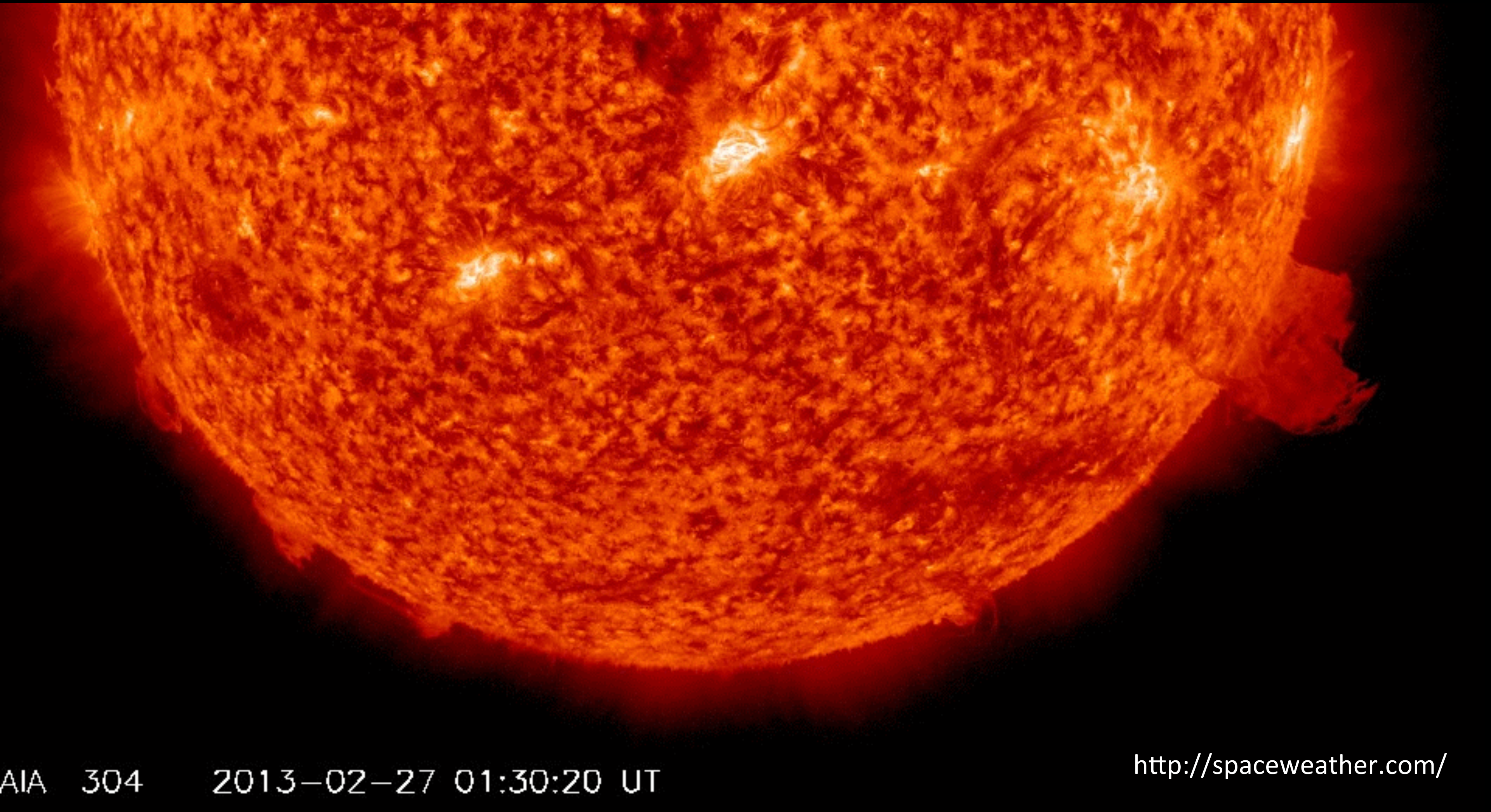
SOHO is a project of international cooperation between ESA and NASA to study the Sun, from its deep core to the outer corona, and the solar wind.

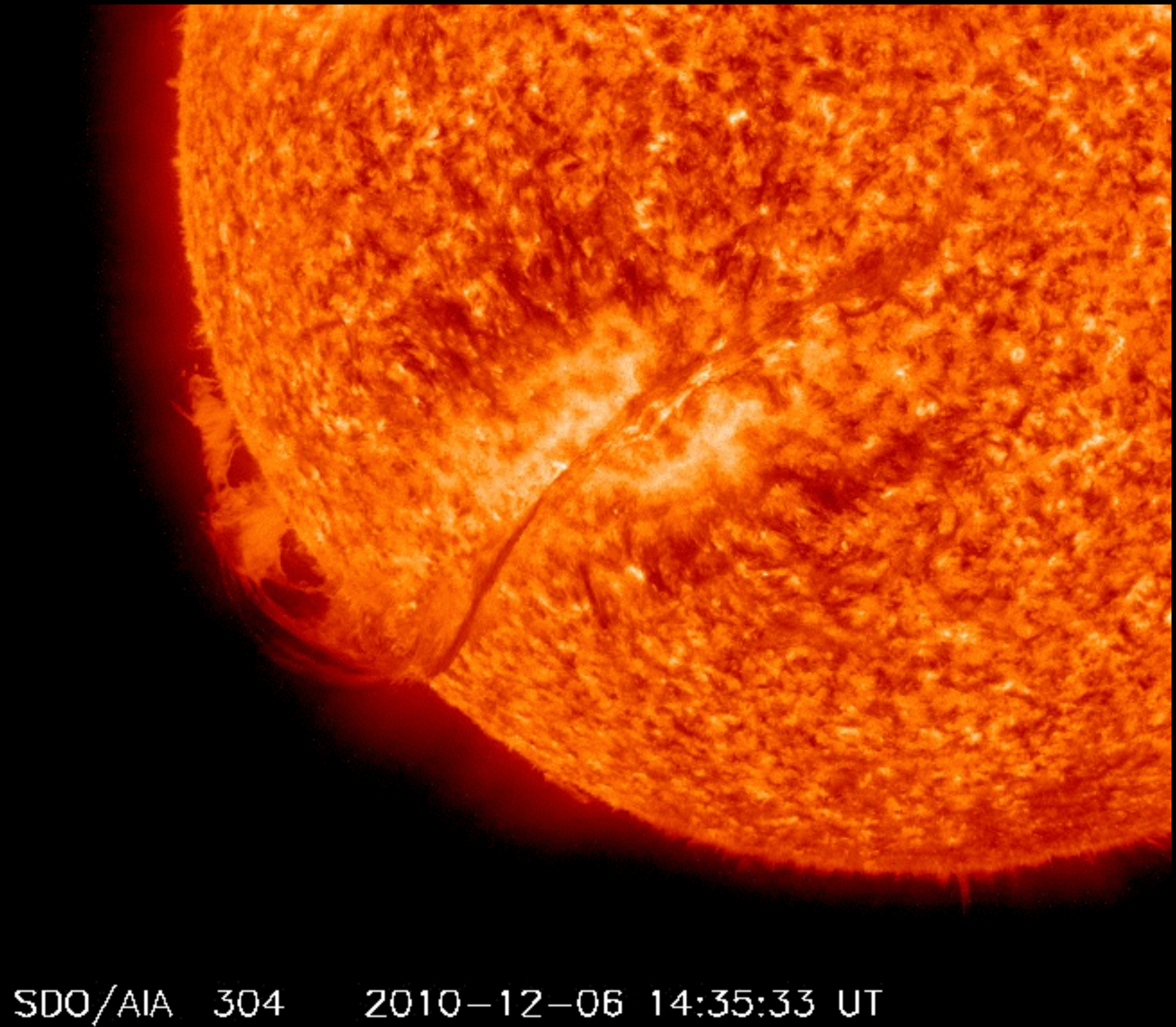




SEP
Eventos solares

JUPITER-SIZED HOLE: A magnetic filament curling around the sun's southwestern limb erupted during the early hours of Feb. 27th. As it flew away, it formed a loop of plasma big enough to pass the entire planet Jupiter.



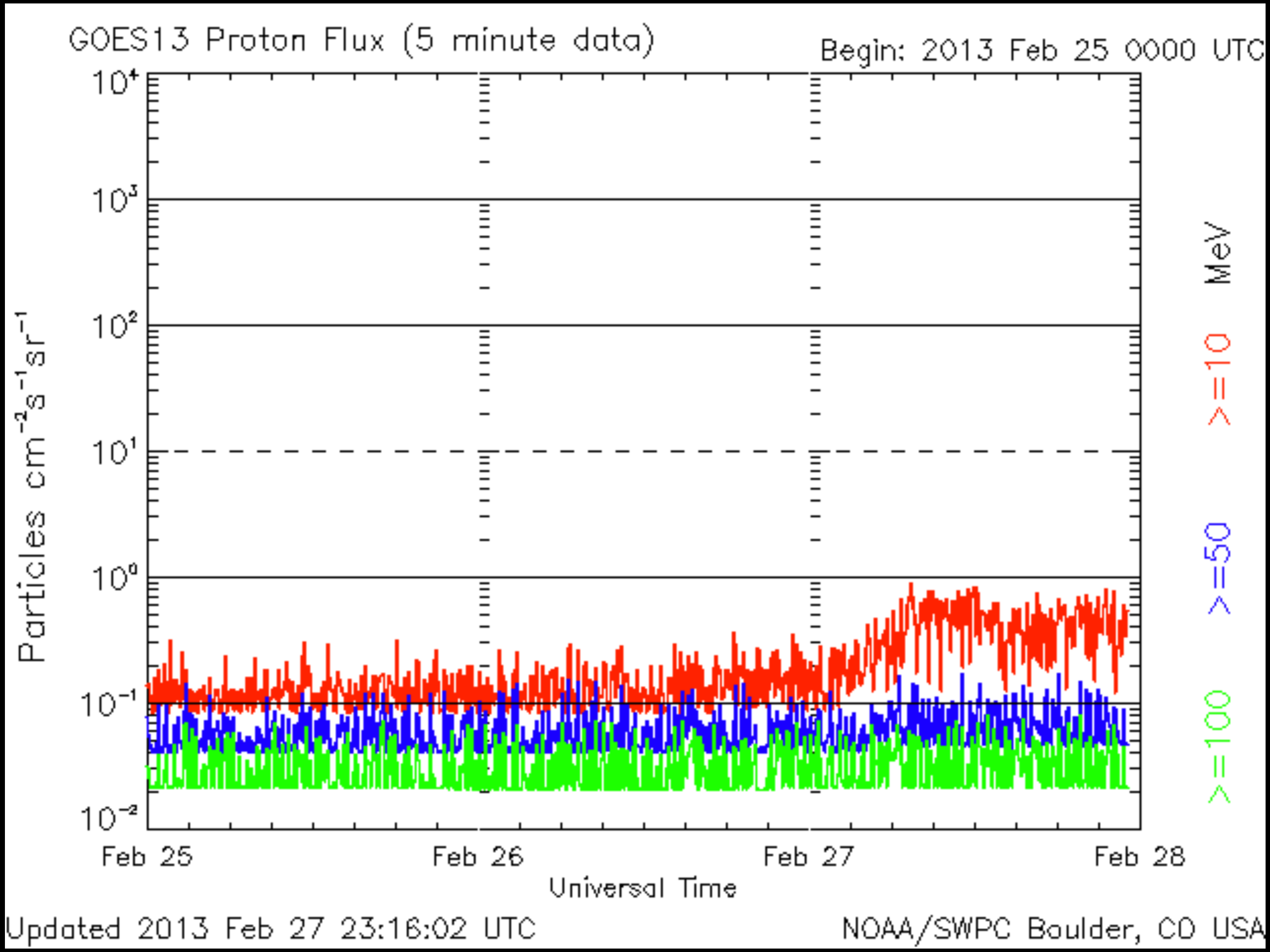


http://spaceweather.com/

Solar Energetic Particle Events

Todays Space weather

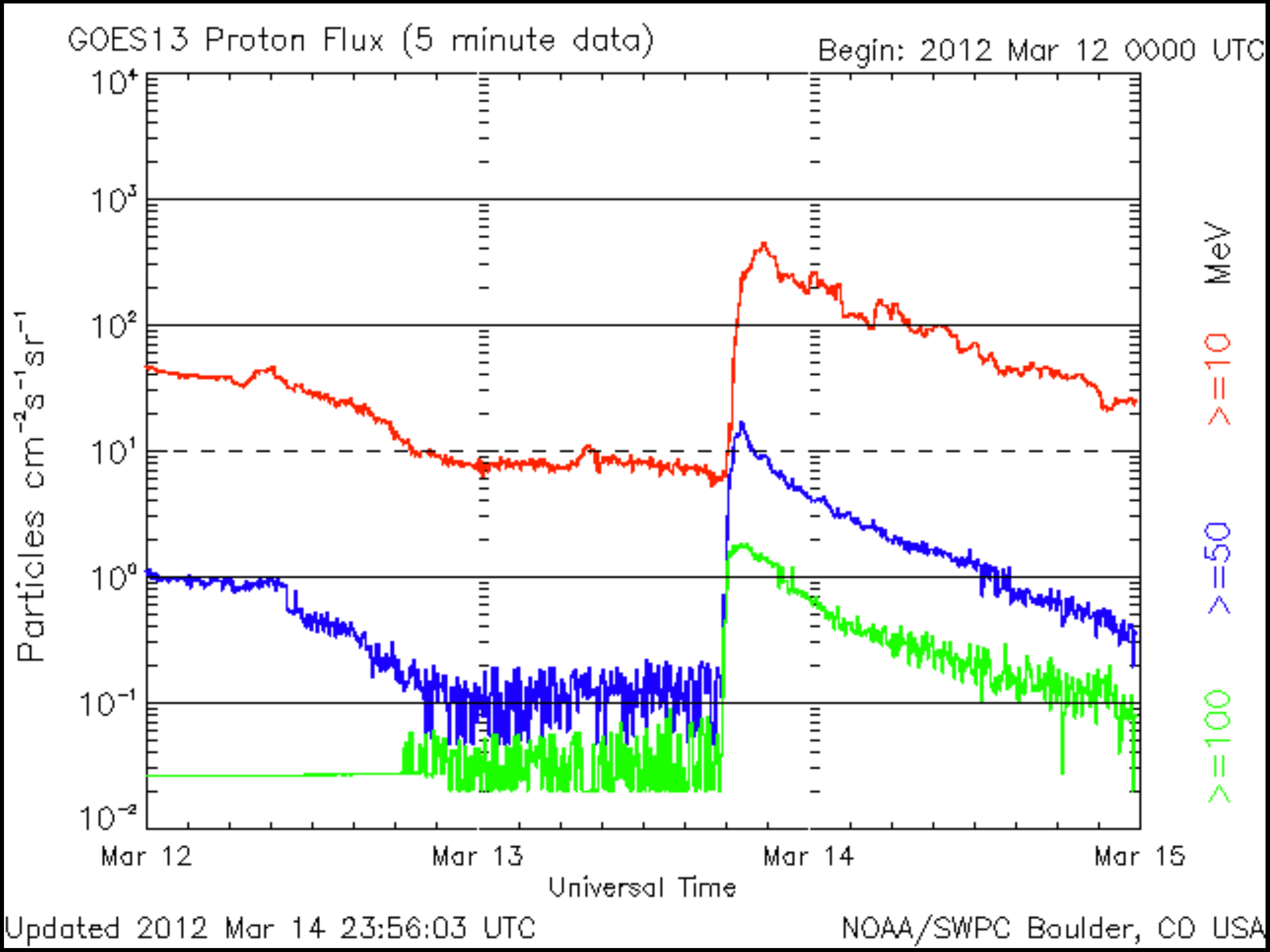
http://www.swpc.noaa.gov



GOES: Geostationary Operational Environmental Satellites

Solar Energetic Particle Events

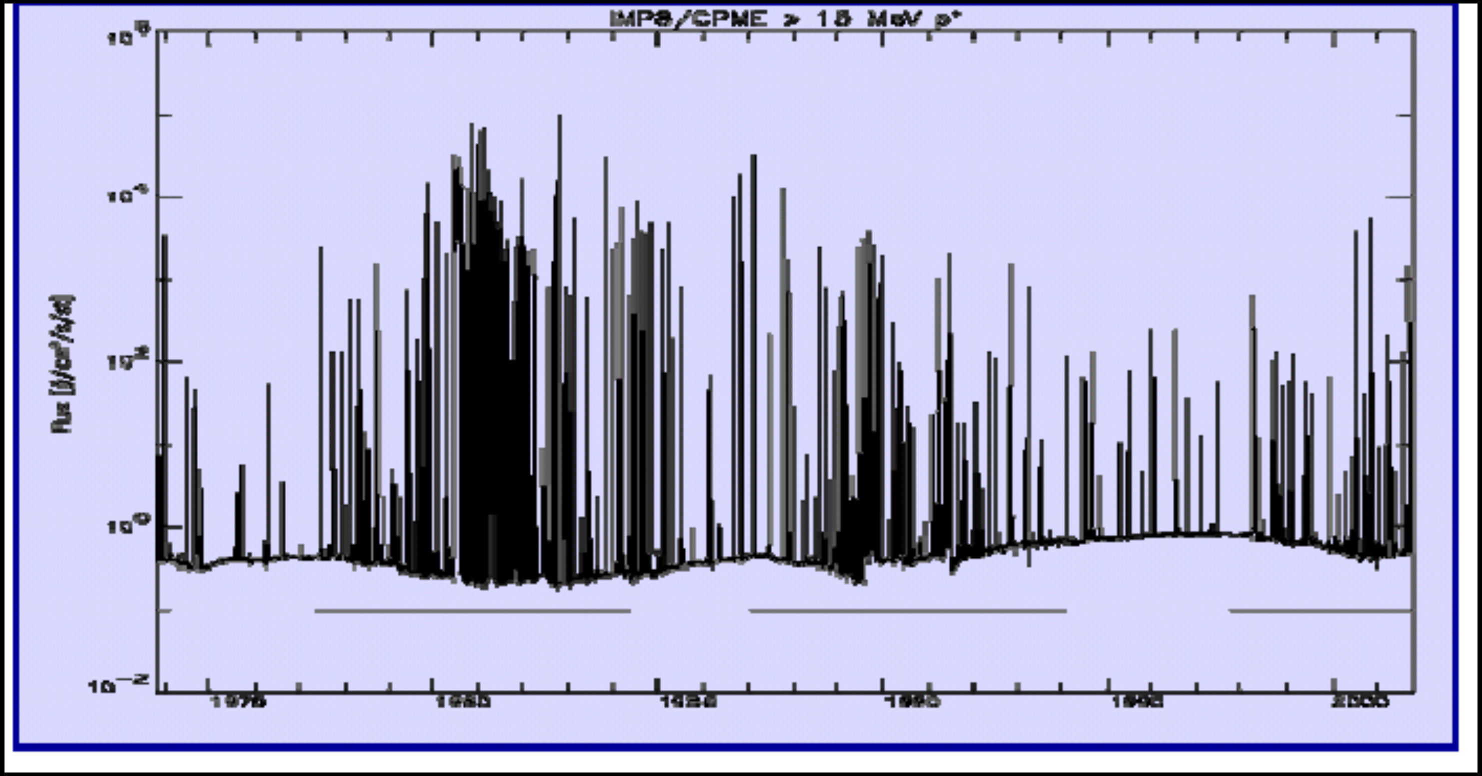
13 May 2012: SPE



http://www.swpc.noaa.gov

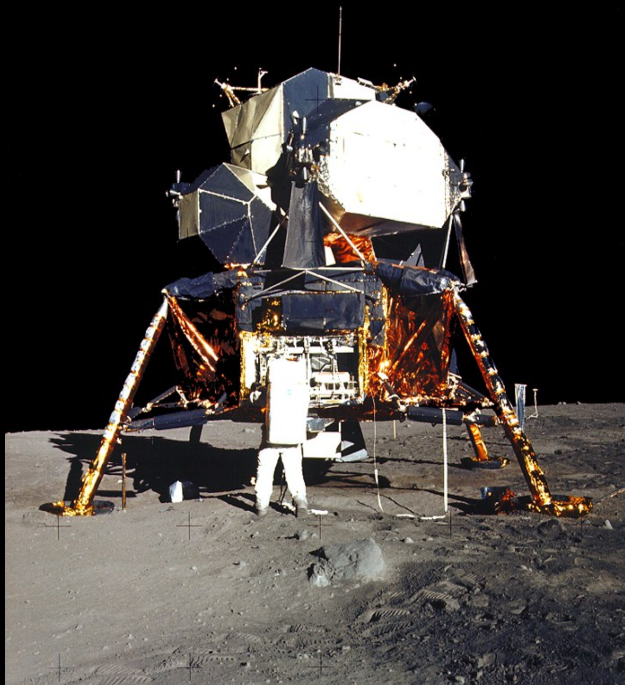
Long term record of SPEs

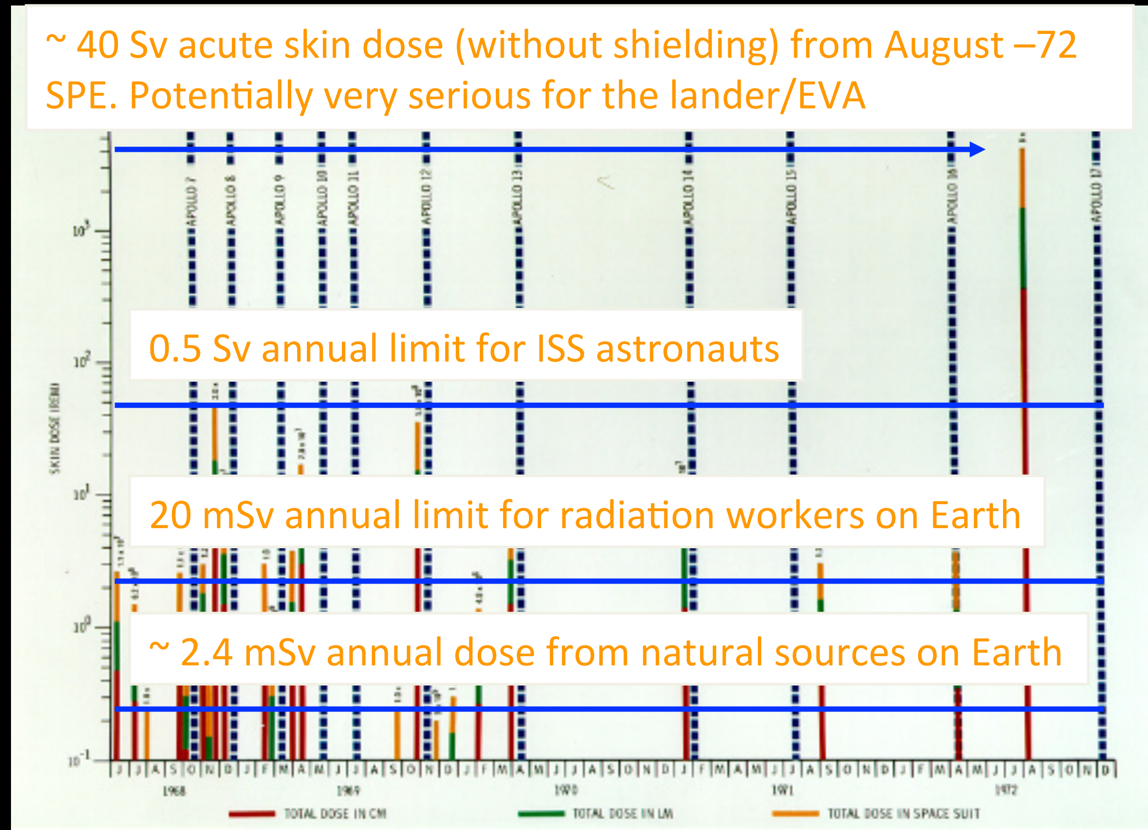
- More in "maximum" solar activity years
- Highly unpredictable
- Design for by making statistical assessment

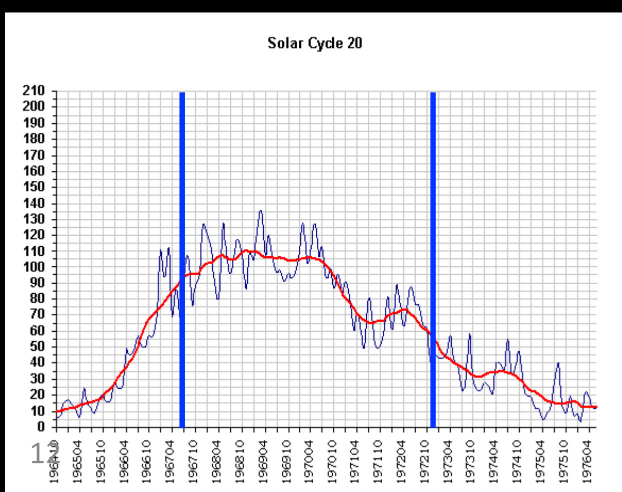


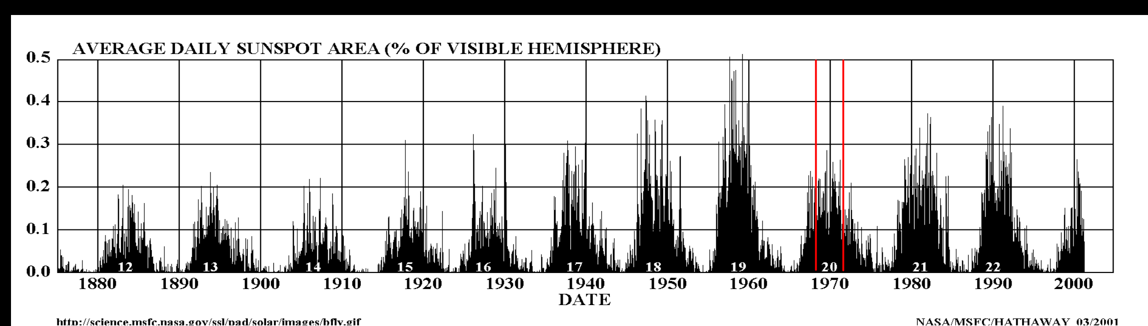
1975 2000

Apollo missions: Solar maximum

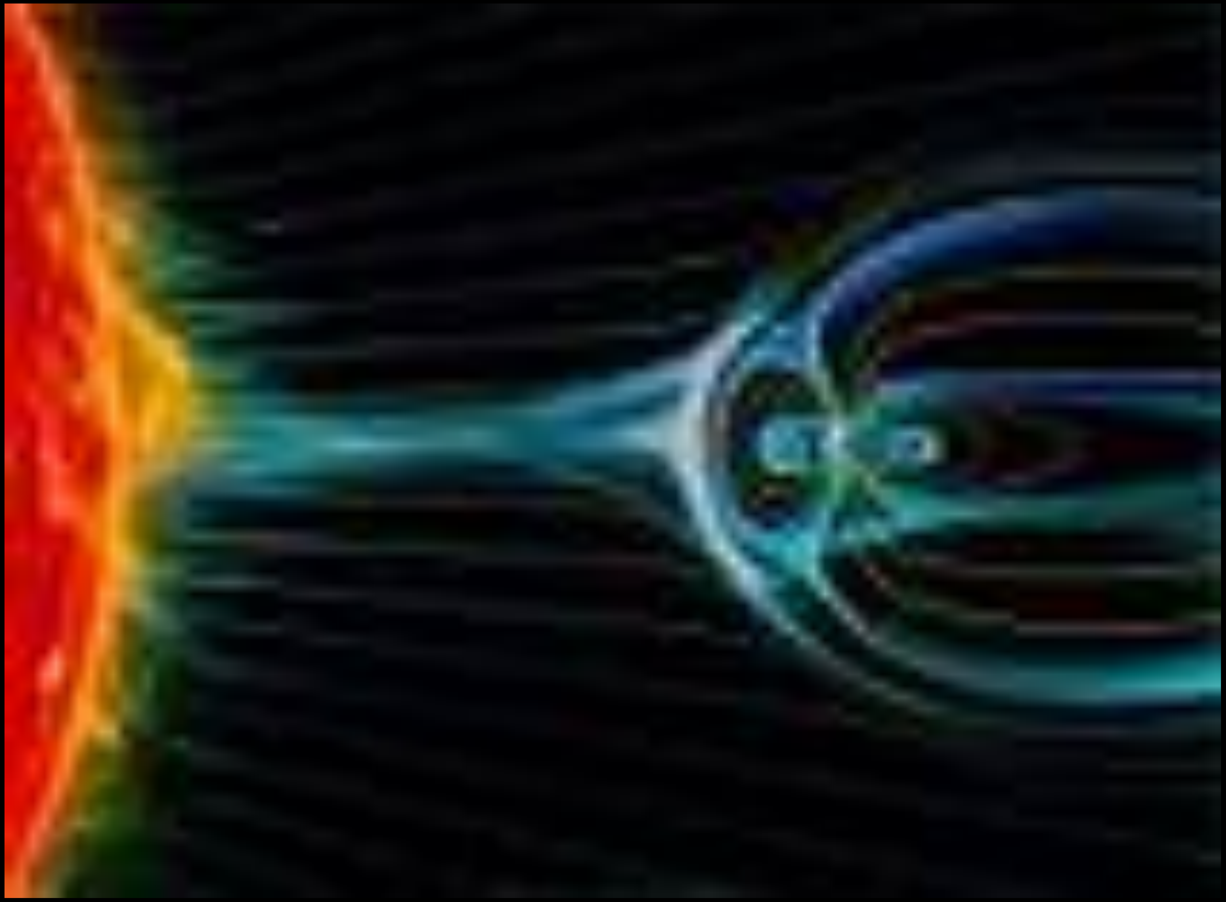








Magnetospheric Storms



See movie in: http://www.youtube.com/watch?v=BDZj1CmsJ64&feature=related

Aurora

Charged particles captured in the radiation belts excite N2 and O2 molecules that emit visible light while returning to the fundamental state.

Earth Radiation Belt Regions

High radiation dose, electrons (<10 MeV) & protons (<250 MeV)

- **Inner belt (700-10000 km)**

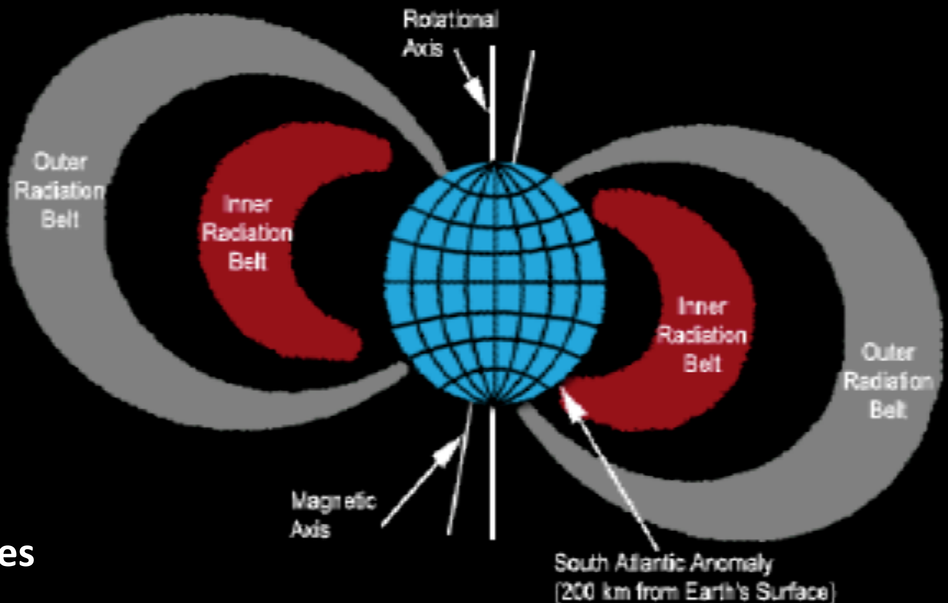
  dominated by protons
  CRAND = Cosmic Ray Albedo Neutron Decay
  ~static
  E~100's MeV

- **Outer belt (~20000-70000 km)**

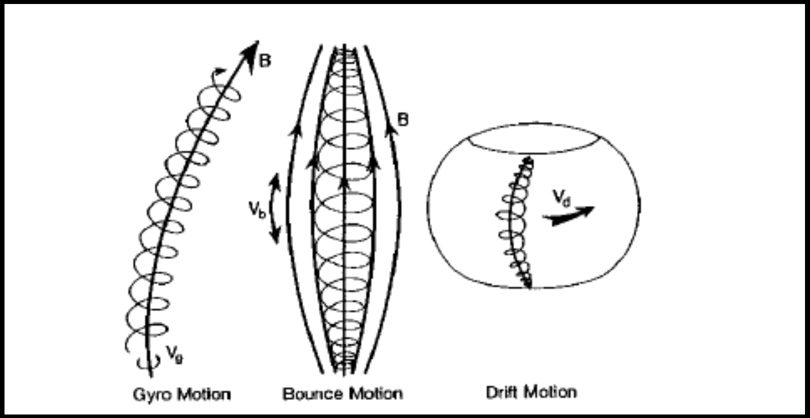
  dominated by electrons
  Controlled by "storms"
  Very dynamic
  E~ MeV

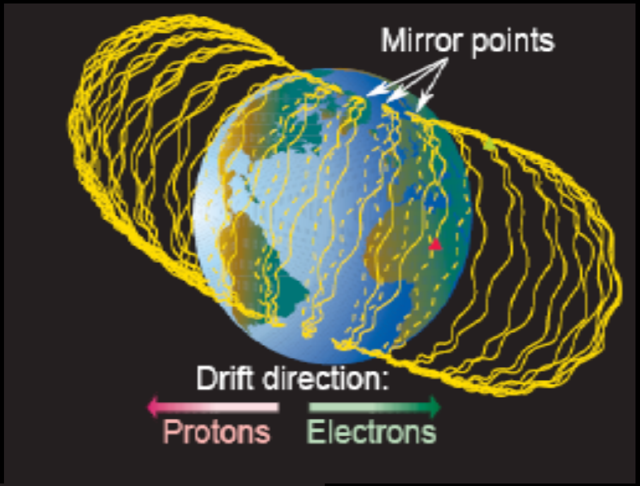
- **Slot**

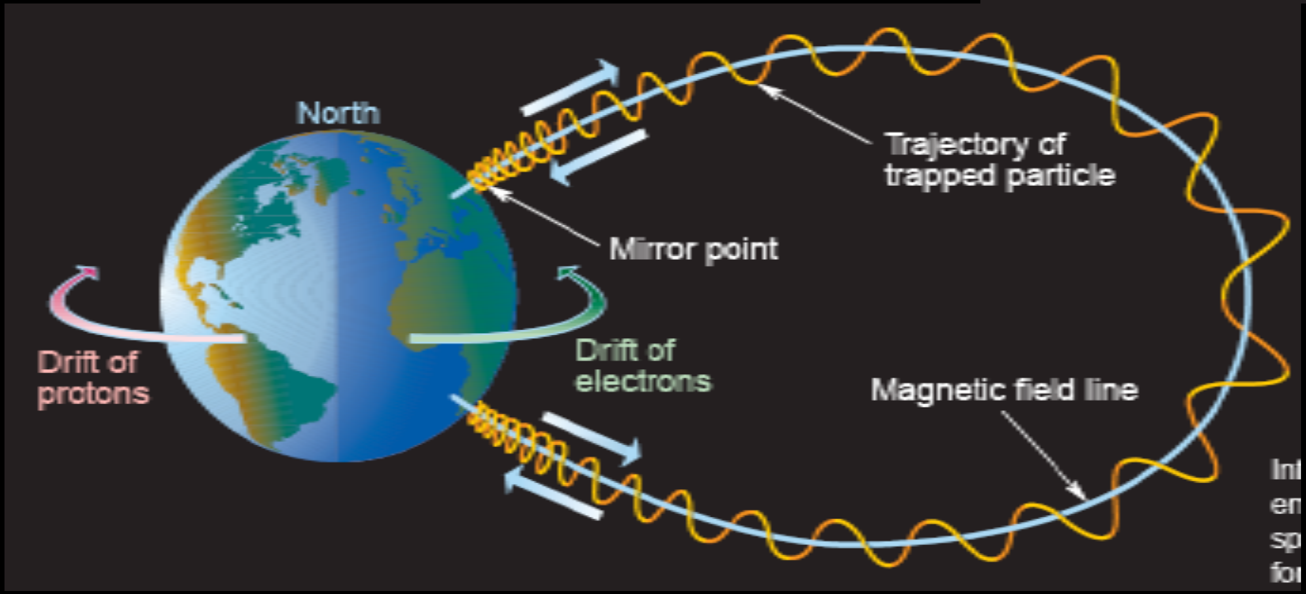
  low intensities of MeV electrons
  occasional injections of more particles



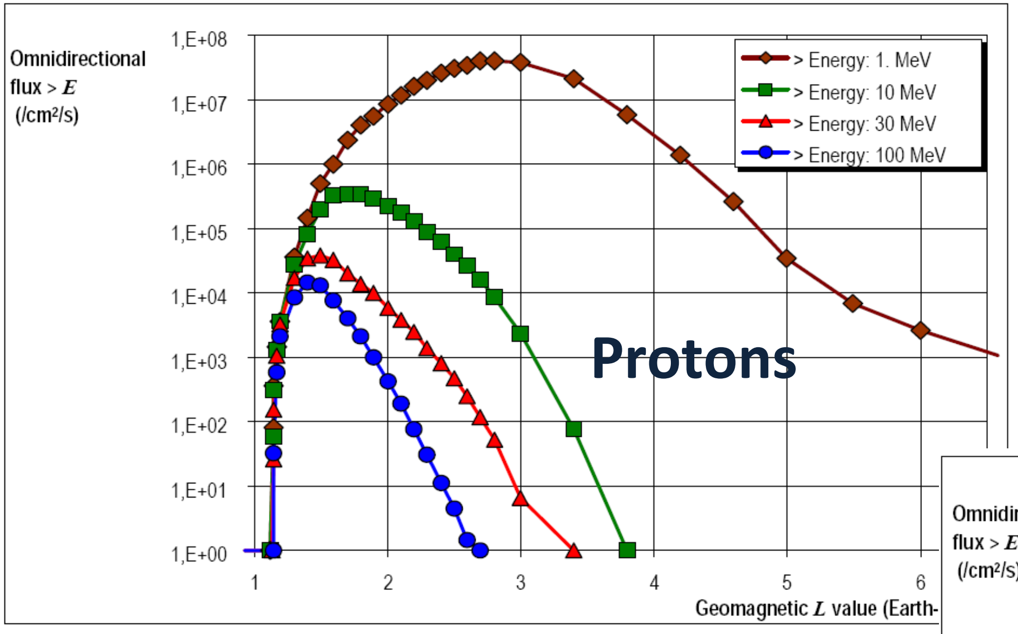
Particles in the magnetosphere

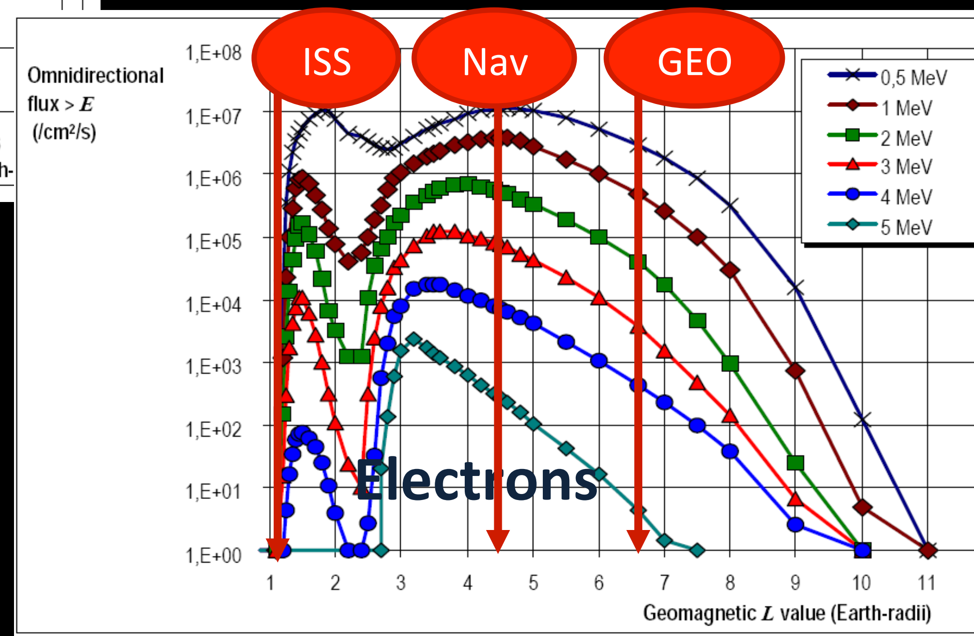






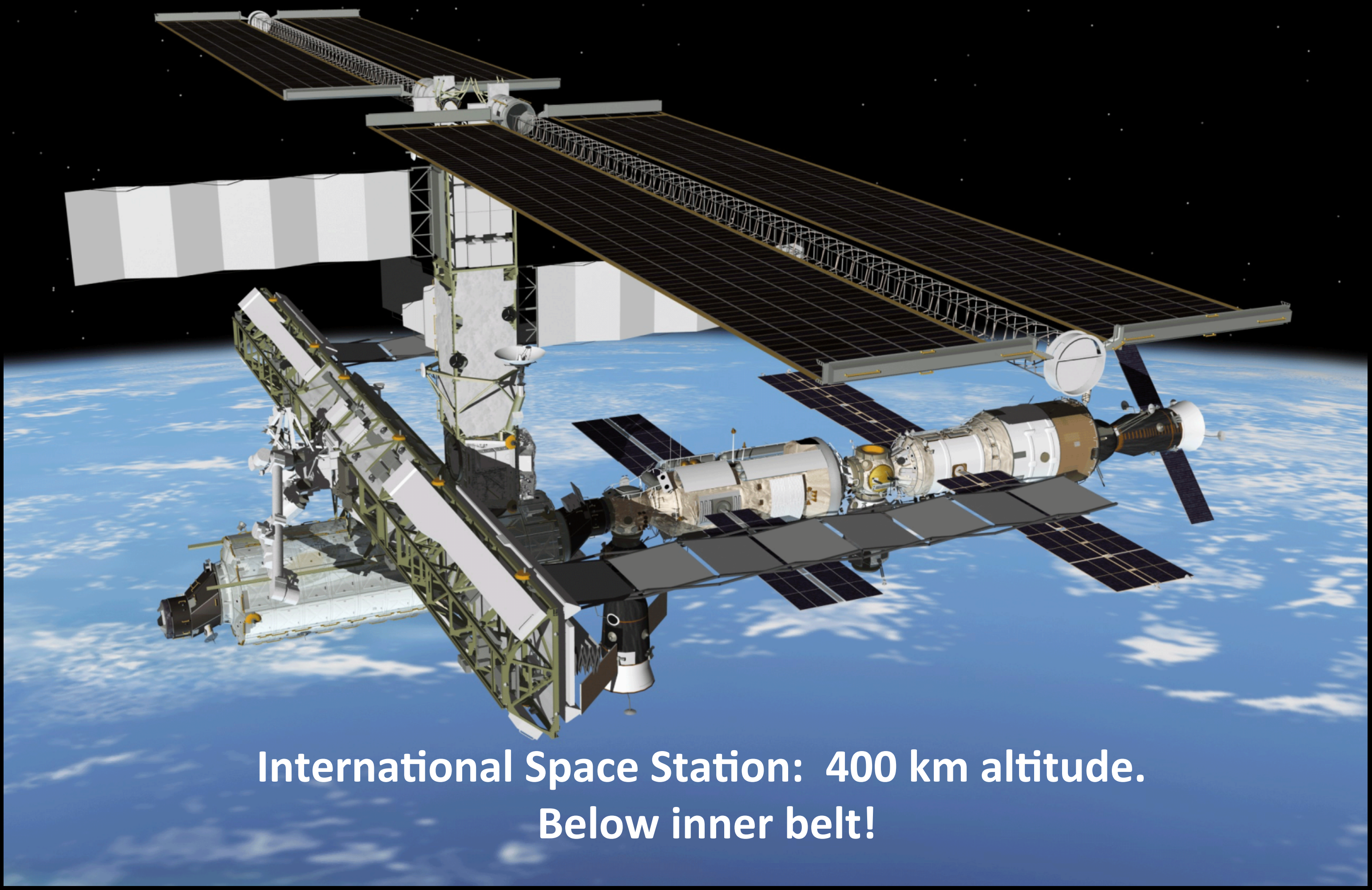
Earth Radiation Belt Models
Models AP8,AE8





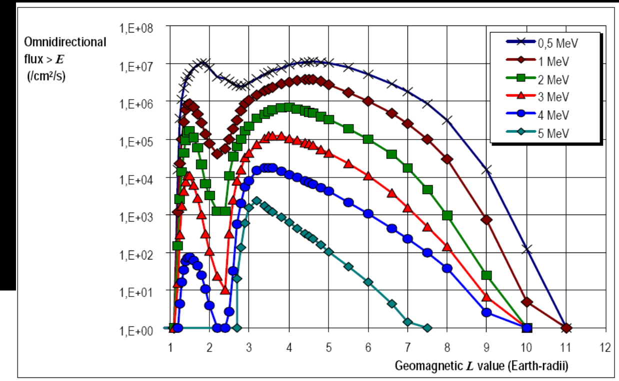
- Based on data from 1960-1970
- Long term averages

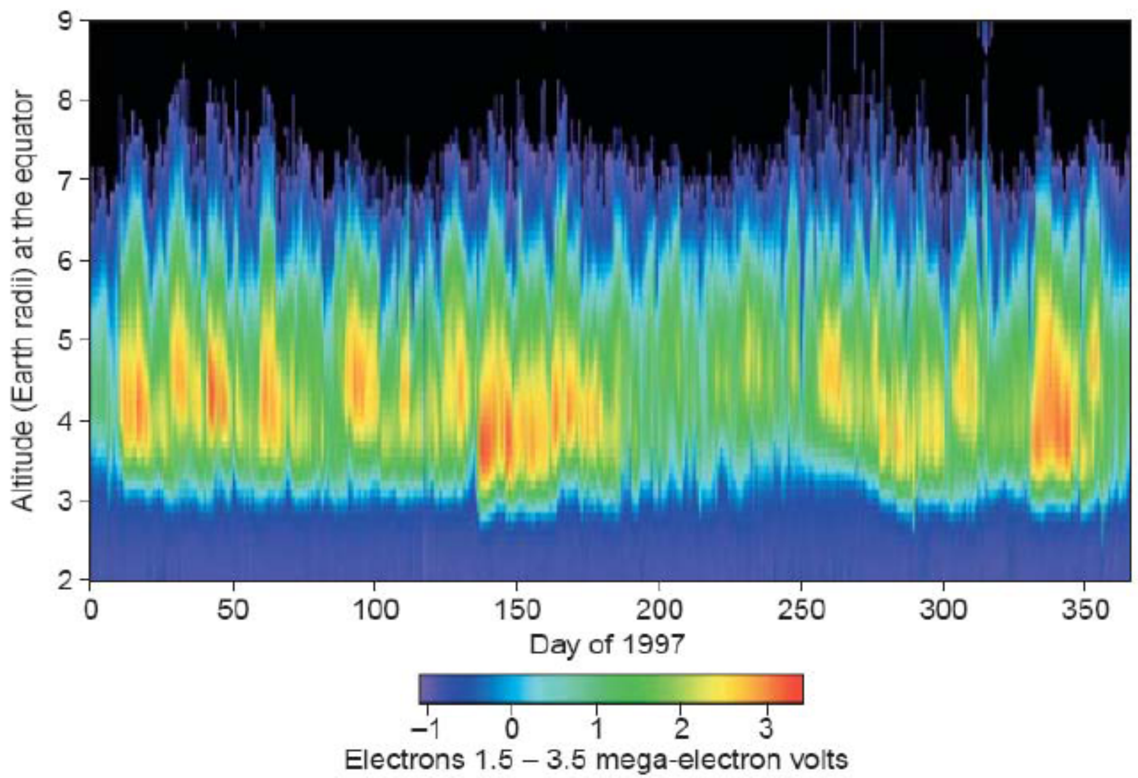
  but : outer belt is very stormy
- ongoing work to update models


International Space Station: 400 km altitude.
Below inner belt!

Aurora seen from the ISS

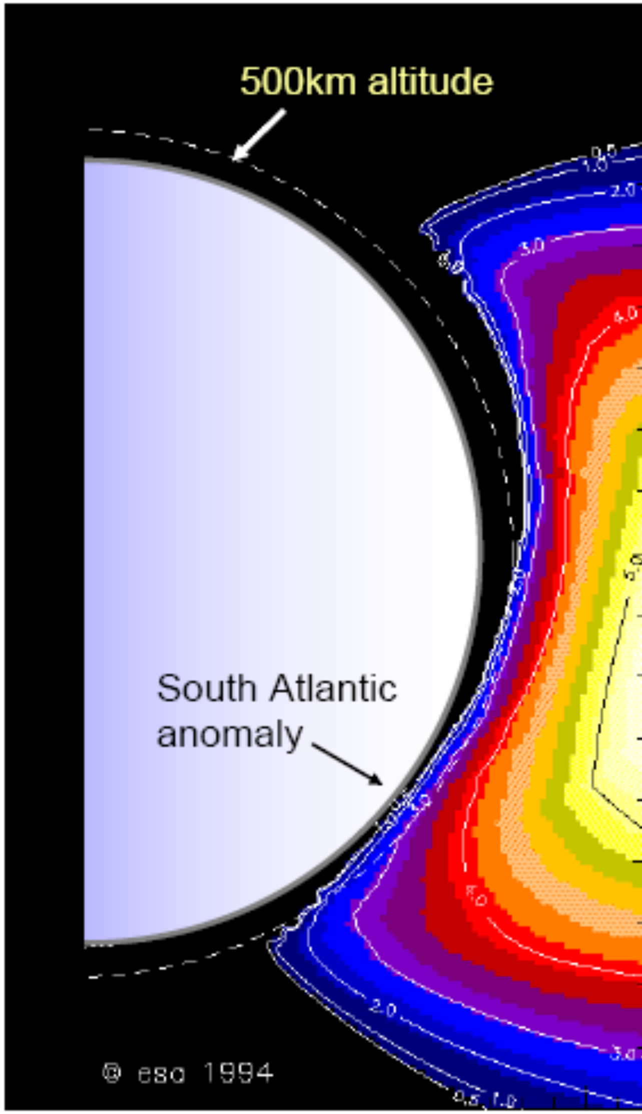
Example of Electron Data

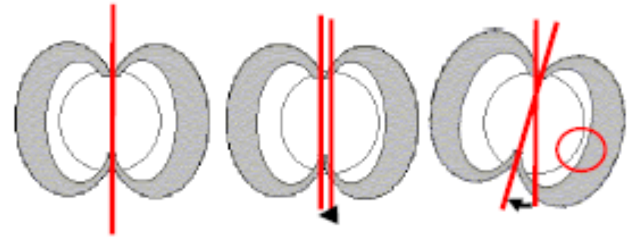


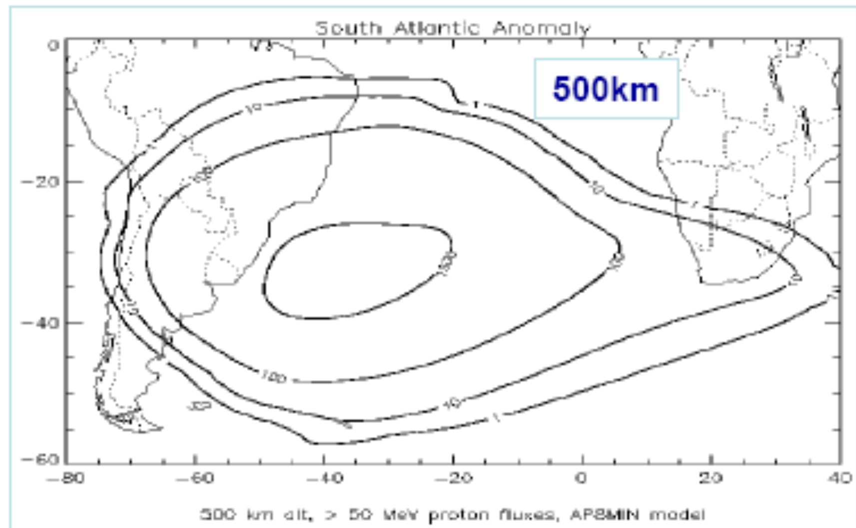


Typical variability of outer-zone electron intensity measured from low Earth orbit on the NASA/SAMPEX satellite, shown for the entire year 1997. The intensity is the logarithm of the electron count rate.

The South Atlantic Anomaly







Earth's magnetic field is an offset tilted and distorted dipole

→ Brings radiation belt down in the South Atlantic

Effect of the SAA

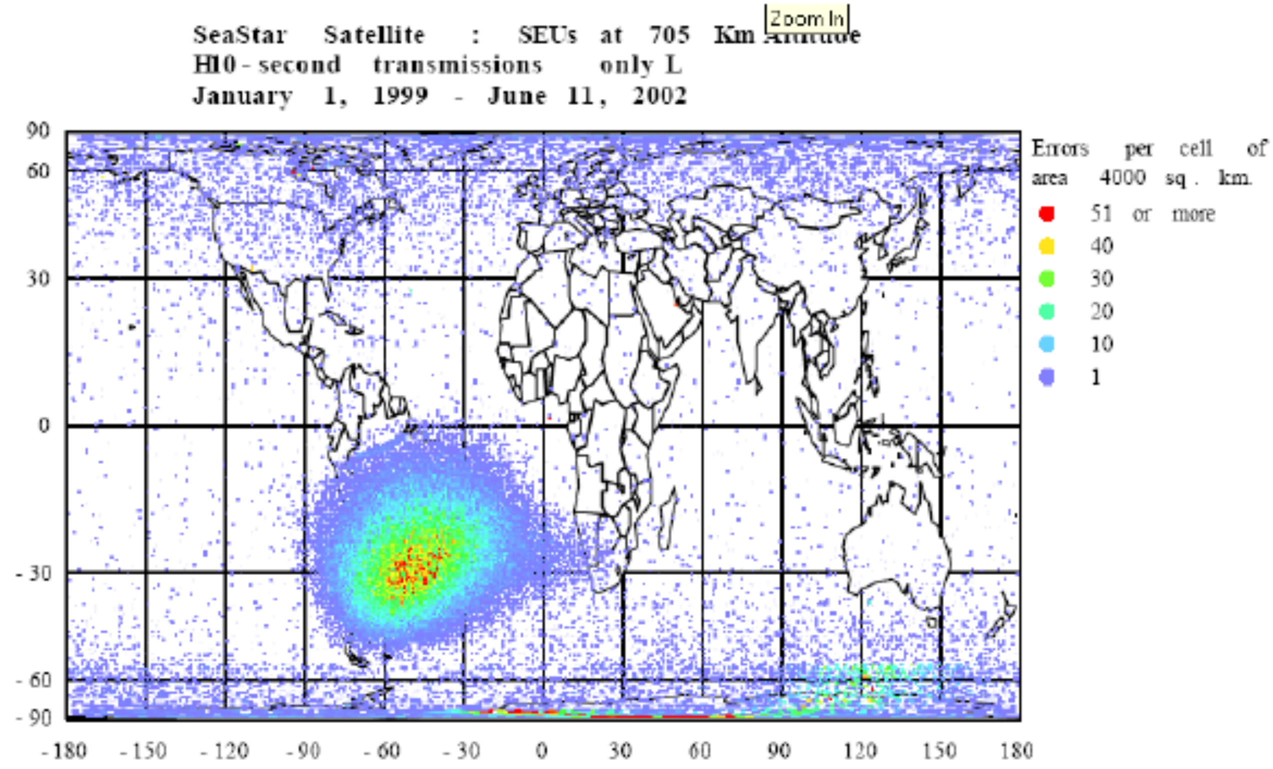
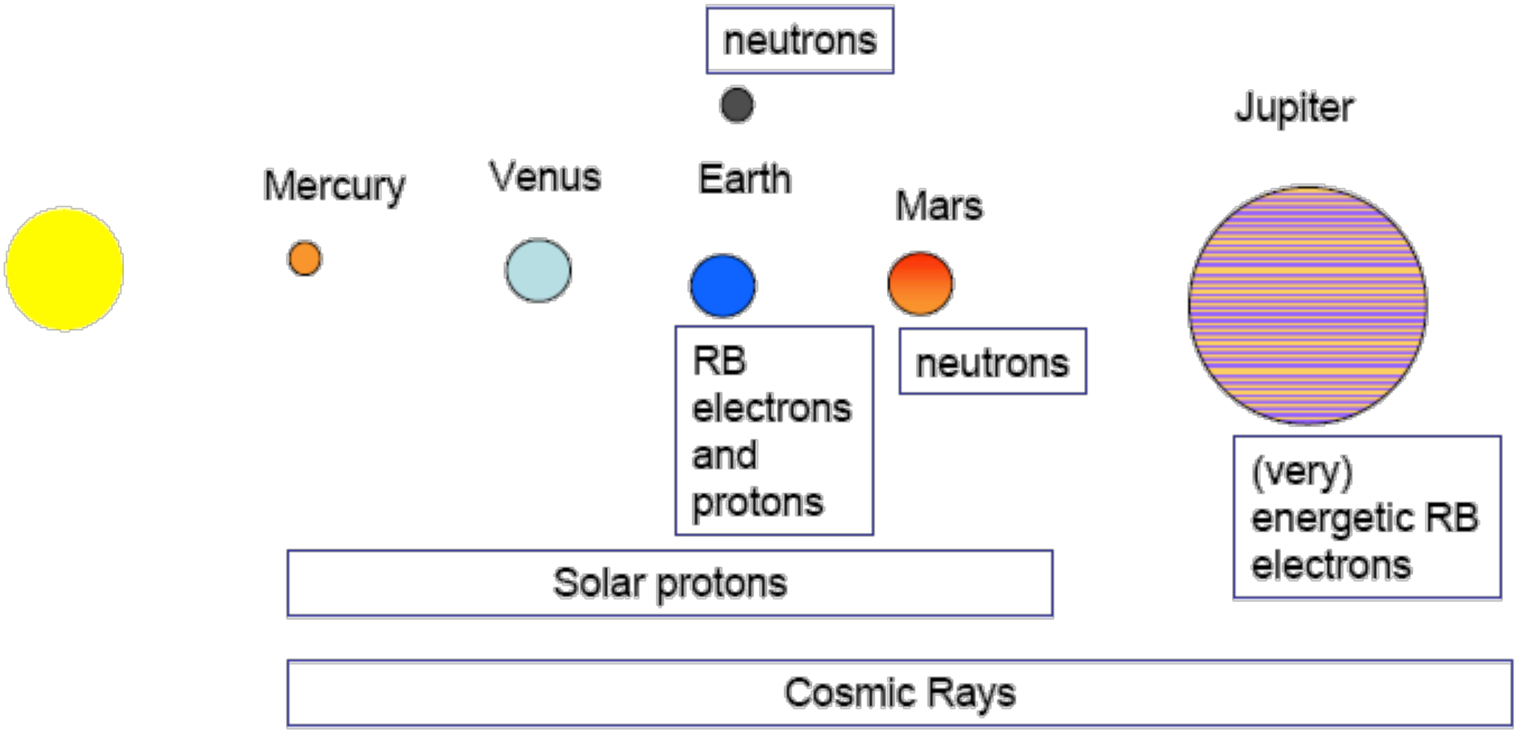


Fig 2: SEU density plot on SEASTAR FDRS from January 1999 to June 2002.

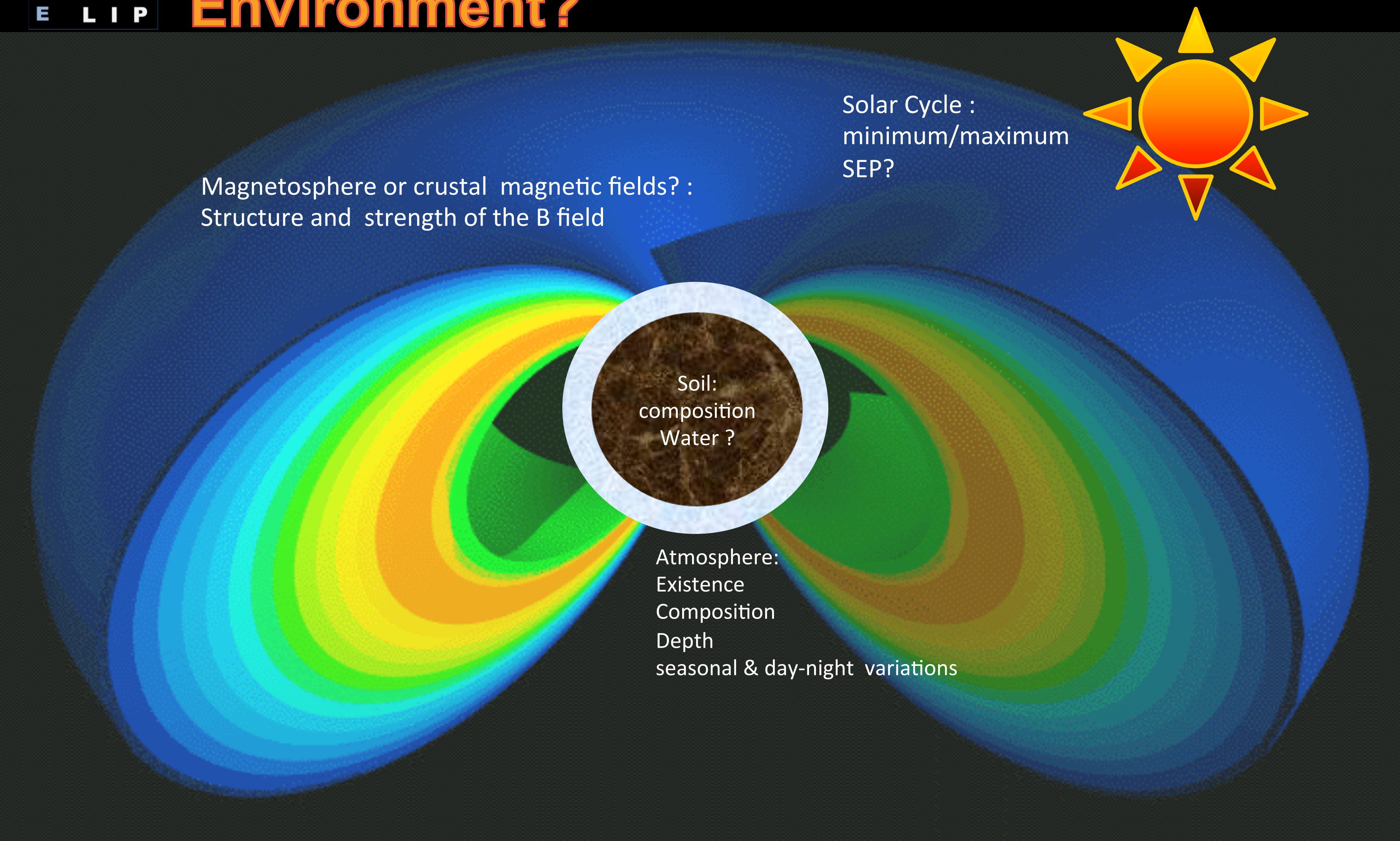
Radiation Environment in the Solar System

Mission specifications and requirements can be variable !



RB= radiation belt

How to model the Radiation Environment?

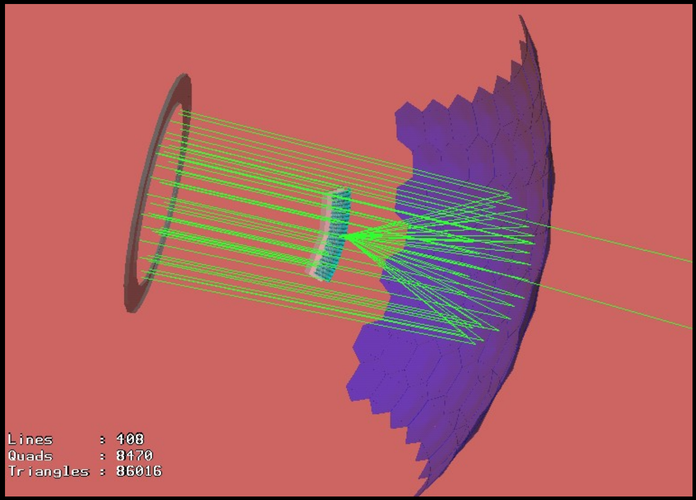


Modeling tool : Geant4
http://geant4.cern.ch

Geant4 is a complete toolkit to simulate the interaction of particles with matter in setups of arbitrary complexity.

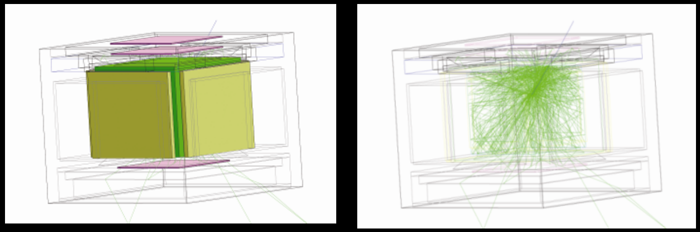
In HEP it is the C++ successor of GEANT3 (Fortran).

It includes a variety of additional requirements from heavy ion physics, cosmic ray physics, astrophysics, space science and medical applications …

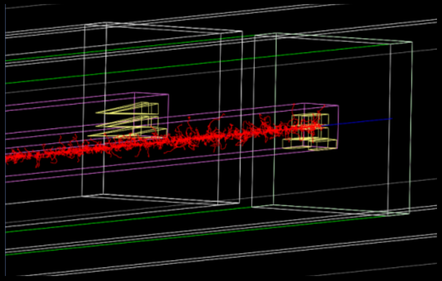


Space applications

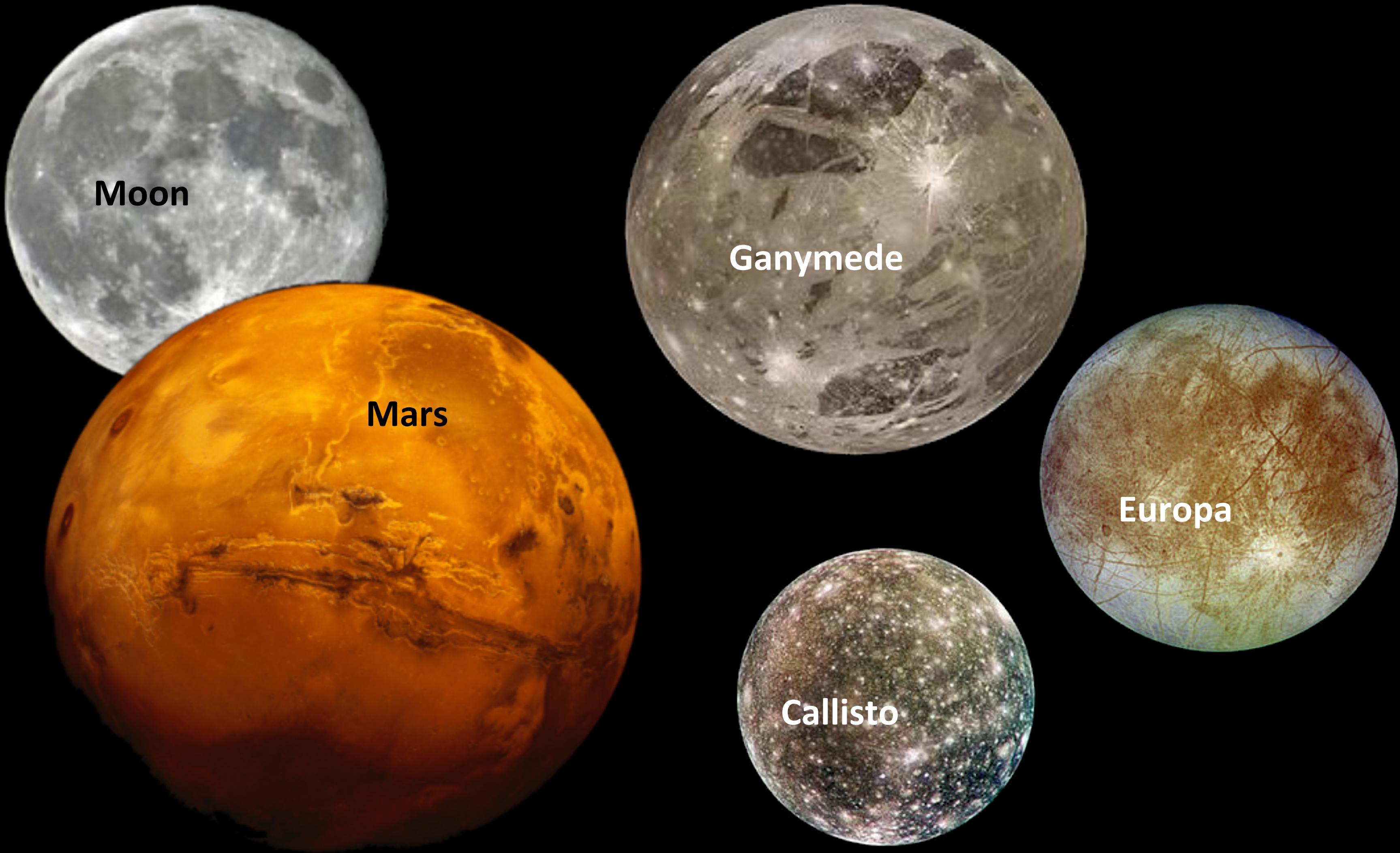
•Model planetary atmospheres, magnetospheres and surfaces and simulate the interactions of sources of radiation with planetary surfaces, atmospheres, etc.



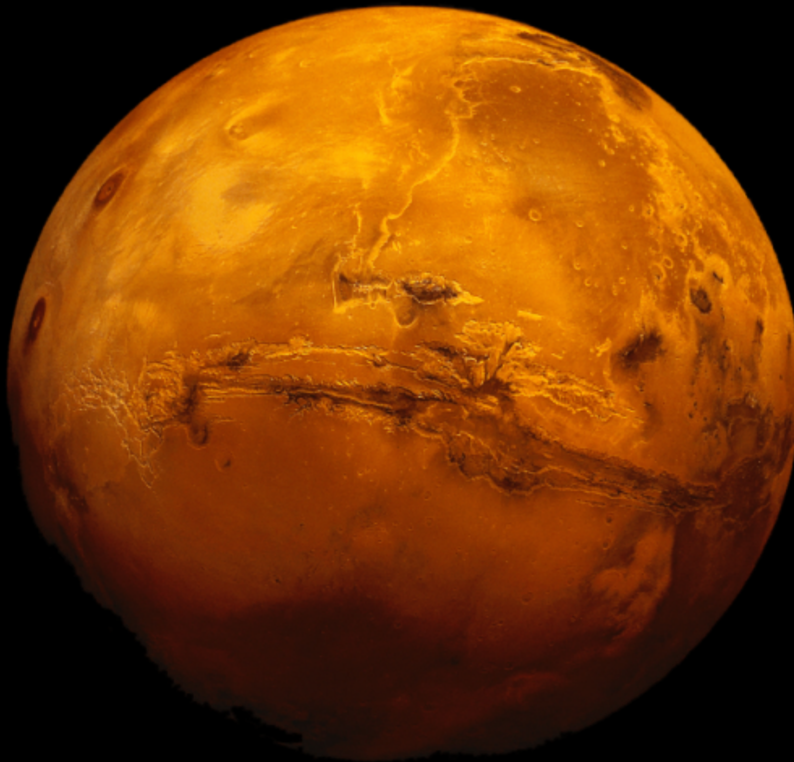
•Model detector and component materials and simulate detectors performances for specific radiation environments



Moon, Mars, Jupiter Icy Moons...
Constraints to future human exploration?
Mission Hazards?



Mars



- **Atmospheric depth and composition**
  - **> 95% CO_2,**
  - **0.01 Earth's atmospheric depth**
- **Localized crustal magnetic fields**
  - **(umbrellas)**
- **Radiation environment**
  - **SEP and GCR @ ~1.5 AU**
  - **Albedo neutrons (modulated by soil composition)**
  - **No radiation belts**
  - **"umbrella" electrons and low energy protons**

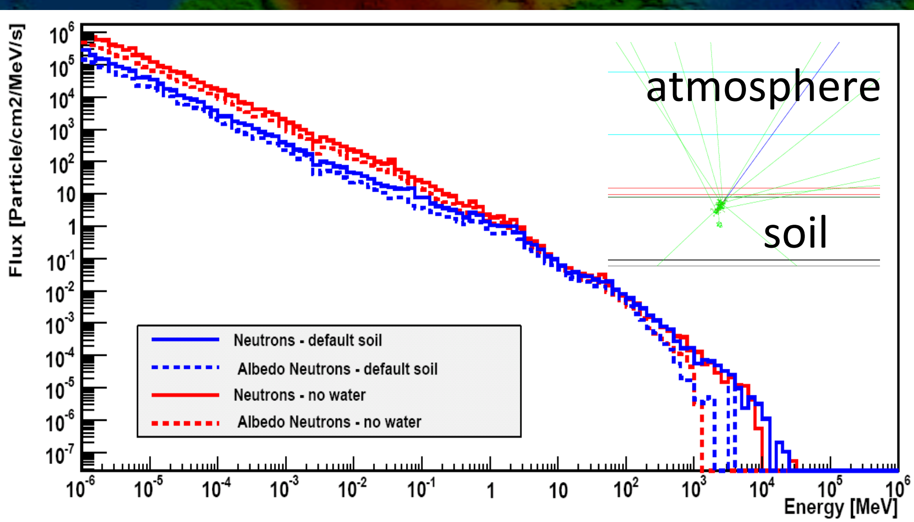
MarsREM: the Mars Energetic Radiation Environment Models

LIP developed dMEREM, a Geant4 based model for the radiation environment on Mars, Phobos and Deimos, including local treatment of surface topography and composition, atmospheric composition and density (including diurnal + annual variations) and local magnetic fields.

Examples of dMEREM results:

Inputs given as a function of latitude, longitude, in a 5 x 5 degree grid, and season.

the effect of soil water content on albedo neutron absorption



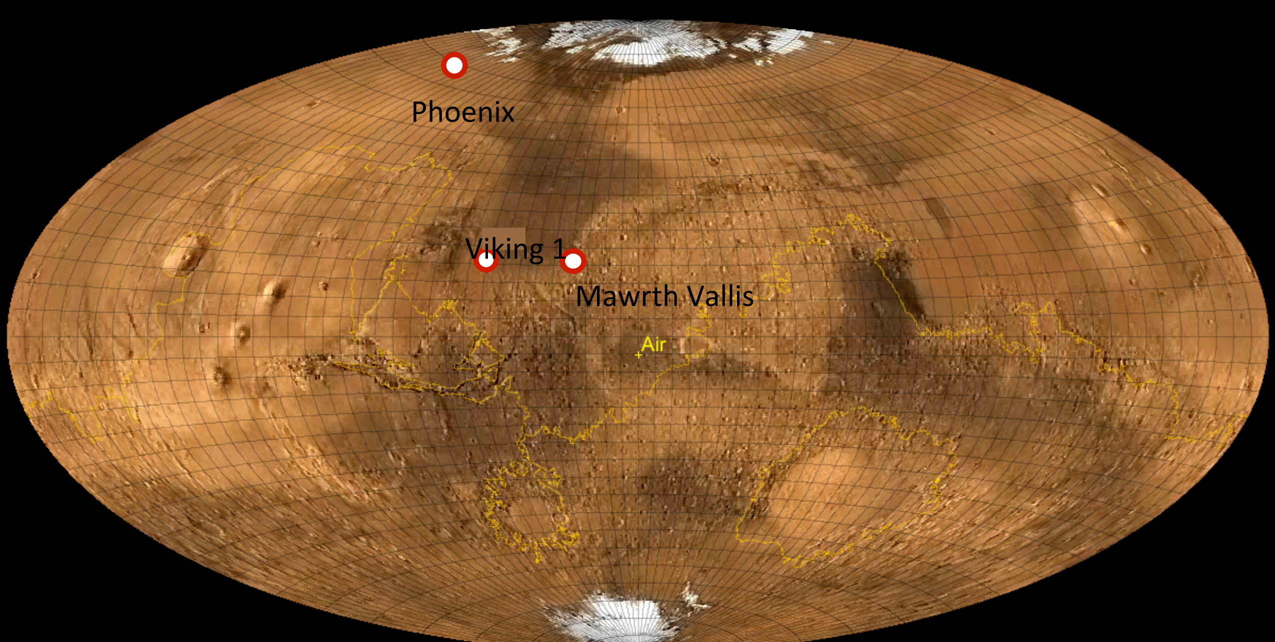
Location Radiation Enviroment Study with dMEREM

"Characterization of the Martian radiation environment on selected locations using the ESA Mars Energetic Radiation Environment Models",

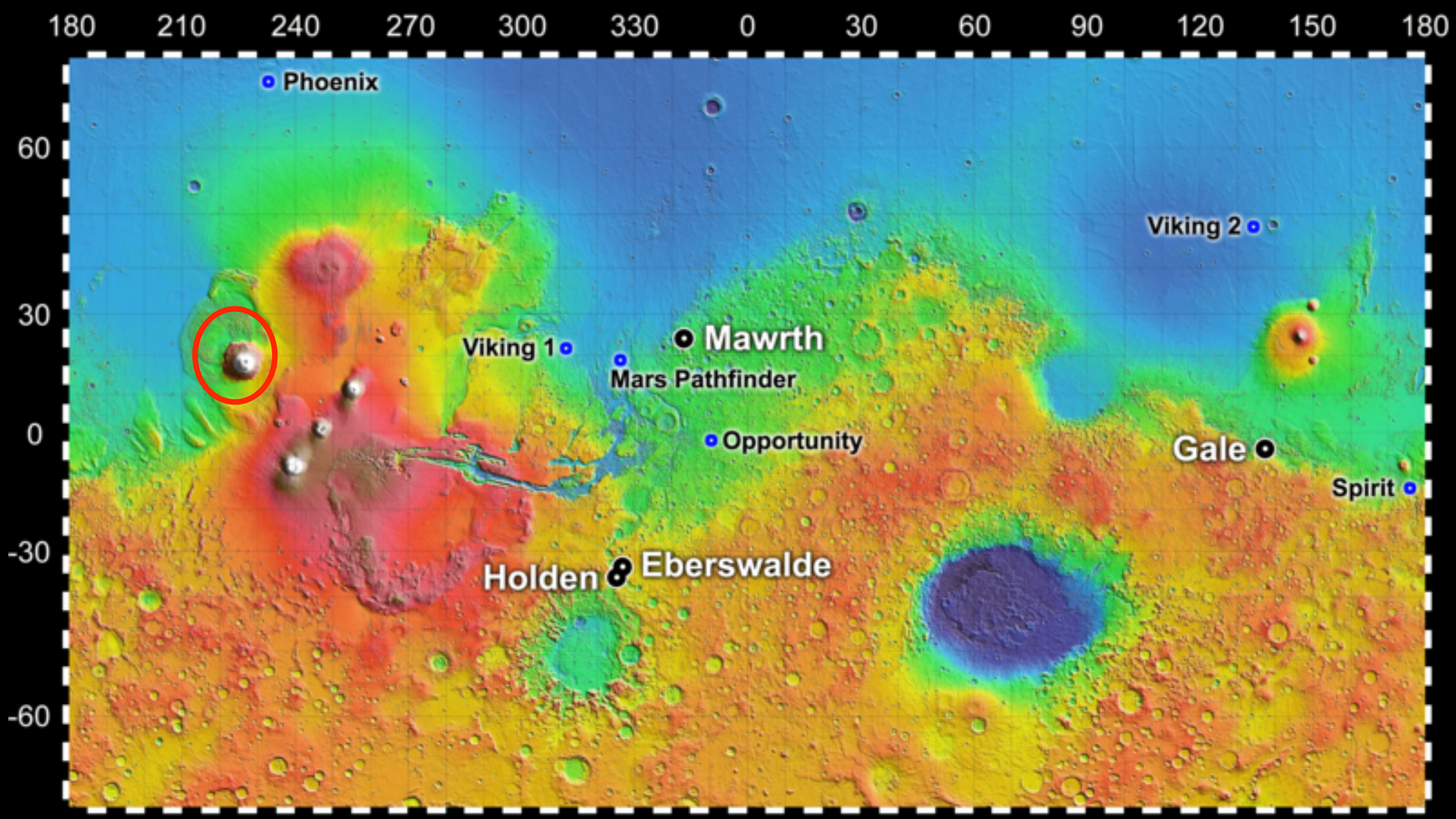
Icarus 218 (2012) 723–734

S. McKenna-Lawlor[1], P. Gonçalves[4], A. Keating[4], B.Morgado[4], D. Heynderickx[2], P. Nieminen[3], G. Santin[3], P, P. Truscott[5], F. Lei[5], B. Foing [6], and J. Balaz[1,7].

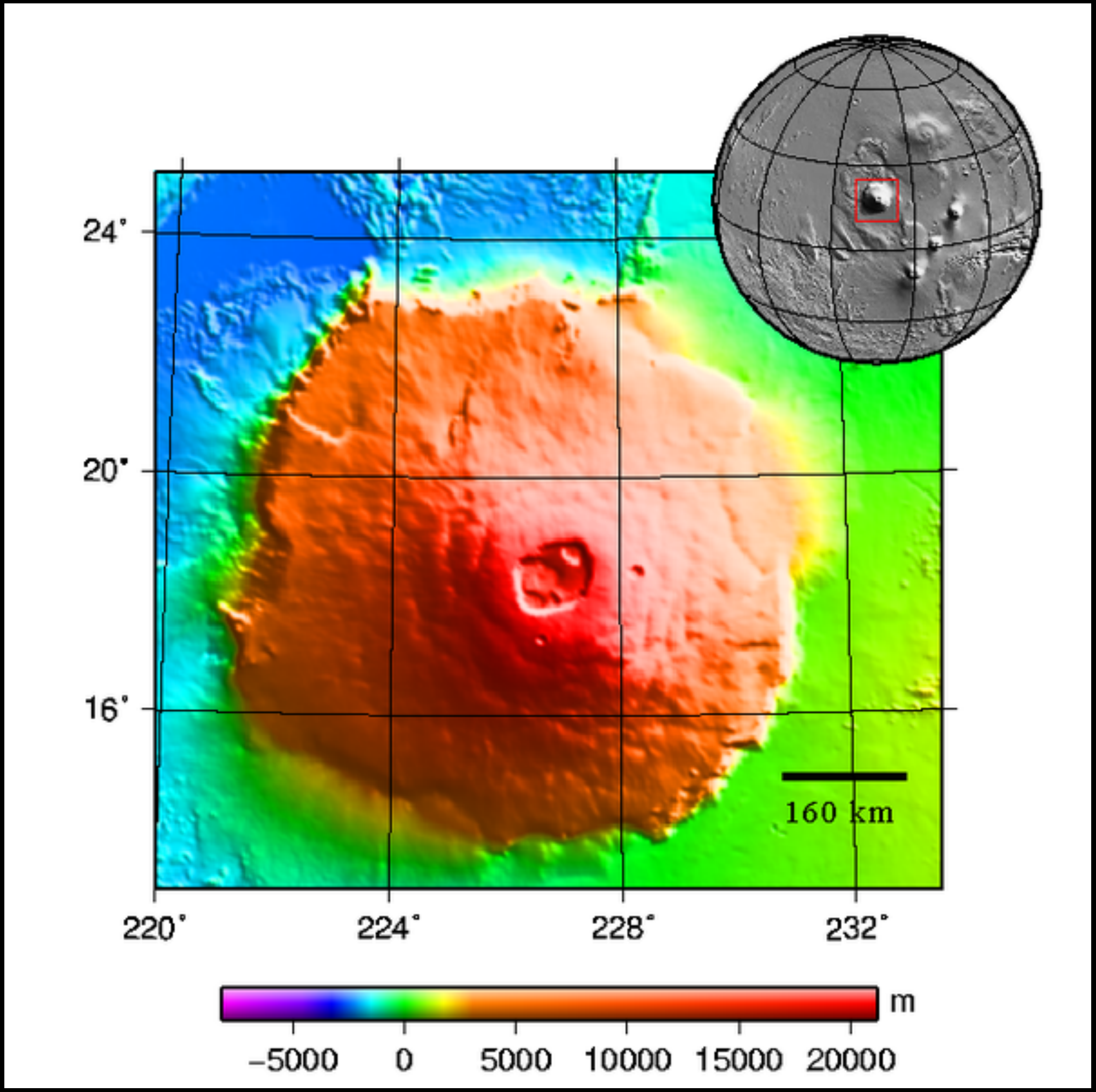
Three Martian landing sites characterised by significantly different topological conditions were studied during two significant flares for solar minimum and solar maximum conditions



Mars Topography and sites



Olympus Mons



The three sites

Site 1:
Viking 1 landing site (22.5N, 48W)

- Relatively smooth region in Chryse Planitia (Plains of Gold)
- soil is Regolith
- low hydrated.

Site 2:
Phoenix landing site (68.5N, 125.8W)

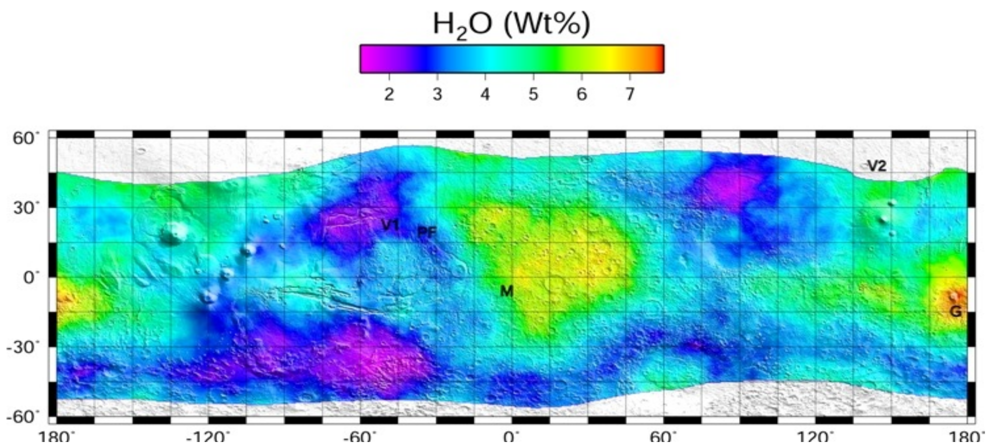
- upper layer containing a small amount of water (5%) over an ice rich layer
  CO_2 ice layer in winter!

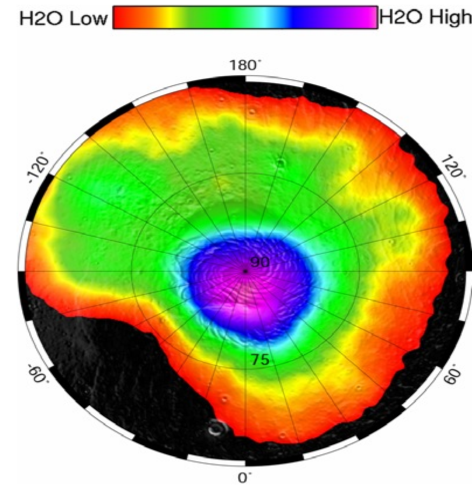
Site 3:
Mawrth Valley (23N, 19W)
(One of the 4 Curiosity candidate landing sites)

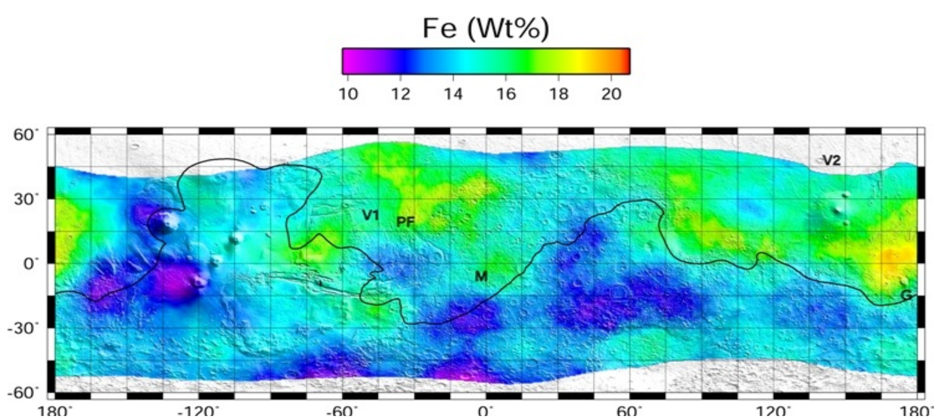
- Astrobiological interest.
- Situated in an apparent flood channel near the edge of the Martian highlands.
- Characterized by different types of clearly layered clays.
- Candidate landing site for the Mars Science Laboratory

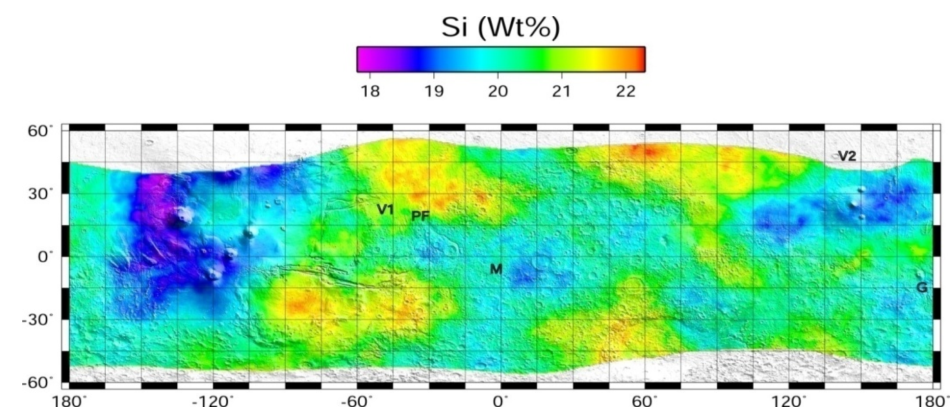
GRS data

- Soil Composition from analysis of data from Gamma Ray Spectrometer aboard Mars Odyssey, including water content and CO_2 ice.









Soil composition

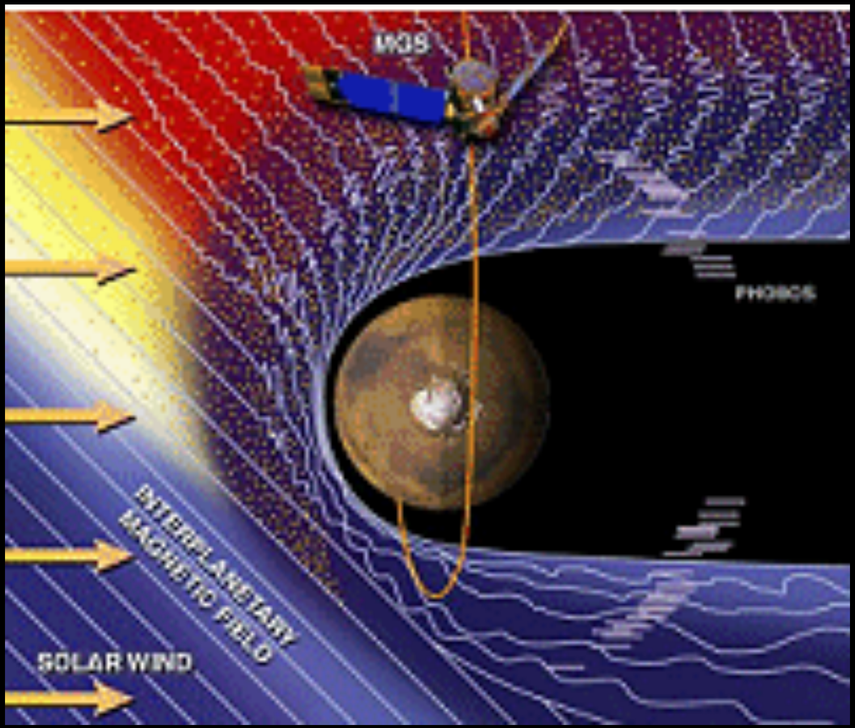
	COMPOUND	Default	Viking	Phoenix	Mawrth Vallis
Percentage composition by weight	SiO_2	51.2	48.4	27.0	55.0
	Fe_2O_3	9.3	15.7	4.0	38.0
	Bulk($Al_2MgCaNa_2K_2O_7$)	32.1	32.1	19.0	0.0
	H_2O	7.4	3.8	50.0	7.0
	Total	100.0	100.0	100.0	100.0
Density (g/cm^3)		1.7	1.8	1.2	2.2

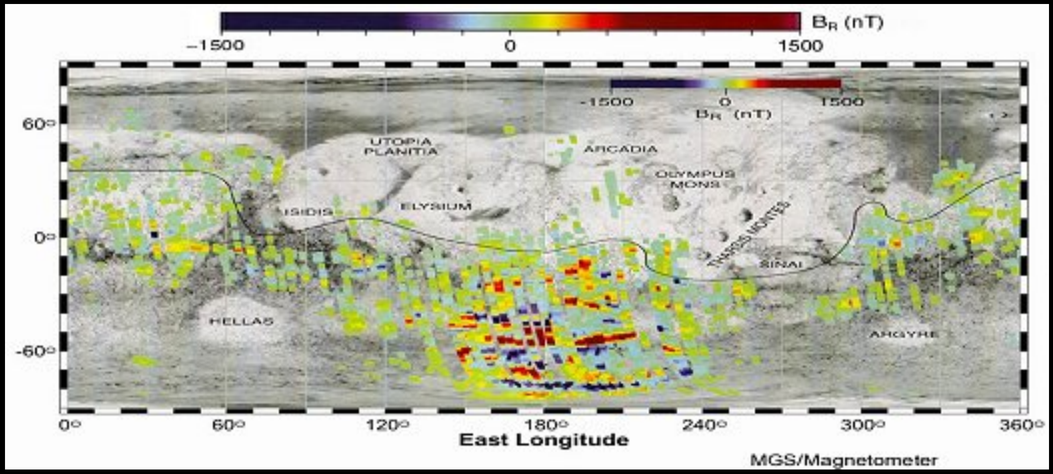
Magnetic field

- Mars magnetic field, unlike Earth's, is not a dinamo, although in some regions there is a localized crustal field.
- Modeled in dMEREM with PLANETOCOSMICS

  by Laurent Desorgher

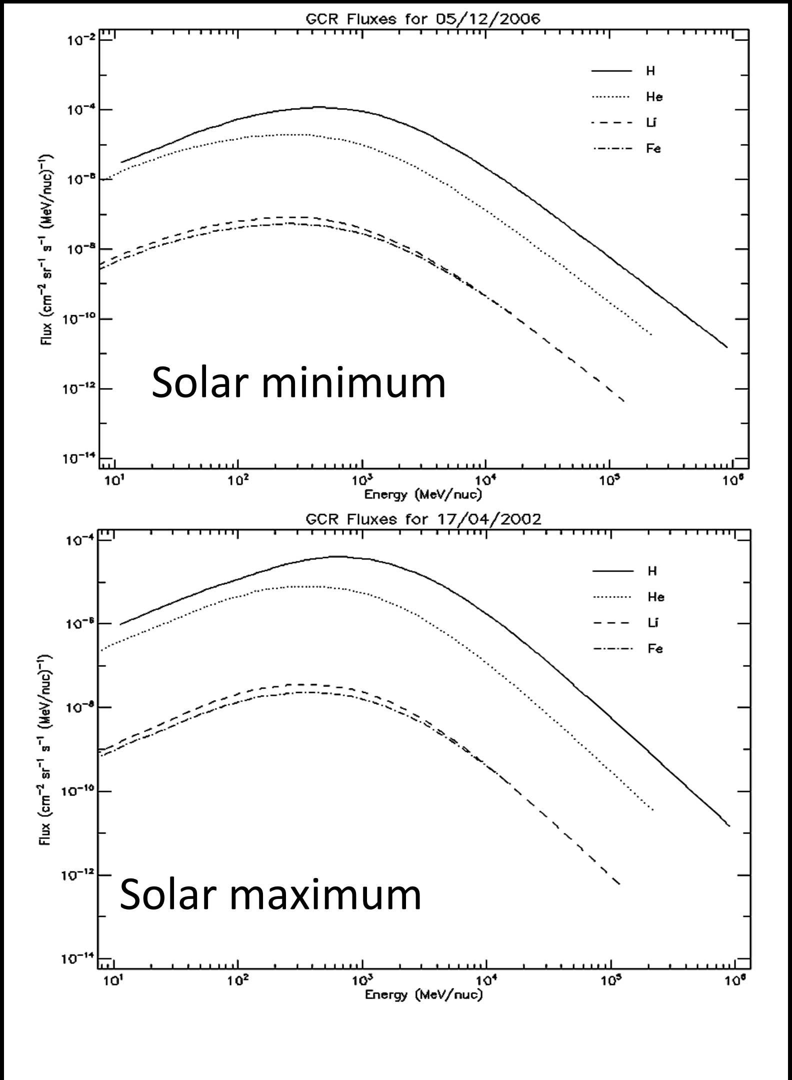
  (http://reat.space.qinetiq.com/jorem/PCJ_SUM_v0.c.pdf)





Data from the Magnetometer aboard Mars Global Surveyor

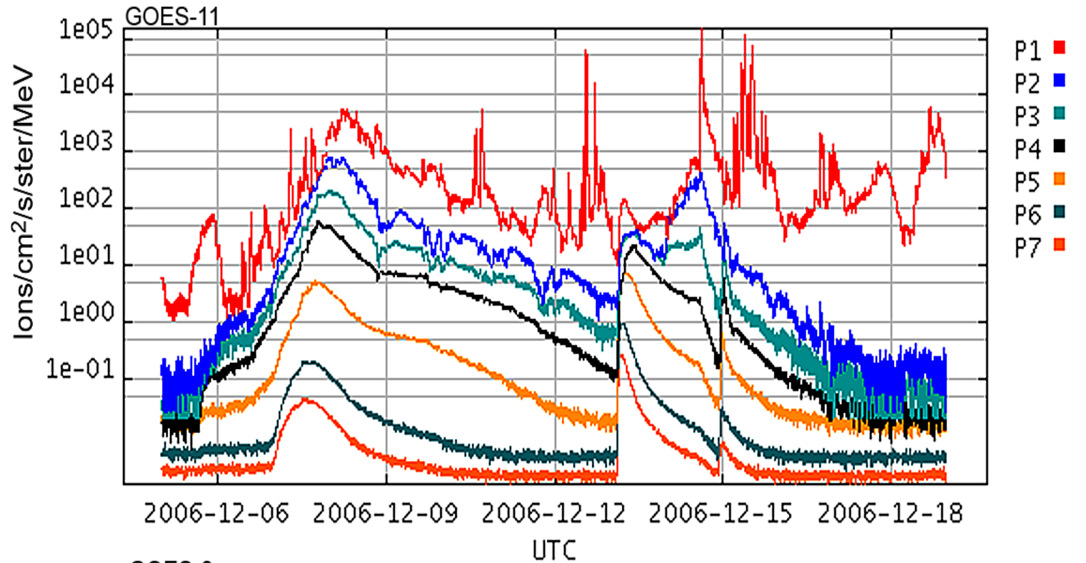
GCR inputs

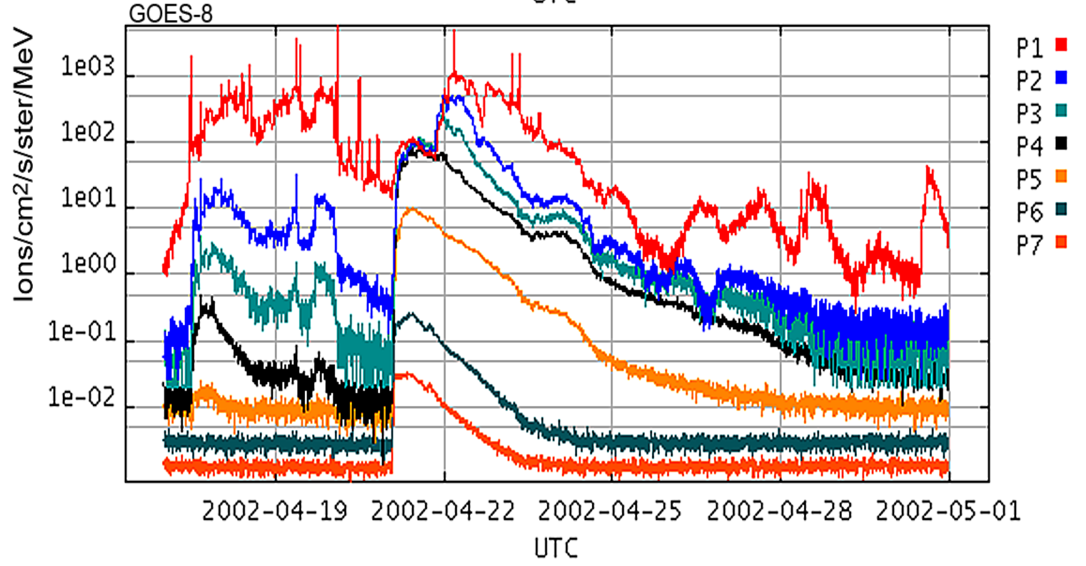


GCR differential flux spectra (cm-2 s-1 sr-1 (MeV/nuc)-1) for H, He, Li and Fe.

The differences are due to the scattering and deceleration of lower energy cosmic rays by the magnetic field embedded in the solar wind at the time of solar maximum.

SEP input





Five minute averaged differential proton fluxes for SEPs.

December, 2006 aboard GOES -11.

April, 2002 aboard GOES-8 .

Fluxes were normalized to Mars orbit.

Efective Dose and Ambient Dose Equivalent

The **Effective Dose (ED)** is the sum of the equivalent doses in all tissues and organs of the body, weighted by an organ/tissue weighting factor such that:

$$ED=\sum_T w_T H_T$$

The Ambient Dose Equivalent (ADE) is the dose equivalent which would be generated in an oriented and expanded radiation field at a **depth of 10 mm** on the radius of an ICRU Sphere, oriented so as to be opposite to the direction of the incident radiation.

ICRU* Sphere

D=30cm
ρ =1g/cm3
76,2% O
11,1%C
10.1%H
2.6%N

* International Comission on Radiation Units & Measurements

Results

Viking 1	Effective Dose (mSv)				Ambient Dose Equivalent (mSv)			
	Apr-02 Solar Maximum		Dec-06 Solar Minimum		Apr-02 Solar Maximum		Dec-06 Solar Minimum	
Model	dMEREM	eMEREM	dMEREM	eMEREM	dMEREM	eMEREM	dMEREM	eMEREM
GCR	11,11	8,85	20,22	15,05	5,71	6,54	9,88	9,87
SEP	0,17	0,64	0,33	1,12	0,3	2,35	0,59	3,97
Total	**11,3**	**9,5**	**20,6**	**16,2**	**6,0**	**8,9**	**10,5**	**13,8**

Phoenix	**Effective Dose (mSv)**				**Ambient Dose Equivalent (mSv)**			
	Apr-02 Solar Maximum		Dec-06 Solar Minimum		Apr-02 Solar Maximum		Dec-06 Solar Minimum	
Model	dMEREM	eMEREM	dMEREM	eMEREM	dMEREM	eMEREM	dMEREM	eMEREM
GCR	10,75	8,7	18,89	14,74	5,09	6,22	7,47	9,41
SEP	0,22	0,55	0,2	0,96	0,4	1,97	0,329	3,34
Total	**11,0**	**9,3**	**19,1**	**15,7**	**5,5**	**8,2**	**7,8**	**12,8**

Mawrth Vallis	**Effective Dose (mSv)**				**Ambient Dose Equivalent (mSv)**			
	Apr-02 Solar Maximum		Dec-06 Solar Minimum		Apr-02 Solar Maximum		Dec-06 Solar Minimum	
Model	dMEREM	eMEREM	dMEREM	eMEREM	dMEREM	eMEREM	dMEREM	eMEREM
GCR	10,79	8,98	20,03	15,31	4	6,43	7,22	9,75
SEP	0,21	0,79	0,32	1,32	0,31	2,92	0,44	4,71
Total	**11,0**	**9,8**	**20,4**	**16,6**	**4,3**	**9,4**	**7,7**	**14,5**

Results

Dependence of ED and ADE on soil compoisition

dMEREM	Apr-2002, "Solar maximum"			Dec-2006, "Solar minimum"		
	Viking	Phoenix	Mawrth	Viking	Phoenix	Mawrth
ED (mSv)	11.30	11.00	11.00	20.6	19.10	20.4
ADE (mSv)	6.02	5.49	4.30	10.5	7.8	7.67
ADE(i) / ADE (Viking)	**1.00**	**0.91**	**0.71**	**1.00**	**0.74**	**0.73**
H_2O	**3.0 %**	**50.0 %**	**9.4 %**	**3.0 %**	**50.0 %**	**9.4%**
Dry Ice	**No**	Yes	**No**	**No**	**No**	**No**
Atmospheric depth (g/cm^2)	17.8	19.2	16.5	17.8	17.8	15.1
Soil density (g/cm^3)	1.8	1.2	2.2	1.8	1.2	2.2

Results

- GCR reach the surface of Mars and originate albedo neutrons increasing the ADE values.

- Most SEPs are degraded in the atmosphere and do not reach the surface.

- Both MEREM models agree on GCR but not on SEP prediction (to be investigated)

- There is a resonable agreement between the MEREM and the HZTERN model used by NASA.

Regolith soil type	Dose Equivalent (mSv)	
	"Solar minimum"	"Solar maximum"
HZETRN (De Angelis et al.,2007)	11.2	4.5
eMEREM – Viking 1*	13.8	8.0
dMEREM – Viking 1*	10.5	6.0

(*) ADE values

Mission scenarios

- Mars Swingby
- Mars Short Surface Stay (sss)
- Mars Long Surface Stay (lss)

Scenario	Duration Days	Deep Space Days	Surface Stay Days
Mars Swingby	600	600	0
Mars sss	430	400	30
Mars lss	1000	400	600

These values are the mission parameters presently used by NASA in estimating mission risk and they may also be used for Mars mission radiation analysis.

30 days on Mars

30 Day Stay on Surface - solar minimum GCR induced dose	Dose Equivalent (mSv)	
	Skin	BFO
Ionizing Radiation Exposure Limits for LEO (Simonsen et al. ,1993)	1500	250
eMEREM Viking 1/Phoenix/Mawrth *	21.2/ 16.0/21.0	
dMEREM Viking 1/Phoenix/ Mawrth *	21.0/20.3/14.4	

Radiation exposure on Mars surface

Most SEPs are degraded in the atmosphere and do not reach the surface!

Higher energy GCR reach the surface and originate albedo neutrons, increasing the ambient dose values – need mitigation strategies for longer periods on the surface.

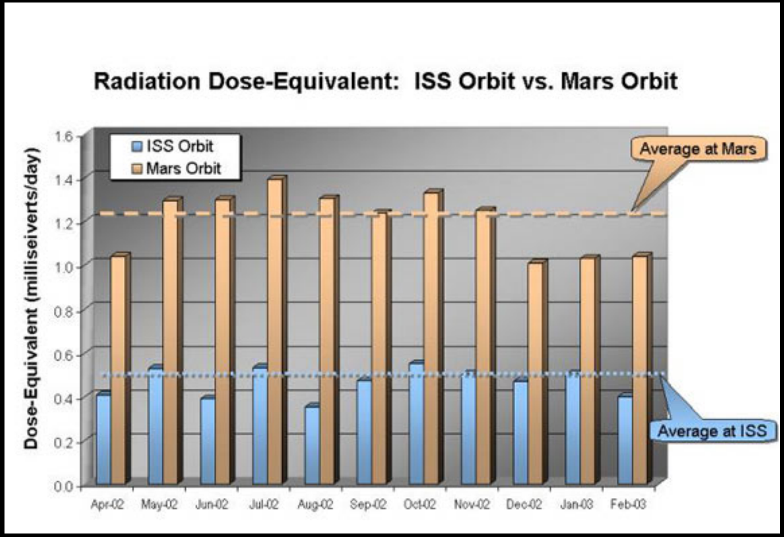
It is possible to remain on Martian surface for some time with no serious risk for the astronauts!

For longer permanences shelters are required…

LIP

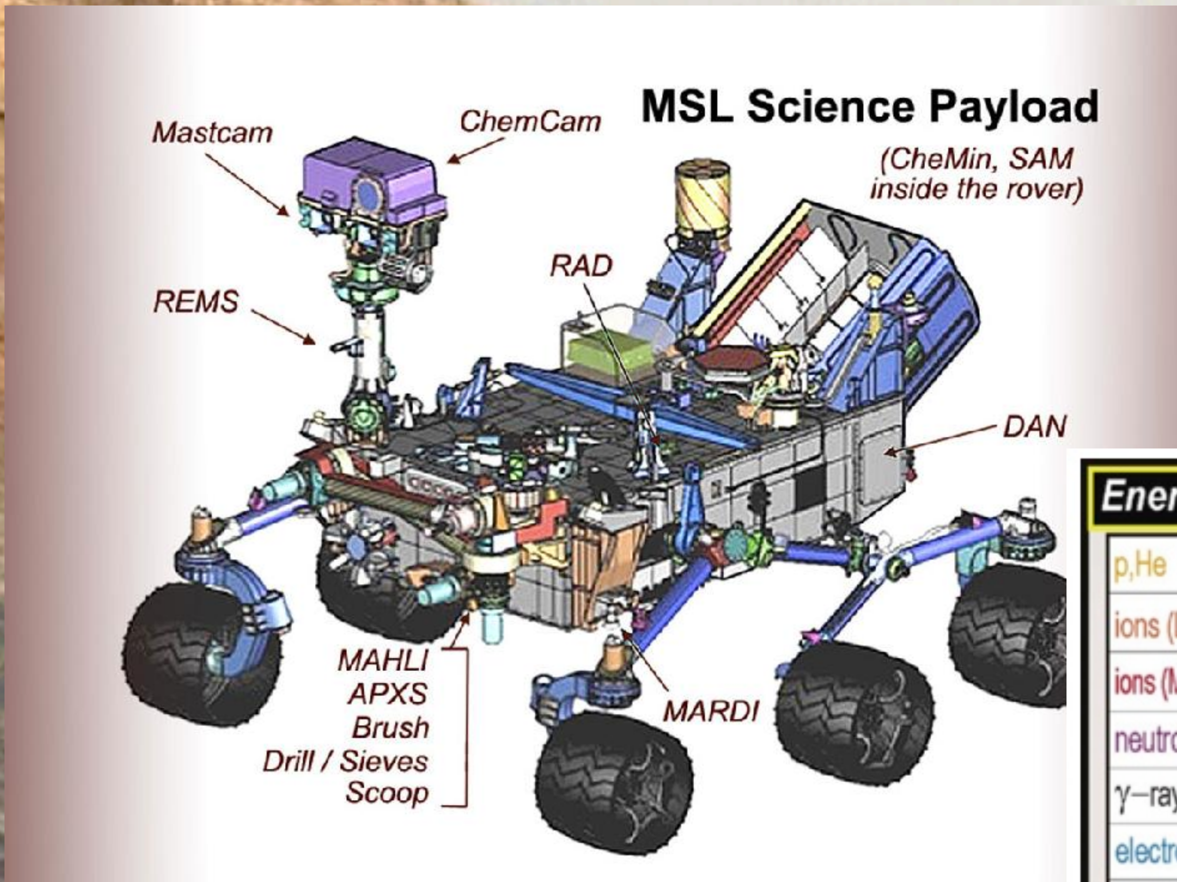
Validation of dMEREM with data

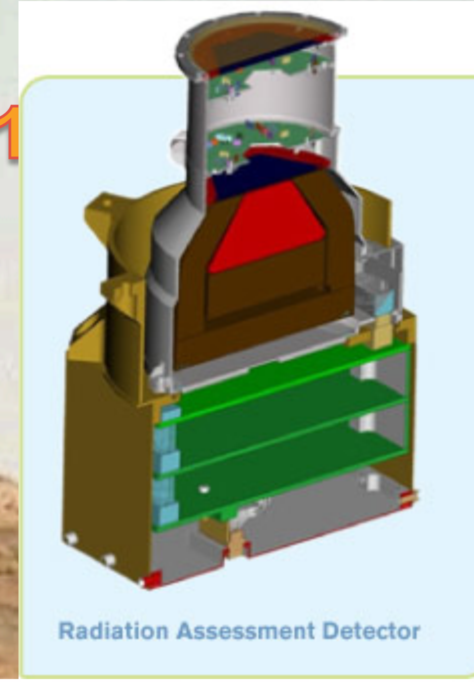
MARIE, the Mars Radiation Environment Experiment aboard the Mars Odyssey collected data during the cruise from Earth to Mars and on Mars orbit (2002-2003). It was "killed" by a large solar event on October 28, 2003. Mission engineers believe the most likely cause is that a computer chip was damaged by a solar particle smashing into the MARIE computer board!

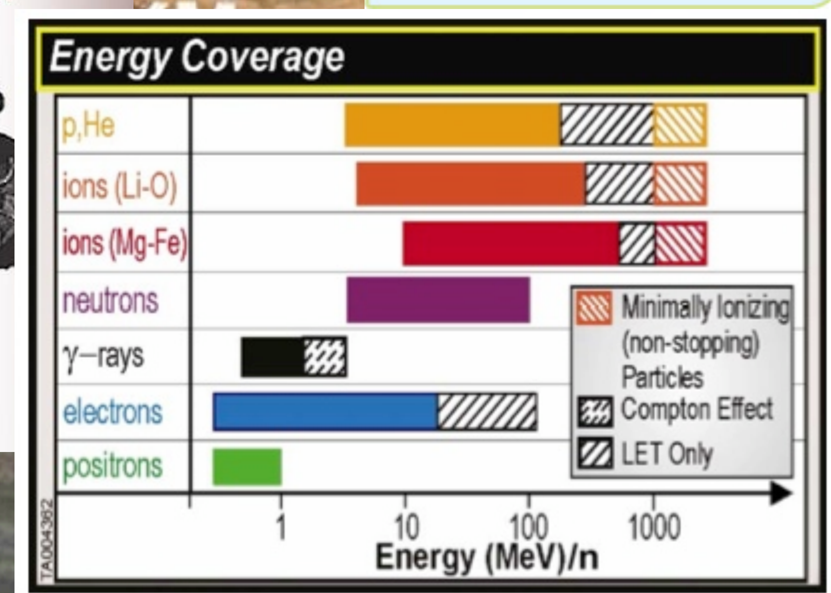


dMEREM predictions for ADE at altitude ~50 km were of the order of 0.6 mSv/day from GCR only (ADE != DE)

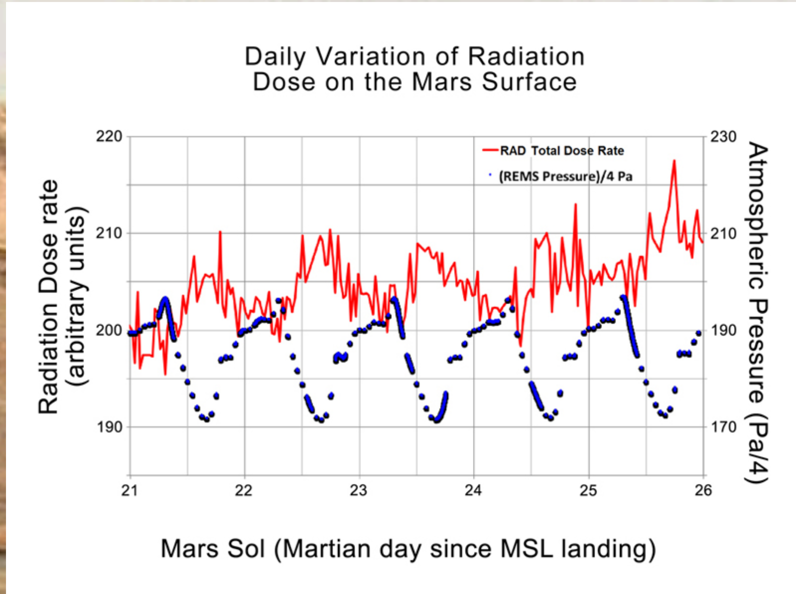
Curiosity
On Gale Crater since August 5, 201

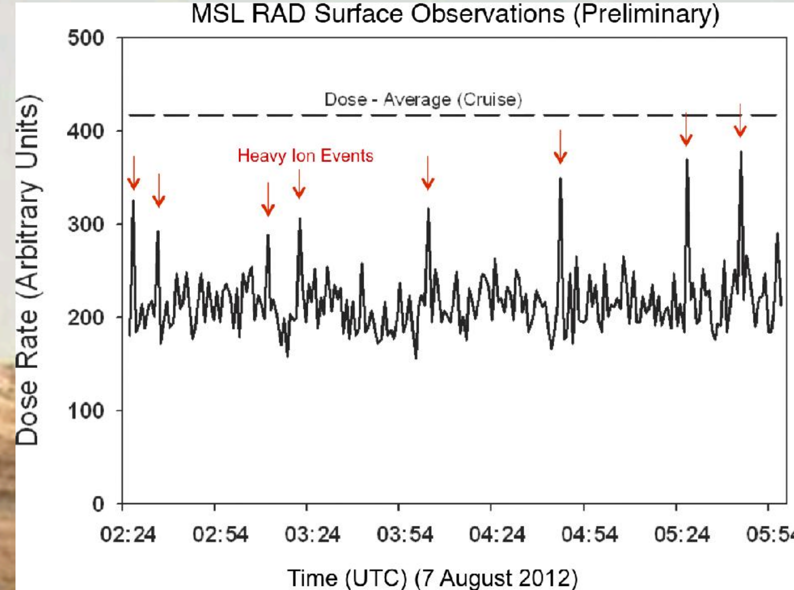






Curiosity RAD data





"…preliminary data collected using the rover's Radiation Assessment Detector (or RAD for short) revealed that levels on the ground are similar to what astronauts encounter on the International Space Station *. What's that mean for space travel? : The astronauts can live in this environment"

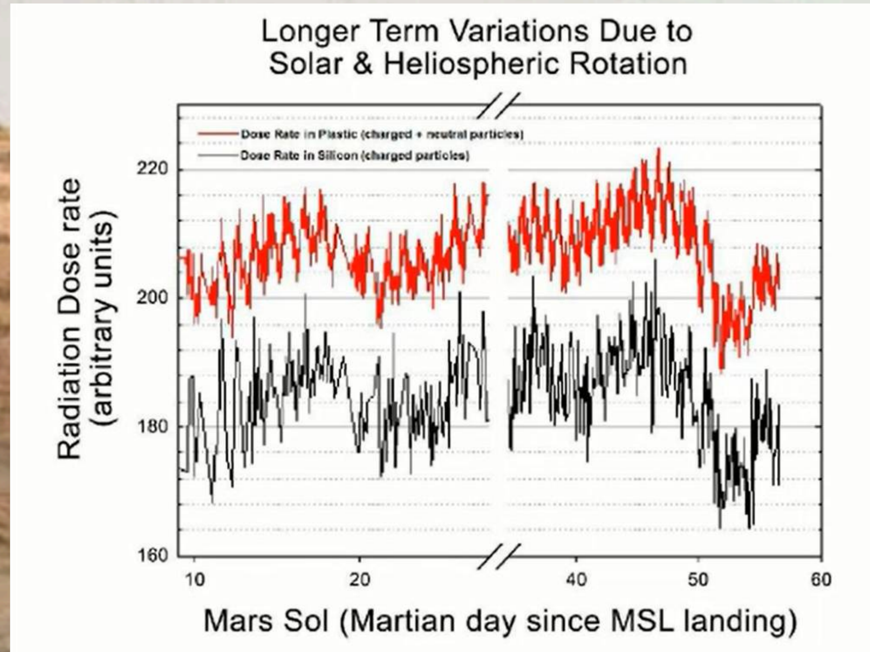
Don Hassler, Curiosity PI - *November 2012*

http://www.engadget.com/2012/11/17/curiosity-rover-mars-radiation-levels-safe-for-humans/

*** ~0.5 mSv/day**

" ..astronauts should be able to stay on the planet for at least six months without significant health risks."

Curiosity RAD data



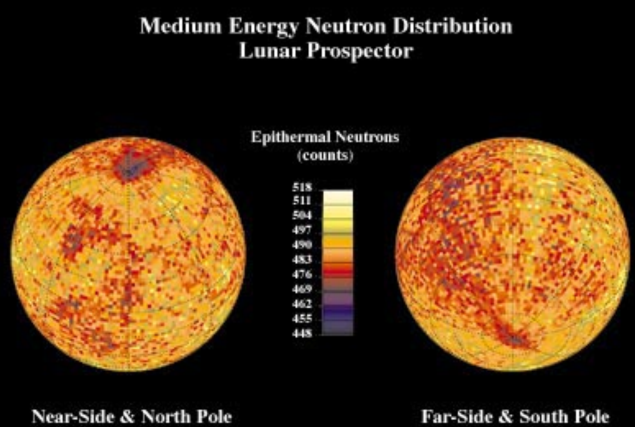
" ..astronauts should be able to stay on the planet for at least six months without significant health risks."

At LIP we are preparing a paper on Gale Crater dMEREM predictions and waiting for RAD published data to finally validate dMEREM with data from Mars surface !

The Moon

Radiation environment: similar to Mars

- **No Atmosphere**
- **Very weak localized crustal magnetic field**
- **Radiation environment**
  - **SEP and GCR @ 1AU**
  - **Albedo neutrons (modulated by H_2O)**
  - **No radiation belts**



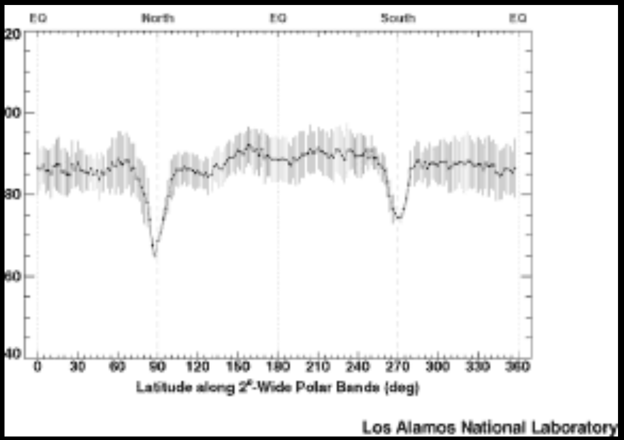
Measured Neutron spectra (Lunar Prospector)

Lunar Radiation Environment Model

Map the radiation Environment on the Moon as a function of latitude-longitude & season

Inputs:

- data characterizing the topography & the soil composition for the whole moon (with good spatial resolution)
- GCR and SEP fluxes @ 1 AU (from different data & models)



Validation & **benchmarking**

- **With existing data**
  (instruments in orbiters: LEND, CRATER,RADOM)
- Comparison with other models (Langley, etc.)

Further work - measurements on the Lunar surface:

- Knowledge of the Radiaton Environment of the moon has to be improved
- ***BUT European Lunar Lander programme was suspended in November 2012…***

(monitor in Lunar lander payload? many small detectors on the surface ?)

Interplanetary environment

The most dangerous mission phase from the point of view of human spaceflight is the interplanetary space travel !

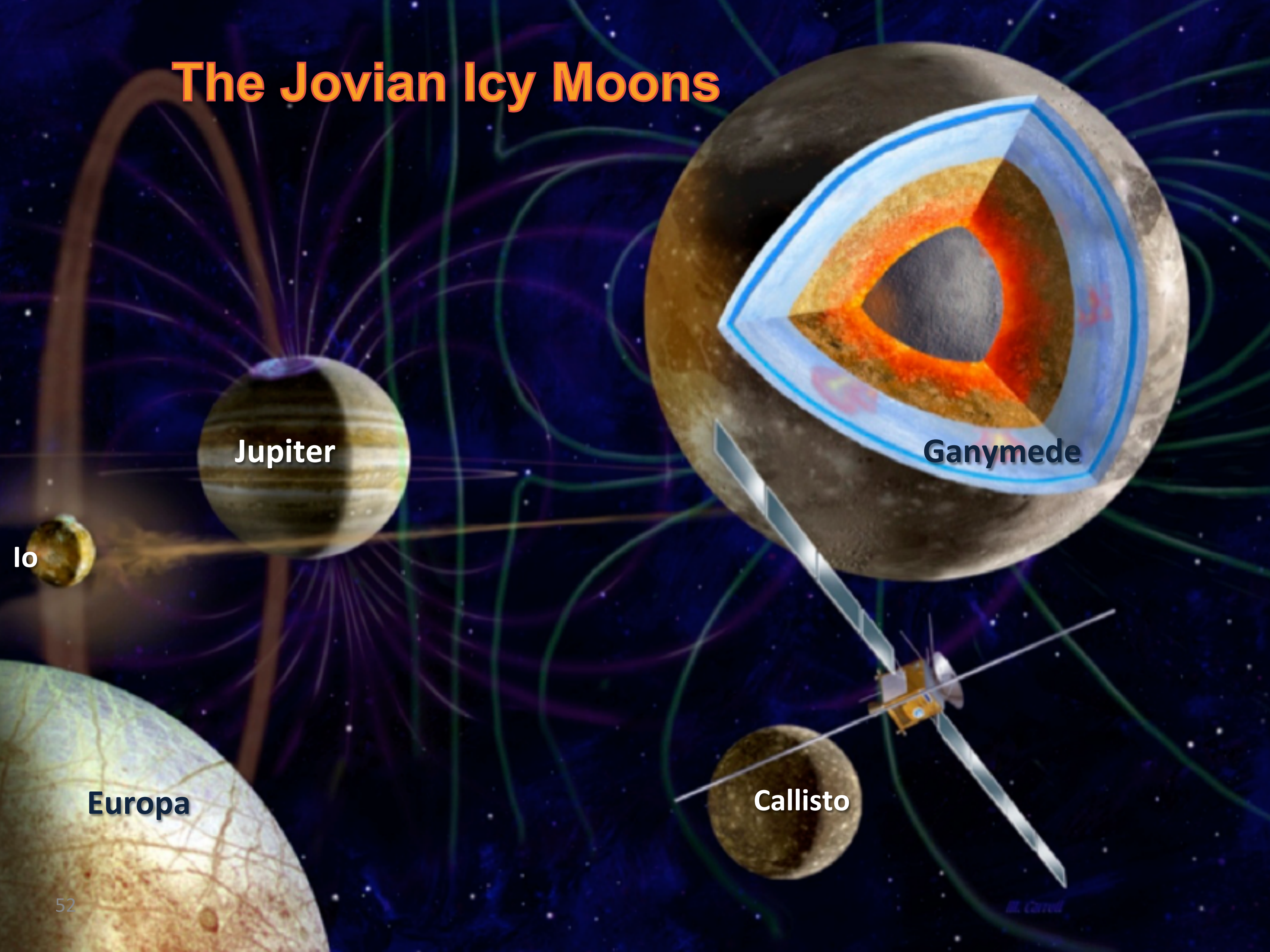
The biggest danger is the possibility of a SEP reaching the mission.

Mitigation Strategies are under development:

- **Shelters inside water compartments or other**
- **Faster propulsion systems**
- **SEP Forecasting tools and alarms**

"Overview of energetic particle hazards during prospective manned missions to Mars",
Susan McKenna-Lawlor , P.Gonçalves , A.Keating , G.Reitz , D.Matthiä
Planetary and Space Science 63–64 (2012) 123–132

The Jovian Icy Moons



JUICE
The Jupiter Icy Moons Explorer

Next Class-L (Large) ESA Mission

Objective:
Study the emergence of habitable worlds around gas giants

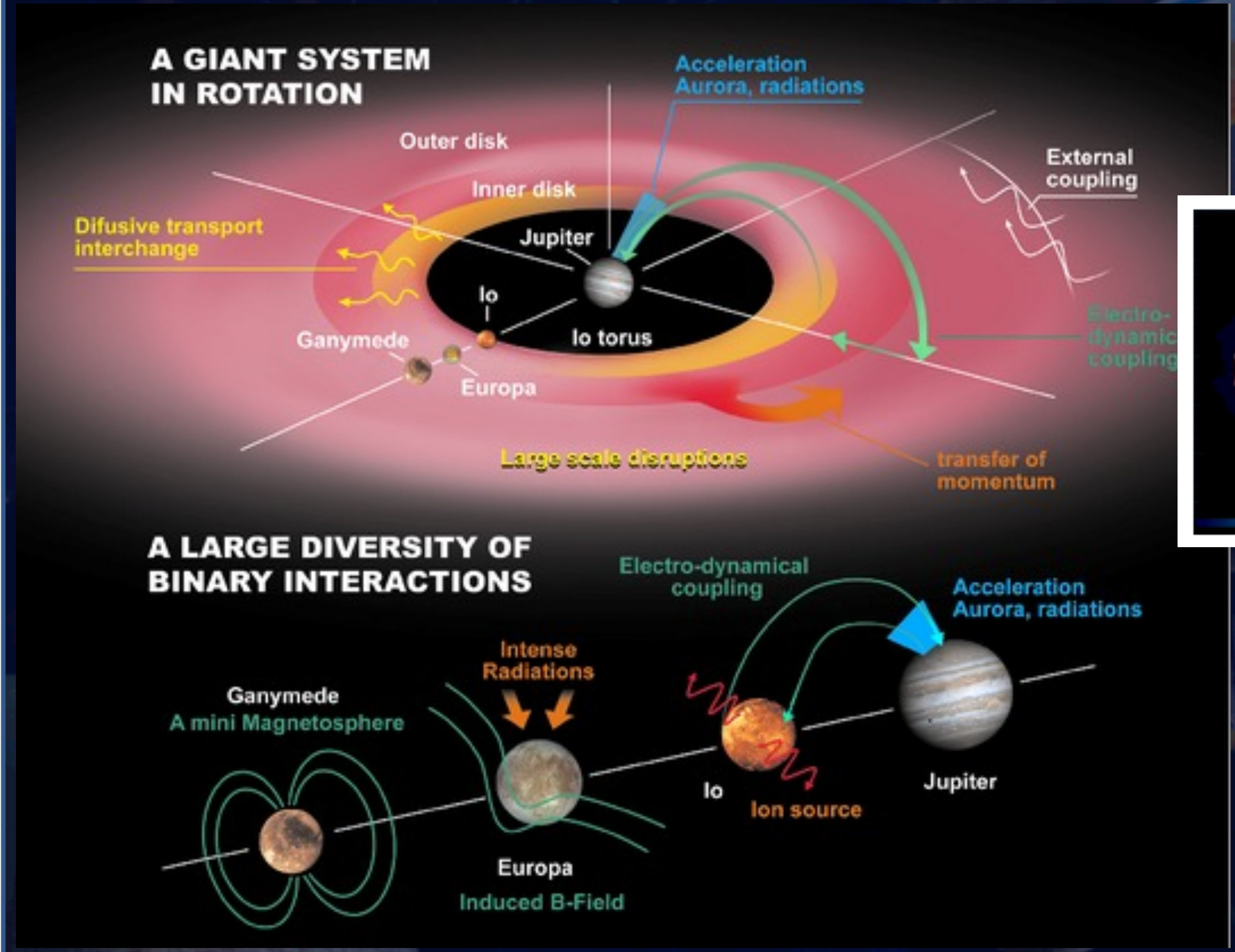
Characterise Ganymede, Europa and Callisto as planetary objects and potential habitats

Explore the Jupiter system as an archetype for gas giants

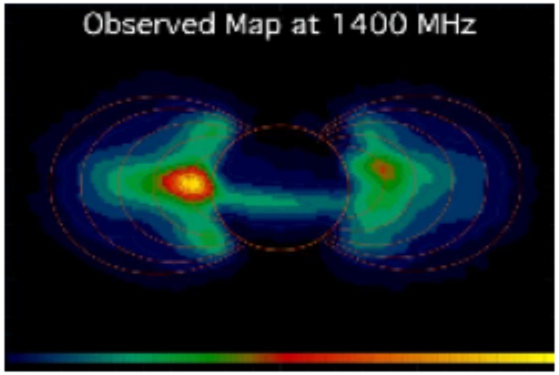
Current JUICE mission plan

Jun 2022	Jan 2030					Sep 2032		Jun 2033
		11 months	1 month	9 months	11 months		9 months	
Launch Ariane-5	Jupiter orbit insertion	Transfer to Callisto	Europa phase: 2 Europa + 2 Callisto flybys	Jupiter High Latitude Phase	Transfer to Callisto	Ganymede Orbit insertion	Ganymede tour: Orbits at several altitudes: High altitude 500 km 200km	End of nominal mission

Radiation environment in the Jovian System



Synchrotron emission observations



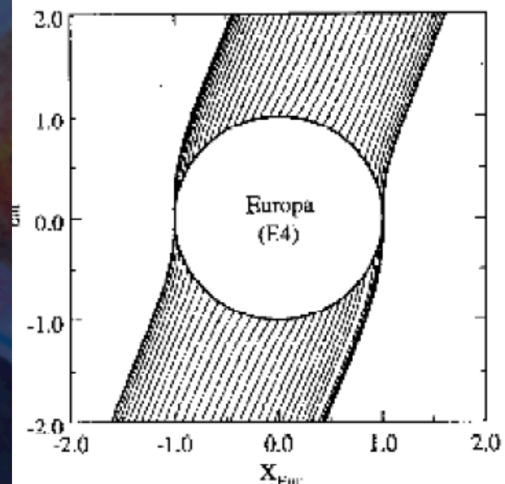
& data from Voyagers, Pioneer Galileo

Modeling the Jovian Radiation Environment

Particle Energies and fluxes in the Jovian system can be much higher that in Earth's magnetosphere and interplanetary space!

Several Radiation models for the Jovian system are being developed and improved:
Desire , Jorem (EU) ...

Europa's Magnetic Field Environment



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.

Ganymede

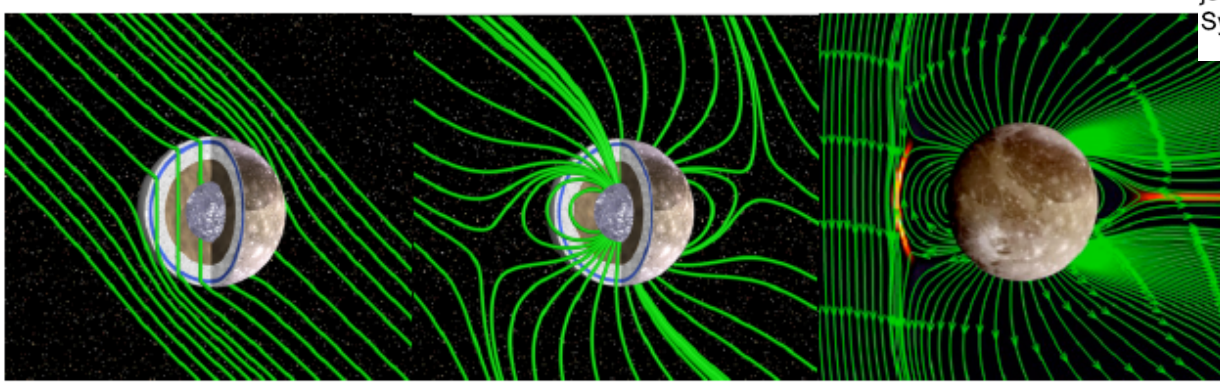
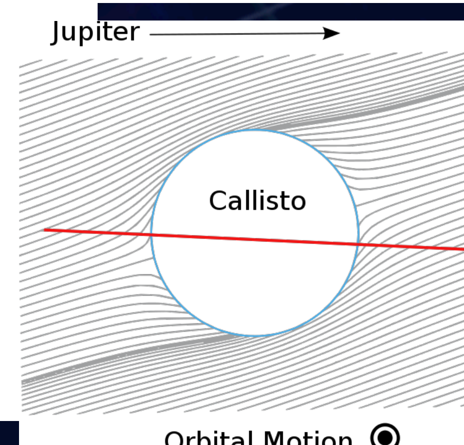
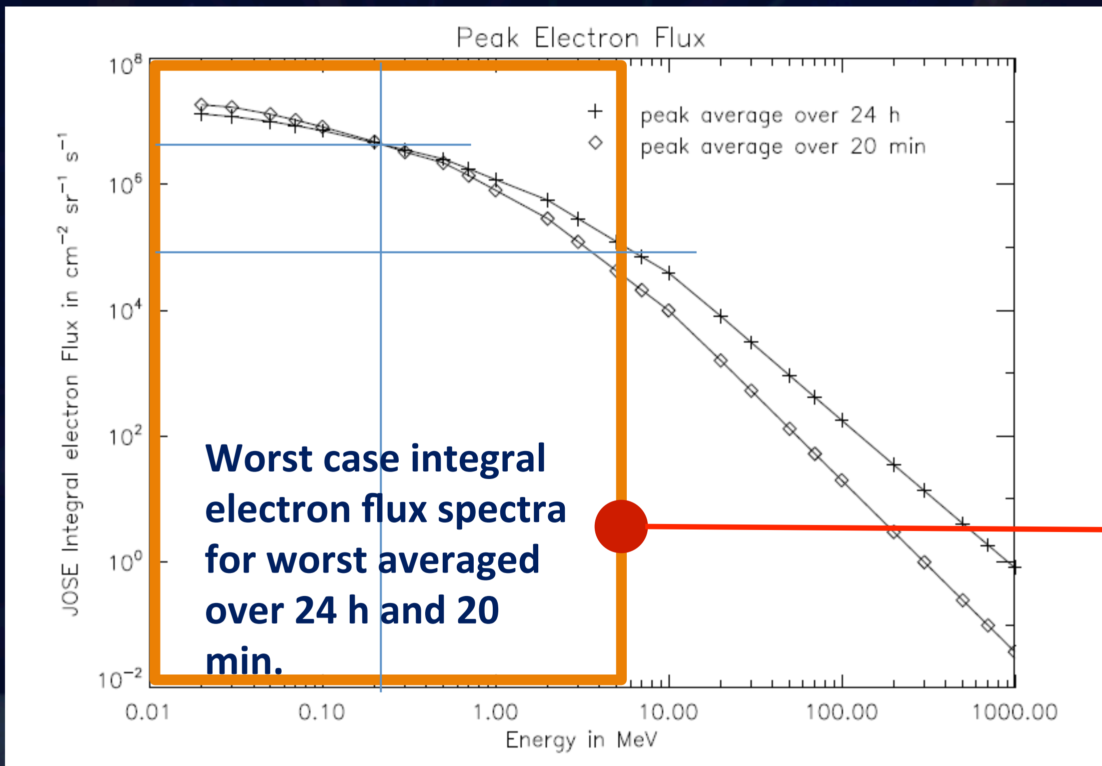


Figure 4-8 *Ganymede's induced field (left), internally generated magnetic field (middle), and resulting miniature magnetosphere (right). Credits: X.Jia (Univ. Michigan) and M. Kivelson (UCLA)*

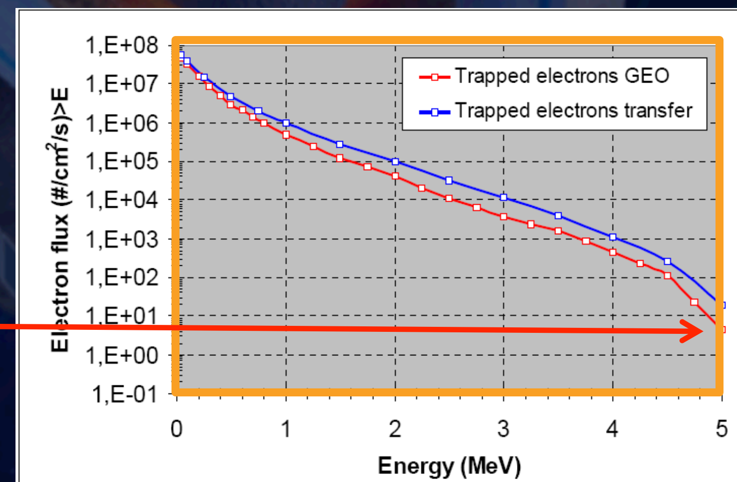


Very Hard Electron Spectrum

Jupiter - JUICE



Earth - GEO



Electron Flux #/(cm^2.sr.s)	0.2 MeV	5 MeV
Jupiter -JUICE	~5 x E+7	~5 x E+5
Earth - GEO	1 x E+7 /4π	1 x E+1 /4π

Measuring the Jovian Radiation Environment
RADEM - Radiation Hard Electron Monitor

LIP is colaborating with european institutes and industry in a proposal for the design and development of RADEM (phases B2, C & D).

Instrument requirements

Electron detector

Spectral range 300 keV – 40 MeV

Peak flux 10^9 e/cm2/s

Proton and heavy ion detector

Spectral range 5 MeV – 250 MeV

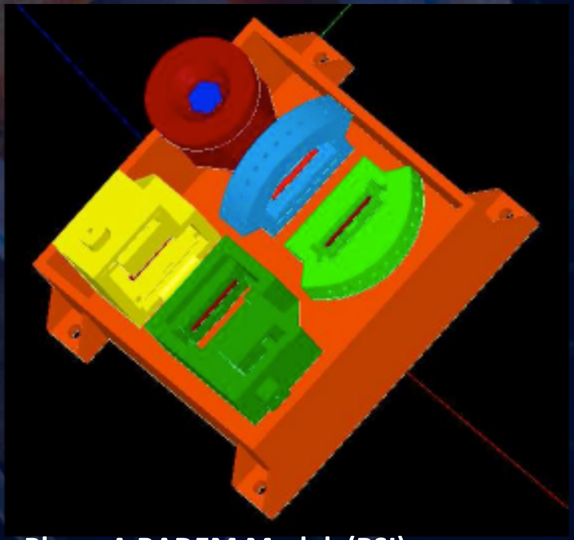
peak flux 10^8 p/cm2/s

Radiation hard

dose determination and alarm function

Particle separation

from Helium to Oxygen; LET spectra

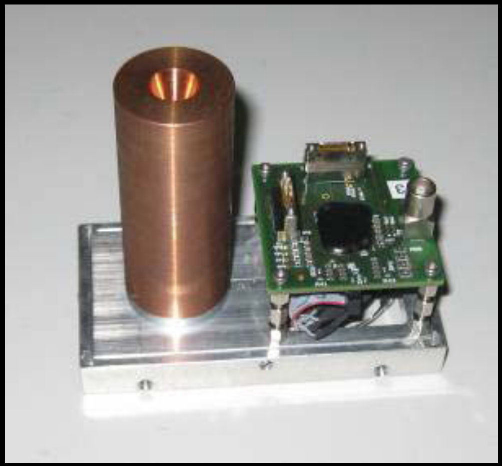


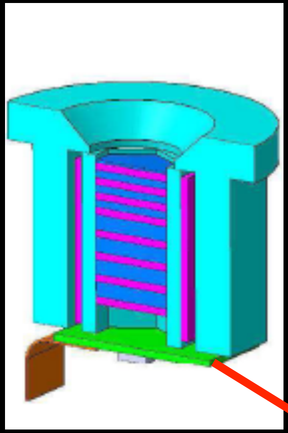
Phase A RADEM Model (PSI)

Preliminary Analysis and Definition Phase A and B1

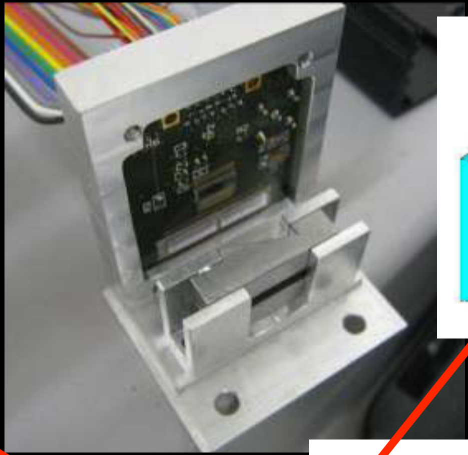
(PSI & Gamma-medica & RUAG) - Complete

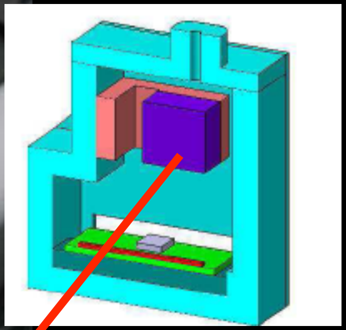
Proton Telescope
8 Si layers, 8mm Copper shielding)

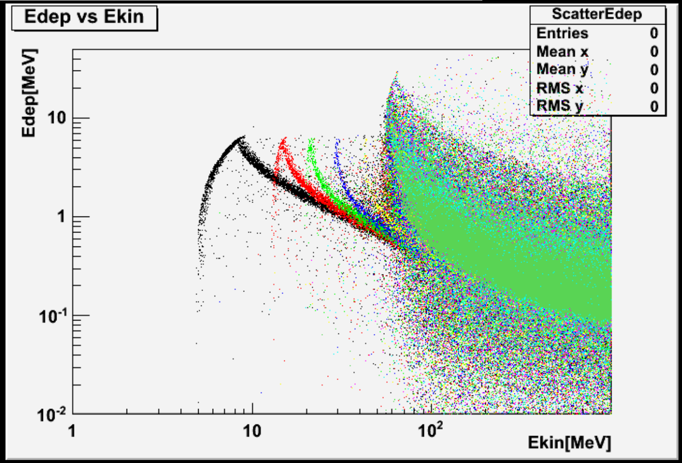


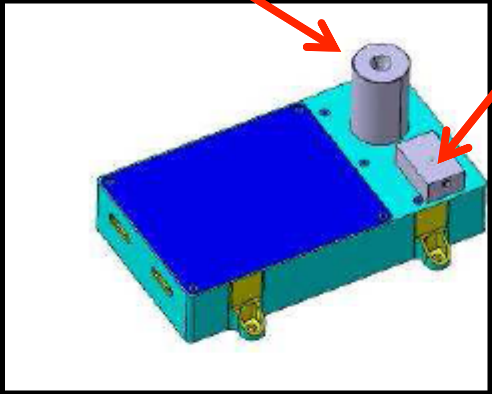


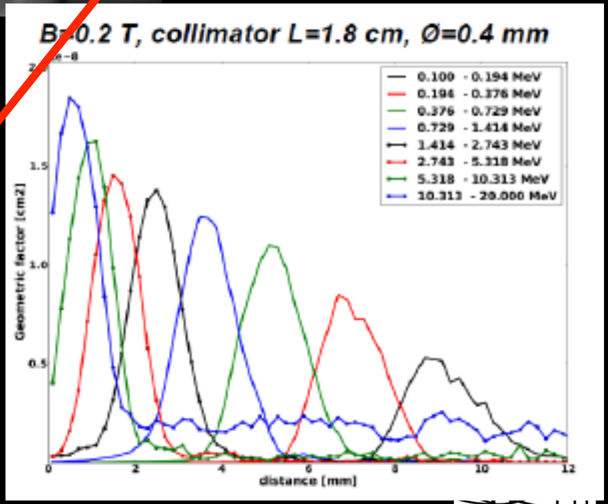
Electron Spectrometer
permanent magnet











Credits to Wojtec Hadjas & Laurent Desorgher (PSI) @ ESA Space Radiation Workshop, May 2012

Outlook

Moon to Mars & Beyond

Prepare Lunar exploration (Lunar Lander, other?)

Model the Lunar radiation environment

Analyse data from Lunar missions

Monitor the Lunar Radiation environment

(contribute to the design of a dedicated instrument?)

Assess human Lunar missions hazards and mitigation strategies

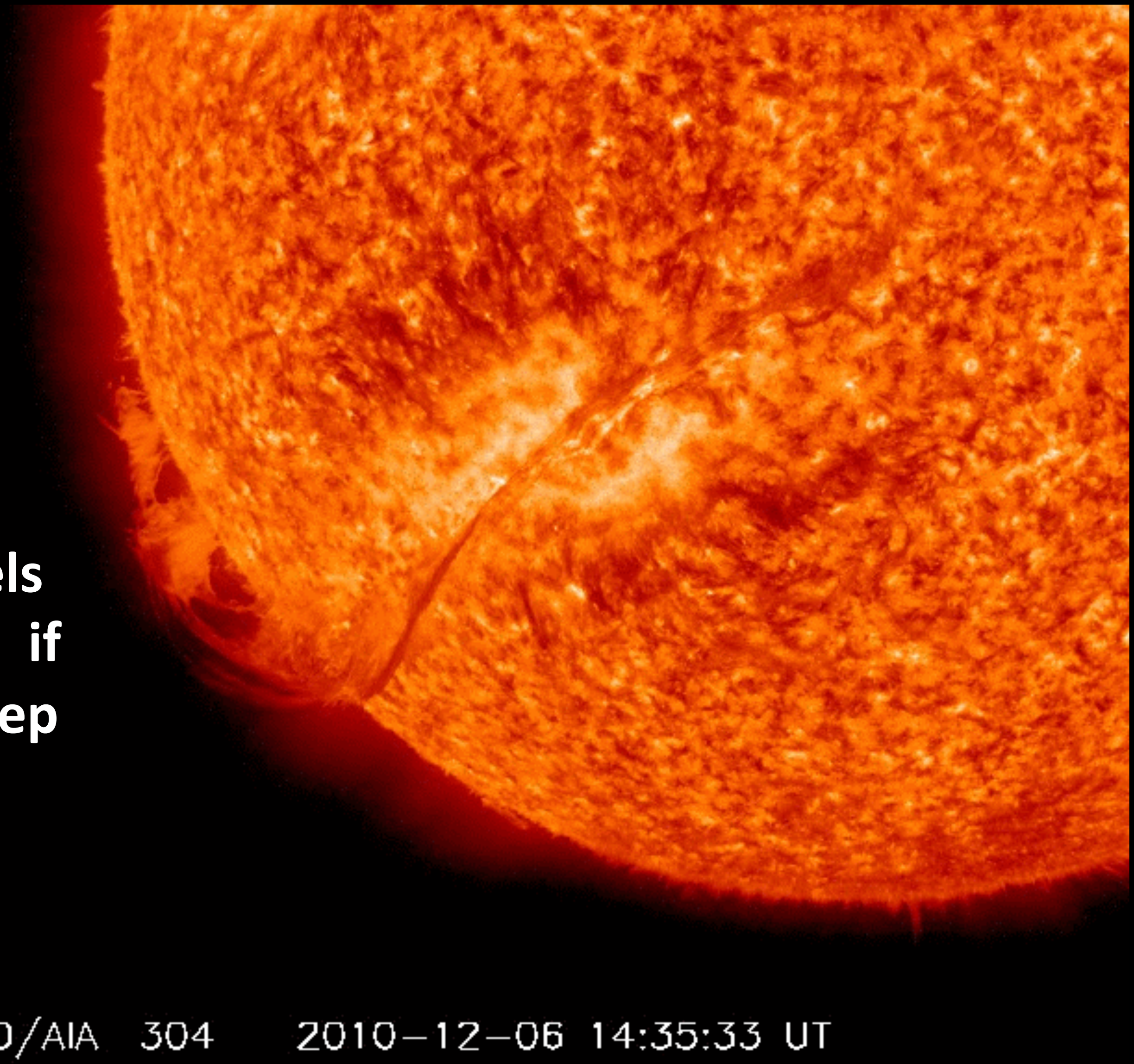
Validate Mars Radiation Environment Models & prepare for Mars (Exomars mission)

NO public radiation data (calibrated)

from Curiosity RAD on Mars surface yet ... publication soon ?

Study and prepare Models and Detectors for JUICE mission to:

Important !



SEP Forecasting models and tools are essential if we want humans to step beyond LEO...

http://spaceweather.com/


SPACE
RADIATION ENVIRONMENT & EFFECTS
LIP
Thank you !
LIP