MSFC-031-ABSTRACT

Heliospheric Physics and NASA's Vision for Space Exploration

Joseph Minow
NASA, Marshall Space Flight Center

The Vision for Space Exploration outlines NASA's development of a new generation of human-rated launch vehicles to replace the Space Shuttle and an architecture for exploring the Moon and Mars. The system—developed by the Constellation Program—includes a near term (~2014) capability to provide crew and cargo service to the International Space Station after the Shuttle is retired in 2010 and a human return to the Moon no later than 2020. Constellation vehicles and systems will necessarily be required to operate efficiently, safely, and reliably in the space plasma and radiation environments of low Earth orbit, the Earth's magnetosphere, interplanetary space, and on the lunar surface. This presentation will provide an overview of the characteristics of space radiation and plasma environments relevant to lunar programs including the trans-lunar injection and trans-Earth injection trajectories through the Earth's radiation belts, solar wind surface dose and plasma wake charging environments in near lunar space, energetic solar particle events, and galactic cosmic rays and discusses the design and operational environments being developed for lunar program requirements to assure that systems operate successfully in the space environment.

MSFC-031-PRESENTATION

Heliospheric Physics and NASA's Vision for Space Exploration

Joseph I. Minow
NASA, Marshall Space Flight Center

Utah State University, Logan, UT
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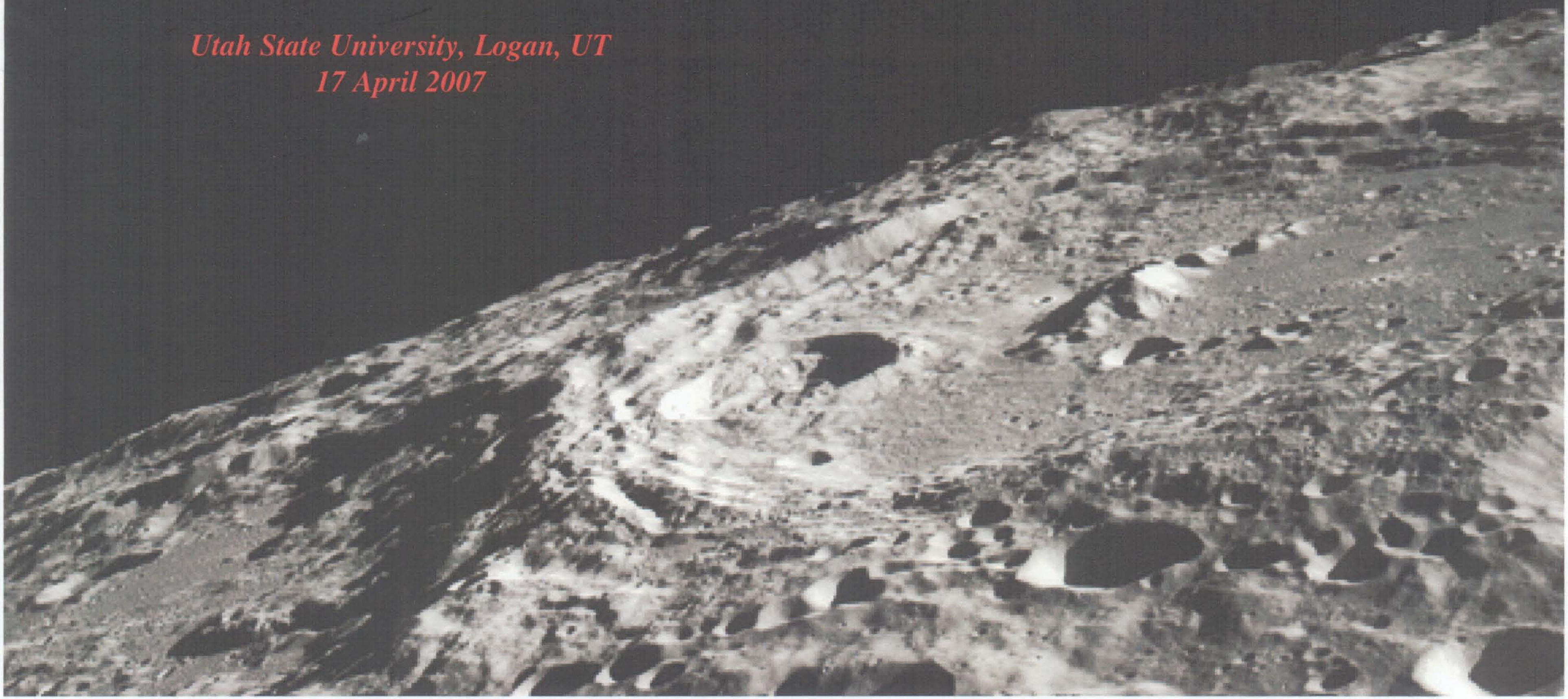


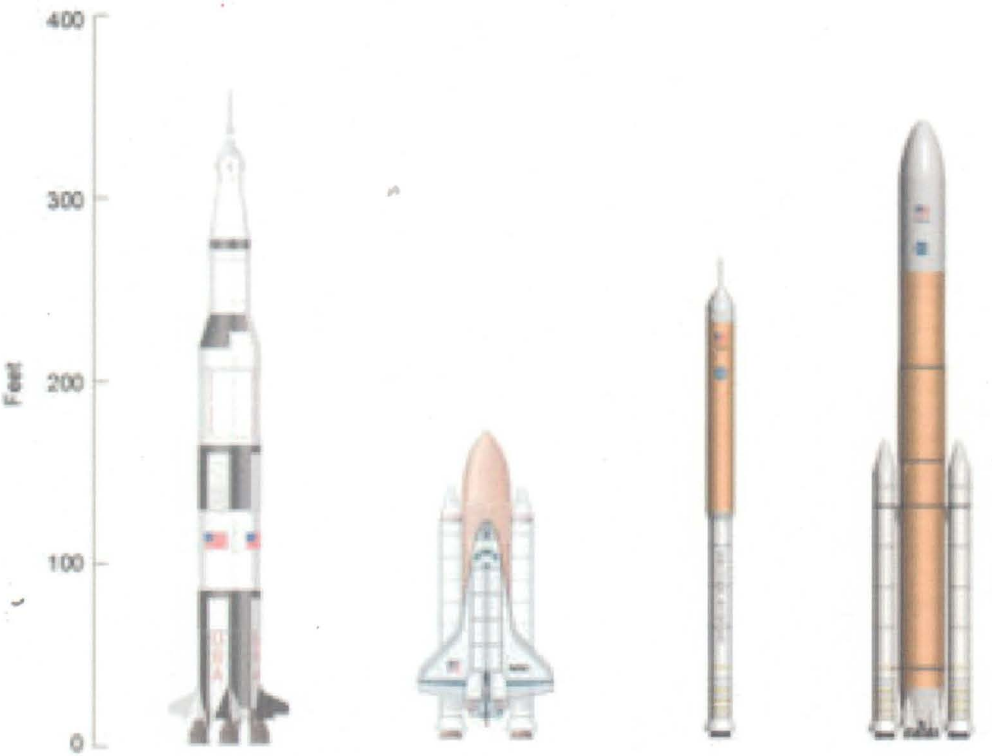
Overview

- Constellation Program architecture
- Heliospheric physics science in design, operations of lunar programs
  - Radiation environments
    - Crew
    - Hardware (electronics), materials
  - Plasma environments
    - Spacecraft charging, surface dose
- Summary

Environments	**Space System Effects**
Galactic cosmic rays	**SEE, crew dose**
Solar particle events	**SEE, TID, crew dose, charging**
Trapped radiation belts	**SEE, TID, crew dose, charging**
Solar wind, magnetosheath magnetospheric plasma	**TID, charging**
Lunar photoelectrons	**charging**

Constellation Program

- New human-rated space transportation system to replace Space Transportation System (Shuttle)
  - ISS support ~2014
  - Lunar exploration ~2020
  - Mars exploration

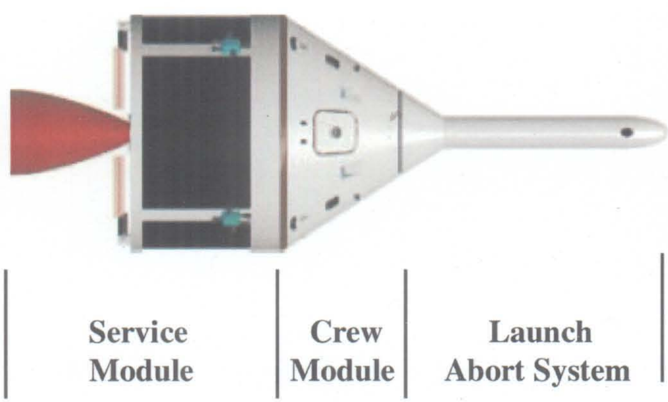


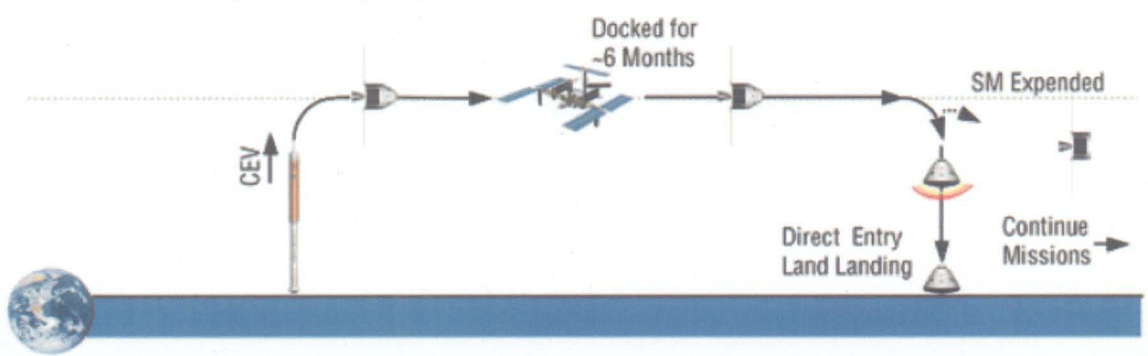
Saturn-V Shuttle Ares-I Ares-IV

[NASA's Exploration Systems Architecture Study—Final Report, Nov 2006]

ISS Support

- Crewed Exploration Vehicle
  - Capability for transferring crew members (4-6) to ISS
  - Unmanned cargo delivery
    - Pressurized
    - Unpressurized





Lunar Exploration Architecture

Composite Shroud

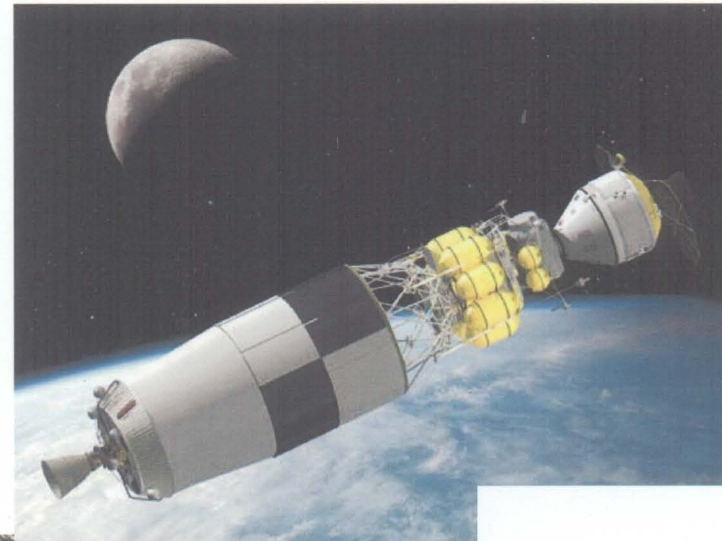
Lunar Surface Access Module (LSAM)

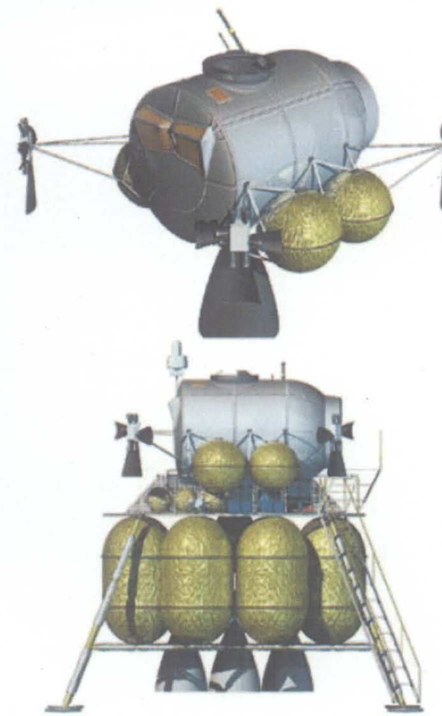
Earth Departure Stage
LOx/LH_2
1 J-2X Engine
Al-Li Tanks/Structures

Interstage

Core Stage
LOx/LH_2
5 RS-68 Engines
Al-Li Tanks/Structures

5-Segment
2 RSRB's

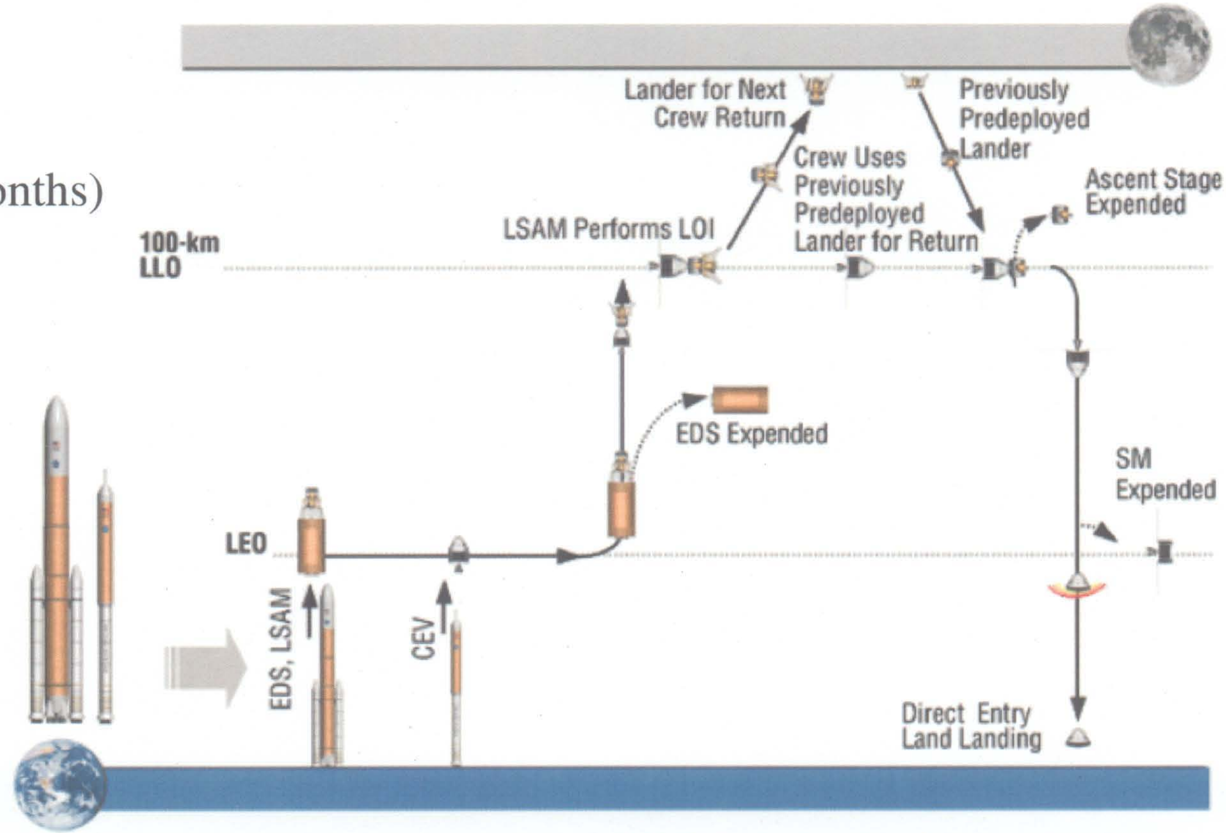




[NASA's Exploration Systems Architecture Study—Final Report, Nov 2006]

Example Lunar Reference Mission

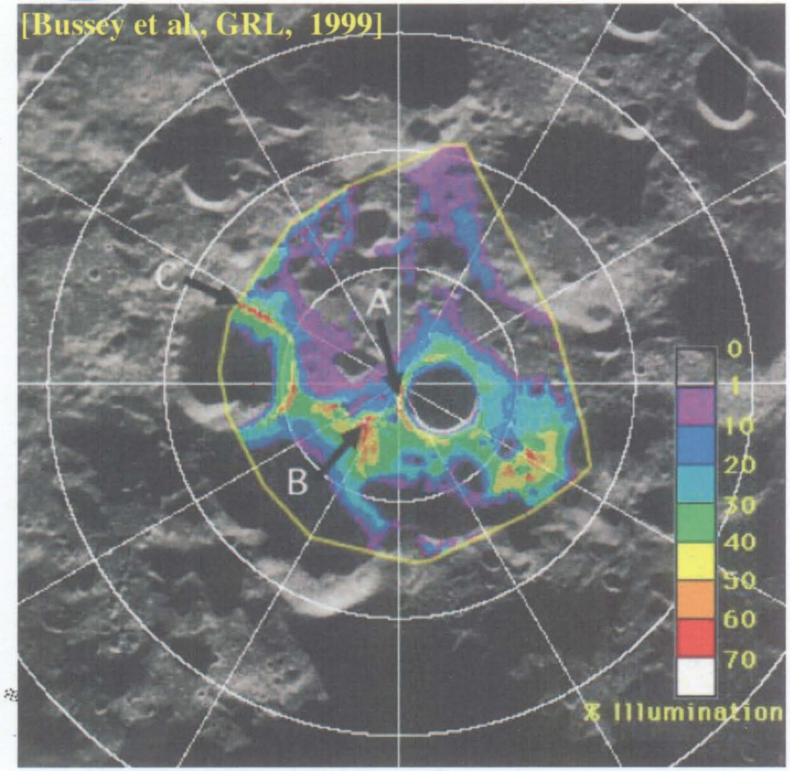
- Lunar architecture
  - Lunar sortie (7 days)
  - Lunar outpost (~6 months)



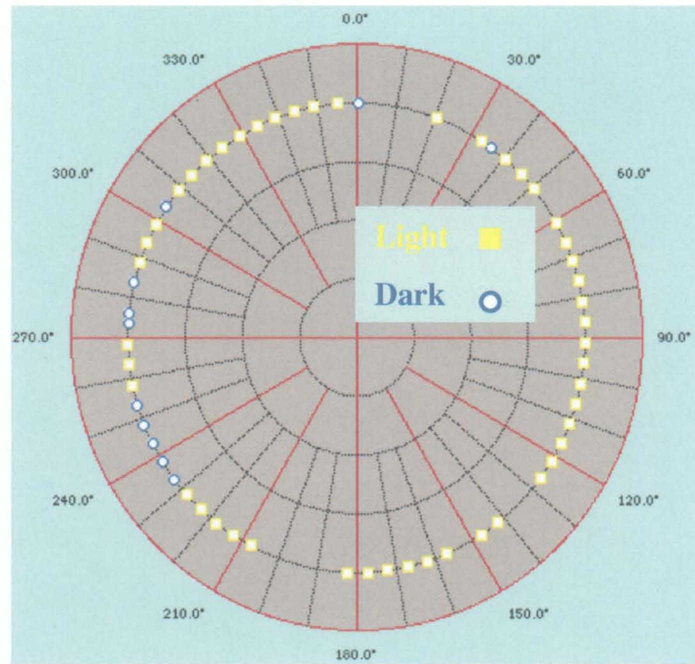
[NASA's Exploration Systems Architecture Study—Final Report, Nov 2006]

- Current program focus is on developing an outpost at one of the lunar poles with access to other locations on lunar surface

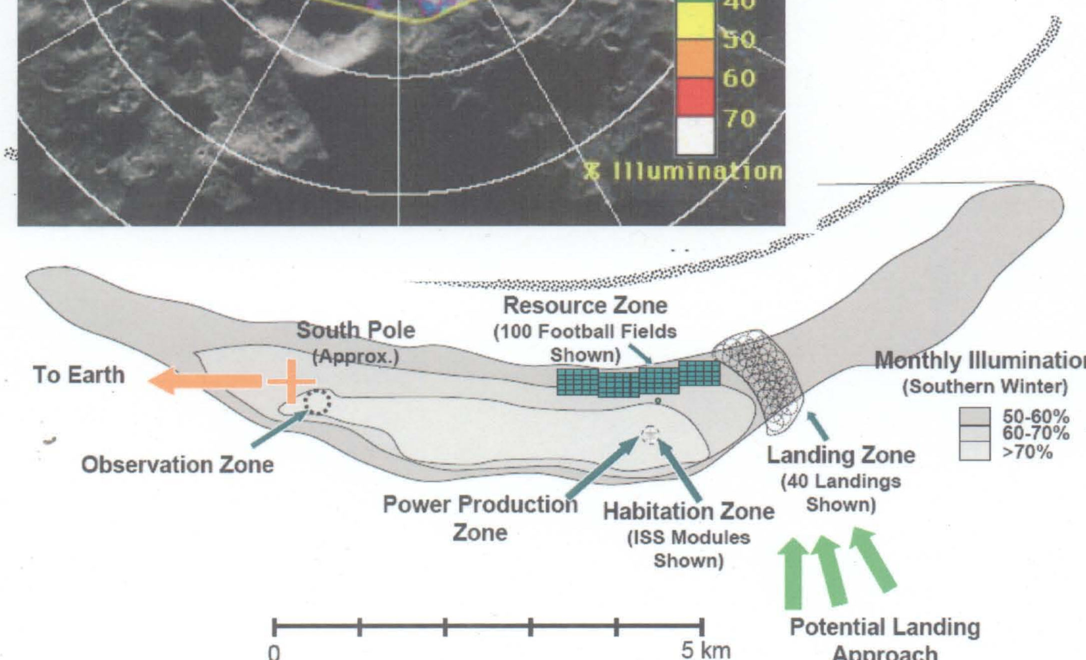
Lunar South Pole



- >70% illumination on rim of Shakelton Crater
- T ~ 220±10 K…relatively benign
- Night temperatures near equator are T~ 100K
- T~40K to 50K in permanently dark craters



[adapted from Bussey et al., LPSC 1999]



[Dale, 2nd Space Expl. Conf., 2006]

Longest period of shadow ~49 hours based on ~29.5day/Sol or 12.2 deg/day

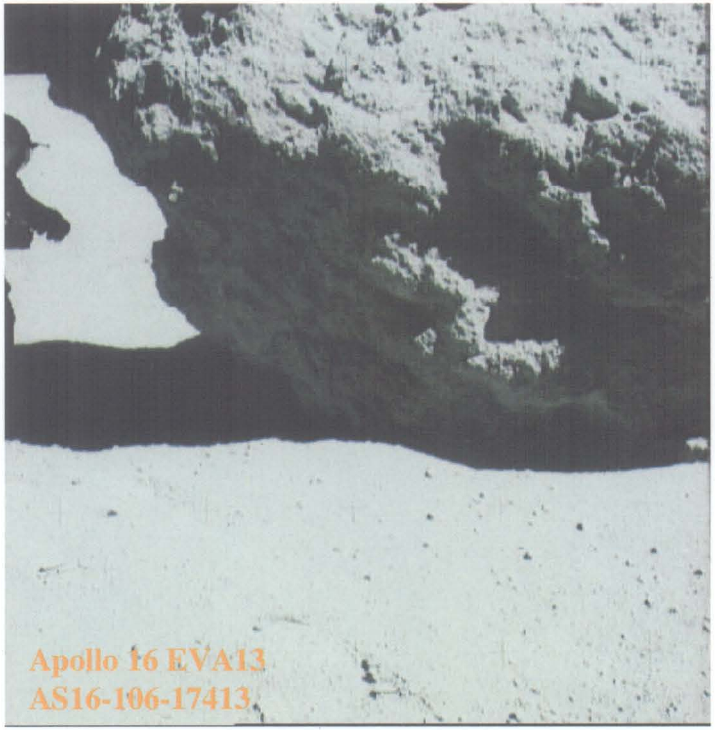
Apollo Experience

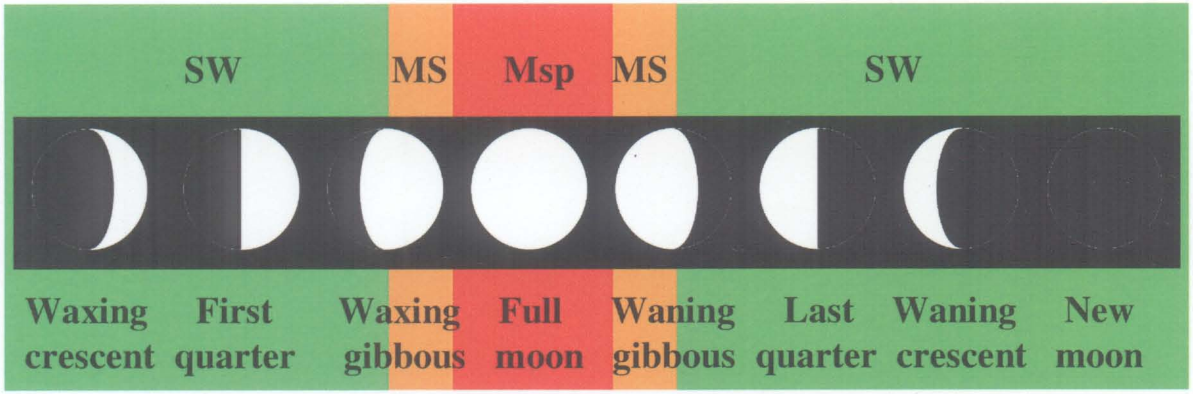
Mission	Landing Date (GMT)	SEA[a] (deg)	Lunar[c] Phase
• Apollo 11	20 Jul 69	10.8	WxC, 31%
• Apollo 12	19 Nov 69	5.1	WxG, 81%
• Apollo 13	----	18.5[b]	----
• Apollo 14	5 Feb 71	10.3	WxG, 81%
• Apollo 15	30 Jul 71	12.2	1Qtr, 50%
• Apollo 16	21 Apr 72	11.9	WxG, 62%
• Apollo 17	11 Dec 72	13.0	WxC, 29%

[a]Solar elevation angle data from *Orloff* [2000]

[b]Planned

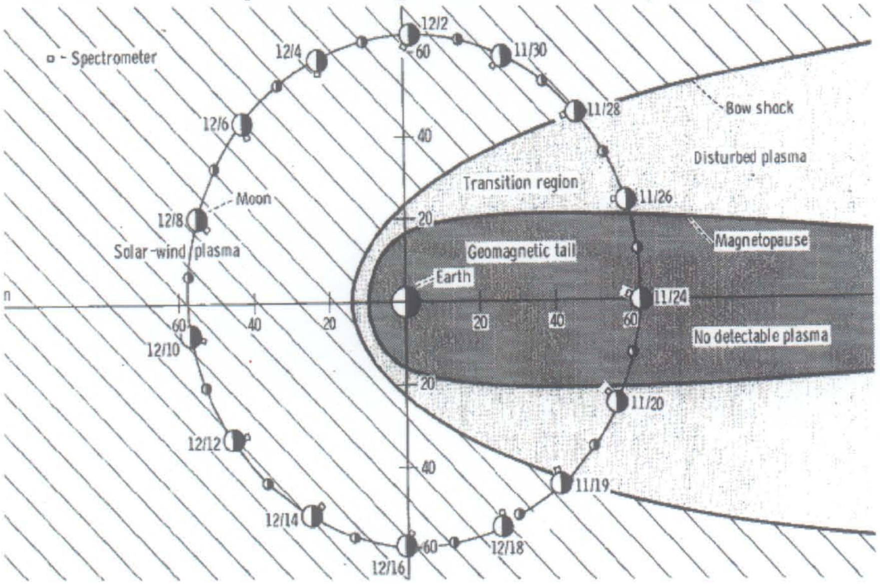
[c]http://aa.usno.navy.mil/data/docs/RS_OneDay.html





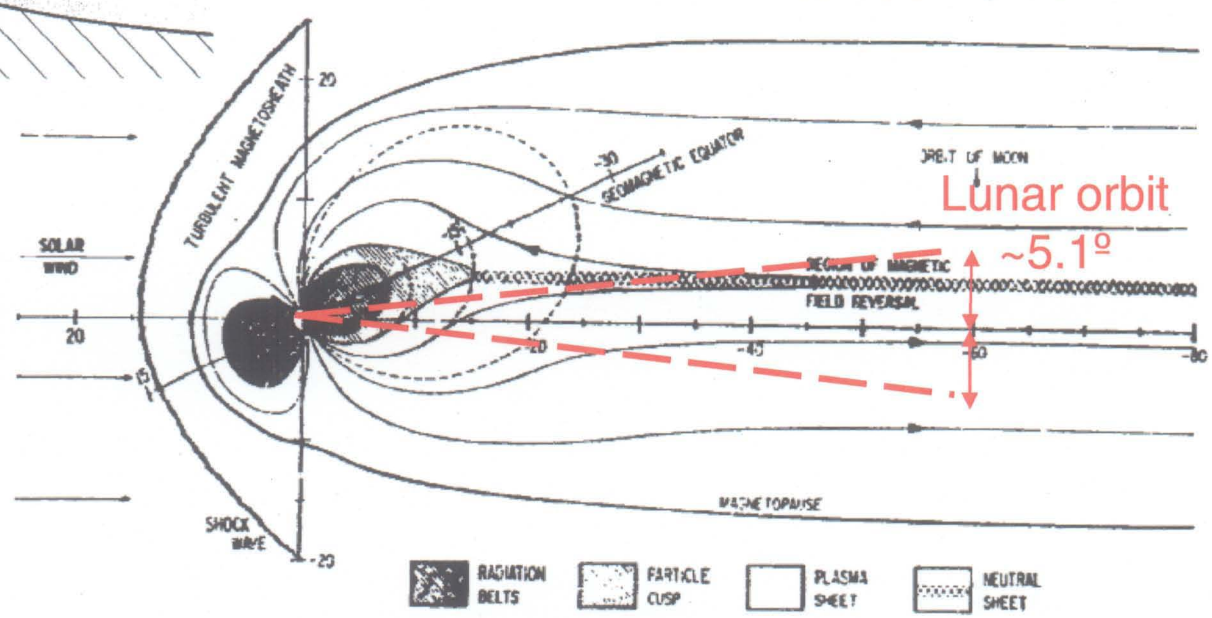
Magnetosphere and Lunar Orbit

Apollo 12 [*NASA SP-235*, 1970]



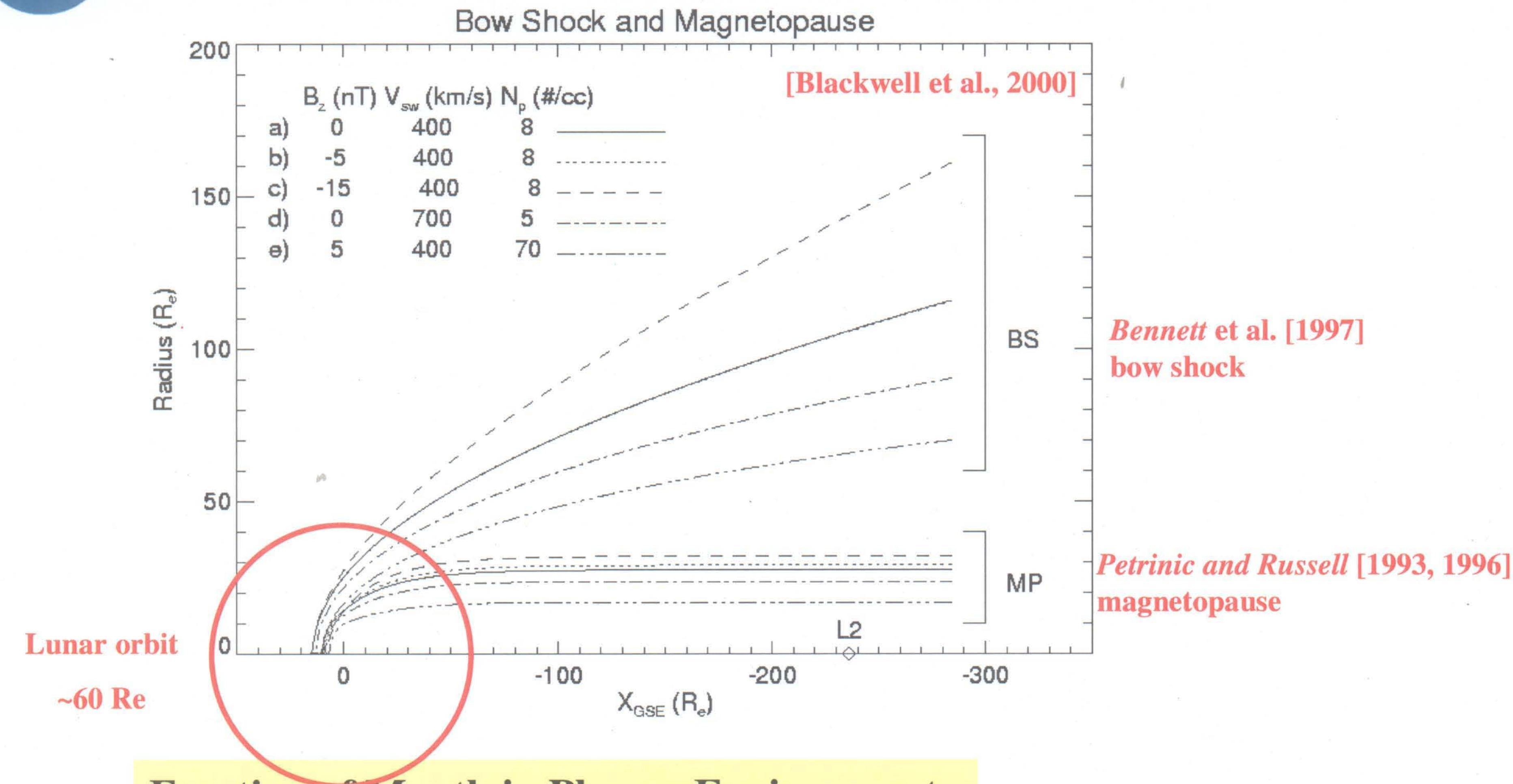
Moon passes through magnetotail and magnetosheath plasma environments every month

Adams et al., 1981



In-situ observations of plasma and radiation environments relevant to lunar exploration are available from pre-Apollo to present

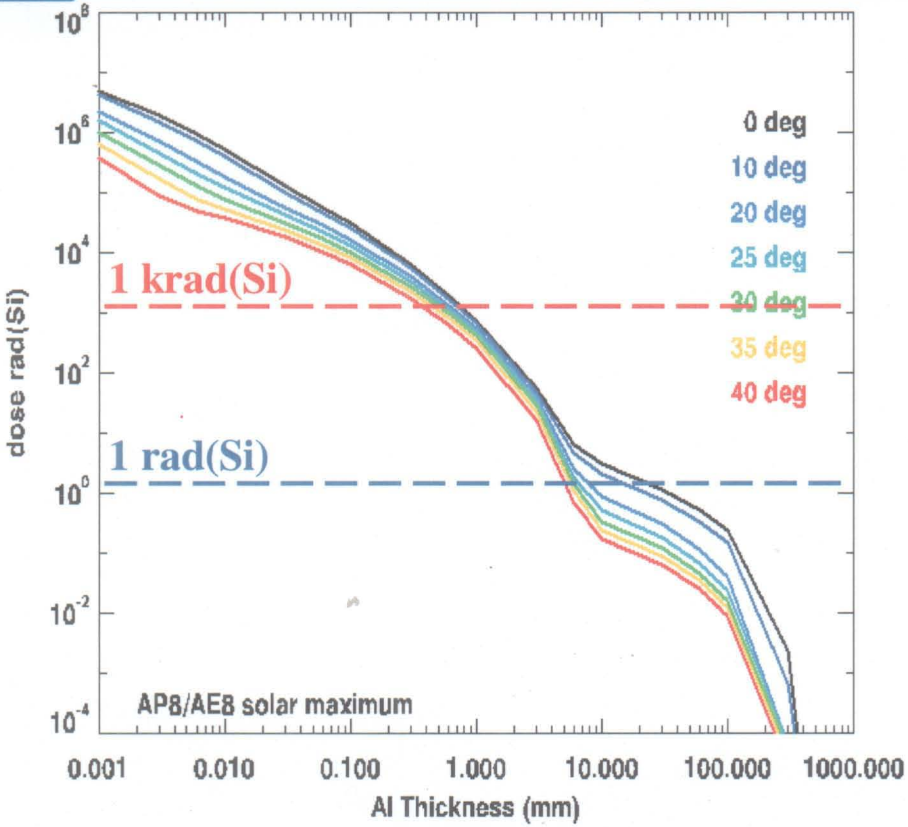
Bow Shock and Magnetopause Variability

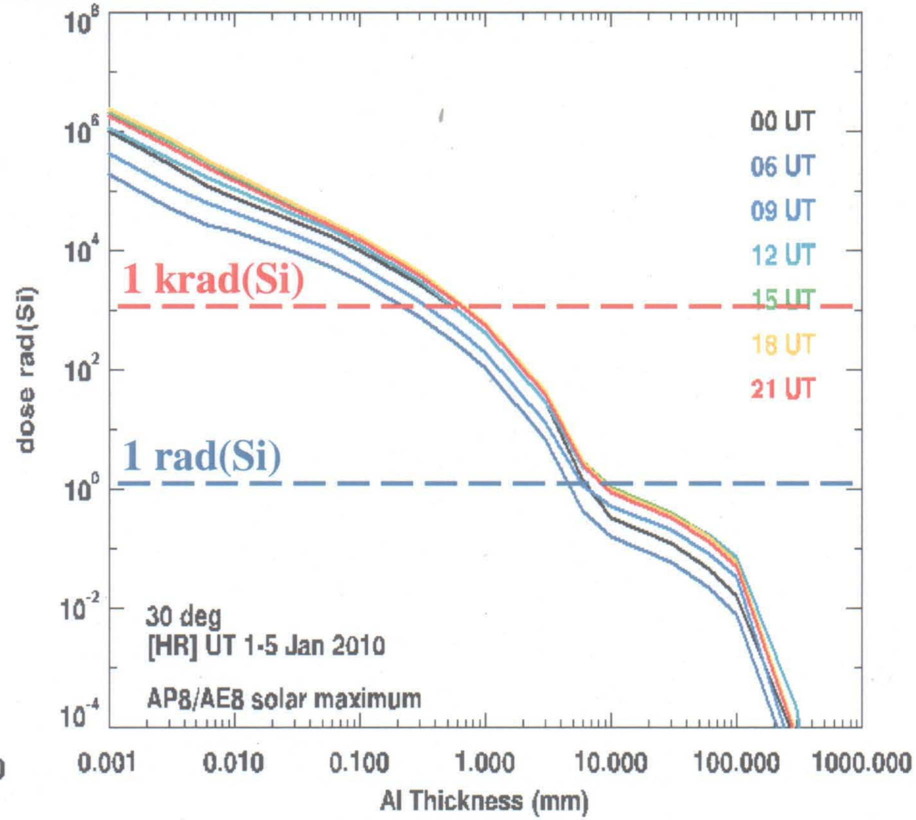


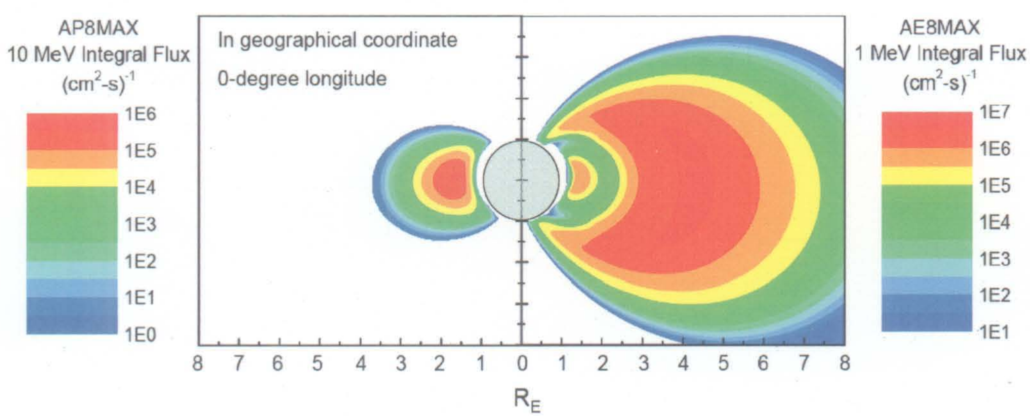
Fraction of Month in Plasma Environments

~73.5% solar wind	~20.6 days
~13.3% magnetosheath	~ 3.7
~13.2% magnetotail	~ 3.7

Inclination, Departure Longitude and Dose





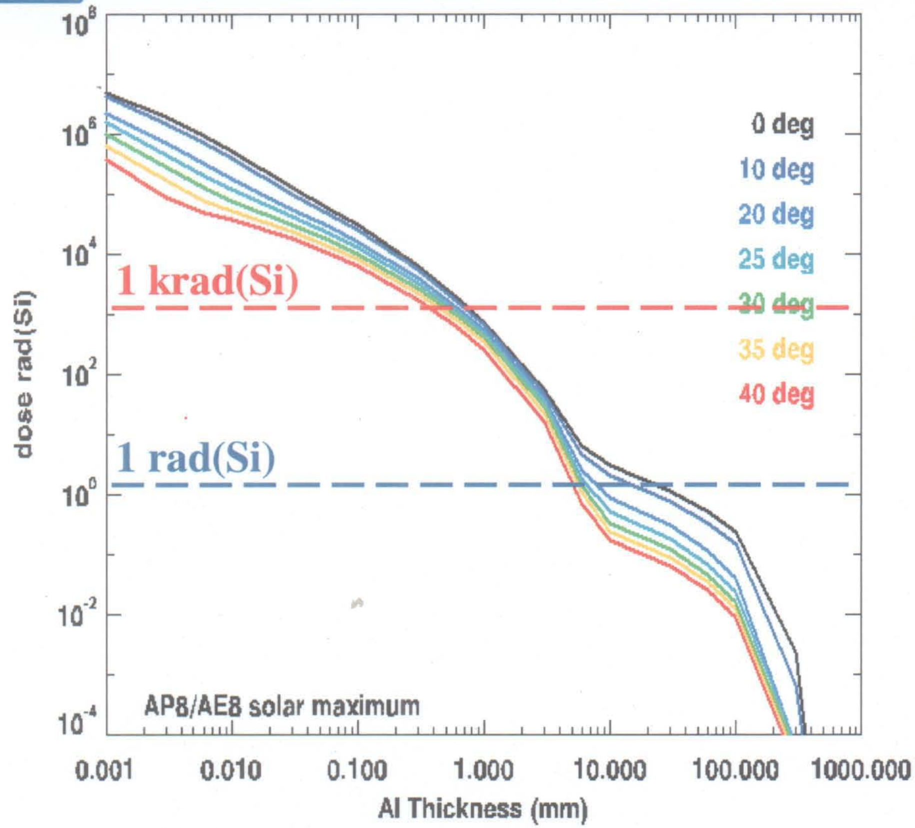


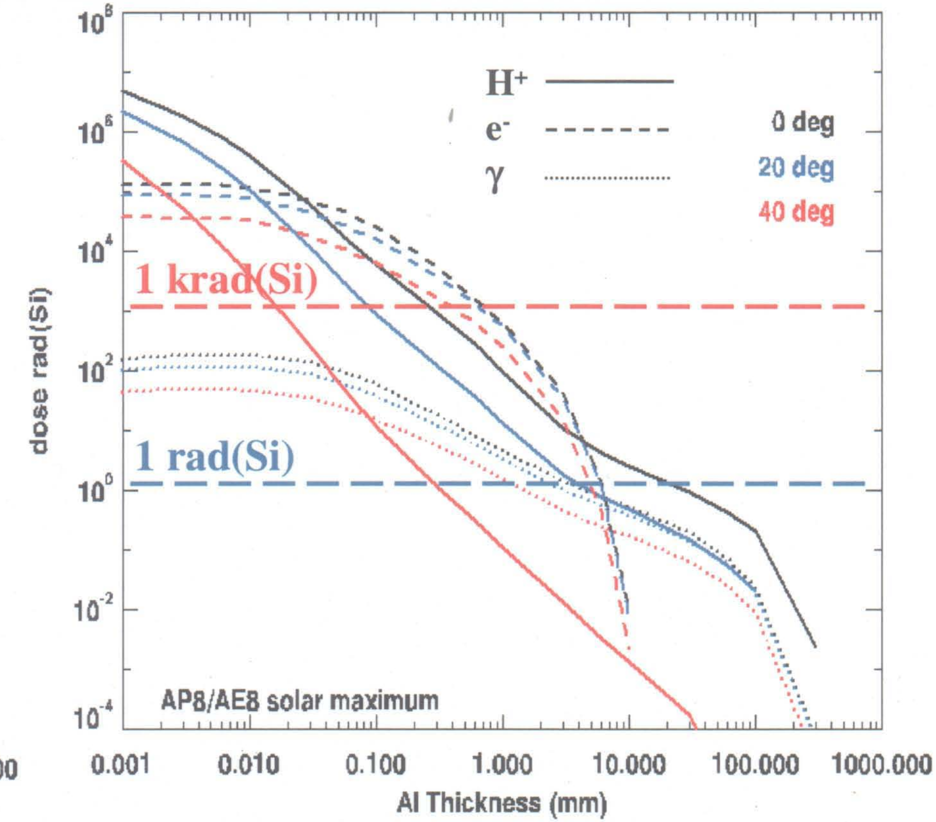
Single TLI orbit

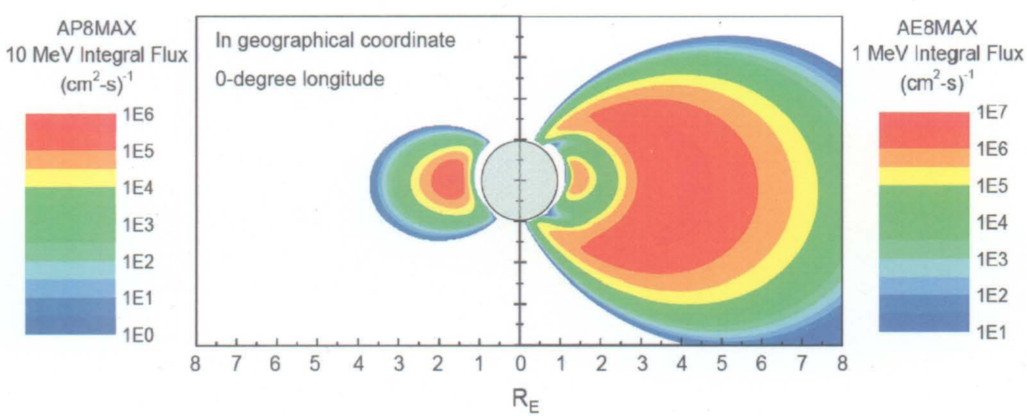
perigee = 300 km

apogee = 379,867 km

Inclination, Departure Longitude and Dose







Single TLI orbit

perigee = 300 km

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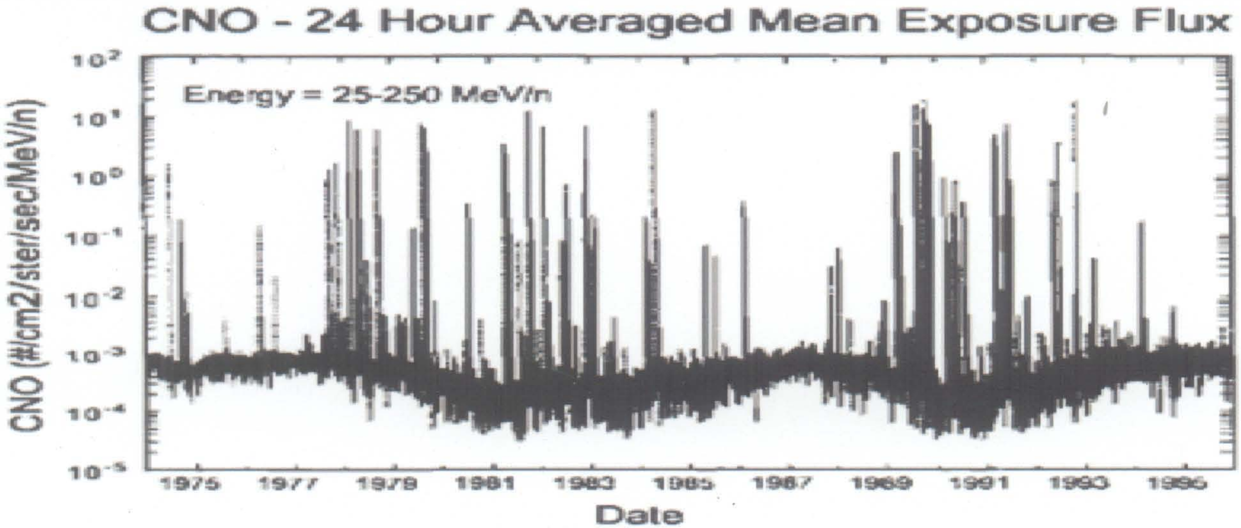
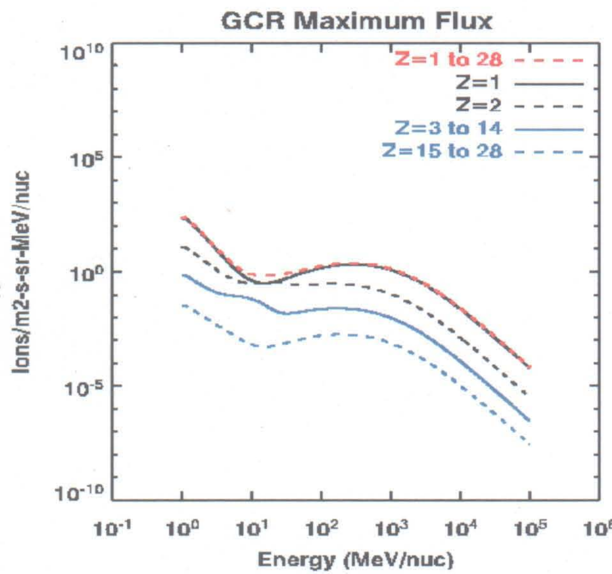
Galactic Cosmic Rays, Solar Energetic Particles

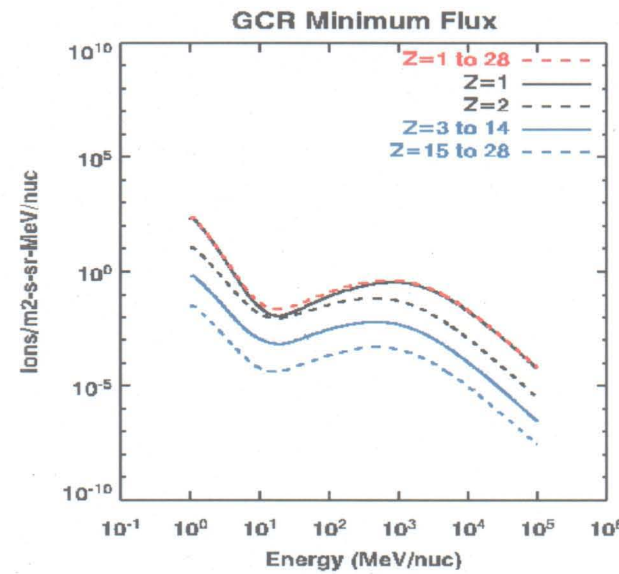


Lunar 60 Re orbit is ~1 ± 0.0026 AU

--Same cosmic ray, solar energetic particle environment as Earth

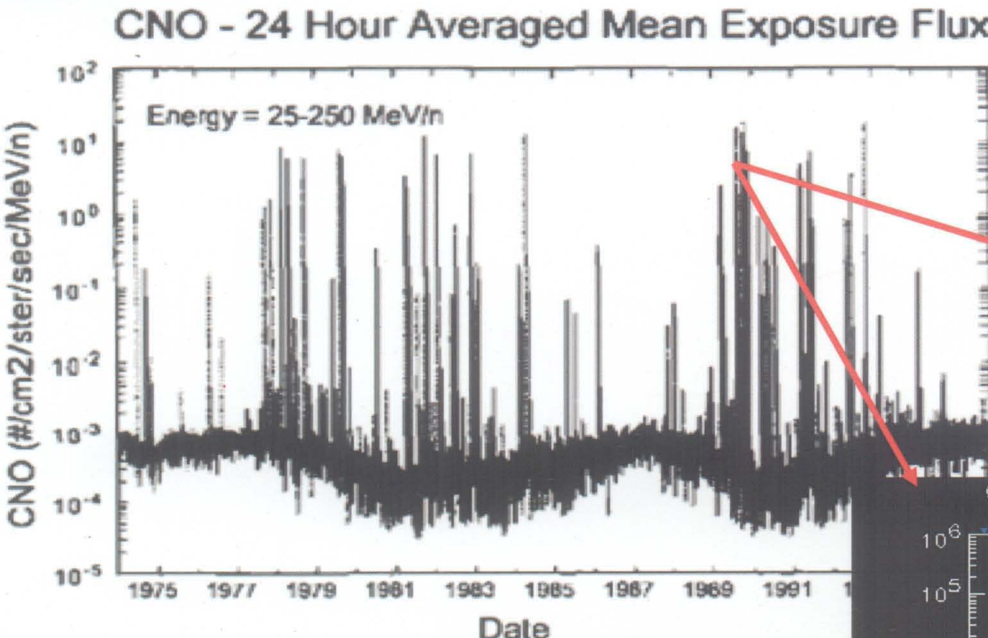
--Magnetotail ~10 nT field at lunar orbit weaker than the 50 nT to 100 nT at GEO





CREME 1996 [Tylka et al., 1997]

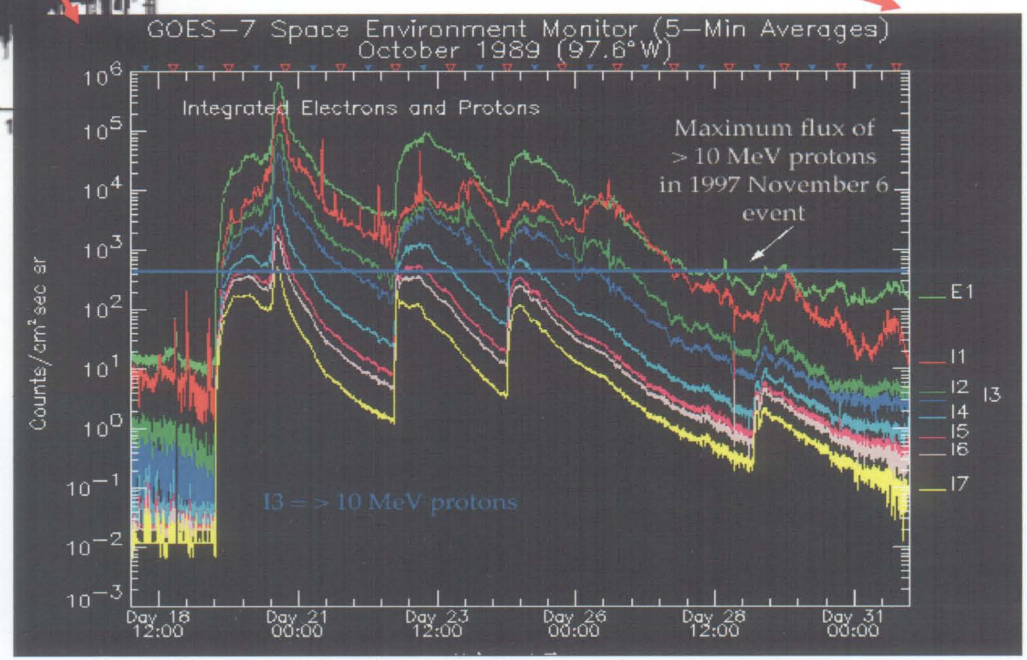
Solar Particle Event ("Flare") Environments



IMP-8 interplanetary ions from the C-N-O group Episodic high flux solar particle events are superimposed on the slowly varying galactic cosmic ray background flux

Frequency and magnitude of solar particle events demonstrates that Shuttle exposure to a high flux solar energetic particle event (or an equivalent fluence due to a number of smaller events) is a credible event during Shuttle life

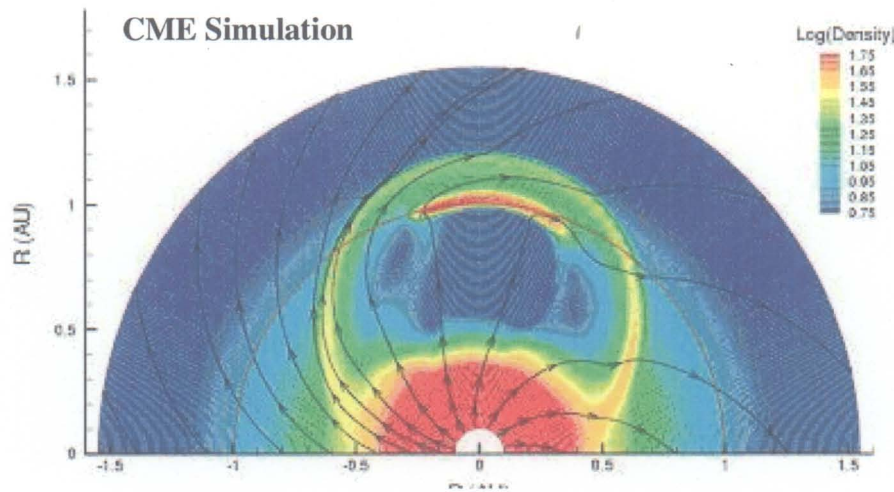
Example flux and duration of large proton solar particle event in October 1989



Flares, CME's

- Impulsive events
  - Minutes to hours
  - Electron rich
  - ~1000/yr at solar max

- Gradual events
  - Days
  - Proton rich
  - ~100/year

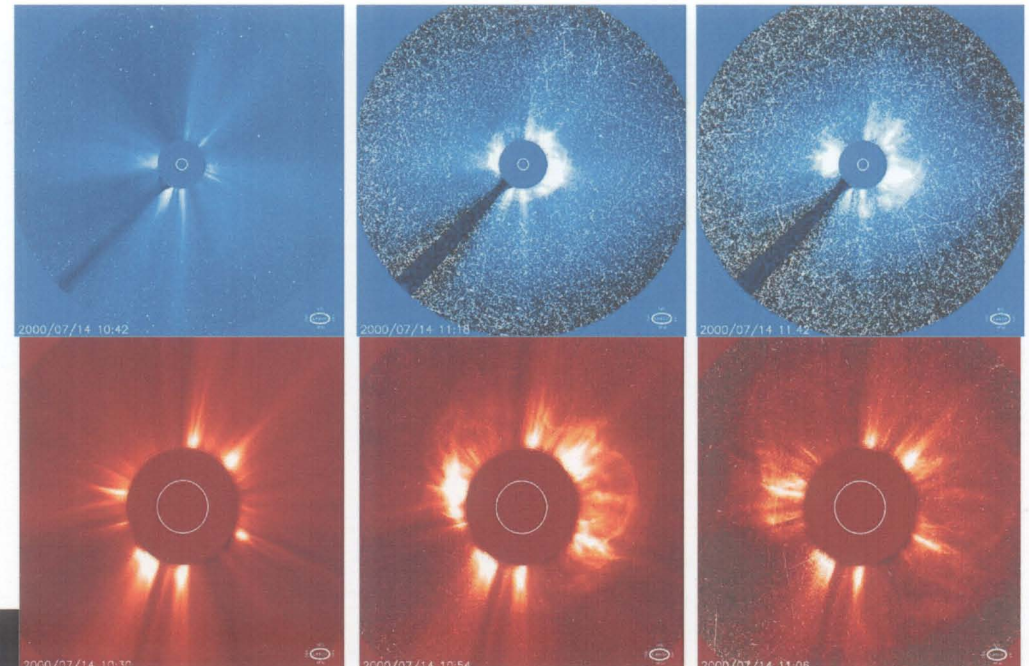


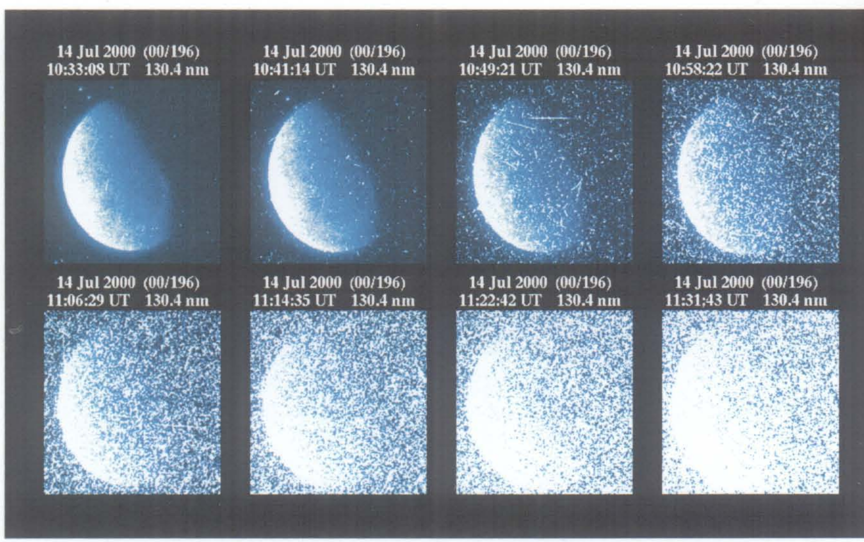
[http://www.srl.caltech.edu/ACE/ACENews/ACENews55.html]

Energetic Particle Impacts on Spacecraft

- Bastille Day 2000 Storm
  - SOHO Lasco
  - Polar VIS

- Similar effects on star trackers used for attitude control can threaten spacecraft



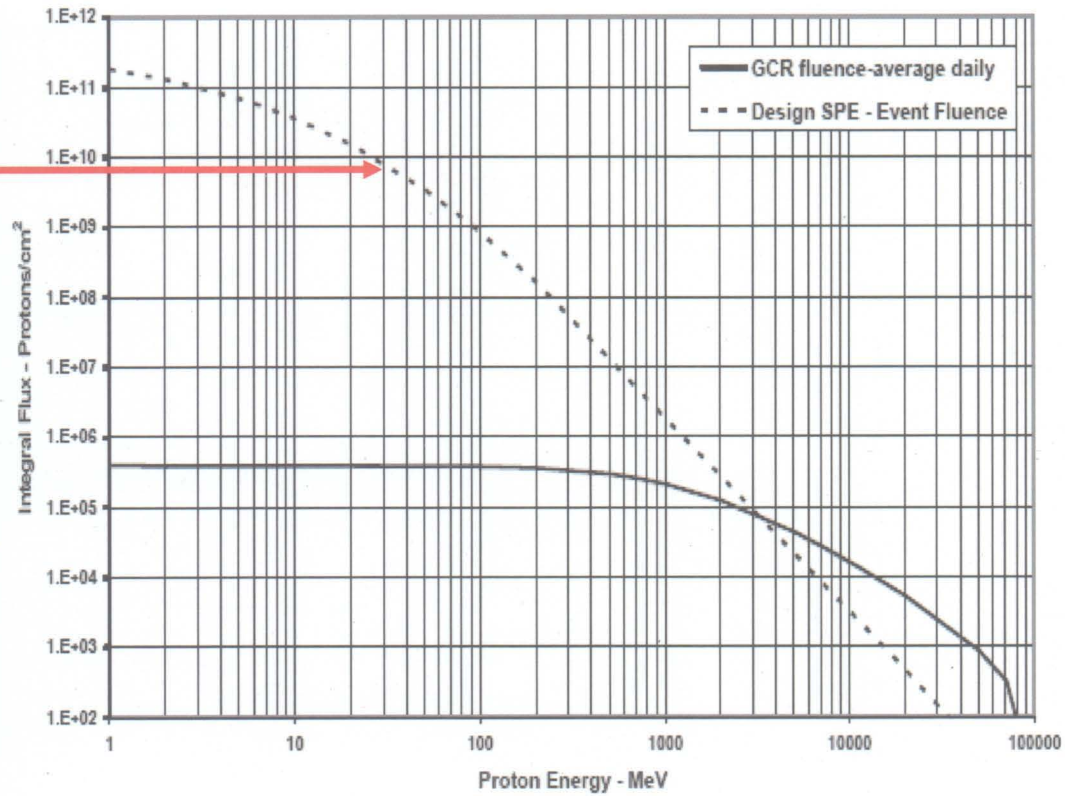


Constellation Design Environments

- Proton SPE, GCR fluence spectra (for total dose analyses)
  - Based on October 1989 flare, solar minimum GCR environments derived from CREME96 model

Event	Max >30 MeV flux (#/cm2-s-sr)		>30 MeV fluence (#/cm2)
1859/09/01	5×10^4		19×10^9
1960/11/15	-------	hardware	9×10^9
1946/07/25	-------		6×10^9
1972/08/04	2×10^4	crew dose	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
2001/09/24	--------		1.2×10^9
2005/01/15	---------		1.0×10^9

Sources: *Smart and Shea*, 2002; *Reedy*, 2006; *Smart et al.*, 2005



Energetic Particle Access to Magnetotail

Protons

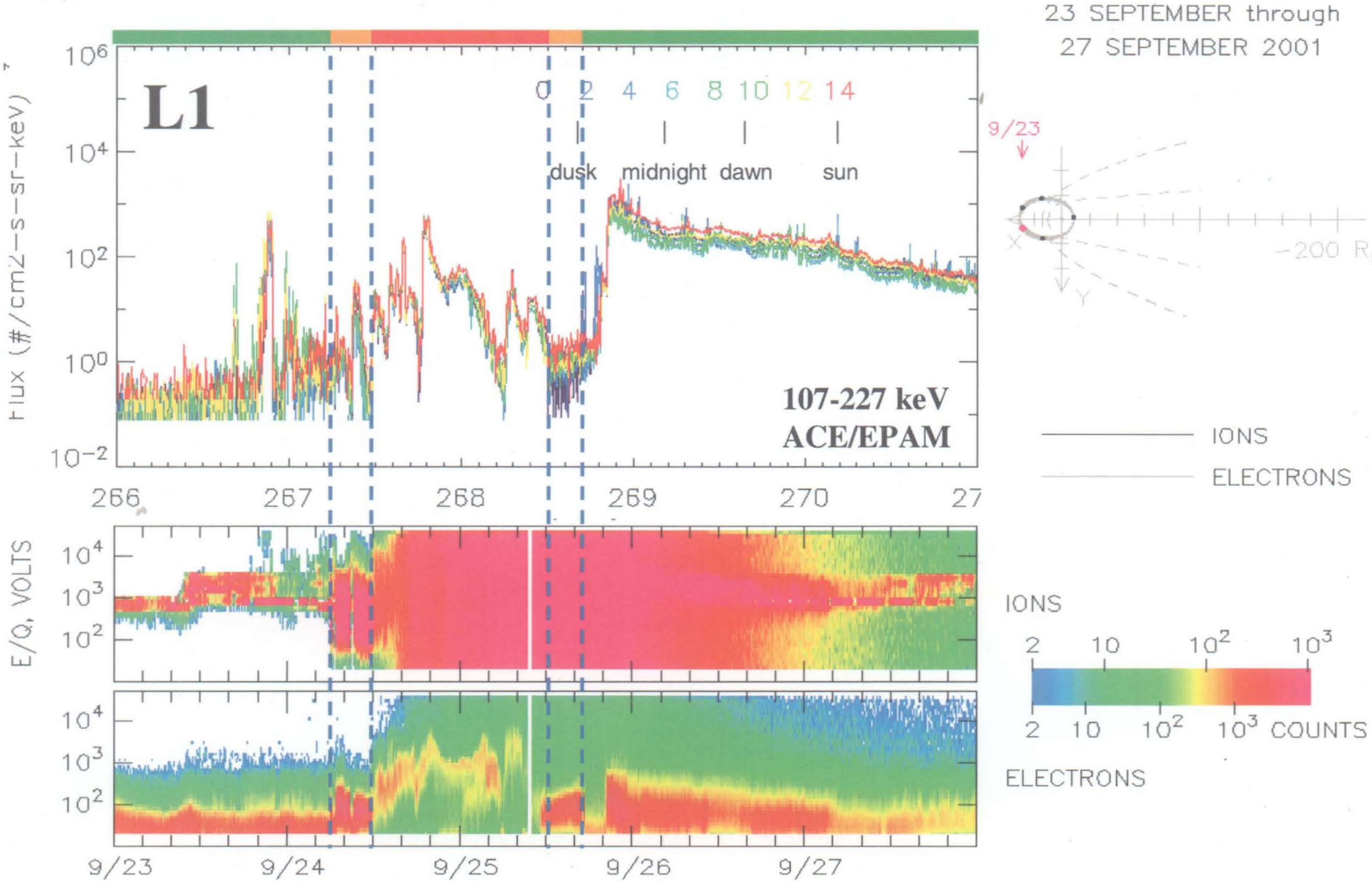
107-227 keV

Ions

0.03-30 keV

Electrons

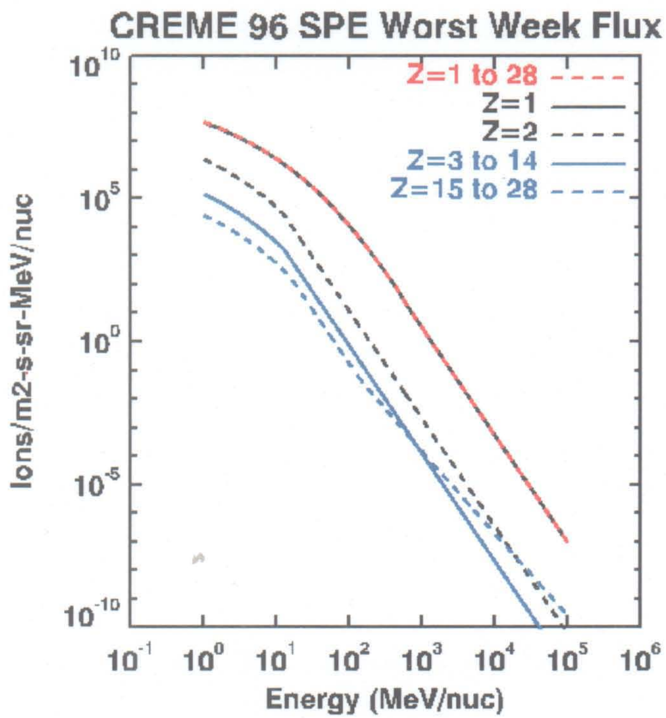
0.03-30 keV

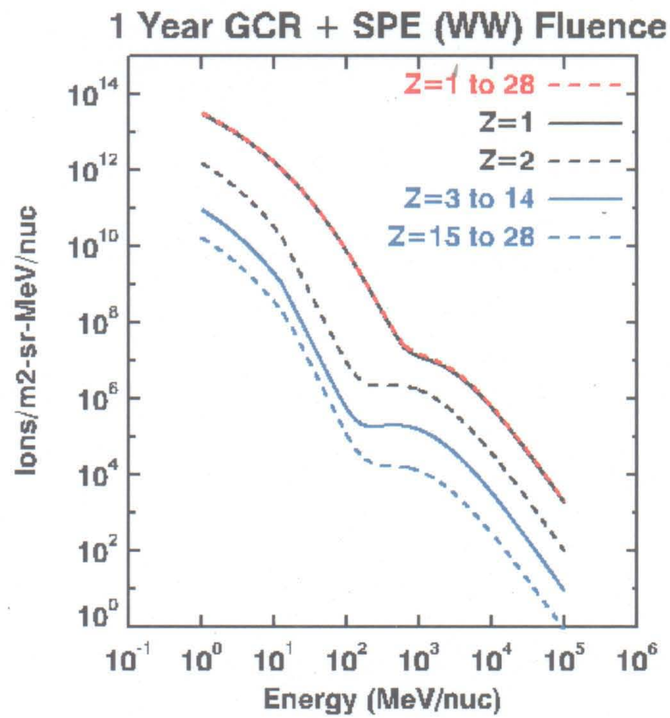


Univ of Iowa
Geotail/CPI/HPA

Solar energetic particles have nearly free access to outer magnetosphere and magnetotail—no protection for Moon when in magnetotail

Galactic Cosmic Rays, Solar Energetic Particles



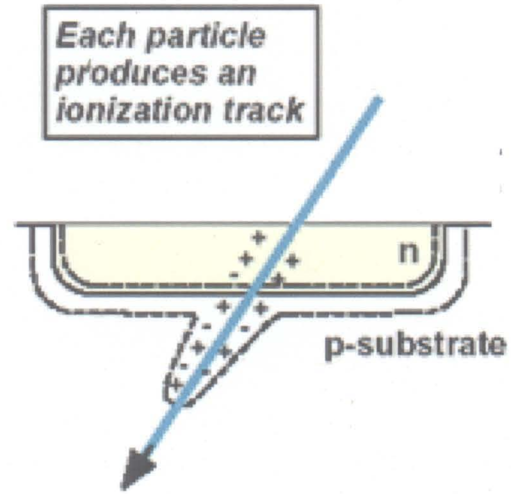


- **CREME96 Worst Week + 1 year GCR (solar min)**
- **Flare environment dominates at energies less than few hundred MeV**
  - **Particles responsible for total dose issues removed by shielding**
  - **Energetic (100's MeV to multiple GeV) particles difficult to shield**
    - **Electronics upsets**
    - **Crew dose**

Single Event Effects (SEE)

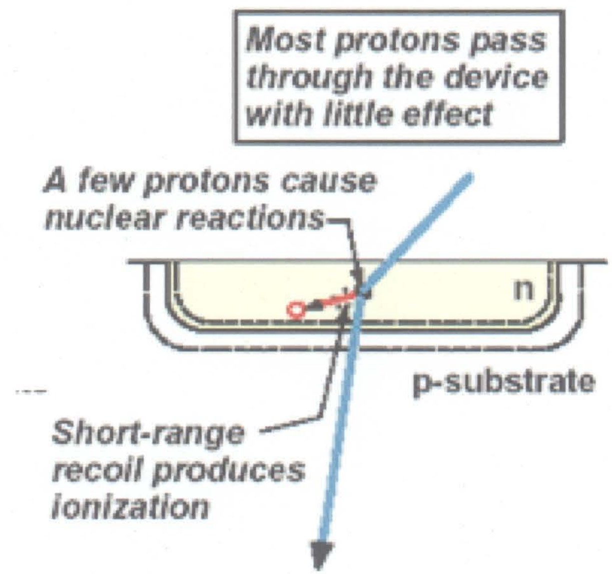
Single event effects (SEE) occur when charge deposited by an ion passing through the sensitive volume of a biased electronic device is of sufficient magnitude to change the operating state of the device. Example SEE types include:

- **Single event voltage transient (SET):** self correcting but could cause system malfunction if propagated as a signal
- **Single event upset (SEU):** operating state change (e.g. memory bit upset)-errors in data and executable output if uncorrected
- **Single event latchup (SEL):** operation ceases-effect may be correctible by power cycling or part may be destroyed
- **Single event burnout (SEB):** part is destroyed by over-current



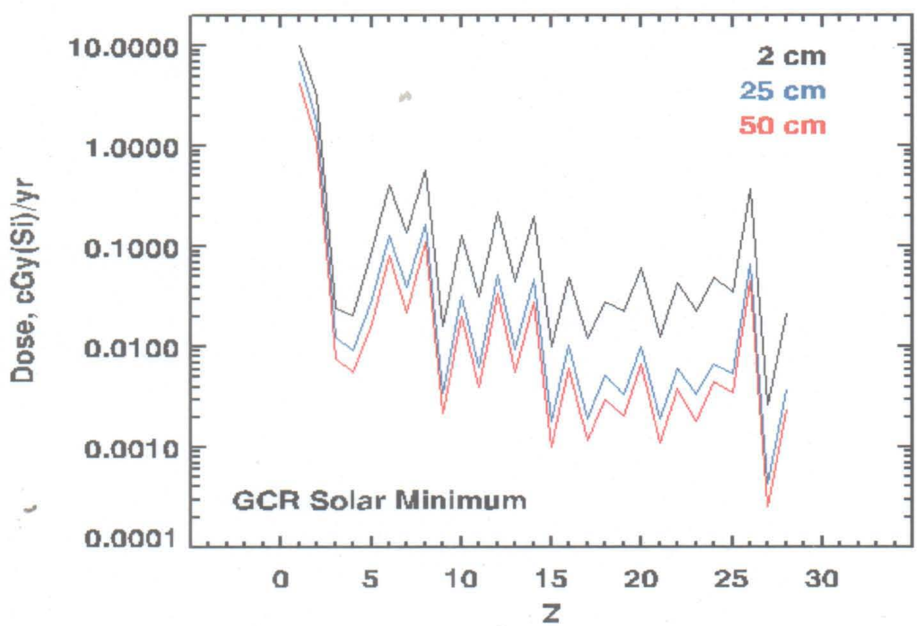
SEE typically produced by heavy Ions (Z=2-92)
Protons produce insufficient ionization to generate upsets directly

--Minor contribution from protons to SEE rates due to (small) cross section for proton induced nuclear reactions generating secondary heavy ions



GCR Dose

Shielding (Apollo-16 soil)	GCR Dose (FLUKA) ($1 \leq Z \leq 28$)
2 cm	15.9 cGy/yr
25 cm	9.3 cGy/yr
50 cm	5.6 cGy/yr



Deterministic LEO Dose Limits*

Dose Equiv. (cSv)

	BFO	Ocular Lens	Skin
30-day	25	100	150
Annual	50	200	300
Career	100-400	400	600

* [NCRP-98-1989] (from Wilson et al., 1997)

Misson Dose (cSv) Estimates (50 cm regolith shielded cylinder)

	GCR	Feb 56 Flare	Mission Dose
30-days	1	7.5	8.5
6 months	6	7.5	13.5
1 year	12	7.5	19.5

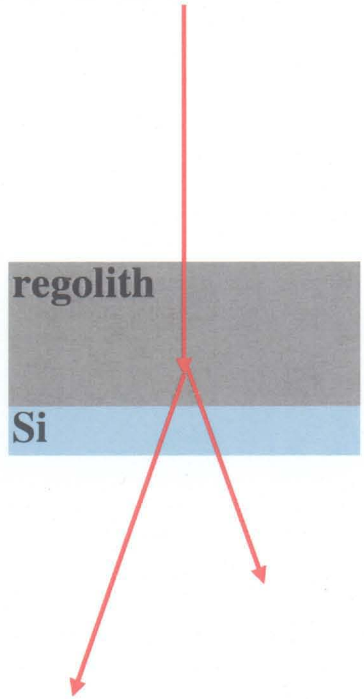
(from Simonson et al., 1997)

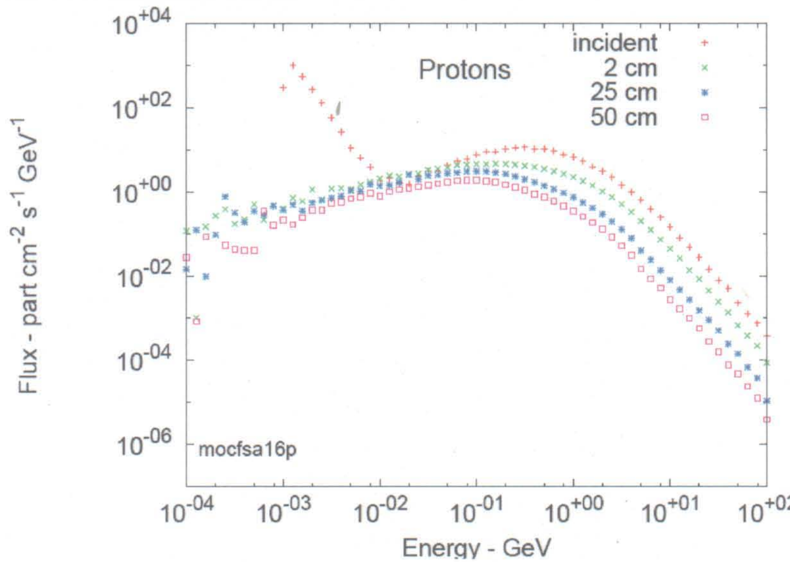
Evaluating stochastic human dose risk requires more detailed analysis!

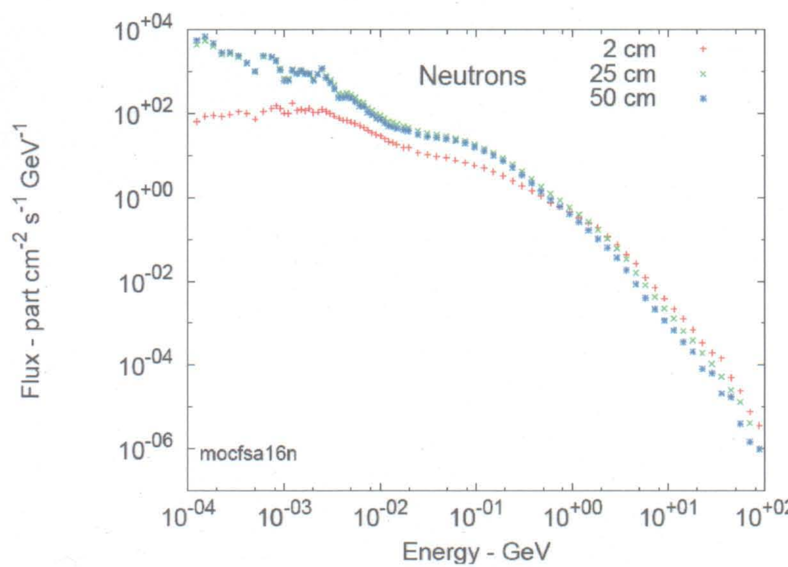
Regolith Shielding Properties for GCR

- **FLUKA transport code**
- **Shield with Apollo-16 lunar soil composition**
- **CREME96 GCR Z=1 solar minimum**
  - **Isotropic incident flux over hemisphere**

Compound	Percent A-16	Percent JSC-1
Na_2O	0.46	2.70
Al_2O_3	27.30	15.02
FeO	5.10	7.35
CaO	15.70	10.42
Fe_2O_3	0.07	3.44
MnO	0.30	0.18
MgO	5.70	9.01
SiO_2	45.00	47.71
K_2O	0.17	0.82
TiO_2	0.54	1.59
P_2O_5	0.11	0.66
Cr_2O_3	0.33	0.04







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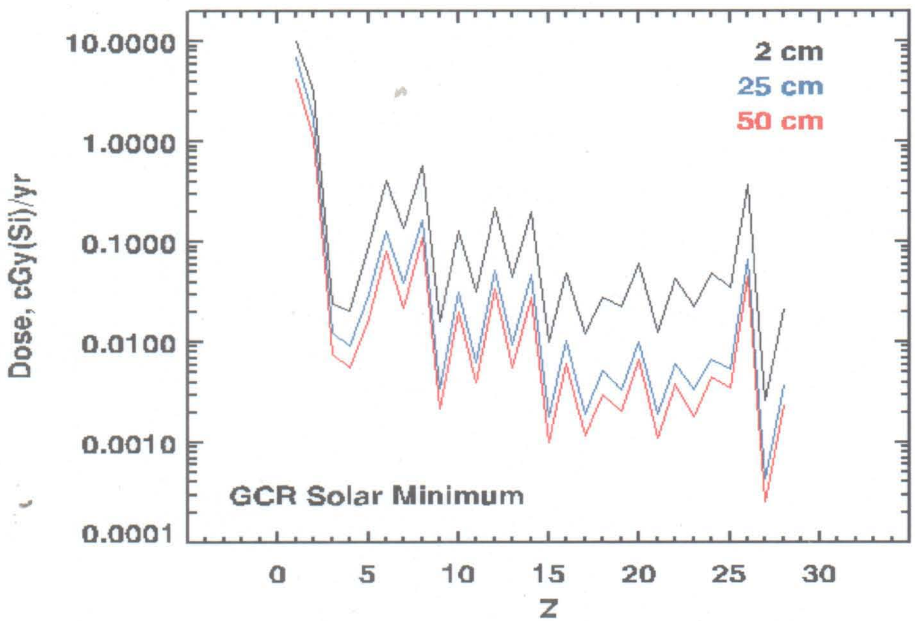

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(from *Simonson et al.*, 1997)

Total Ionizing Dose Comparison

- ESP solar proton model [Xapsos et al., 2000]
- AE-8/AP-8 trapped radiation environments

- Mission:

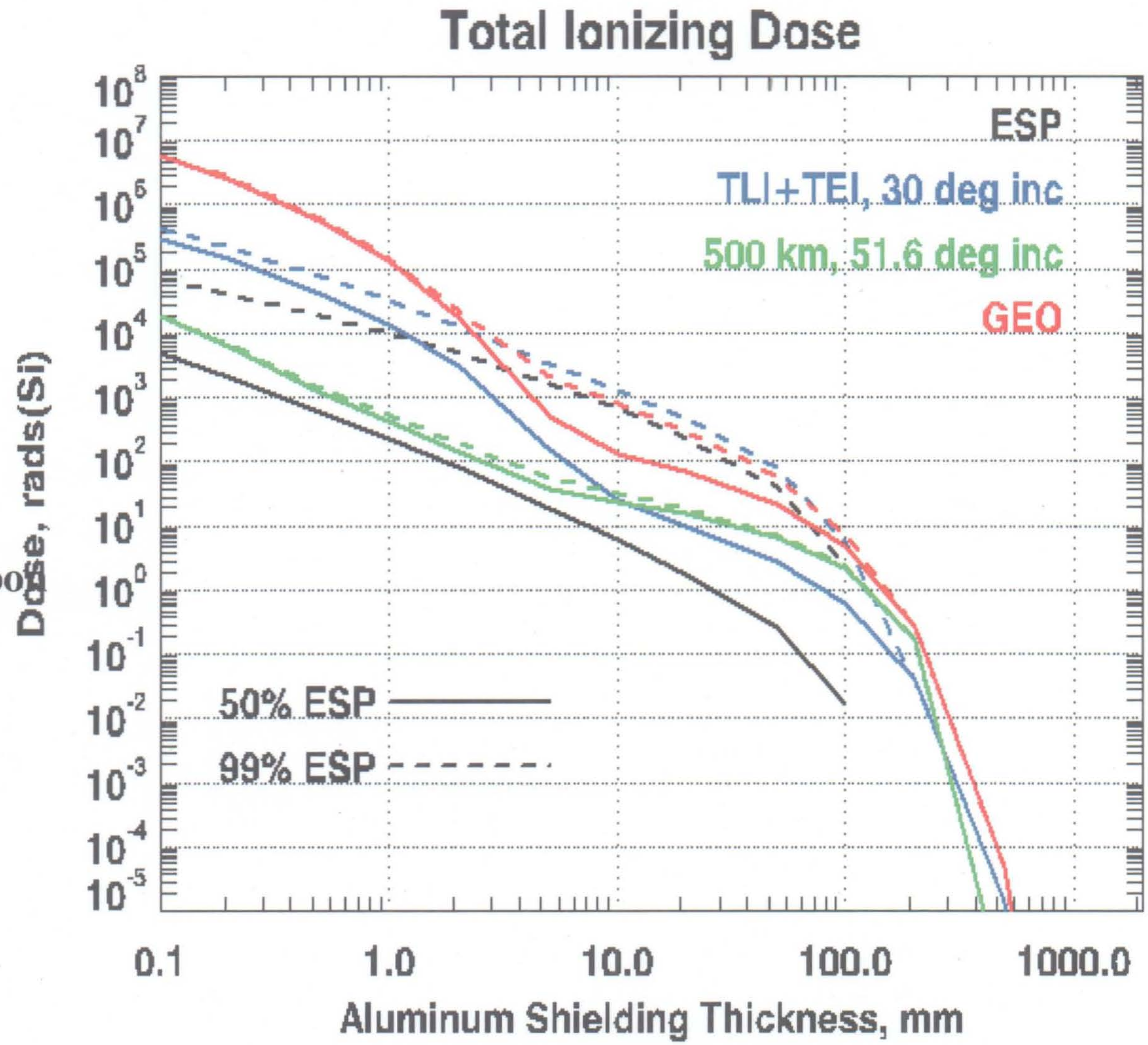
1 TLI trajectory to Moon

1 TEI trajectory from Moon

Single flare during 1 year on Moon

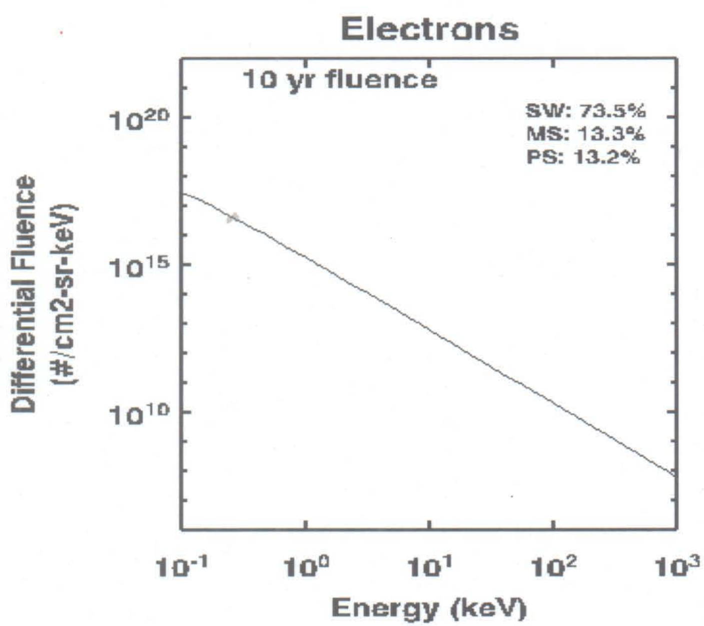
Neglect GCR

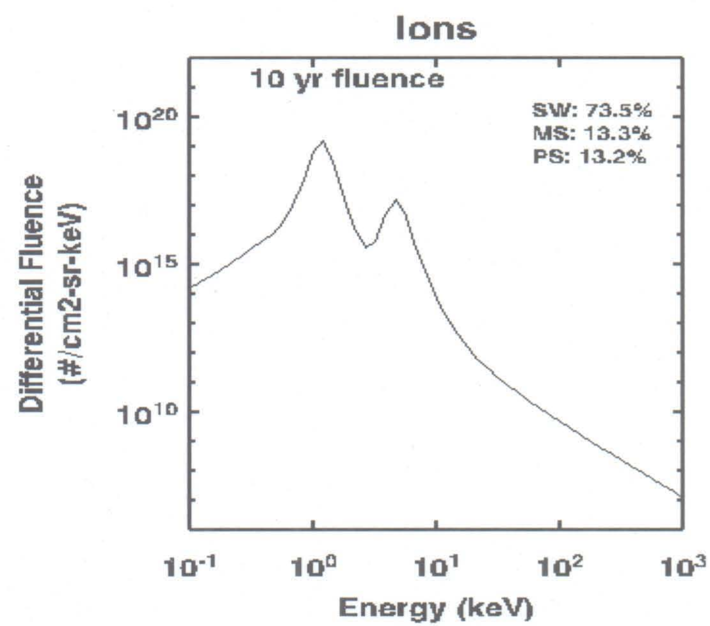
- ISS 1 year
- GEO 1 year



Free Field Plasma Environments

- Moon spends
  - ~73.5% solar wind
  - ~13.3% magnetosheath
  - ~13.2% magnetotail
- Solar wind fluence
  - ~(3×10^{8} protons/cm^2-sec)(3×10^{7} sec/yr)
  - ~9×10^{15} protons/cm^2-yr

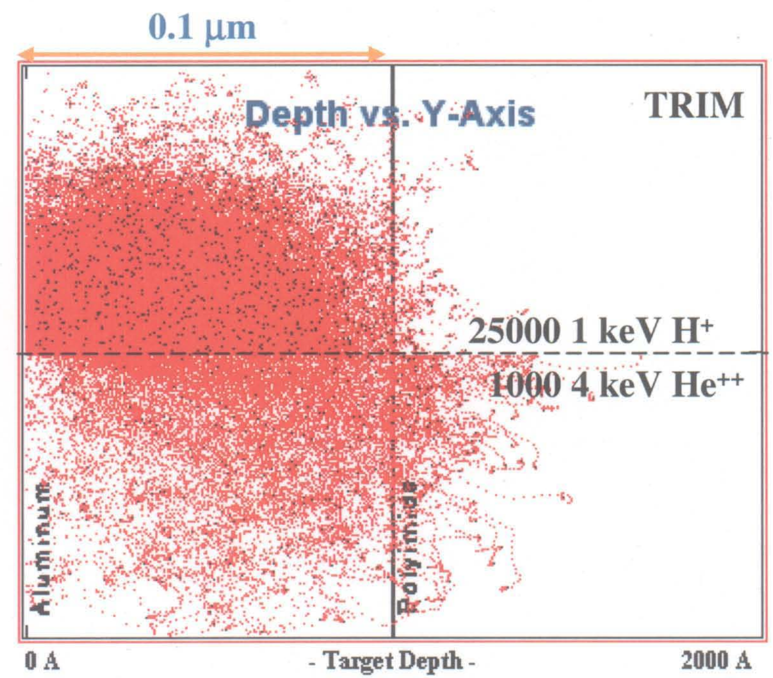




Solar Wind as Radiation Environment

- Solar wind is generally considered a benign radiation environment
  - Solar wind velocity ~400 km/sec to 800 km/sec, mean ~450 km/sec
    - Kinetic energy of H^+ ~ 0.21 keV to 3.3 keV, mean 1.1 keV
    - Kinetic energy of He^{++} ~ 0.84 keV to 13 keV, mean 4.2 keV
  - H^+ flux ~ NV ~ (7 H^+/cm^3)(450 x10^3 m/s) ~ 3.2x10^8 H^+/cm^2-sec
  - He^{++}/H^+ ~ 0.038 He^{++} flux ~ 0.12x10^8 H^+/cm^2-sec
  - Fluence
    - H^+ ~ 9.9x10^{15} H^+/cm^2-year
    - He^{++} ~ 3.8x10^{14} H^+/cm^2-year

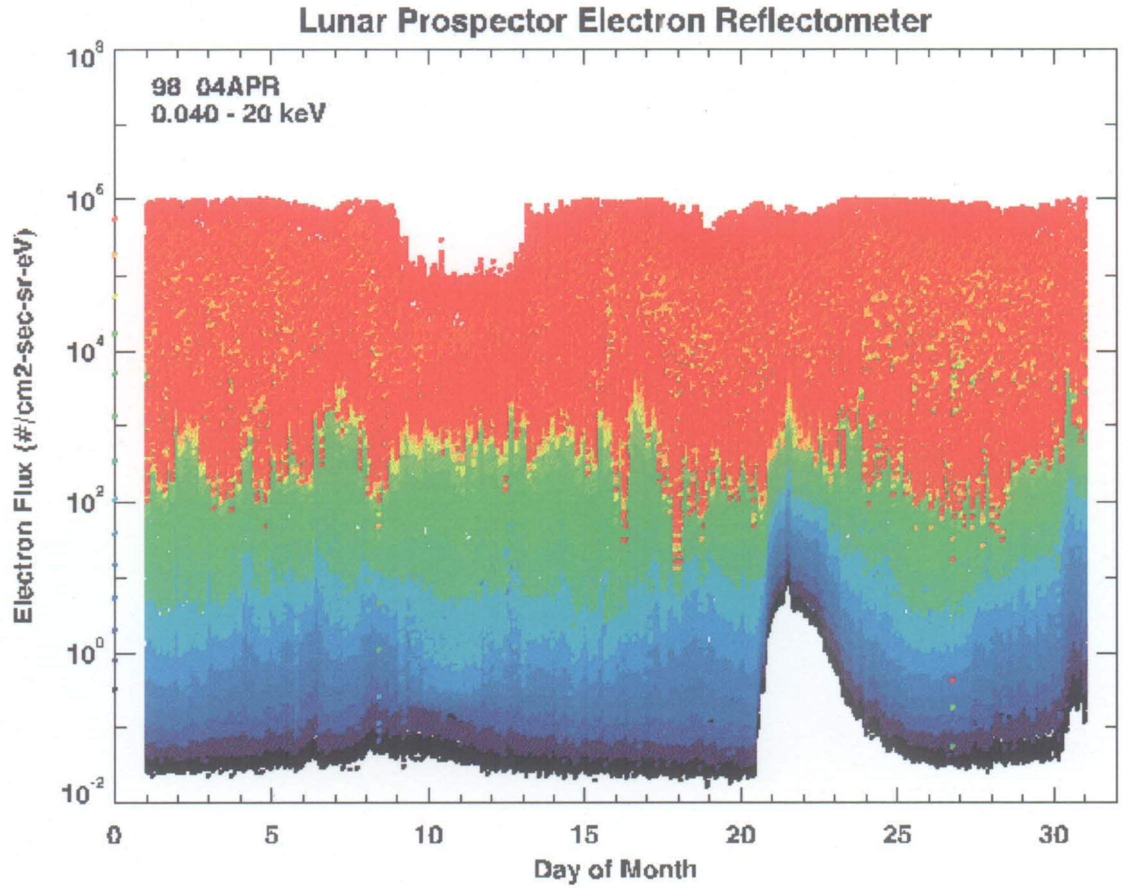
- Solar wind penetration depths are only fractions of a micron
  - Bulk materials impacted only on "surfaces"
  - 1000 Å (0.1 µm) coating is impacted throughout the material



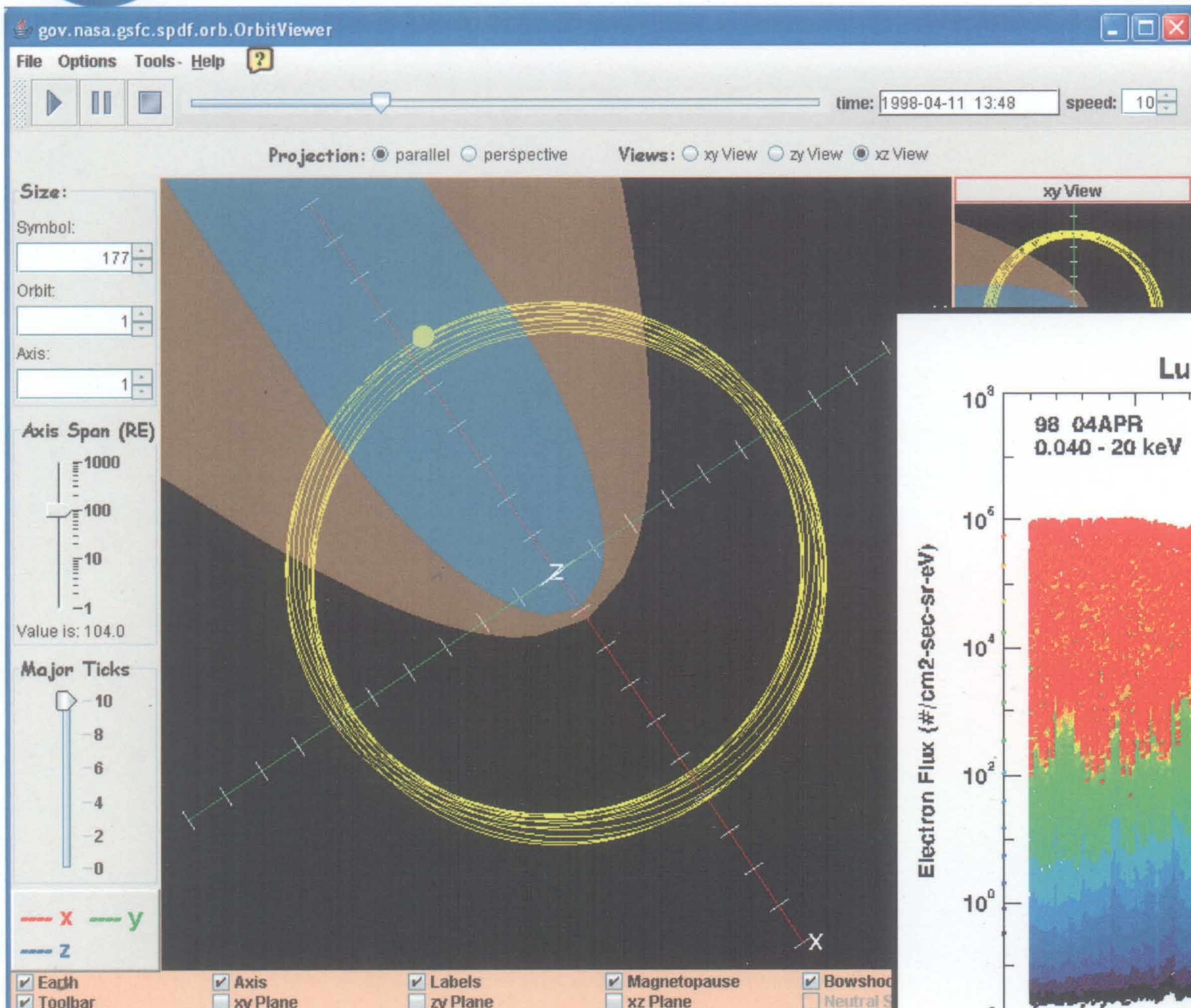
Lunar Radiation Environments

- **Lunar Prospector Electron Reflectometer**
  - Spin average electron flux
  - ~40 eV to ~20 keV

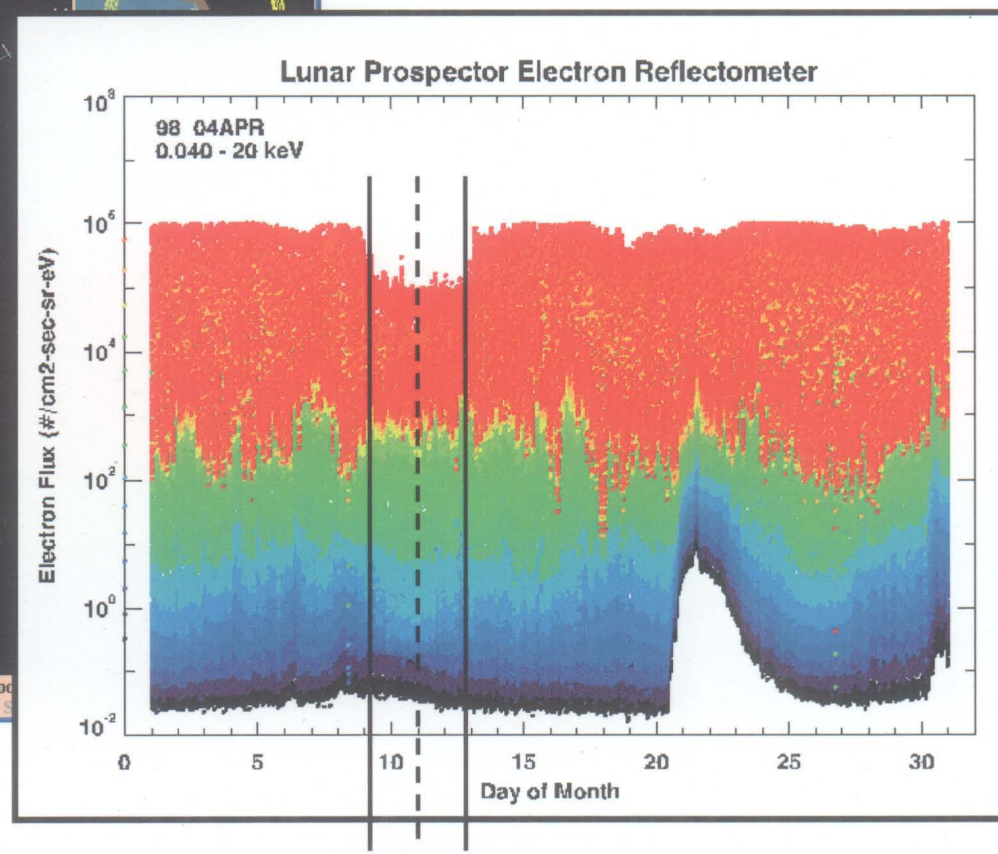
- **April 1998**
  - Earth's magnetotail
  - Solar energetic particle event



Lunar Wake



gov.nasa.gsfc.spdf.orb.OrbitViewer
File Options Tools Help
time: 1998-04-11 13:48
speed: 10
Projection: parallel perspective
Views: xy View zy View xz View
xy View
Size:
Symbol:
177
Orbit:
1
Axis:
1
Axis Span (RE)
1000
100
10
1
Value is: 104.0
Major Ticks
10
8
6
4
2
0
x y
z
Earth
Toolbar
Axis
xy Plane
Labels
zy Plane
Magnetopause
xz Plane

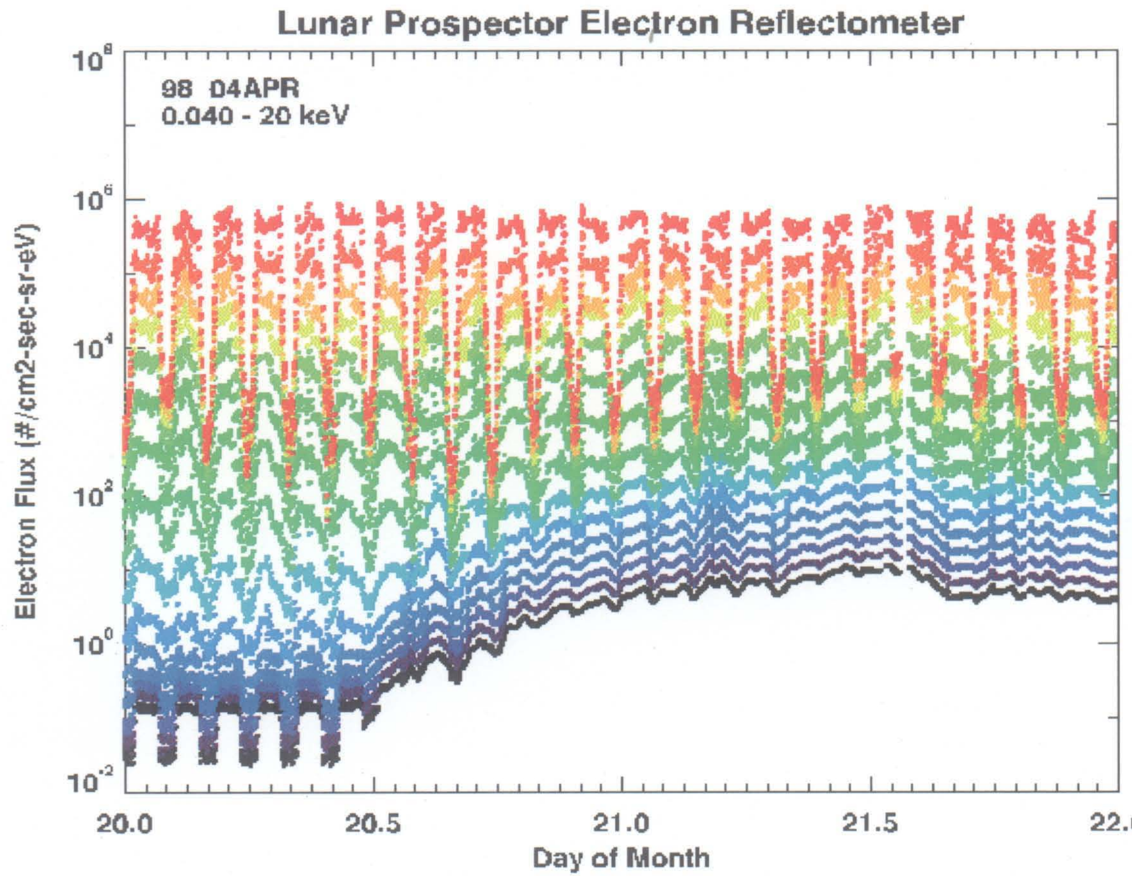


Lunar Prospector Electron Reflectometer
98 04APR
0.040 - 20 keV
Electron Flux (#/cm2-sec-sr-eV)
Day of Month
0
5
10
15
20
25
30

Lunar Radiation Environments

- **Lunar Prospector Electron Reflectometer**
  - Spin average electron flux
  - ~40 eV to ~20 keV

- **4-5April 1998**
  - Moon in solar wind
  - Plasma wake
  - Solar particle event and wake



Surface Charging

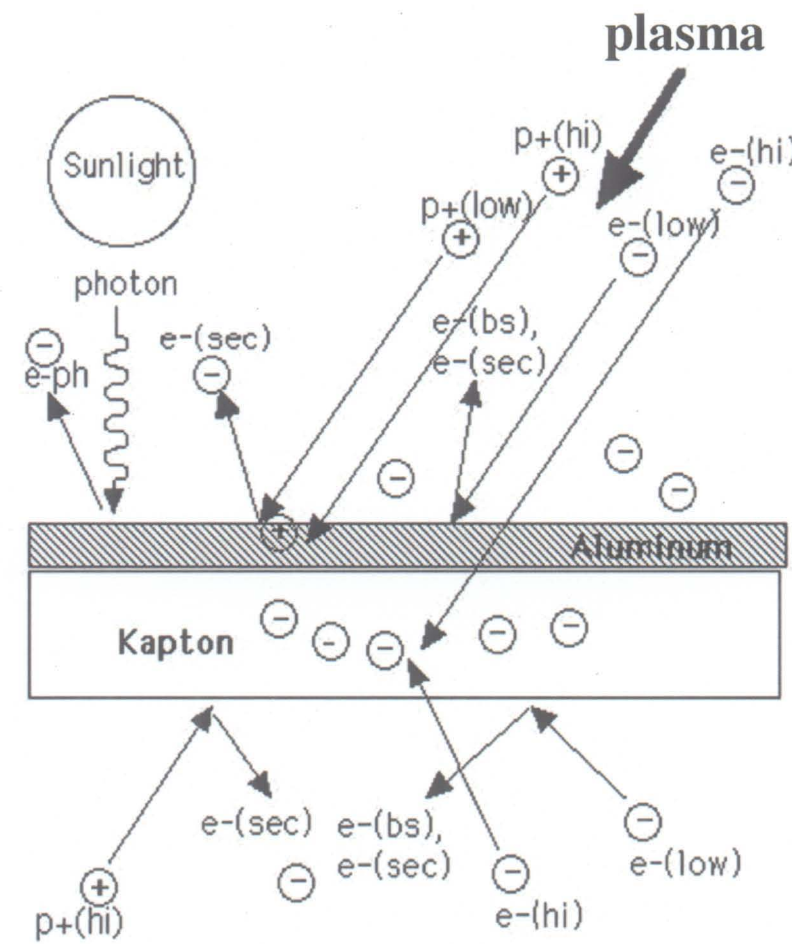
- Time dependent current balance on surfaces

$$\frac{dQ}{dt} = C\frac{dV}{dt} = \sum_k I_k \quad (\sim 0 \text{ at equilibrium})$$

$$\sum_k I_k =$$

$+ I_i(V)$	**incident ions**
$- I_e(V)$	**incident electrons**
$+ I_{bs,e}(V)$	**backscattered electrons**
$+ I_{se}(V)$	**secondary electrons due to I_e**
$+ I_{si}(V)$	**secondary electrons due to I_i**
$+ I_{ph,e}(V)$	**photoelectrons**
$+ I_C(V)$	**conduction currents**
$+ I_B(V)$	**active current sources (beams, electric thrusters, etc.)**

$$C\frac{dV}{dt} = \sum_{k'} I_{k'} + \sigma V$$



(Garrett and Minow, 2004)

Bulk (Deep Dielectric) Charging

- Radiation charging of insulators, isolated conductors

$$\nabla \bullet D = \rho$$

$$D = \varepsilon E$$

$$\varepsilon = \kappa \varepsilon_0$$

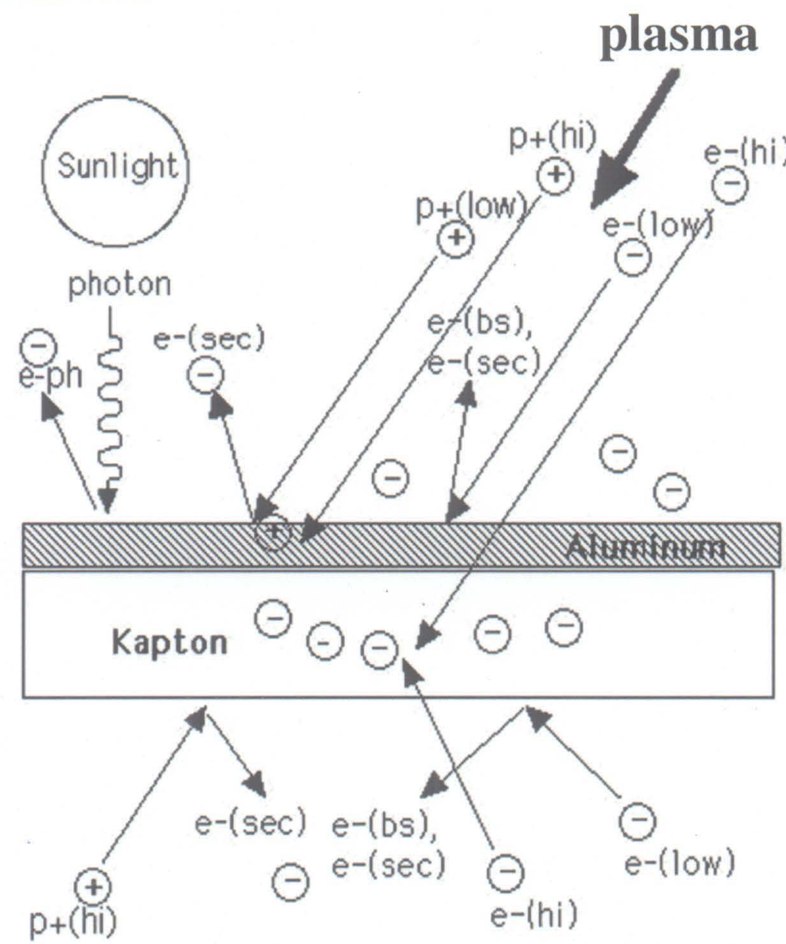
$$\frac{\partial \rho}{\partial t} = -\nabla \bullet J$$

$$J = J_0 + J_C$$

$$J = \sigma E$$

$$= (\sigma_{dark} + \sigma_{radiation})E$$

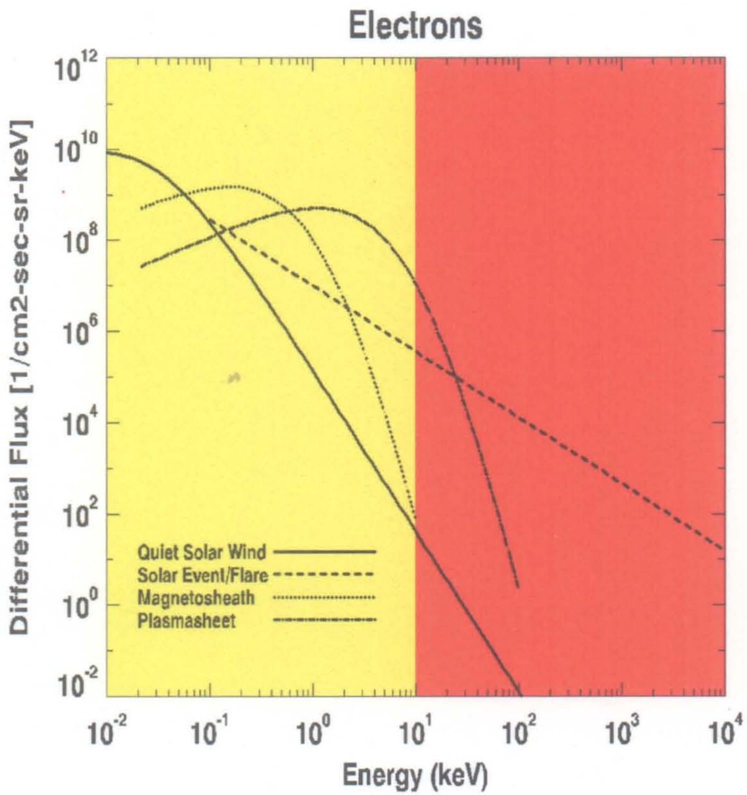
$$\sigma_{radiation} = k\left(\frac{d\gamma}{dt}\right)^{\alpha} \quad 0.5 < \alpha < 1.0$$

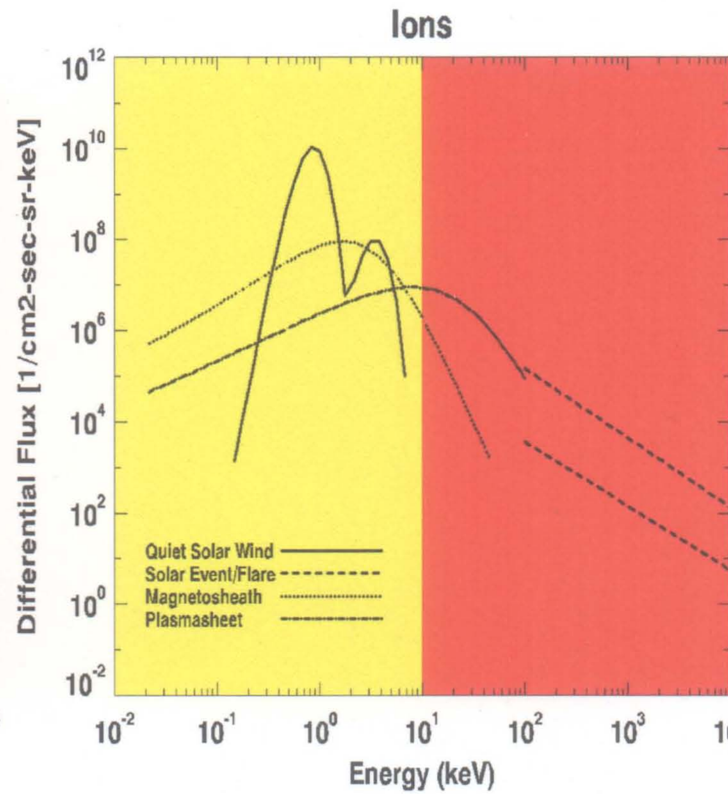


(Garrett and Minow, 2004)

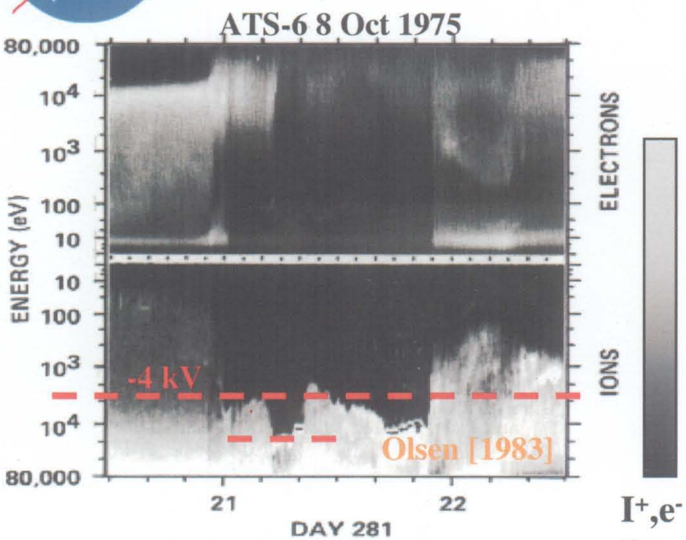
Lunar Plasma Environments

- Plasma/radiation environments relevant to surface and bulk charging due to electrons, ions from thermal to ~MeV energies

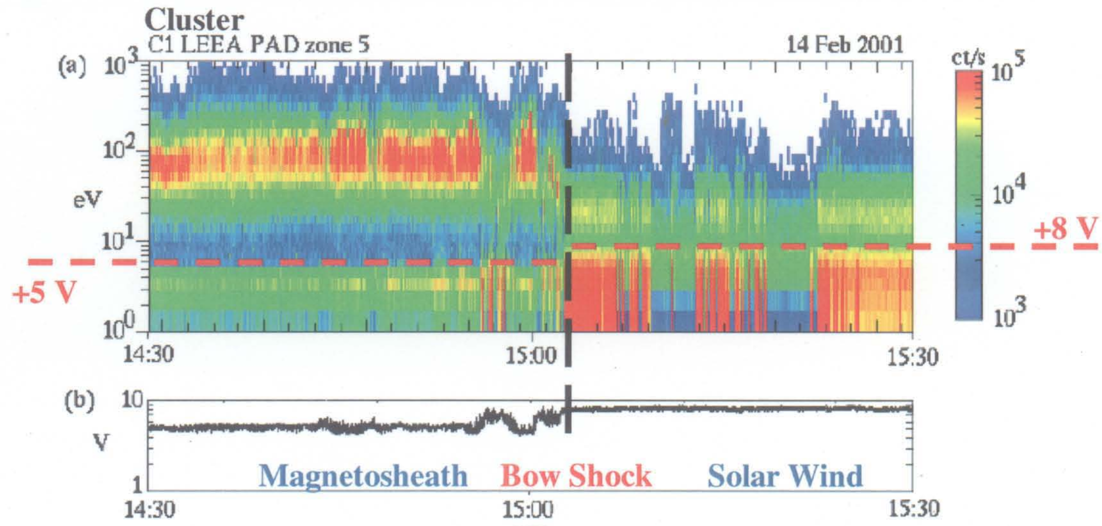




Charging in Lunar Relevant Environments

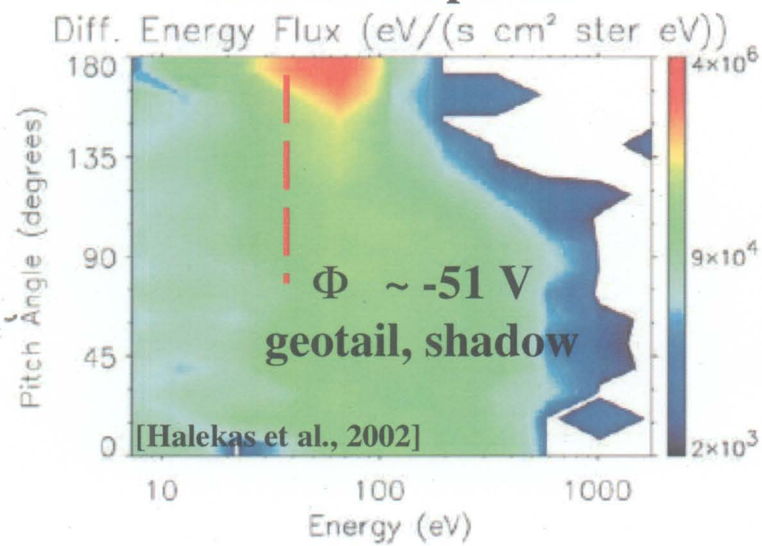


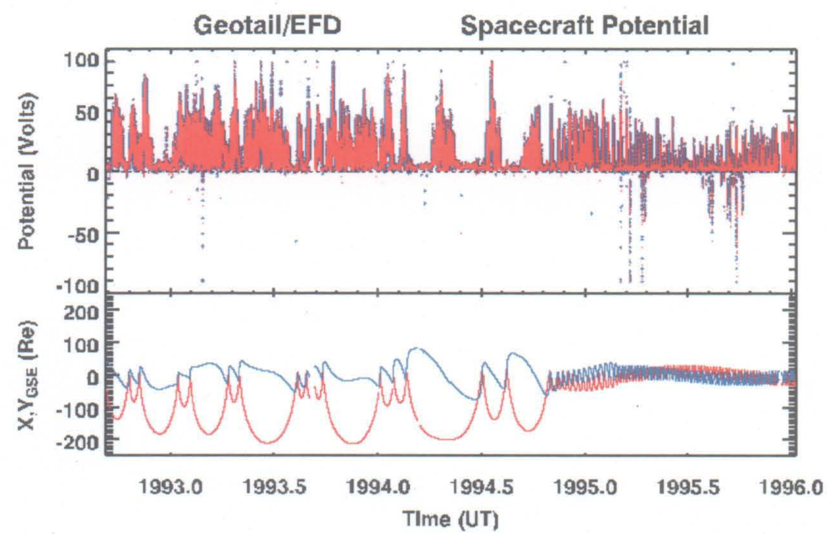
ATS-6 record: Φ ~ -19 kV



[from Szita et al., 2001]

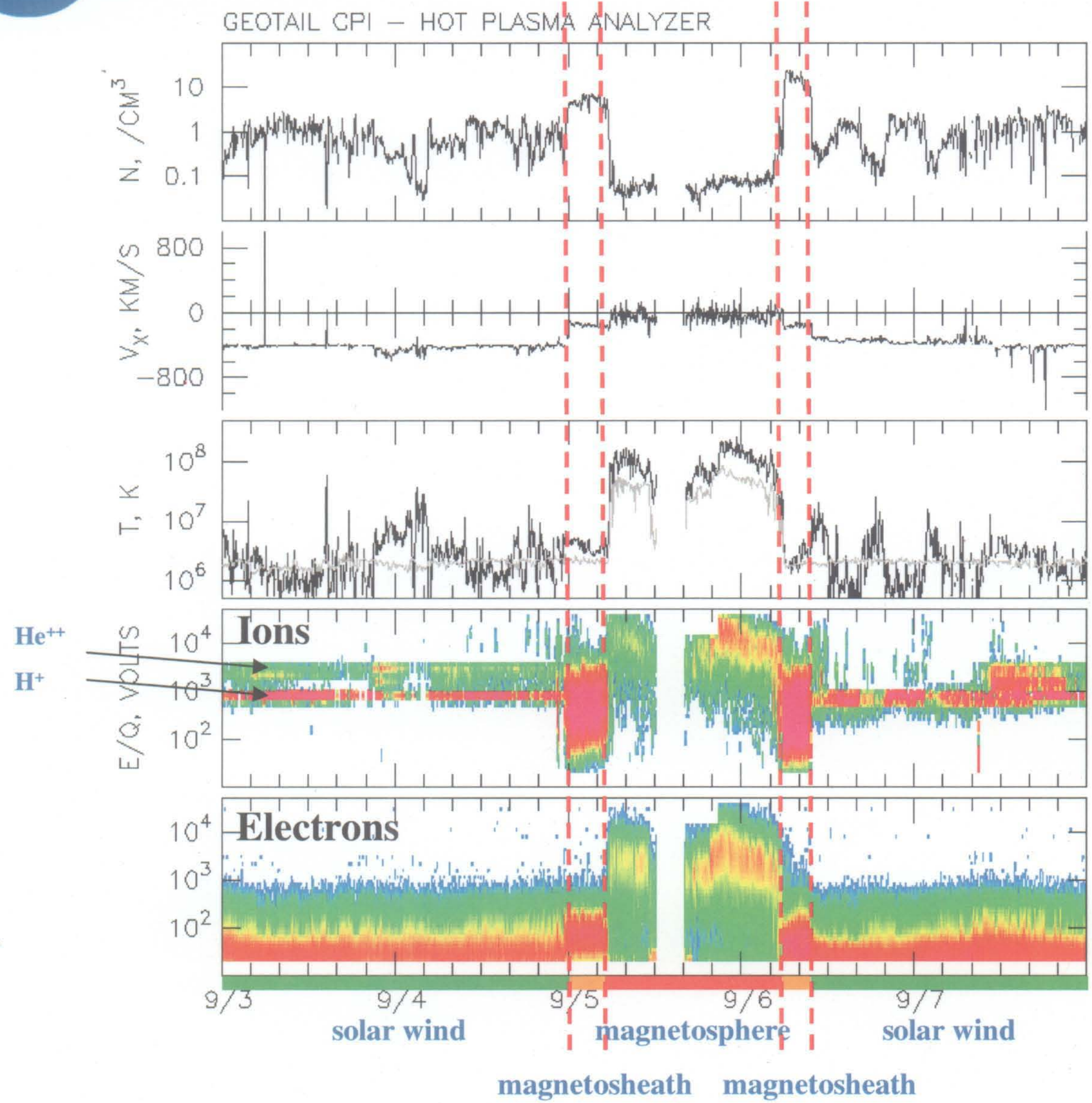
Lunar Prospector

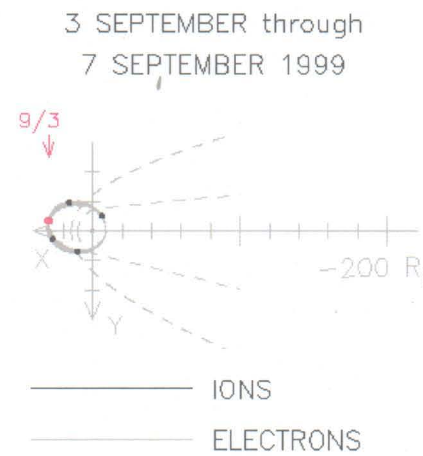




[from Minow et al., 2005]

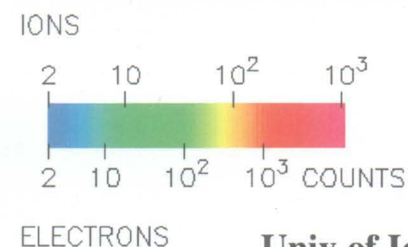
Near Earth Plasma Regimes





Near Earth plasma regimes are well ordered at low energies

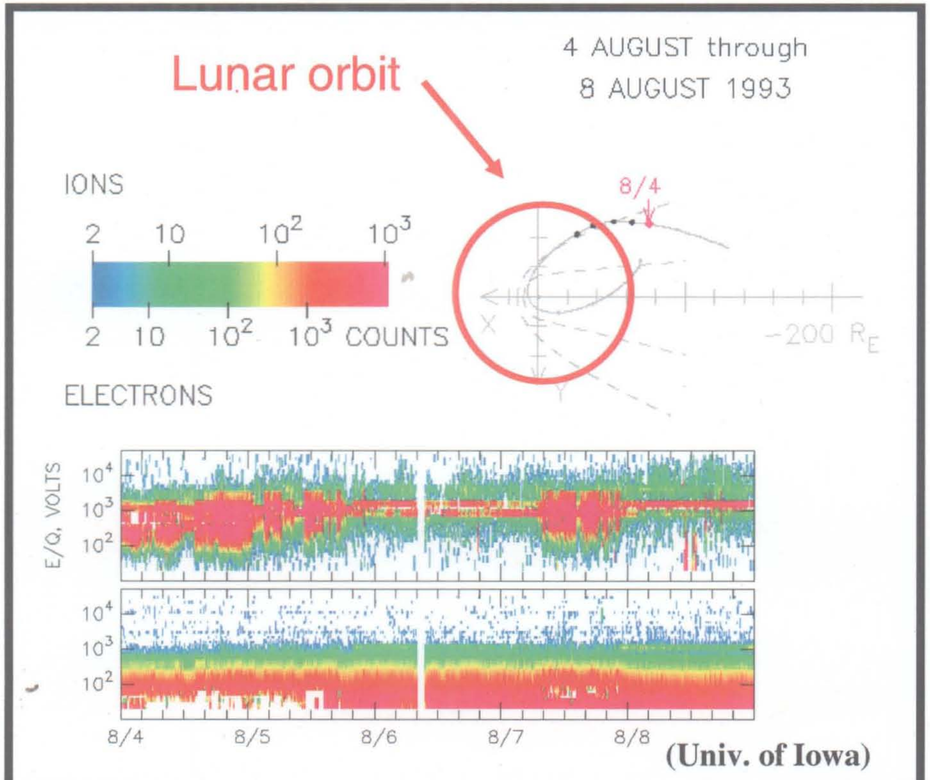
Relatively easy to identify bow shock and magnetopause, plasma regimes by plasma characteristics



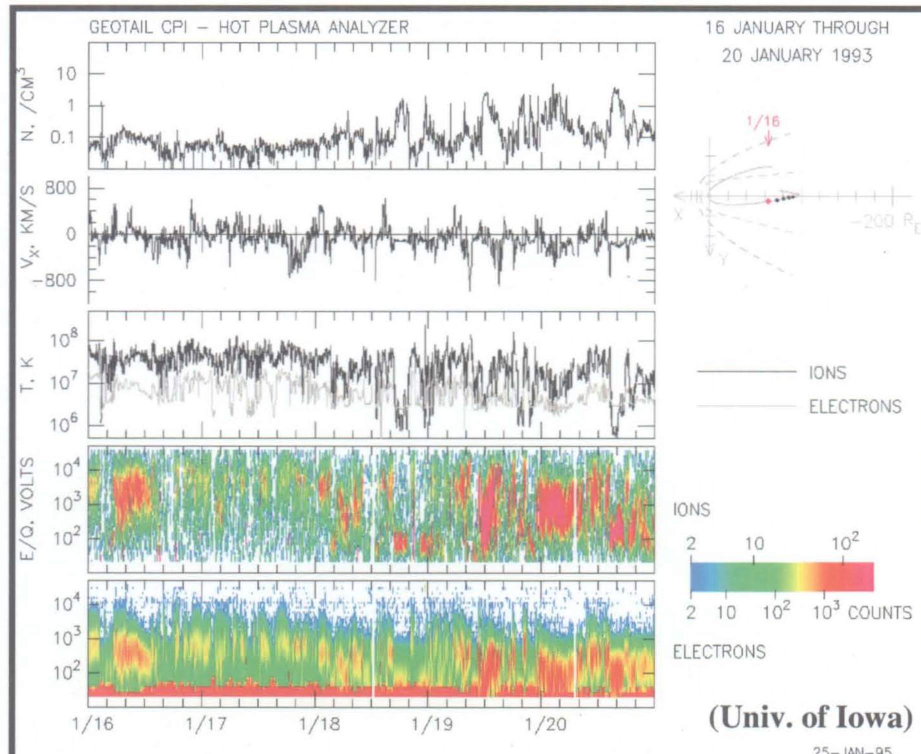
Univ of Iowa
Geotail/CPI/HPA

Magnetotail Plasma at Lunar Distances

- Lunar plasma environment includes encounters with magnetotail and magnetosheath
  - Variability due to solar wind driven motion of magnetotail
- High temperature, low density plasma environments in magnetotail



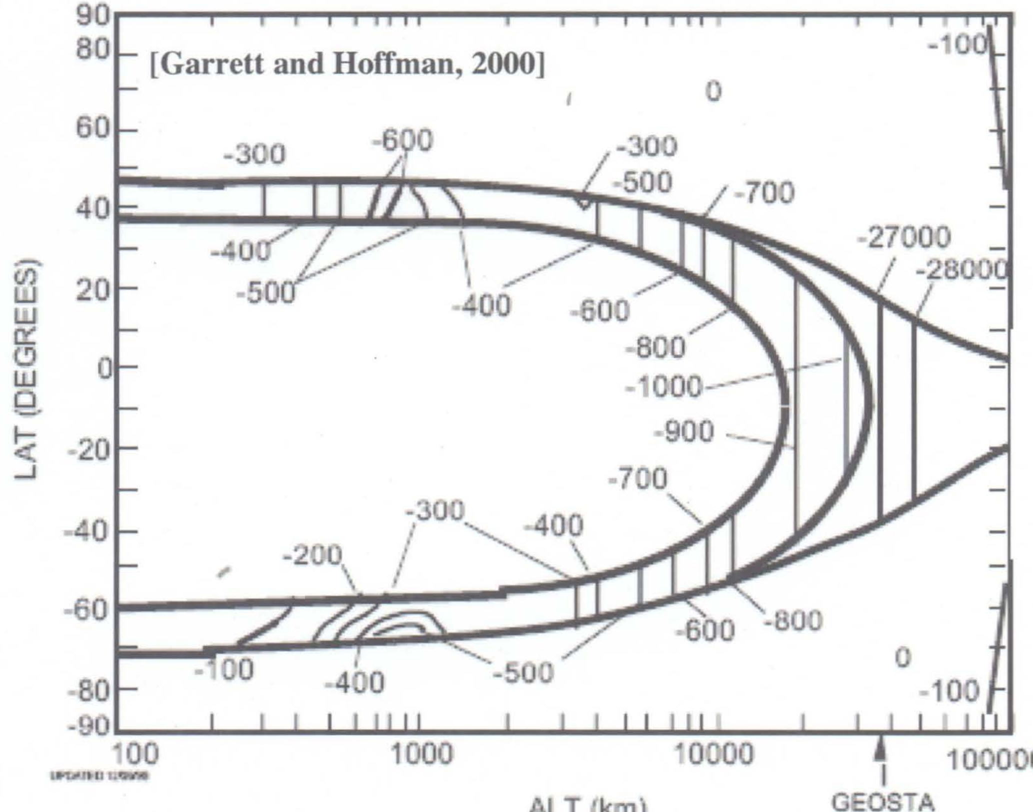
(Univ. of Iowa)

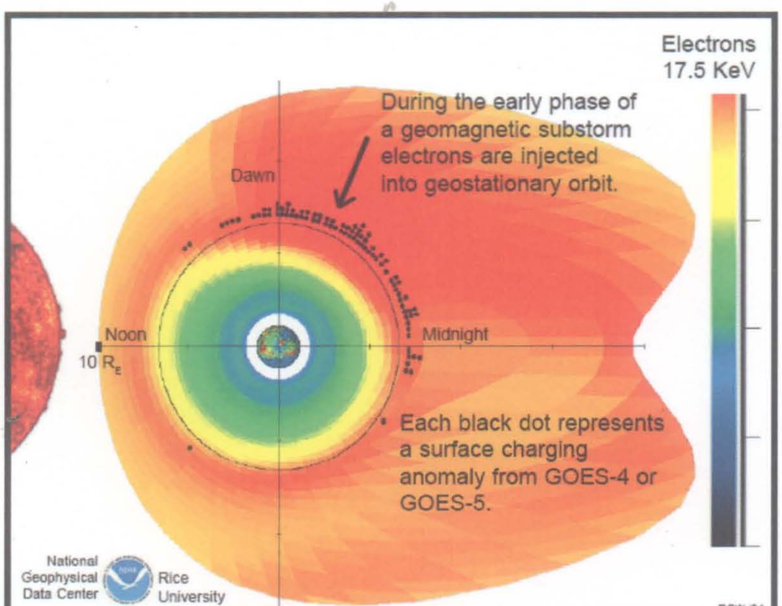


(Univ. of Iowa)

Surface Charging

Environment	Spacecraft Potential
LEO	-0.1 to 0.5 V
GEO	-100 to -20,000 V
Auroral zone	-100 to -3000 V
Magnetotail at lunar orbit	
--eclipse	-100 to -4500 V
--sunlight	+10's V
Solar wind	+10's V

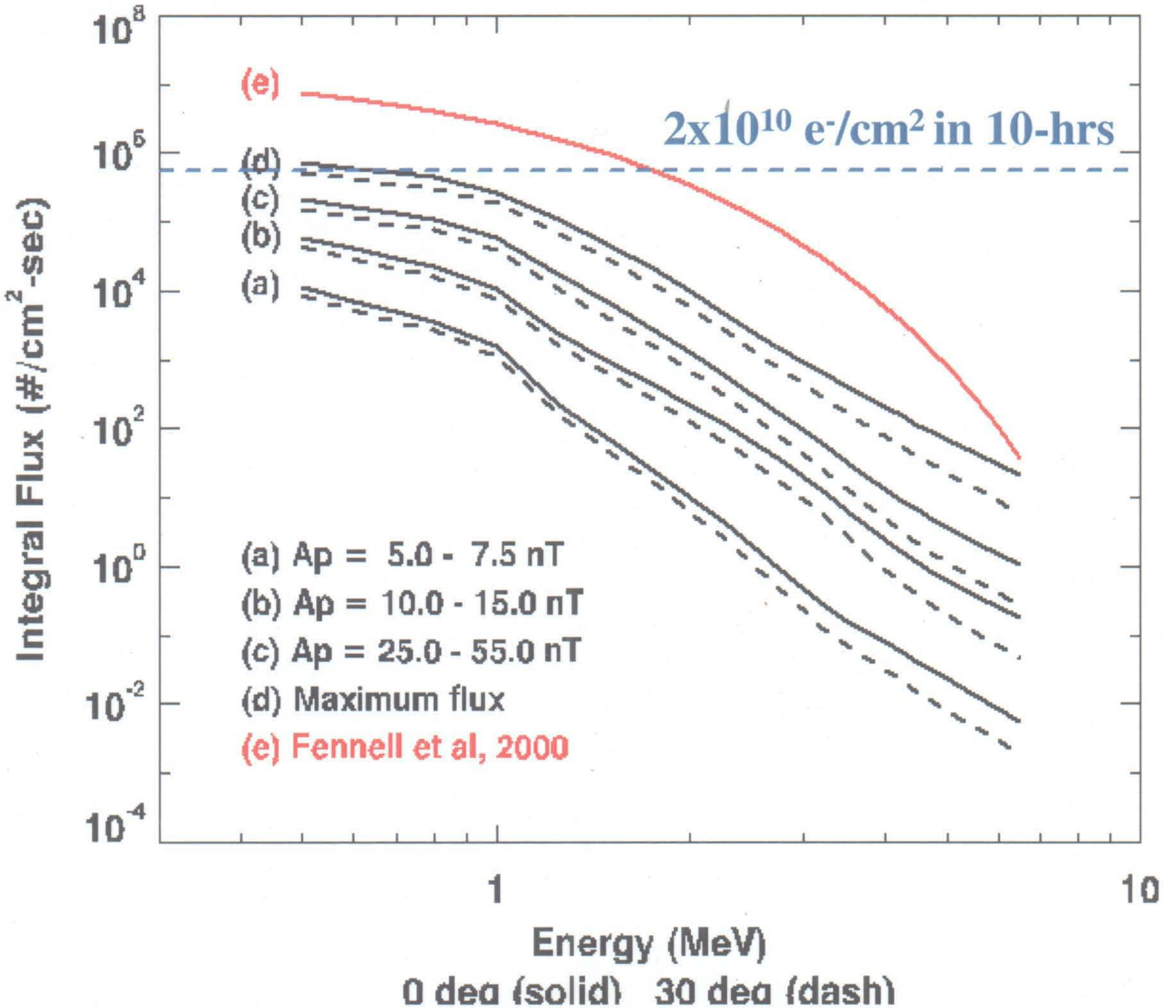




Orbit inclination, departure local time (longitude) important for surface charging

Internal (Bulk) Charging

- Translunar and trans-Earth injection trajectories transit the radiation belts
- TLI/TEI orbits are similar to the geostationary transfer orbit environments encountered by CRRES
  - CRRES T~10 hours
    10 hours in radiation belt
  - TLI/TEI T~8 days
    ≤4 hours in radiation belt



- CRRESELE Ap dependent (a-c), worst case (d) orbit averaged environments
- Fennell et al. 2000 (e) lunar transfer orbit charging environment

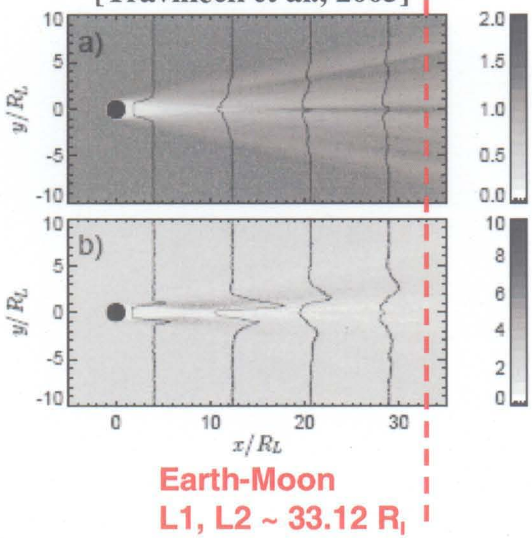
Lunar Wake

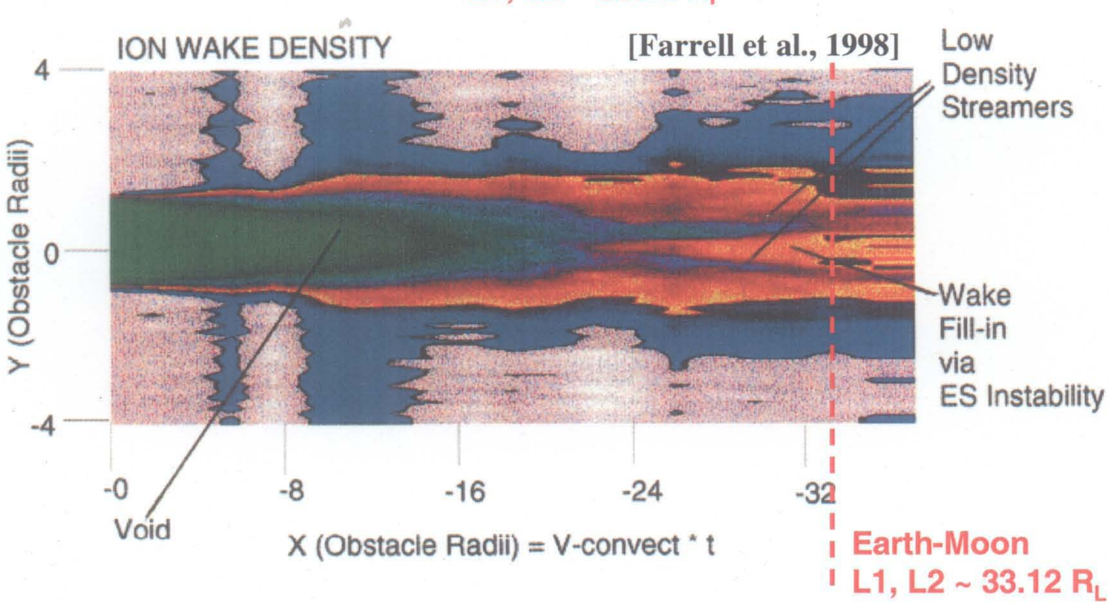
$\theta_{sw} \sim 45$ deg

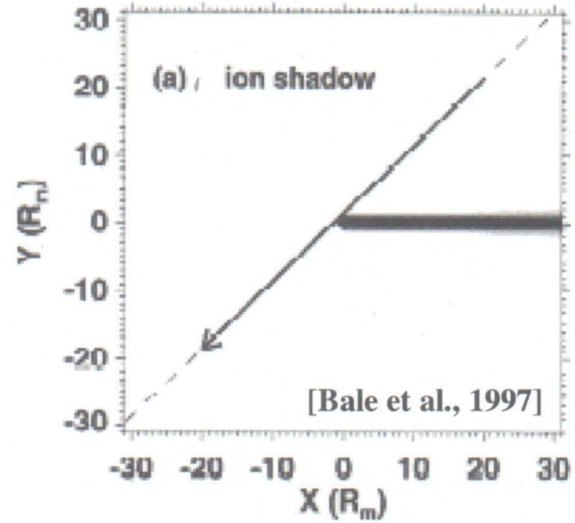
a) Density

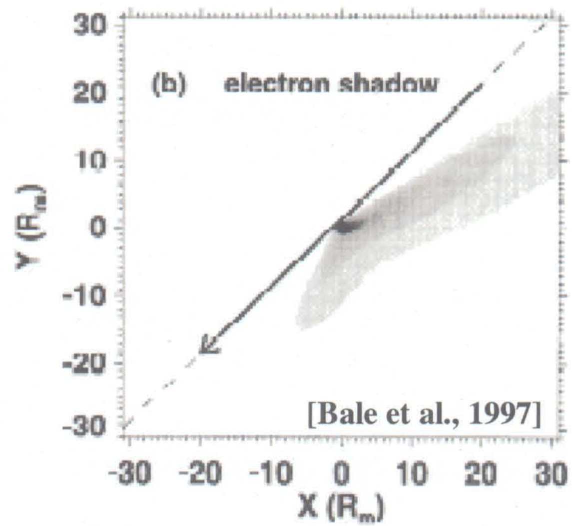
b) $T_{//}/Tper_{\perp}$

[Trávníček et al., 2005]



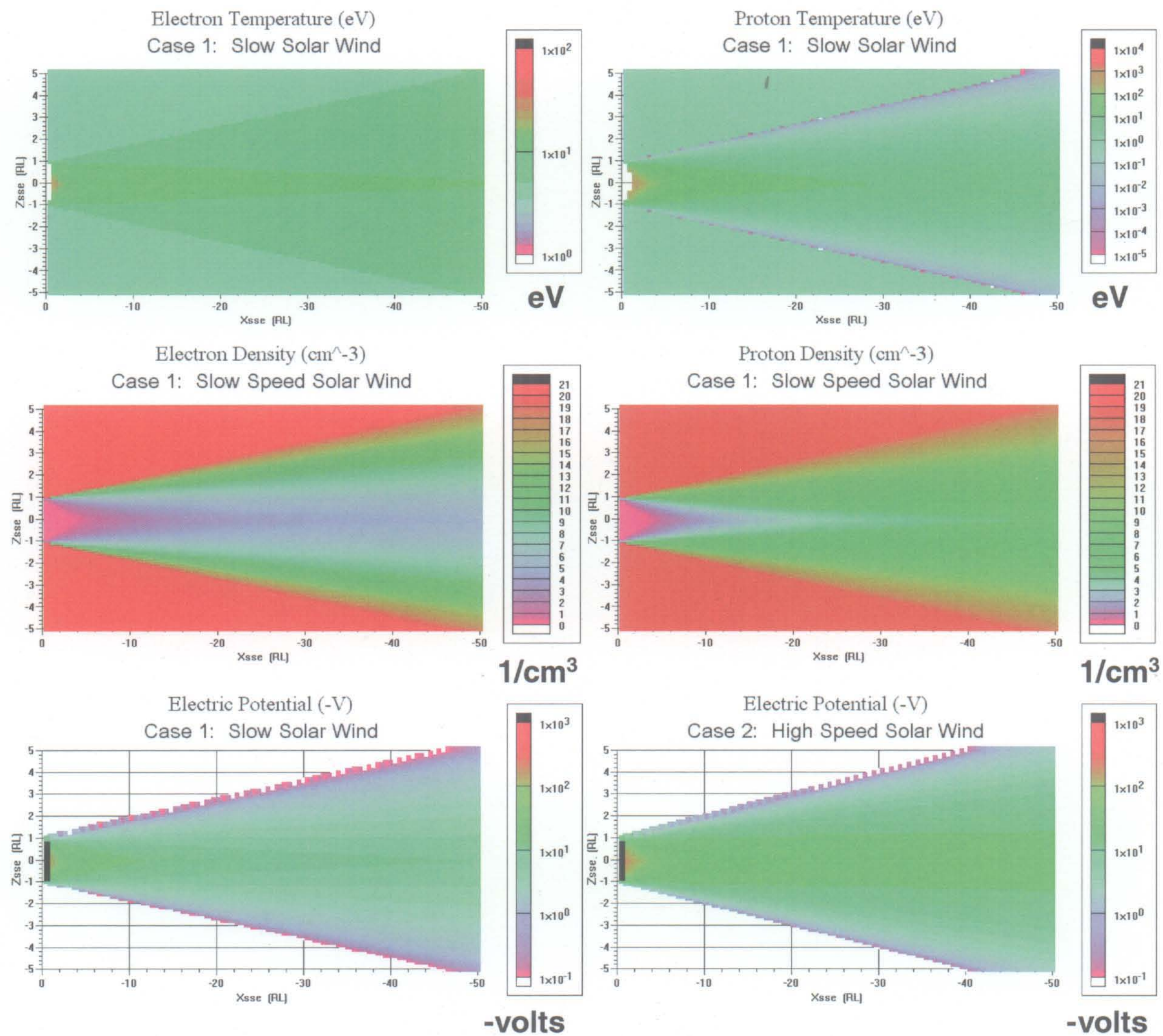






Analytical Lunar Wake Model

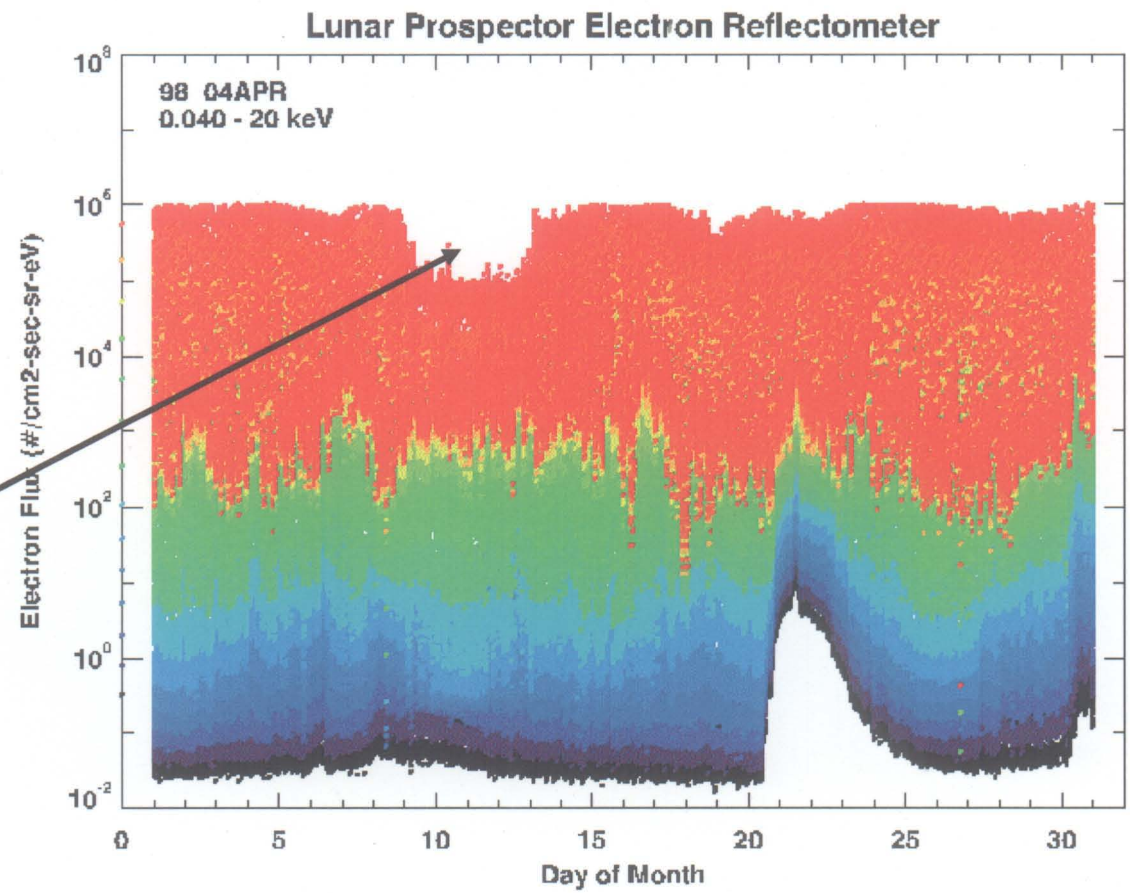
- Analytical models useful for first order estimate of wake plasma environments
  - Analytical models to be imbedded in Luna-CPE model to scale plasma flux to spacecraft surface for surface dose evaluation
- Numerical electrostatic codes required to evaluate details including
  - Particle distribution functions
  - Energetic solar particle events
  - Backflow from distant magnetotail



[Blackwell et al., 2007]

Lunar Plasma Environments

- Lunar Prospector Electron Reflectometer
  - Spin average electron flux
  - ~40 eV to ~20 keV
- April 1998
  - Earth's magnetotail
  - Solar energetic particle event



Lunar Plasma Environments

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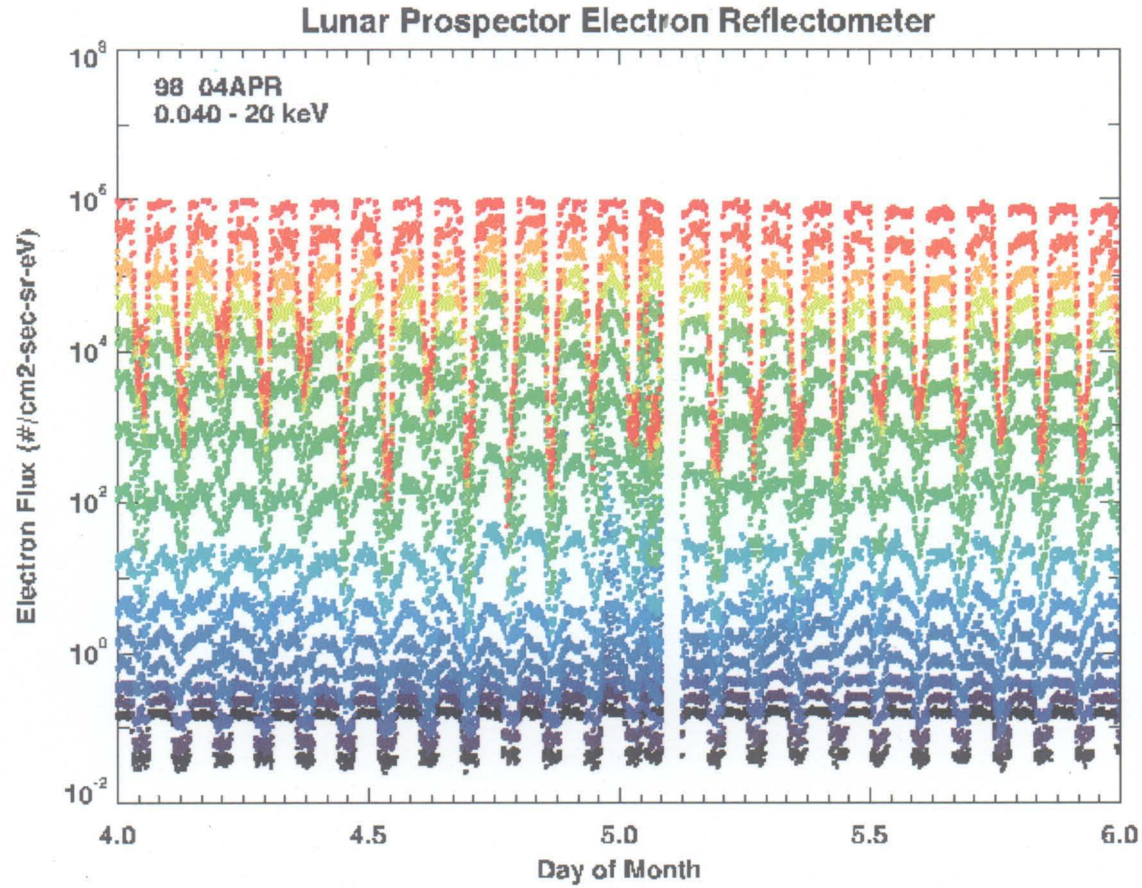
  - Moon in solar wind
  - Plasma wake



Lunar Plasma Environments

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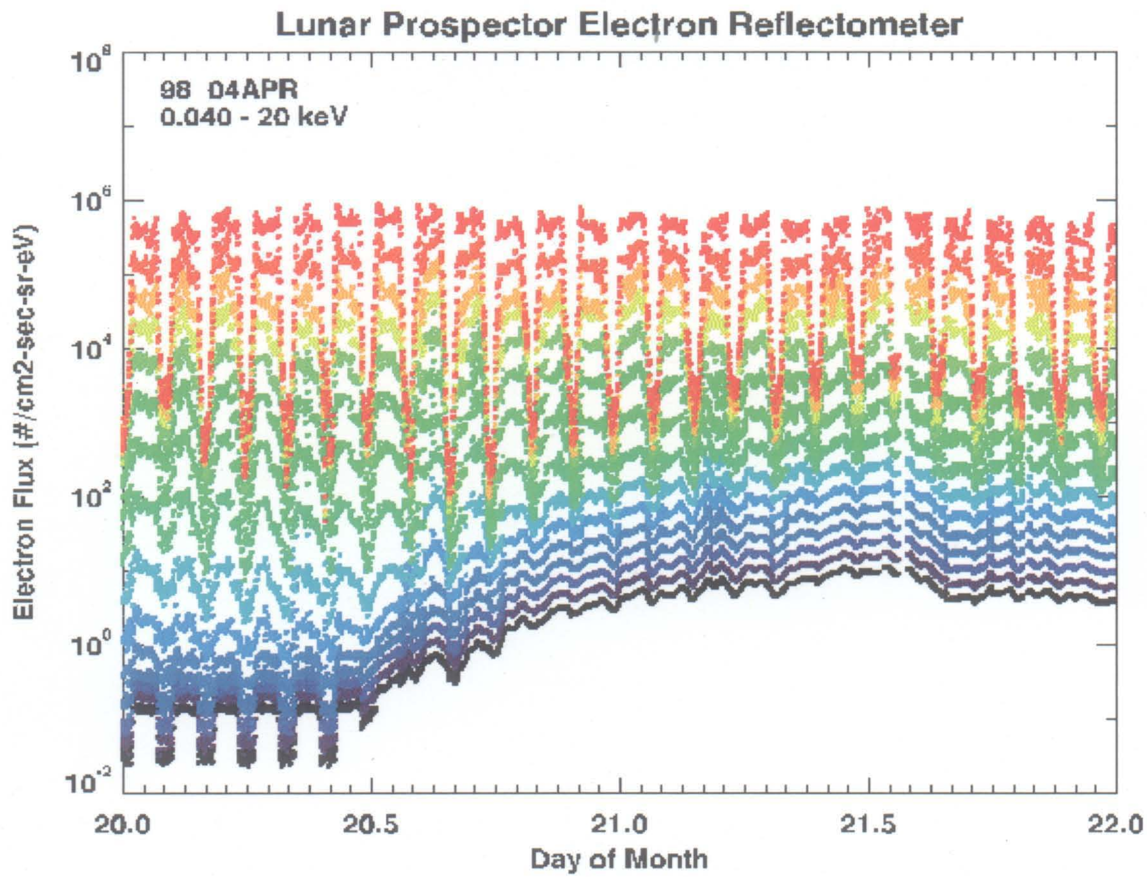
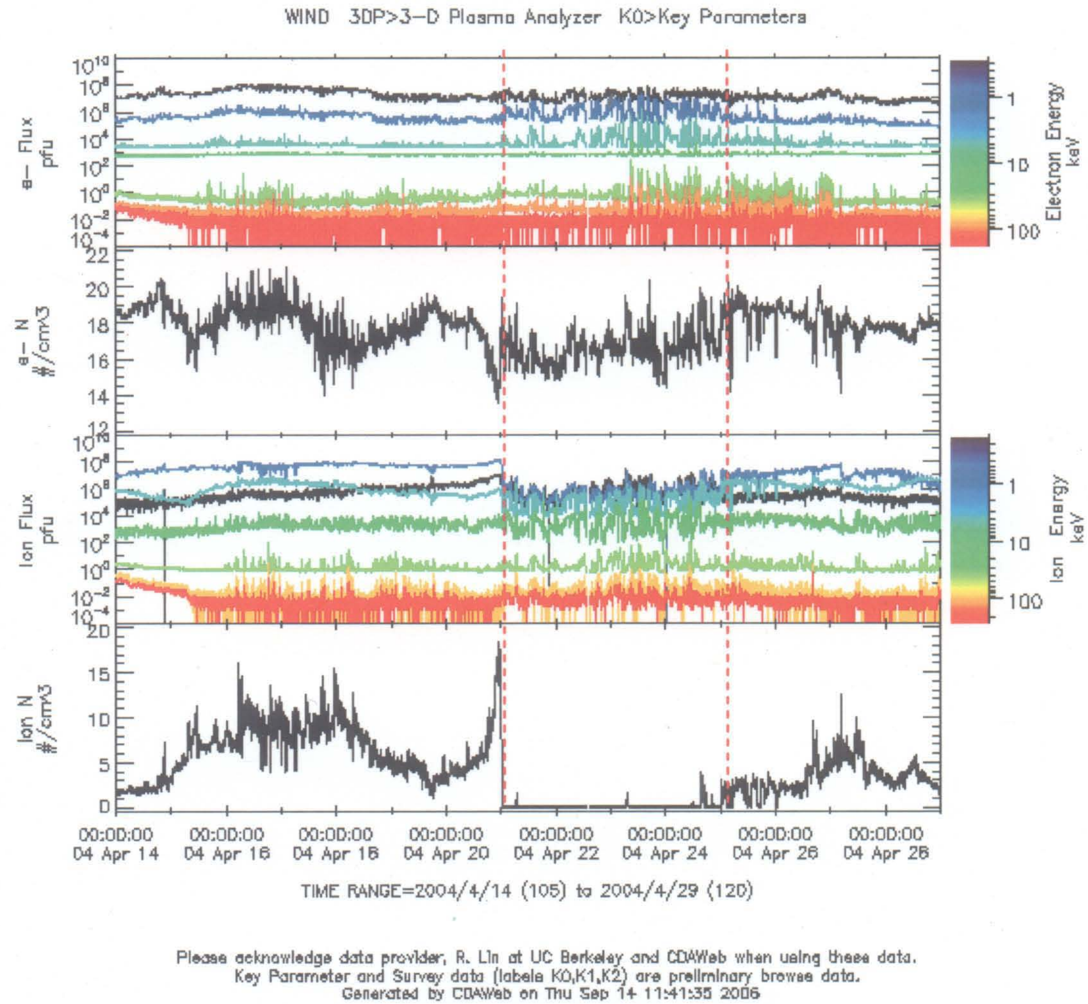
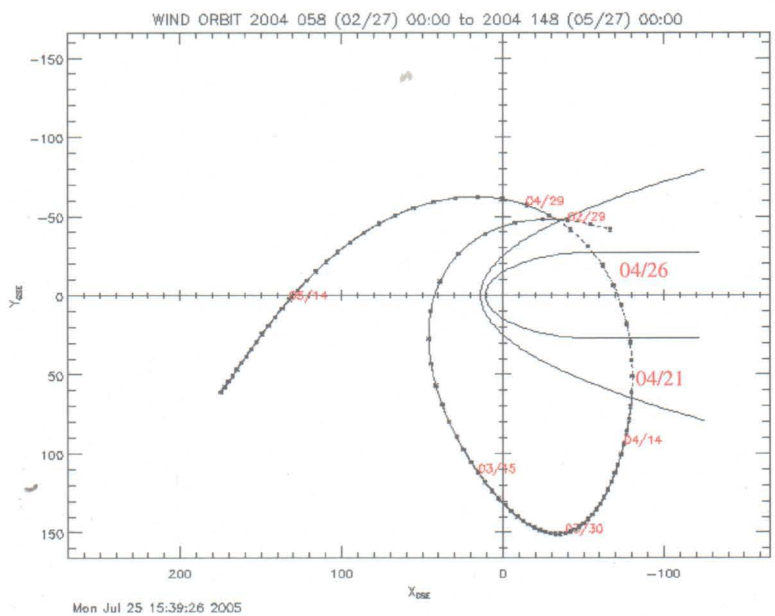


Wind Magnetotail Passage

- Wake plasma environments
  - Cold ion deplections
  - keV electron access to wake produces strong charging environment





Charging in Lunar Wake

Lunar Prospector

20-115 km

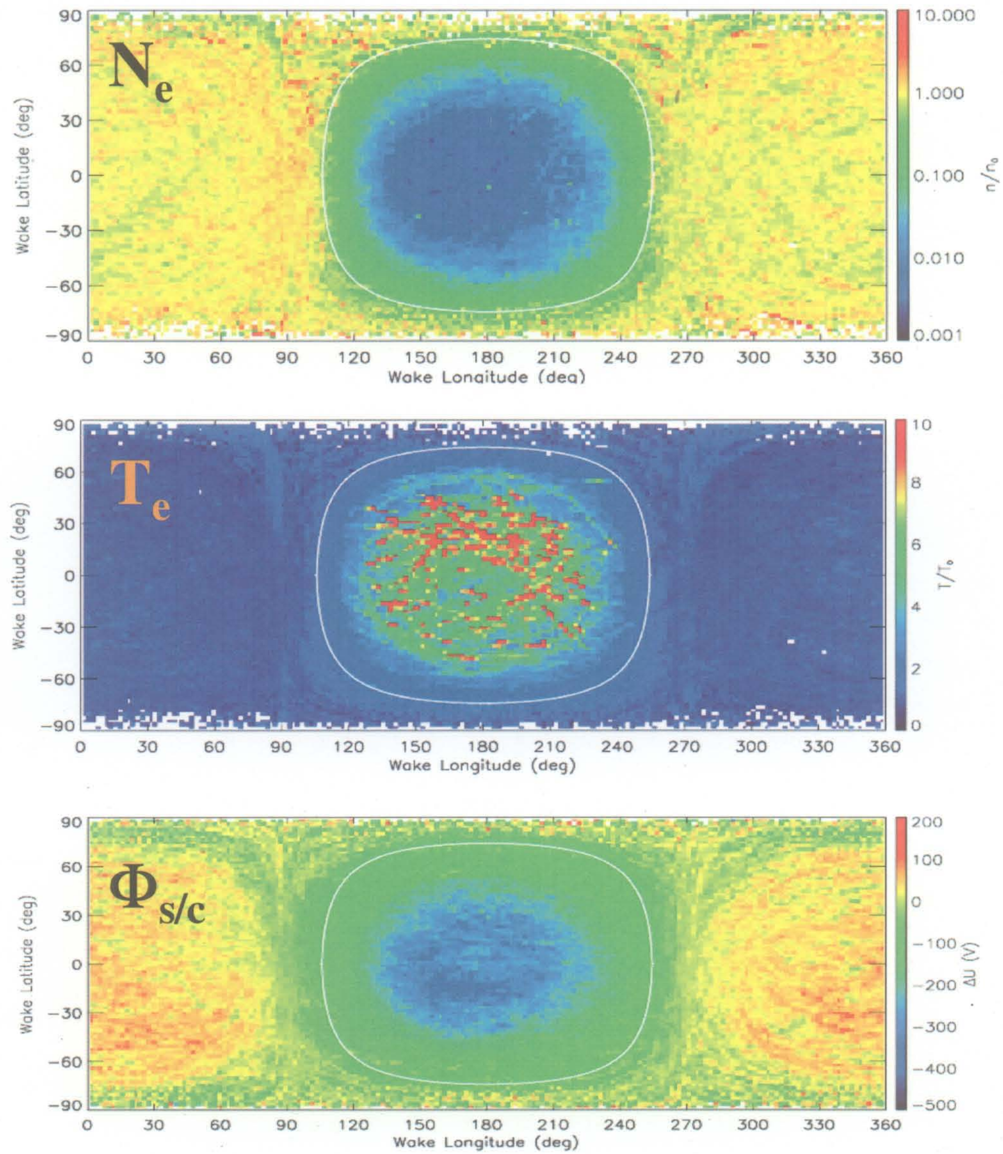
Wake properties relative to ambient solar wind

[Halekas et al. 2005]

Spacecraft potentials

day +10 V to +50V

night -100 V to -300 V



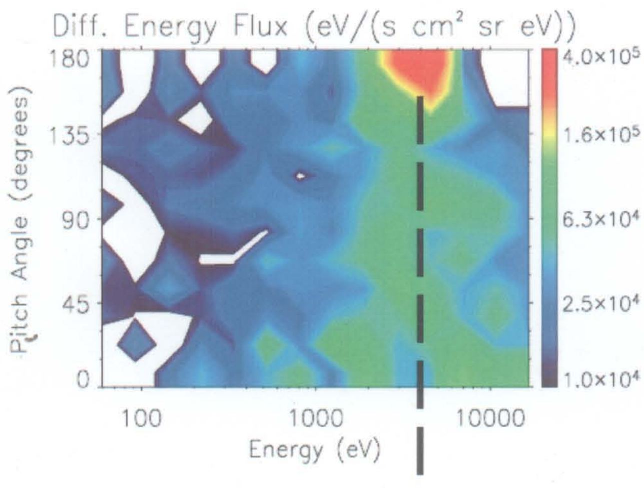
Charging in Lunar Environments

- Solar wind
  - Quiet solar wind $T_{eo} \sim 12.15 \pm 3.27$ eV [*Newbury, 1996*; *Newbury et al.*, 1998]

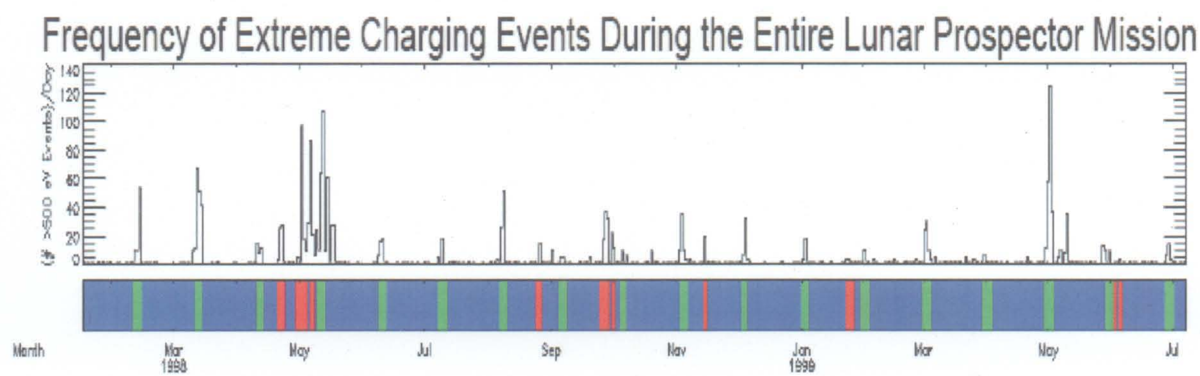
    $N_{eo} \sim 5.87 \pm 5.25$ #/cm^3 [3 years Genesis L1 ion moments]
    - Wake 6x to 10x T_e enhancements yield ~72 to ~122 eV
    - Surface charging rule of thumb

			low	mean	high
– **Darkness**	**Φs/c ~ - few kTe [*Moore et al.*, 1998]**		**-307 V <**	**-194 V <**	**-107 V**
– **Sunlight**	**Φs/c ~ +9[Ne, #/cm^3]$^{-0.44}$ [*Pederson*, 1995]**		**+3 V <**	**+4 V <**	**+11 V**

- Recent analysis of Lunar Prospector records [*Halekas et al.*, 2007] suggest lunar surface potentials ~ 4.5 kV

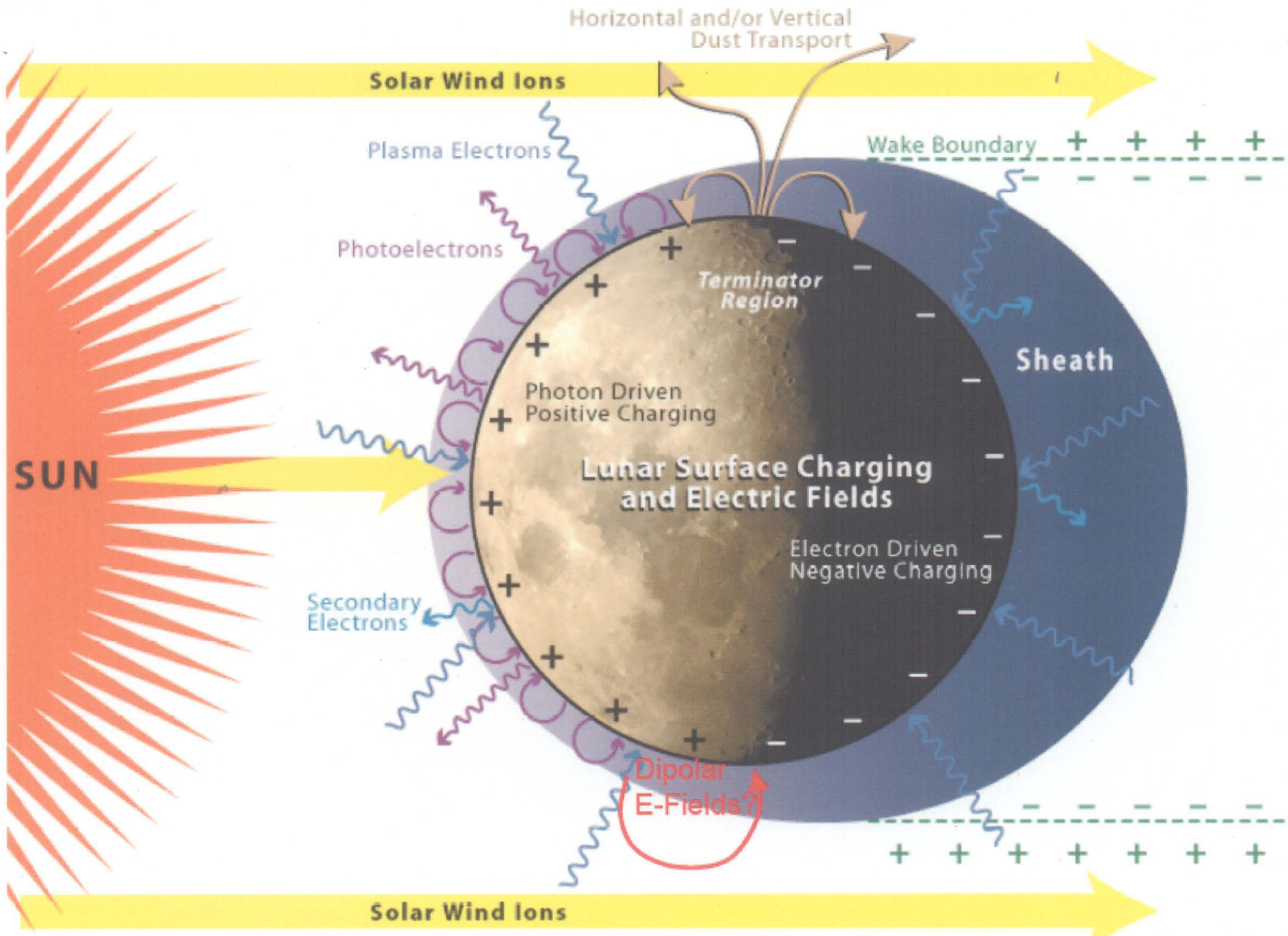


~4.5 kV



Magnetotail SPE

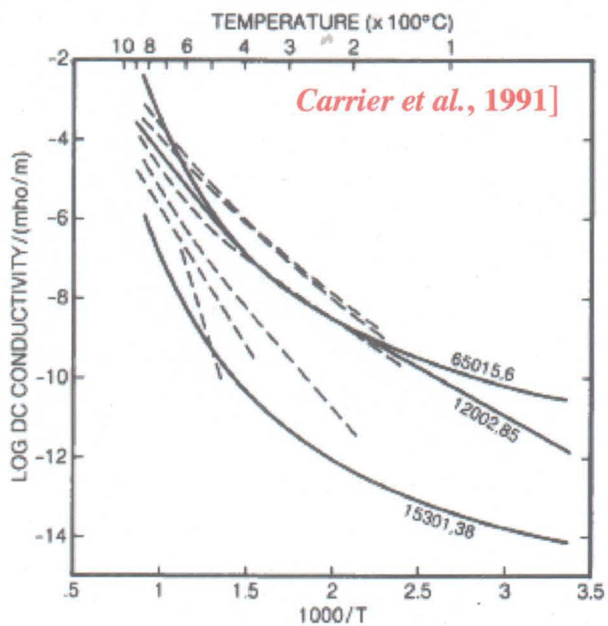
Lunar Plasma Environments/Interactions

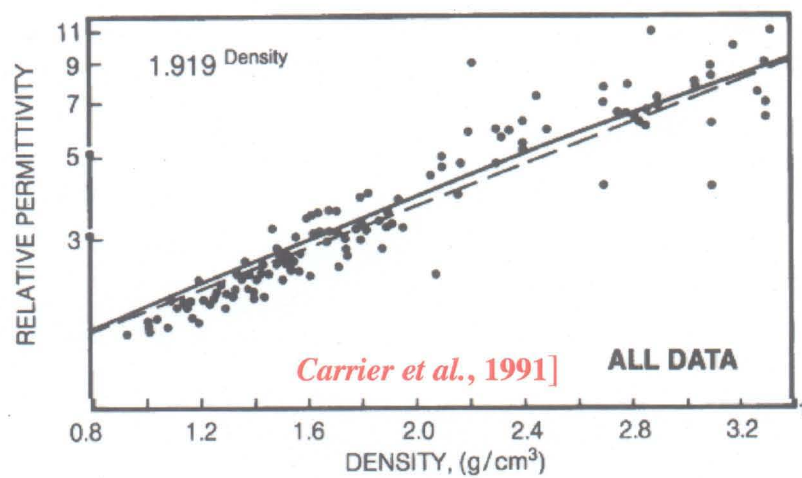


[Lin et al., 2007]

Material Electrical Properties

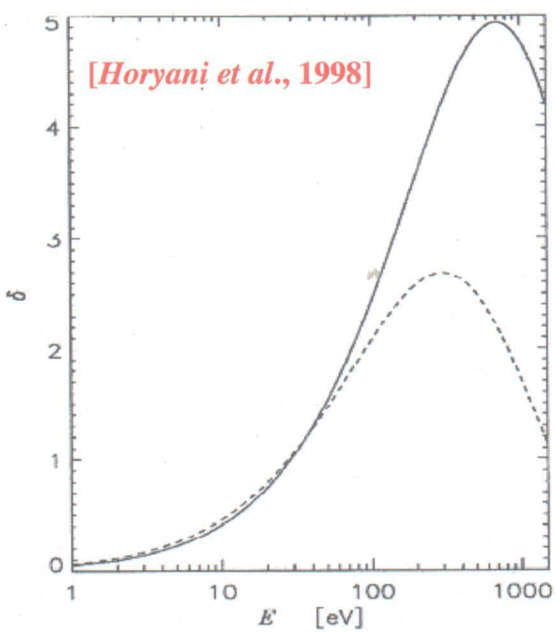
- Charging analyses require electrical properties of materials as a function of temperature
  - $\sigma(T)$ conductivity
  - κ dielectric constant
  - Radiation induced conductivity parameters k_p, Δ
  - Secondary electron yields
- Properties of terrestrial materials measured in laboratory
- Some information is available for lunar regolith





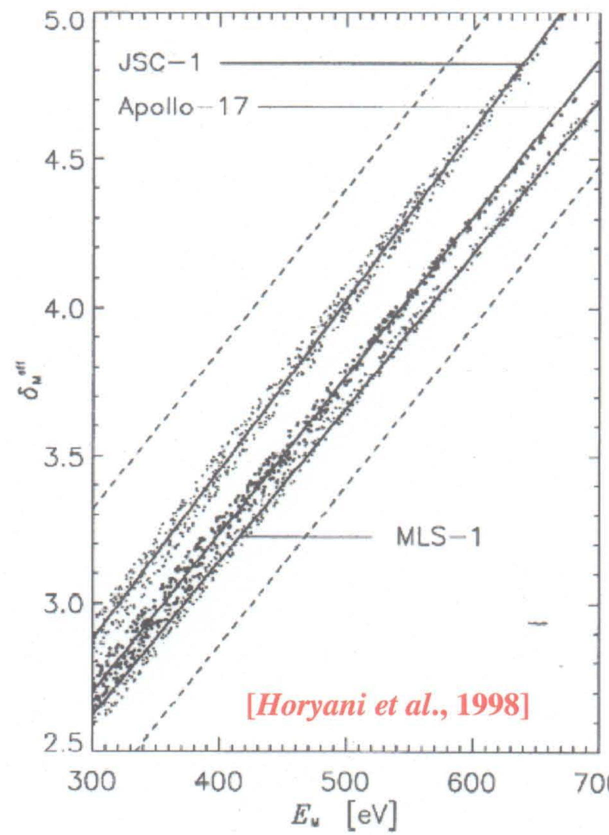
Electrical Properties of Lunar Regolith

- Information on secondary electron emission properties of lunar regolith is available from materials returned by Apollo
- Biased towards low lunar latitudes



$$\delta(E) = 7.4\delta_M \left(E/E_M\right)\exp\left(-2\left(E/E_M\right)^{1/2}\right)$$

[*Sternglass*, 1954]

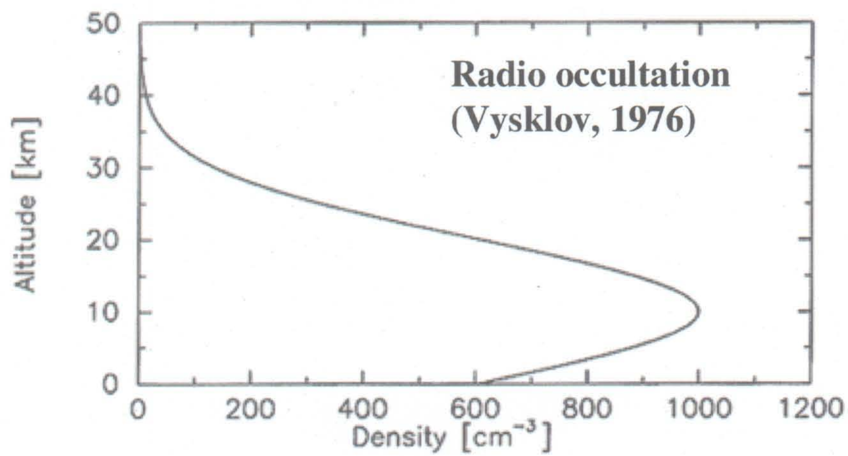


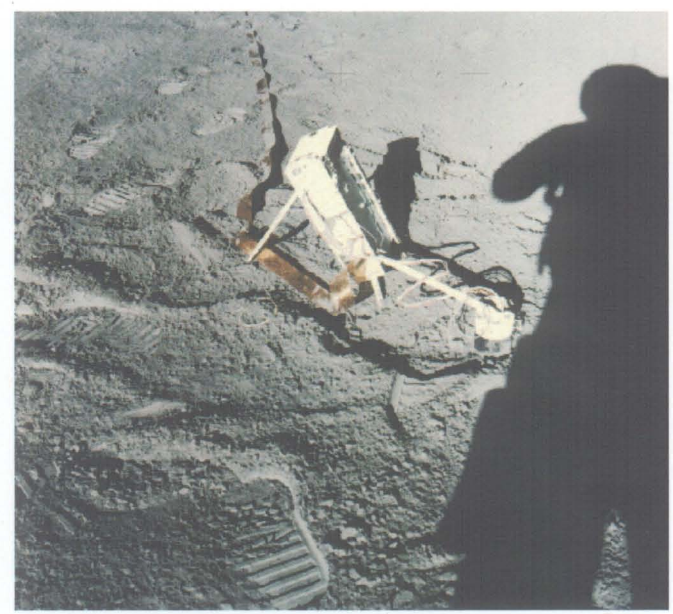
USU, Logan, UT
17 Apr 2007

Lunar Secondary Electron Environments

- **Lunar photoelectron sheath**
  - Vysklov (1976) reported lunar "ionosphere" using radio occultation technique from Luna 22 with peak electron densities of 500-1000 #/cm^3 at altitudes of 5-10 km above sunlit lunar surface
  - In-situ measurements from Apollo 12, 15, 15 Suprathermal Ion Detector Experiment (SIDE) and Apollo 14 Charged Particle Lunar Environment Experiment (CPLEE) show 10^4 #/cm^3 up to altitudes of 100 m (Reasoner and Burke, 1972)
  - For comparison…..
    - Solar wind ~6 e$^-$/cm^3 , large values of 50 e$^-$/cm^3 to 100 e$^-$/cm^3 in shocks (CME's, CIR, etc)
    - Magnetosheath at lunar distances Ne ~ 1 to 100 e$^-$/cm^3
    - Magnetotail at lunar distances Ne ~ 0.01 to 10 e$^-$/cm^3

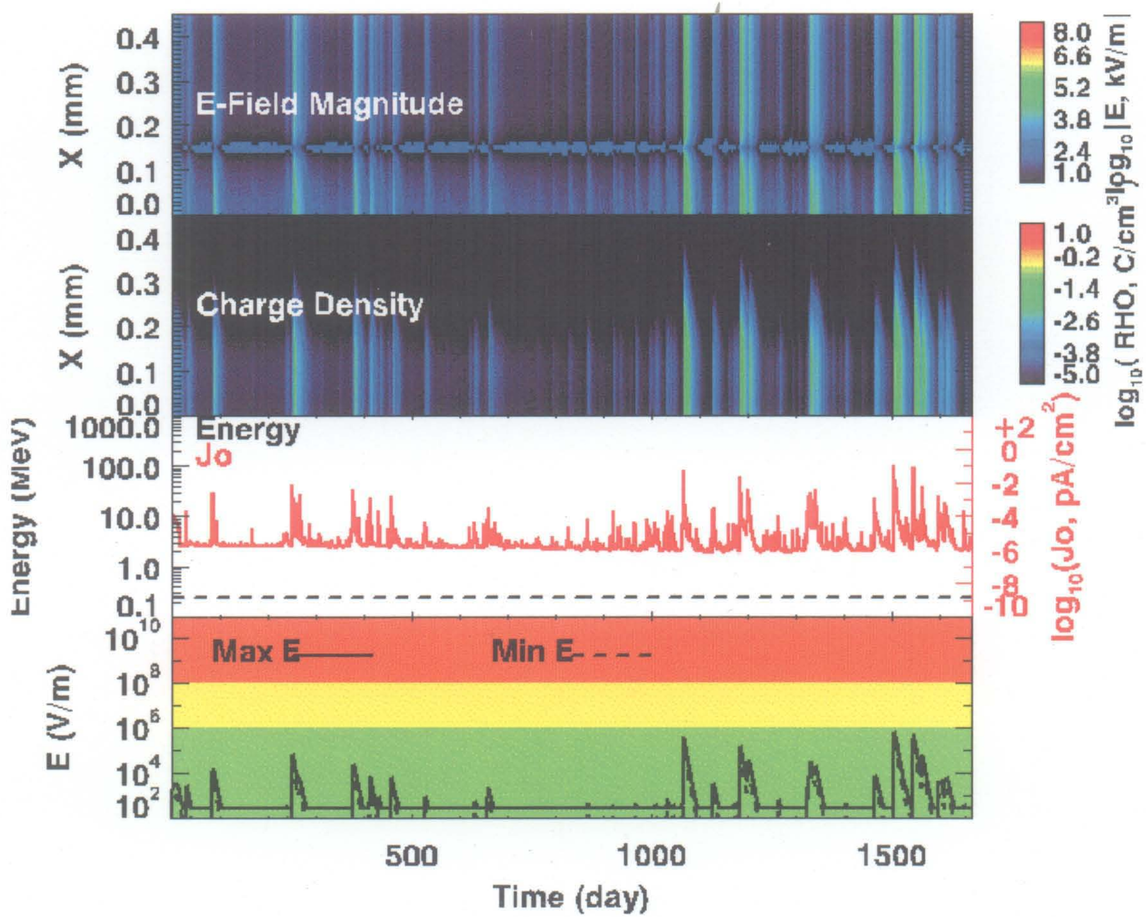
- **Lunar Debye length ~1 meter**
  - ~130 electrons/cm^3 density at surface (Feuerbacher et al., 1972)
  - Photoelectrons dominate daytime charging environments within a few meters of surface





Charging in Cold Environments

- Lunar environments can be very cold
  - ~85K in night just before sunrise
  - ~40K to 50K in permanently dark polar craters
- Insulator charging in these environments will integrate charge for extended periods of time



T ~ 300K

$\sigma \sim 10^{-16}$ S/m

$\kappa \sim 3.706$

$\sigma_{RIC} \sim 2.76 \times 10^{-16} [d\gamma/dt]^{1.0}$ S/m

Charging in Cold Environments

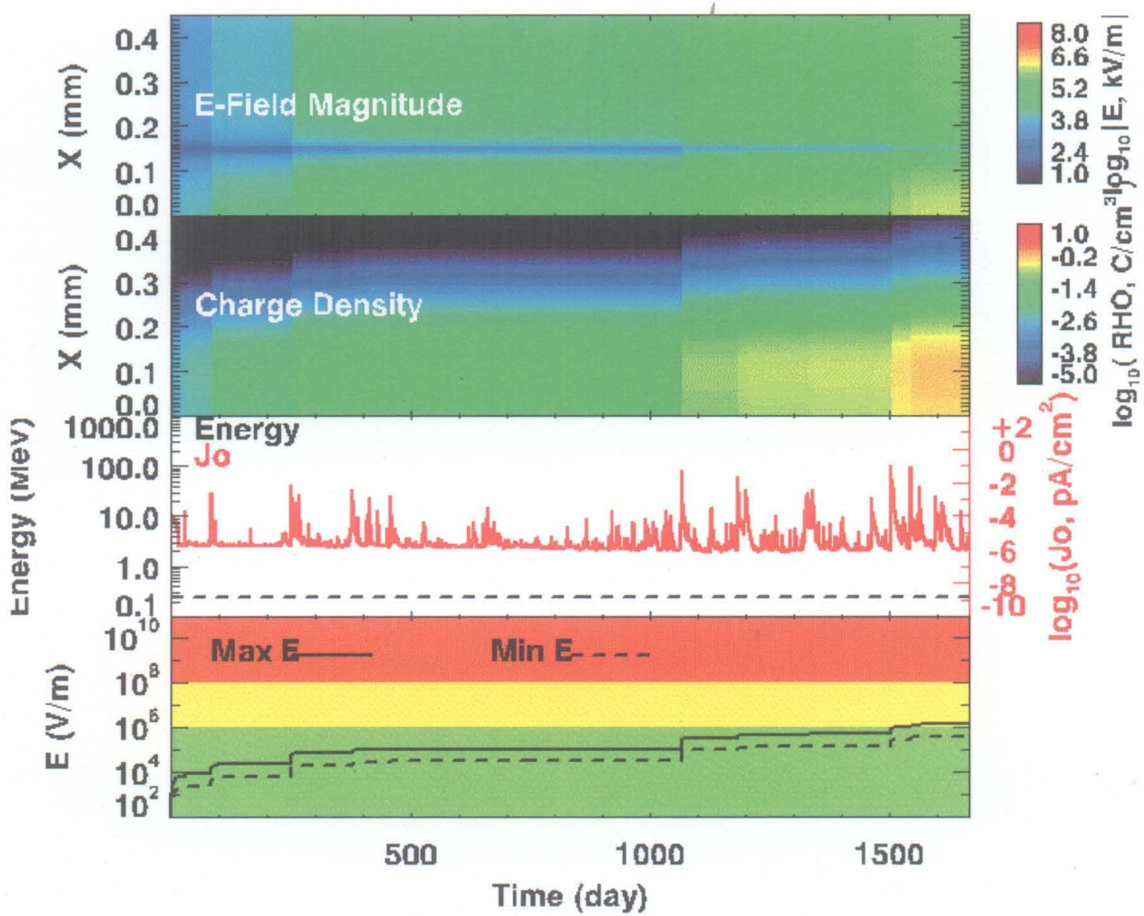
- Lunar environments can be very cold
  - ~85K in night just before sunrise
  - ~40K to 50K in permanently dark polar craters
- Insulator charging in these environments will integrate charge for extended periods of time

$T \sim 100K$

$\sigma \sim 10^{-19}$ S/m

$\kappa \sim 7.412$

$\sigma_{RIC} \sim 2.76\times10^{-16}\,[d\gamma/dt]^{1.0}$ S/m



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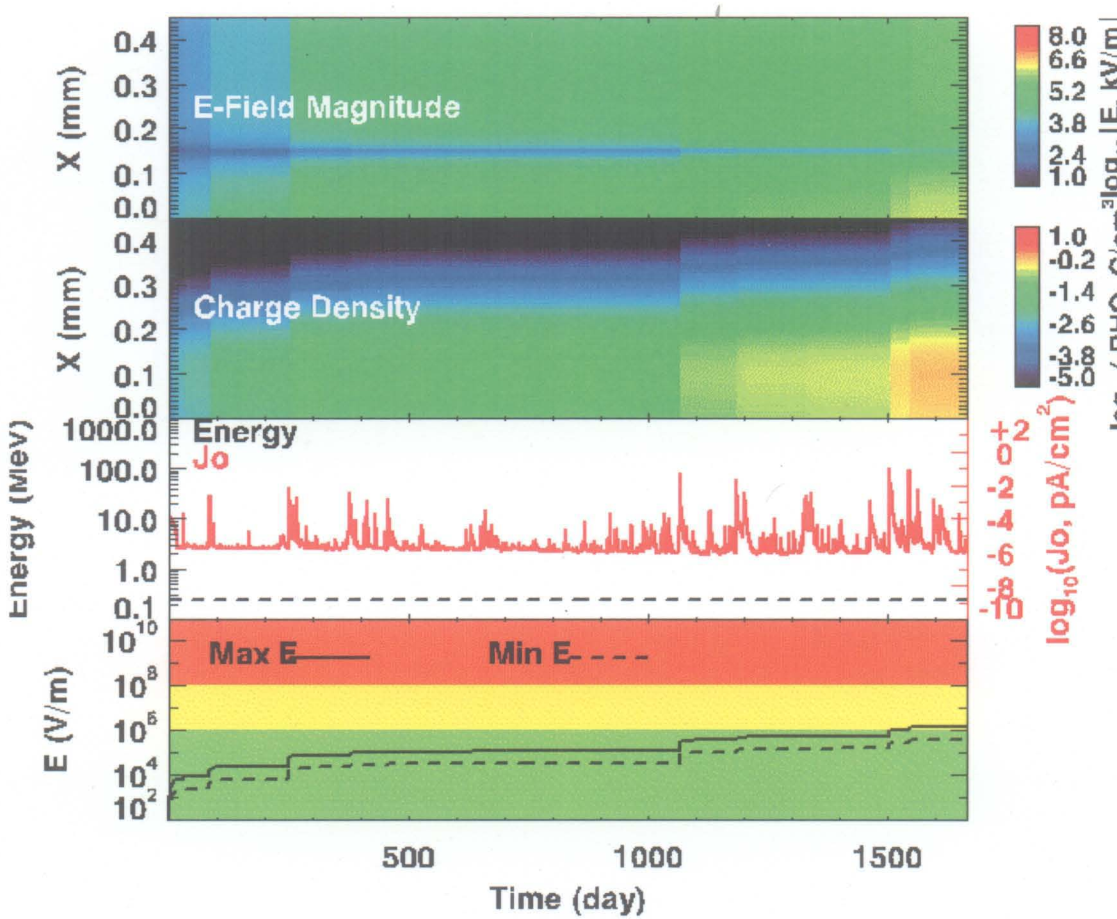


$T < 50K$

$\sigma \sim 10^{-25}$ S/m

$\kappa \sim 7.412$

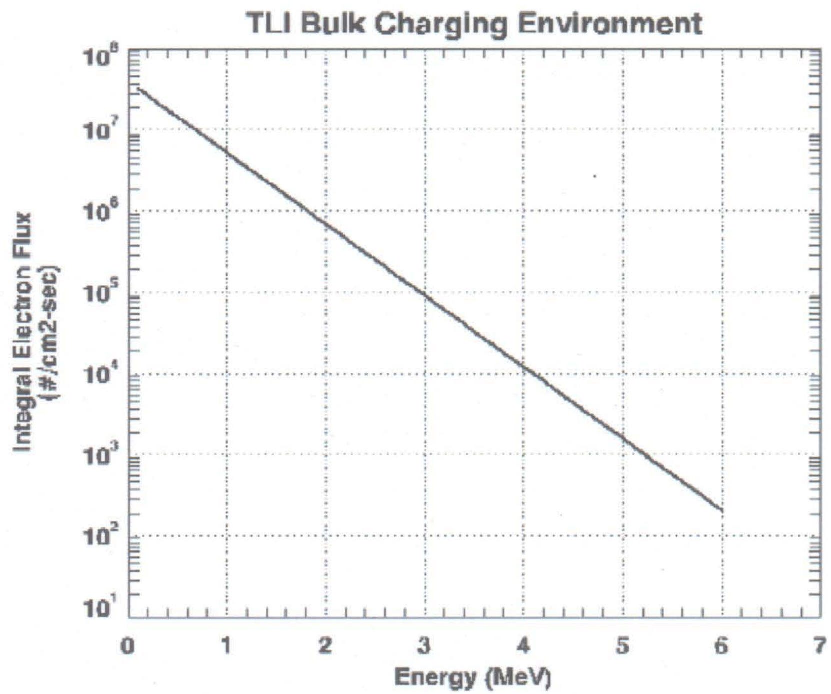
$\sigma_{RIC} \sim 2.76 \times 10^{-16} [d\gamma/dt]^{1.0}$ S/m

No further change in fields once insulator becomes a "charge integrator"

Constellation Design Environments

- Charging design environments:
  - Geostationary orbit extreme surface charging environments [*Purvis et al.*, *NASA TP-2361*, 1984]
  - Trans-lunar injection orbit [*Fennell et al.*, 2000]

Parameter	Case[a] Environment[b] Electrons	Ions
Number density (#/cm^3)	3.00	3.00
Current density (nA/cm^2)	0.501	0.016
Number density, population 1 (#/cm^3)		
Parallel	1	1.1
Perpendicular	0.8	0.9
Temperature, population 1 (eV)		
Parallel	600	400
Perpendicular	600	300
Number density, population 2 (#/cm^3)		
Parallel	1.40	1.70
Perpendicular	1.90	1.60
Temperature, population 2 (eV)		
Parallel	25100	24700
Perpendicular	26100	25600



- **Lunar specific environments are pending, but these cases will certainly drive design**

Summary

- **Plasma environments encountered during lunar missions similar to environments encountered in LEO, GEO missions**

- **Charging environments will need to be evaluated:**
  - **Radiation belt transit**
  - **Lunar wake environments**

- **Charging design environments in place for LEO, magnetosphere transit**

- **Further exploration of lunar charging environments is warranted**