Plasma Environments and Spacecraft Charging for Lunar Programs

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Space systems interacting with the space plasma environment charge to potentials of a few tens of volts positive in interplanetary space or on the lunar surface in daylight, a few hundred volts negative in the dark lunar plasma wake and in some regions of the Earth's radiation belts, and to multiple kilovolt negative potentials for worst case conditions in the Earth's magnetosphere near geostationary orbit. Good design practices are required to assure that space systems operate successfully in these environments without detrimental effects due to transient currents and insulator failure produced by electrostatic discharges. Cold lunar environments in particular are challenging because detrimental effects of charging are often exacerbated by cold, highly resistive dielectrics which can integrate charge for long periods of time. We will describe the cold plasma and energetic particle environments relevant to lunar missions responsible for surface and bulk charging of space systems and discuss program requirements under development for assuring that systems operate successfully in these environments.

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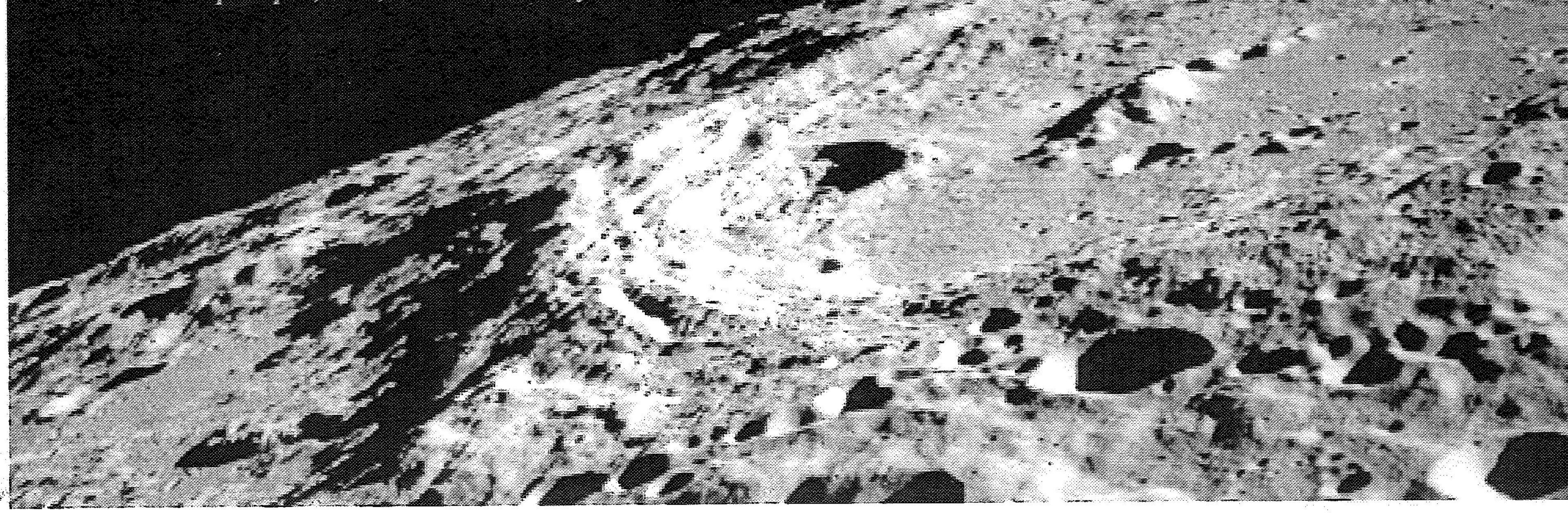


Overview

- What plasma environments are relevant, of concern for lunar missions?
- How different are lunar environments compared to the well characterized LEO, GEO environments?

Overview

- What radiation, plasma environments are relevant for lunar missions?
- How different are lunar environments compared to the well characterized LEO, GEO environments?

Environments	Space System Effects
Galactic cosmic rays	SEE, crew dose
Solar particle events	SEE, TID, crew dose
Trapped radiation	SEE, TID, charging
Solar wind, magnetosphere, plasma sheath	TID, charging
Lunar photoelectrons	dust charging

Surface Charging

- Time dependent current balance on surfaces

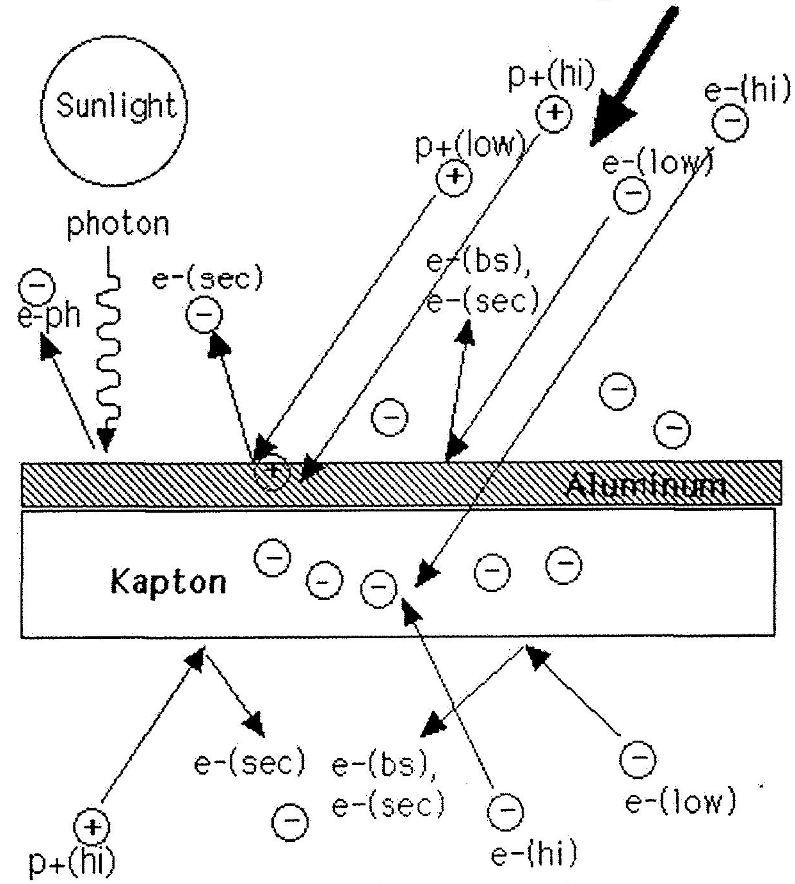
$$\frac{dQ}{dt} = C\frac{dV}{dt} = \sum_k I_k \quad (\sim 0 \text{ at equilibrium})$$

$$\sum_k I_k =$$

+ $I_i(V)$	**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.)**

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

plasma



(Garrett and Minow, 2004)

Bulk (Deep Dielectric) Charging

- Radiation charging of insulators, isolated conductors

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

$$D = \varepsilon E$$

$$\varepsilon = \kappa \varepsilon_0$$

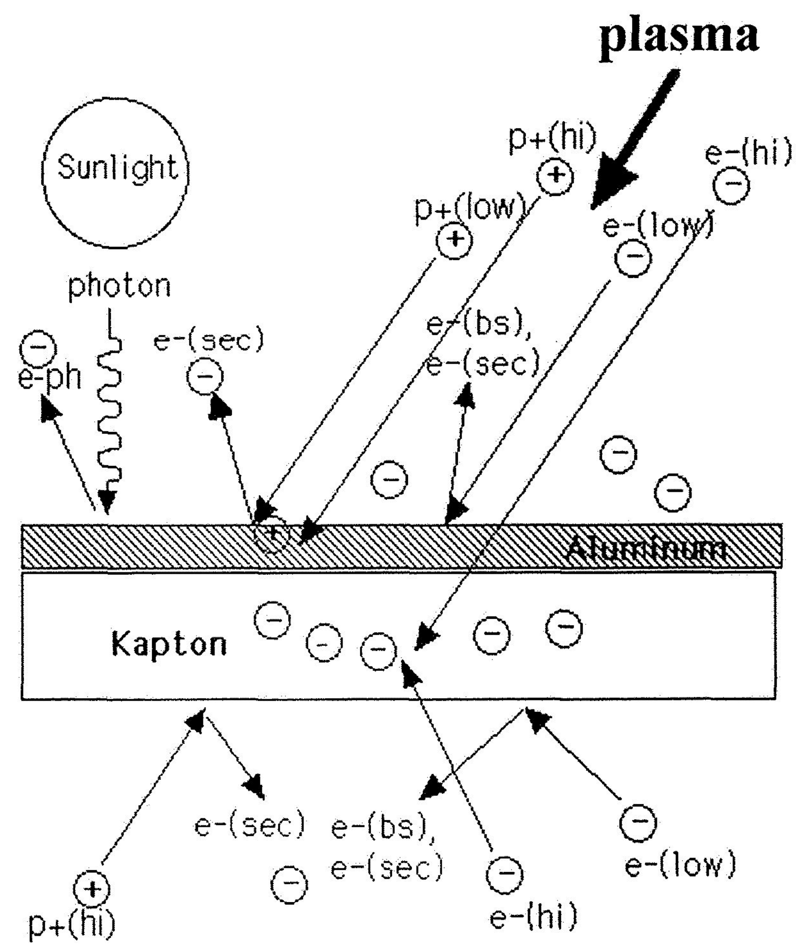
$$\frac{\partial \rho}{\partial t} = -\nabla \bullet J$$

$$J = J_0 + J_C$$

$$J = \sigma E$$

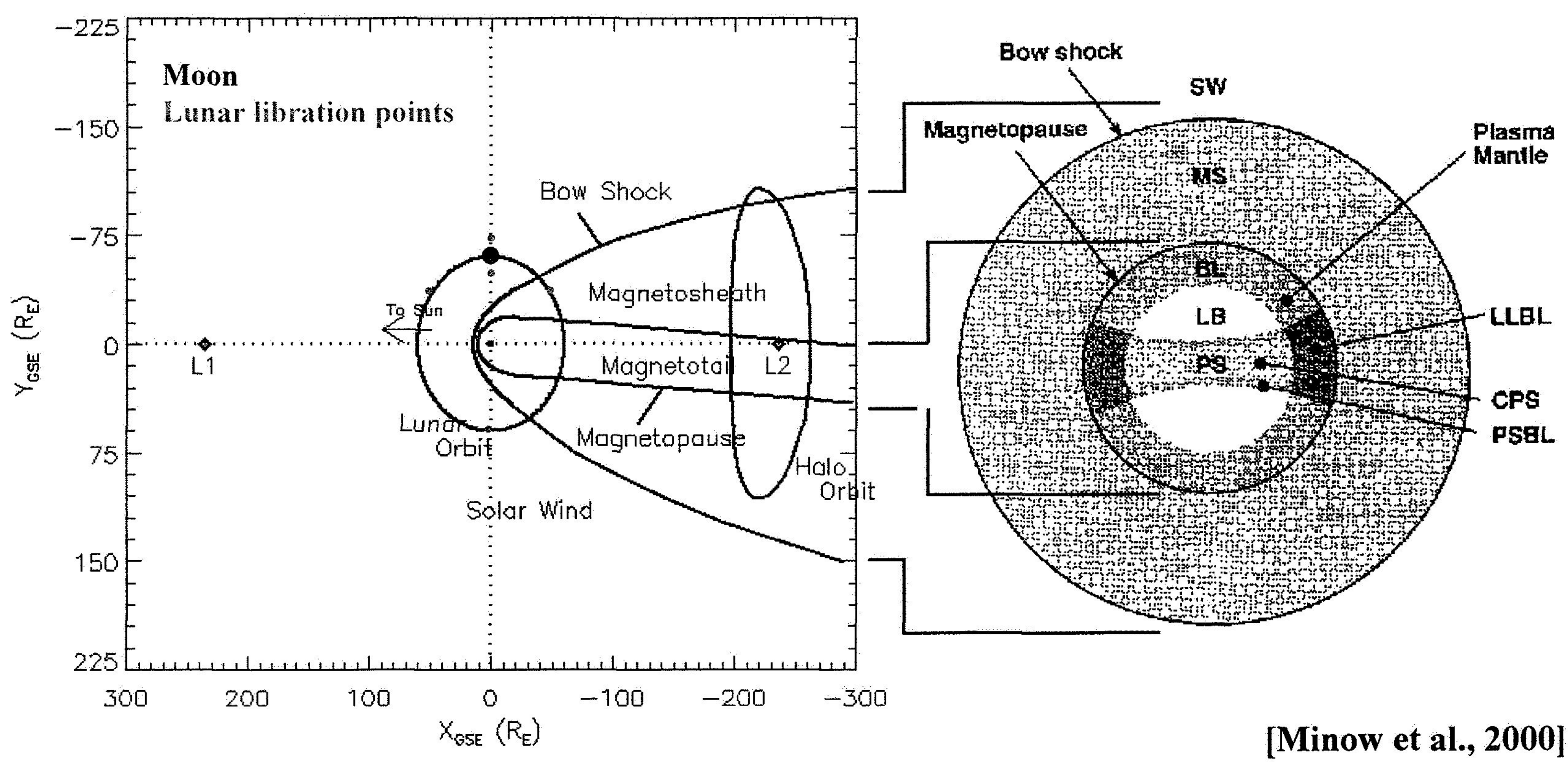
$$= (\sigma_{dark} + \sigma_{radiation}) E$$

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



(Garrett and Minow, 2004)

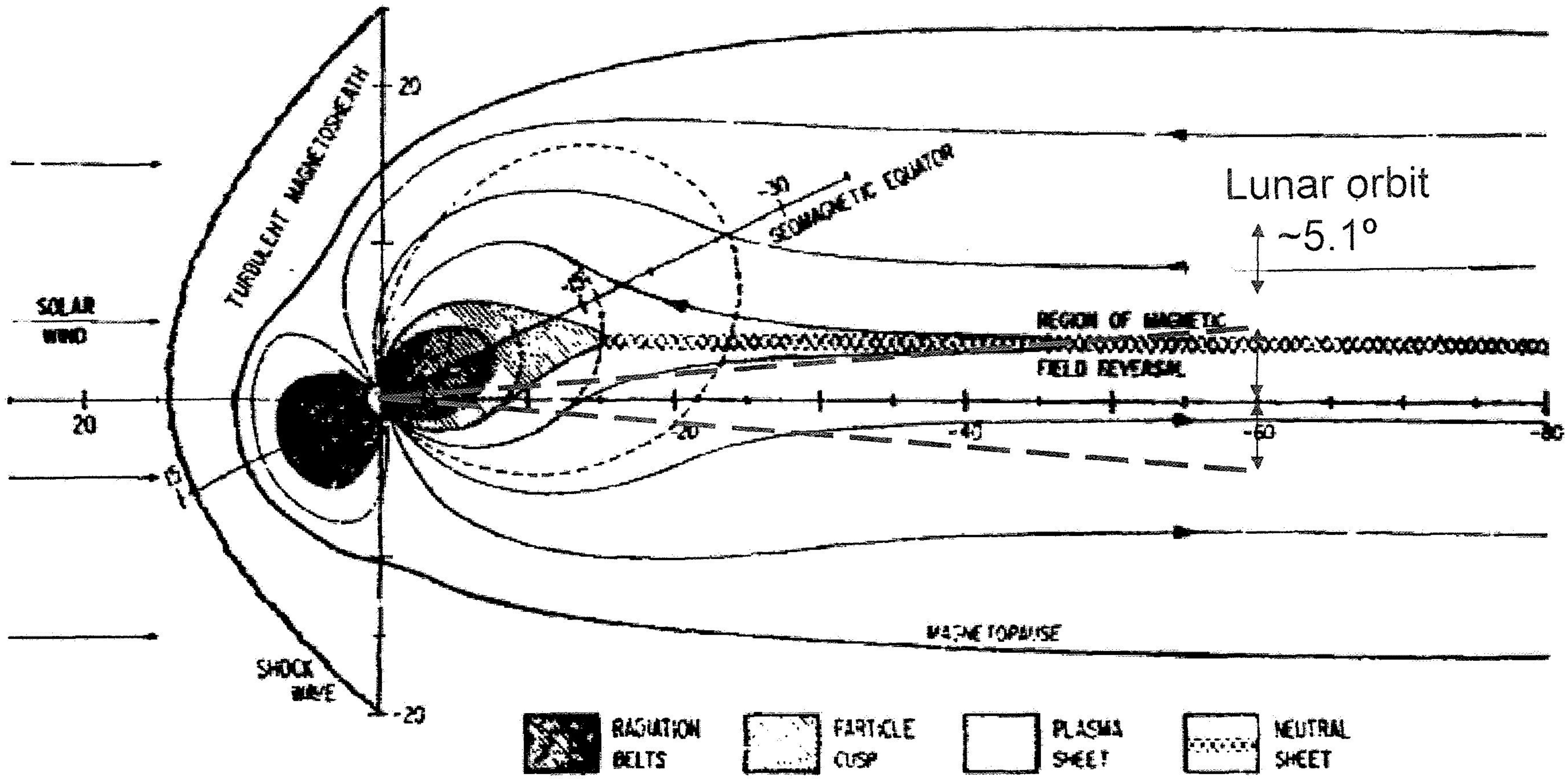
Plasma Environments



[Minow et al., 2000]

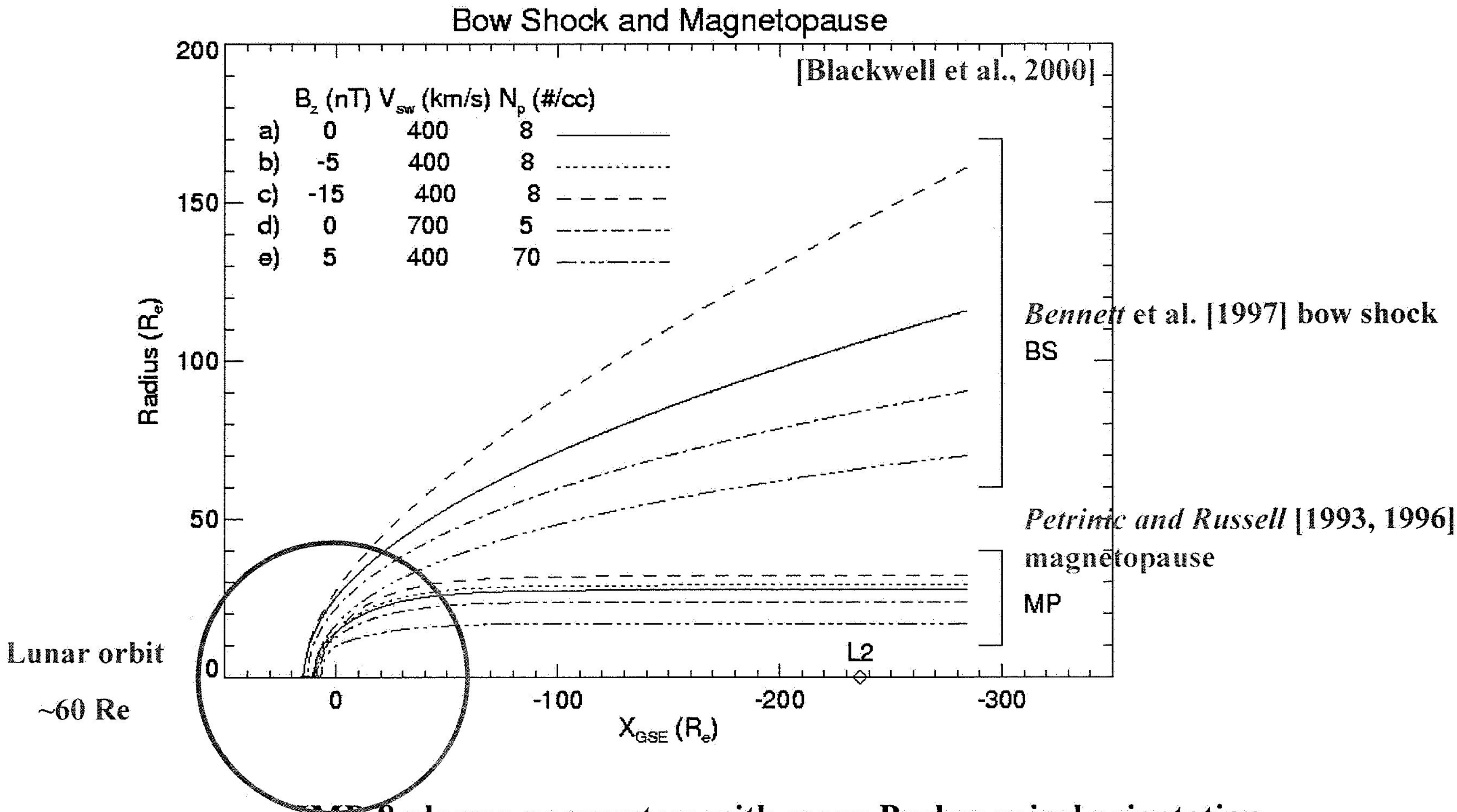
- Sun-Earth L1, L3, L4, L5 all in solar wind
- Sun-Earth L2 located nominally near edge of magnetotail with magnetosheath encounters, solar wind is rare
- Earth-Moon L1, L2, …, L5 all pass through the magnetosheath and magnetotail once a month but spend most time (~75% in solar wind)

Magnetosphere and Lunar Orbit



Adams et al., 1981

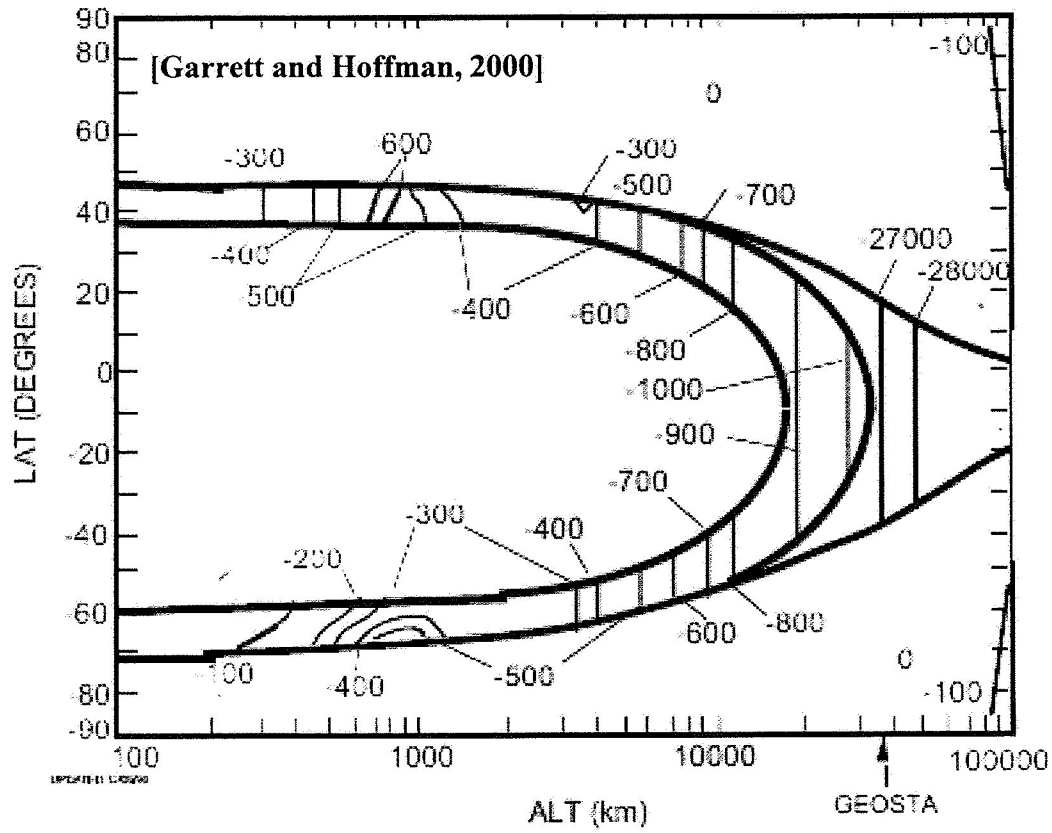
Bow Shock and Magnetopause Variability

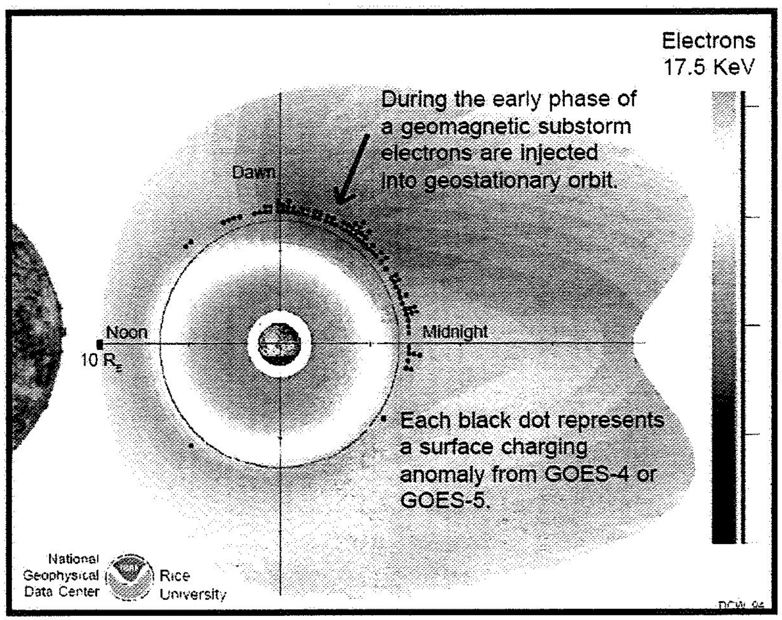


IMP-8 plasma parameters with mean Parker spiral orientation for IMF provide variations in bow shock, magnetopause orientation and dimensions

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 -500 kV
--sunlight	+10's V
Solar wind	+10's V





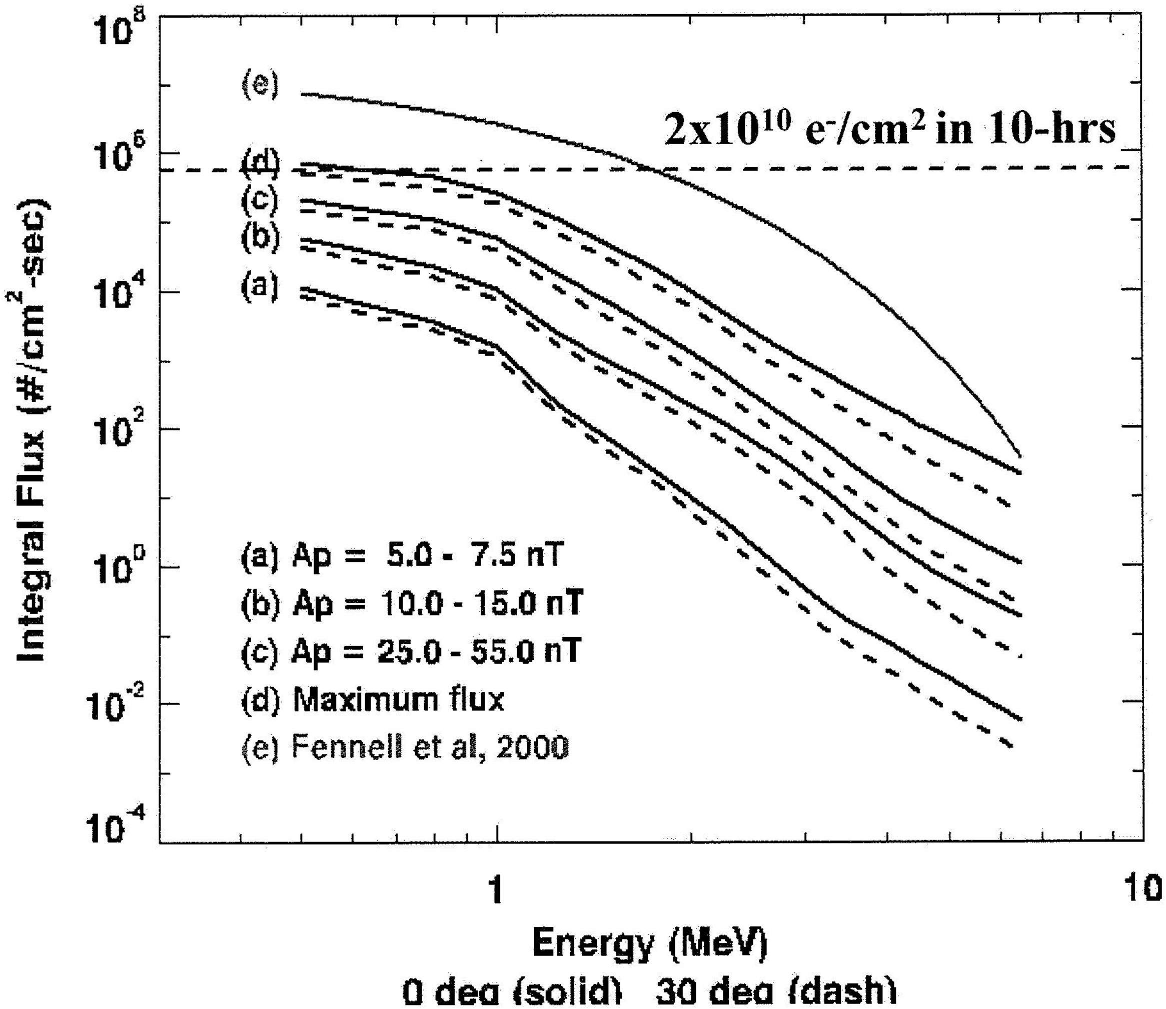
Orbit inclination, departure local time (longitude) important for surface charging

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

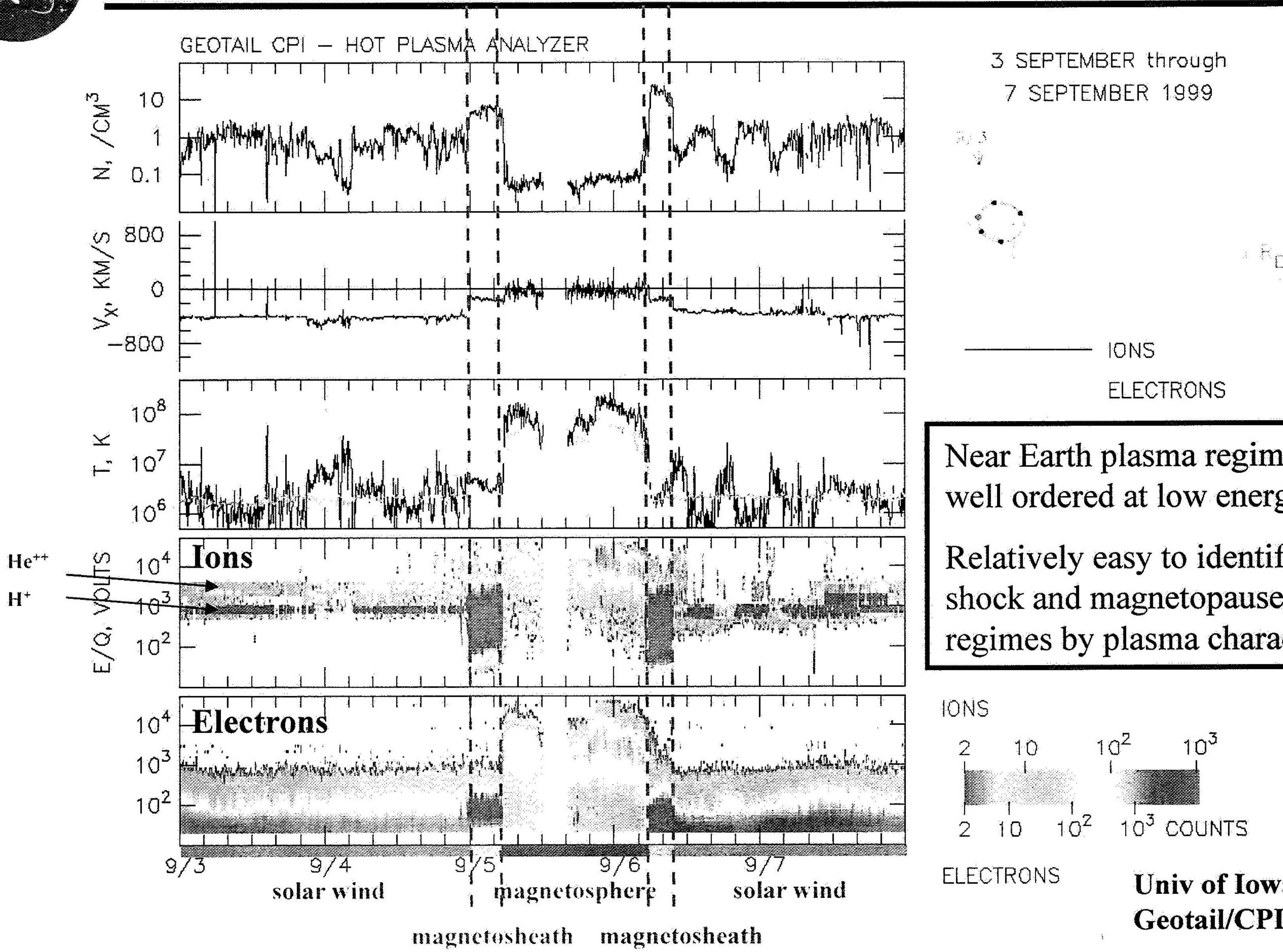
    10 hours in radiation belt
  - TLI/TEI T~8 days

    ≤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

Near Earth Plasma Regims



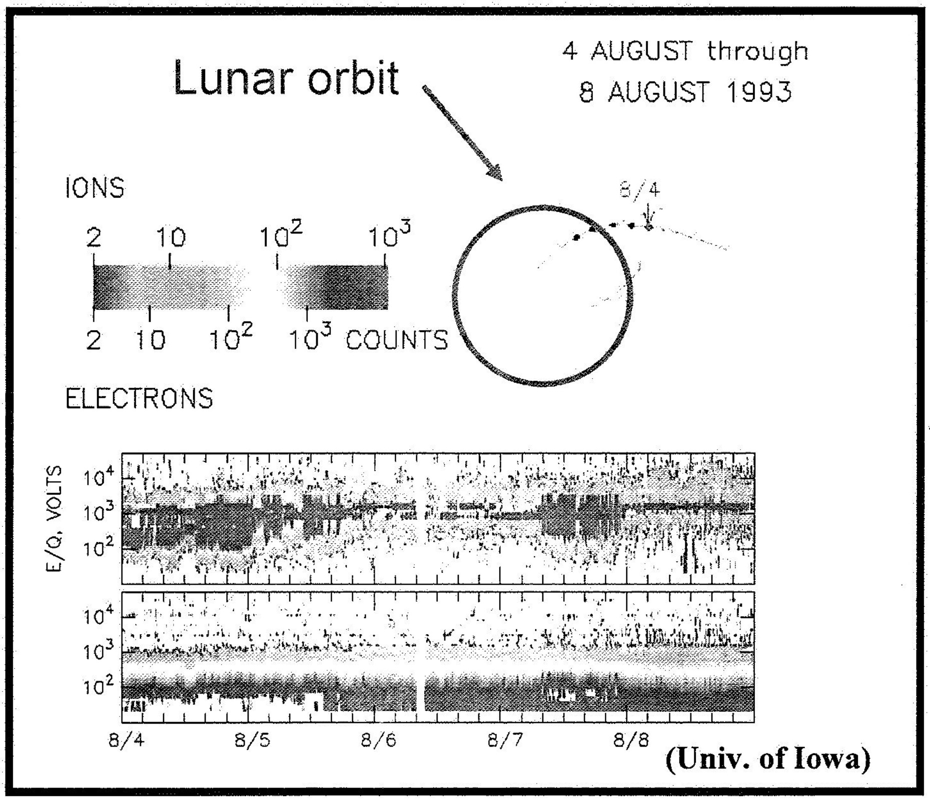
Near Earth plasma regimes are well ordered at low energies

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

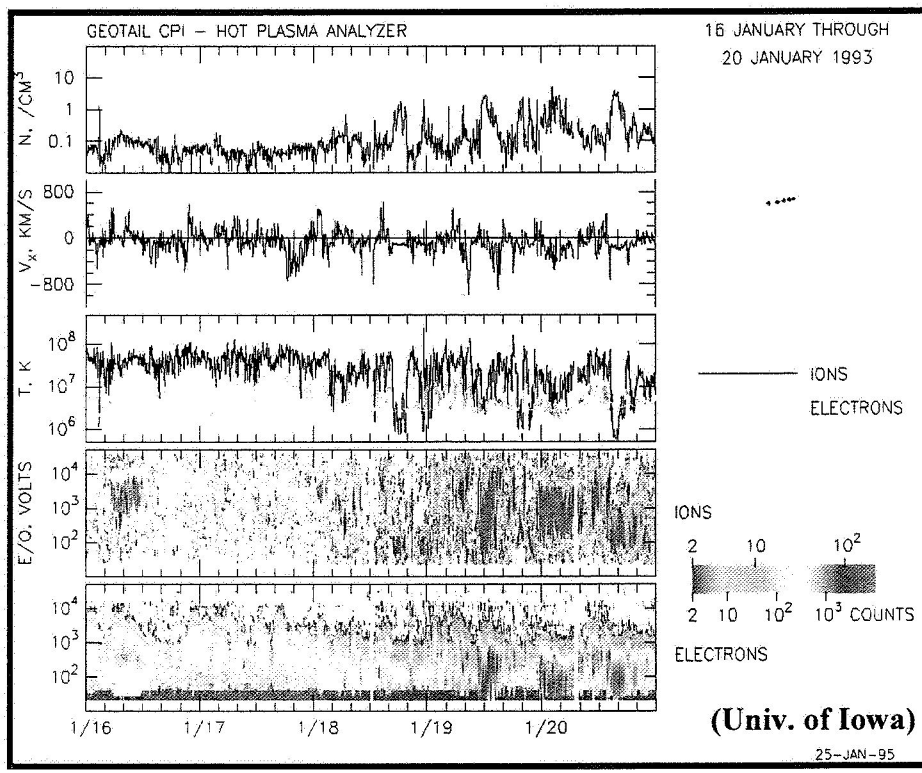
Univ of Iowa
Geotail/CPI/HPA

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)

Ion Foreshock Region

Protons

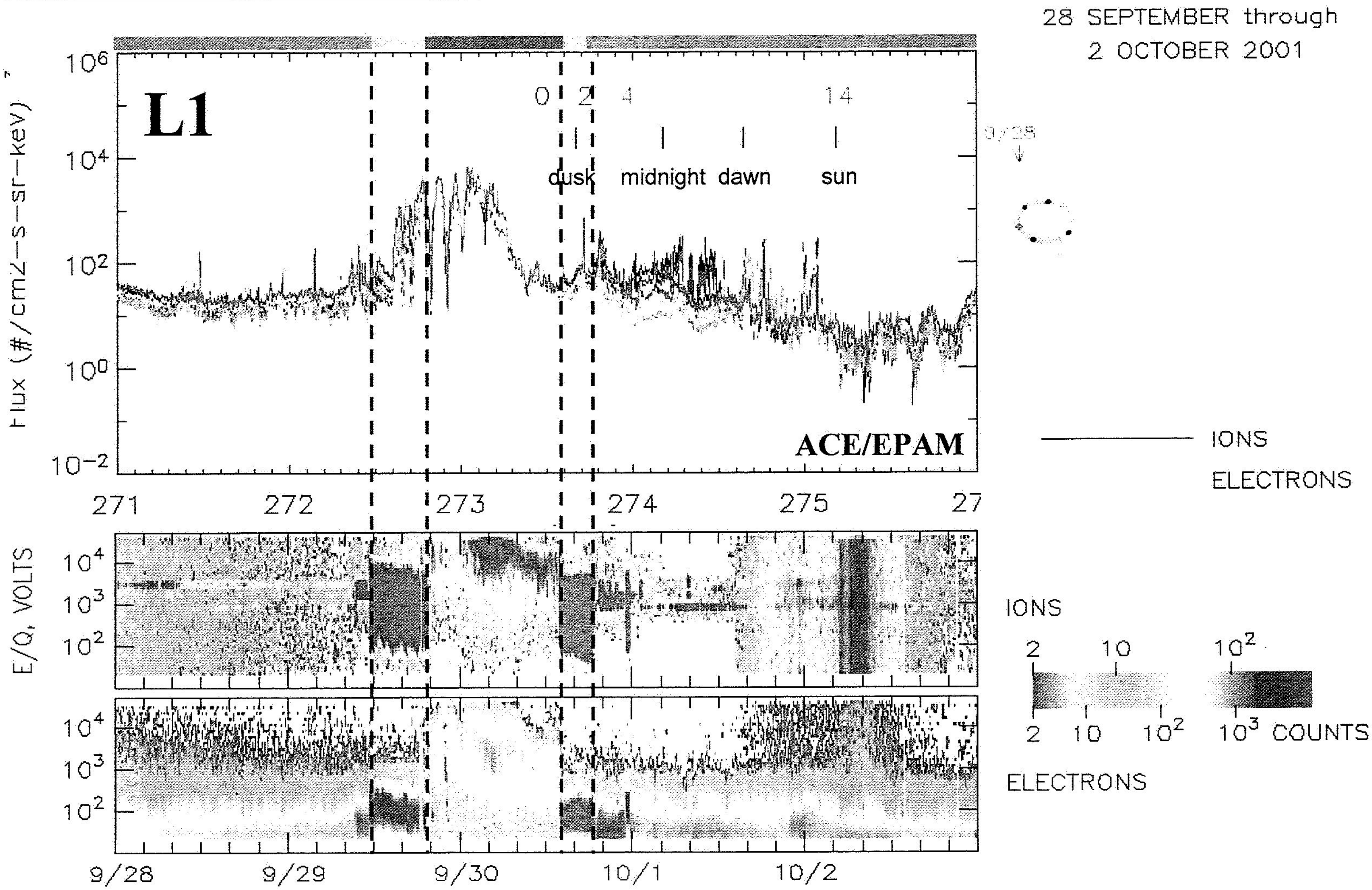
107-227 keV

Ions

0.03-30 keV

Electrons

0.03-30 keV



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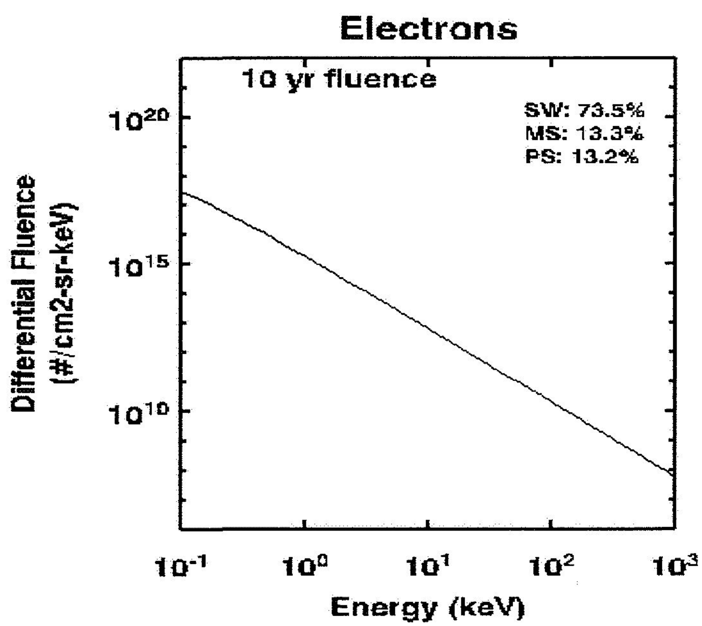
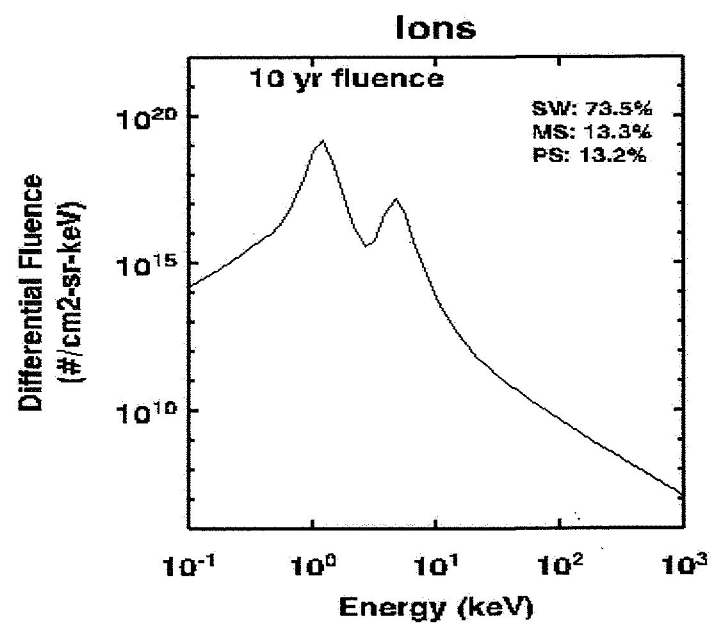
Ion, electron flux enhancements (10x to 100x) from foreshock region at all Earth-Moon libration points and Sun-Earth L1

Free Field Plasma Environments

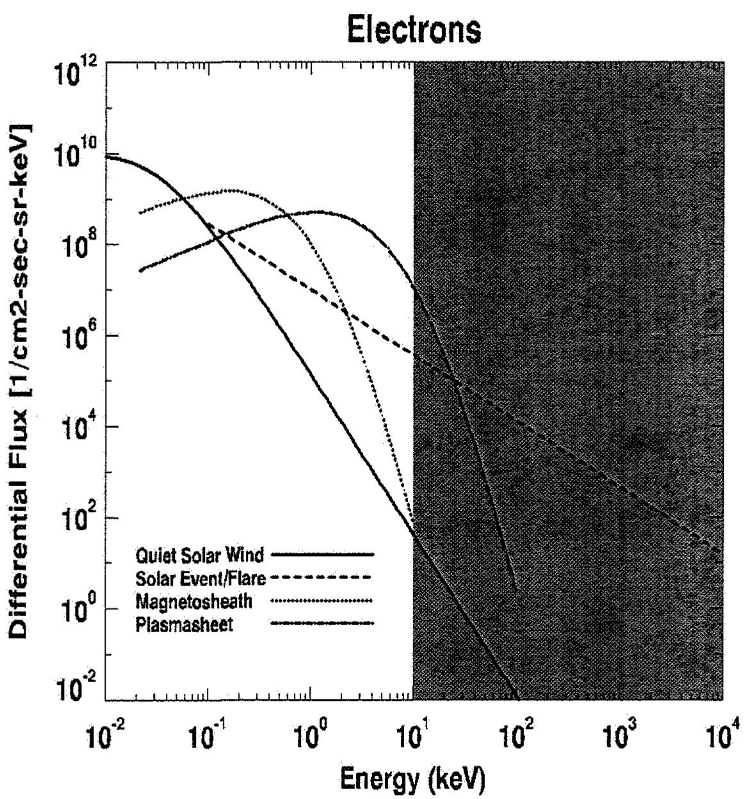
- Moon spends
  - ~73.5% solar wind
  - ~13.3% magnetosheath
  - ~13.2% magnetotail
- Solar wind fluence
  - ~(3×10^8 protons/cm^2-sec)(3×10^7 sec/yr)
  - ~9×10^{15} protons/cm^2

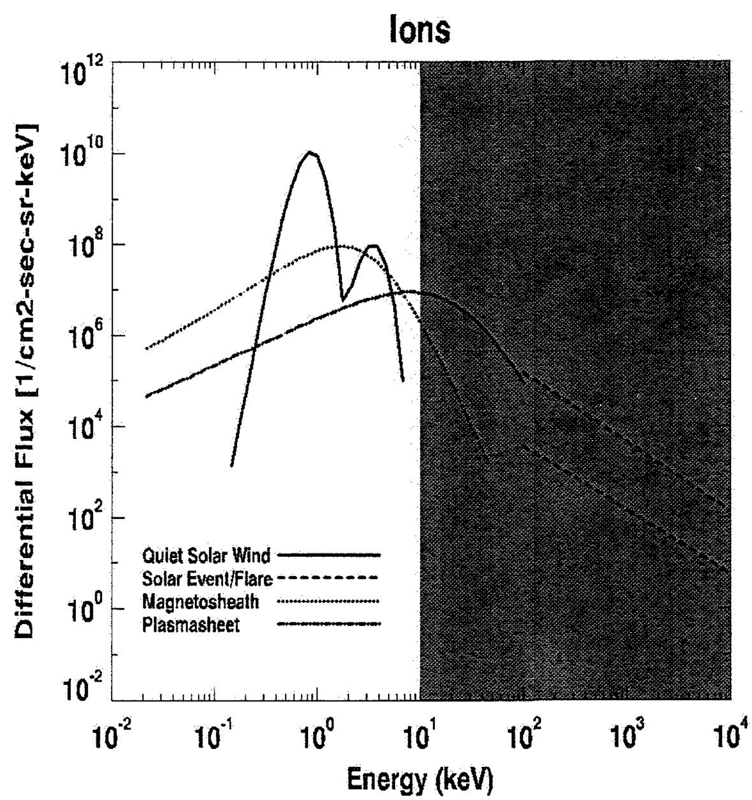




Lunar Plasma Environments

- Plasma/radiation environments to ~MeV energies responsible for surface and bulk charging

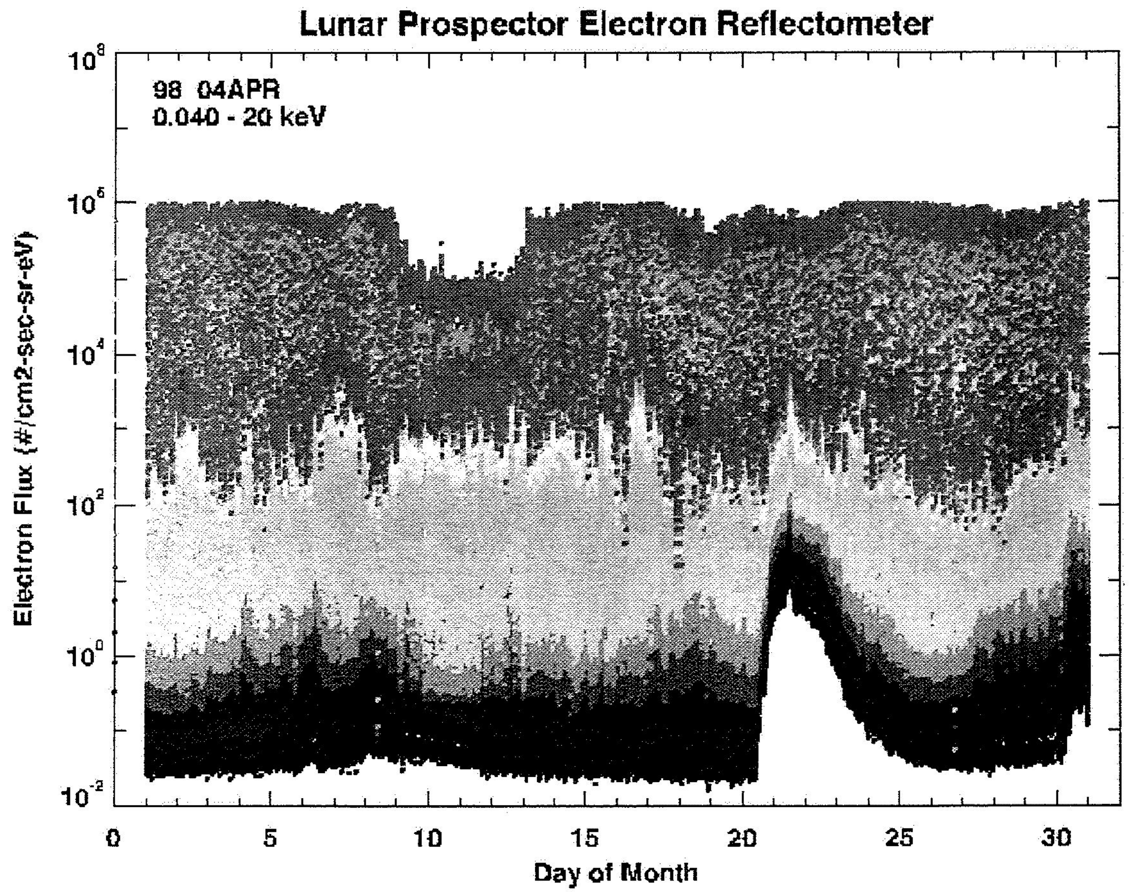




Lunar Plasma Environments

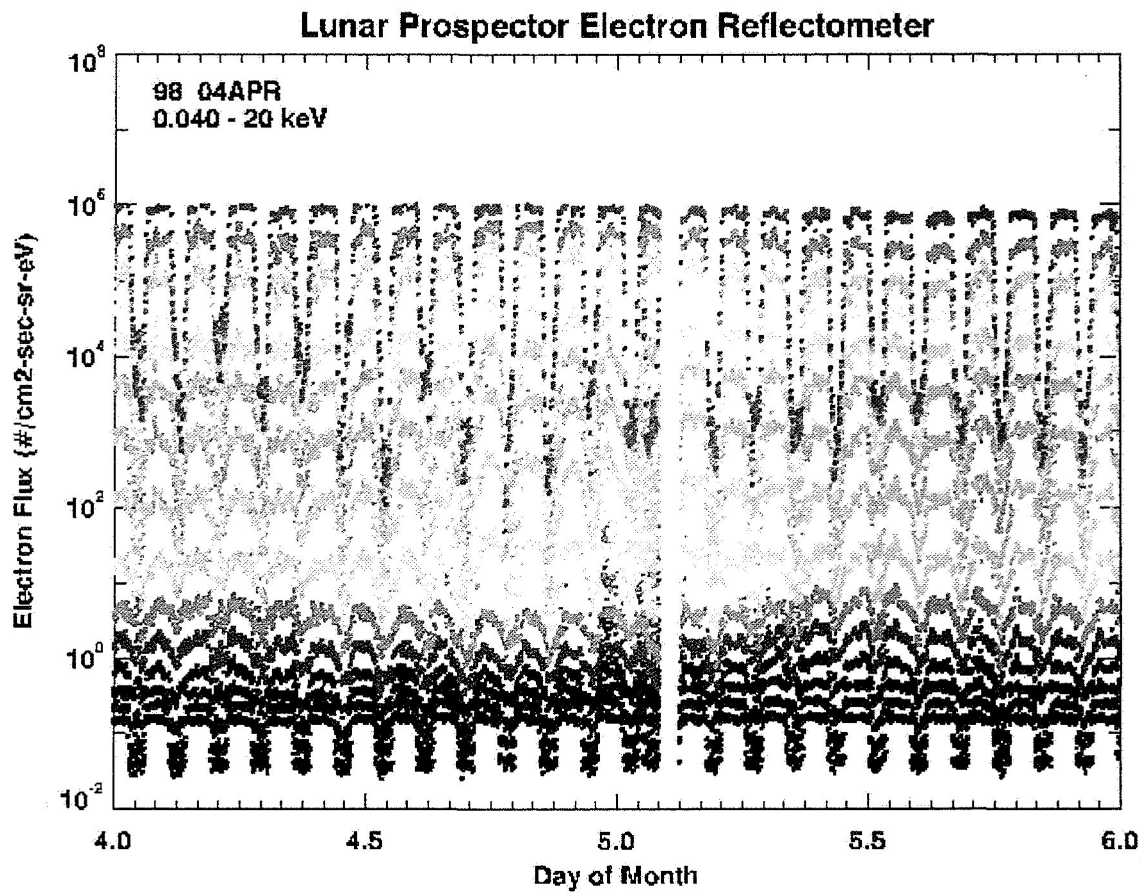
- Lunar Prospector Electron Reflectometer
  - Spin average electron flux
  - ~40 eV to ~20 keV

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



Lunar Plasma Environments

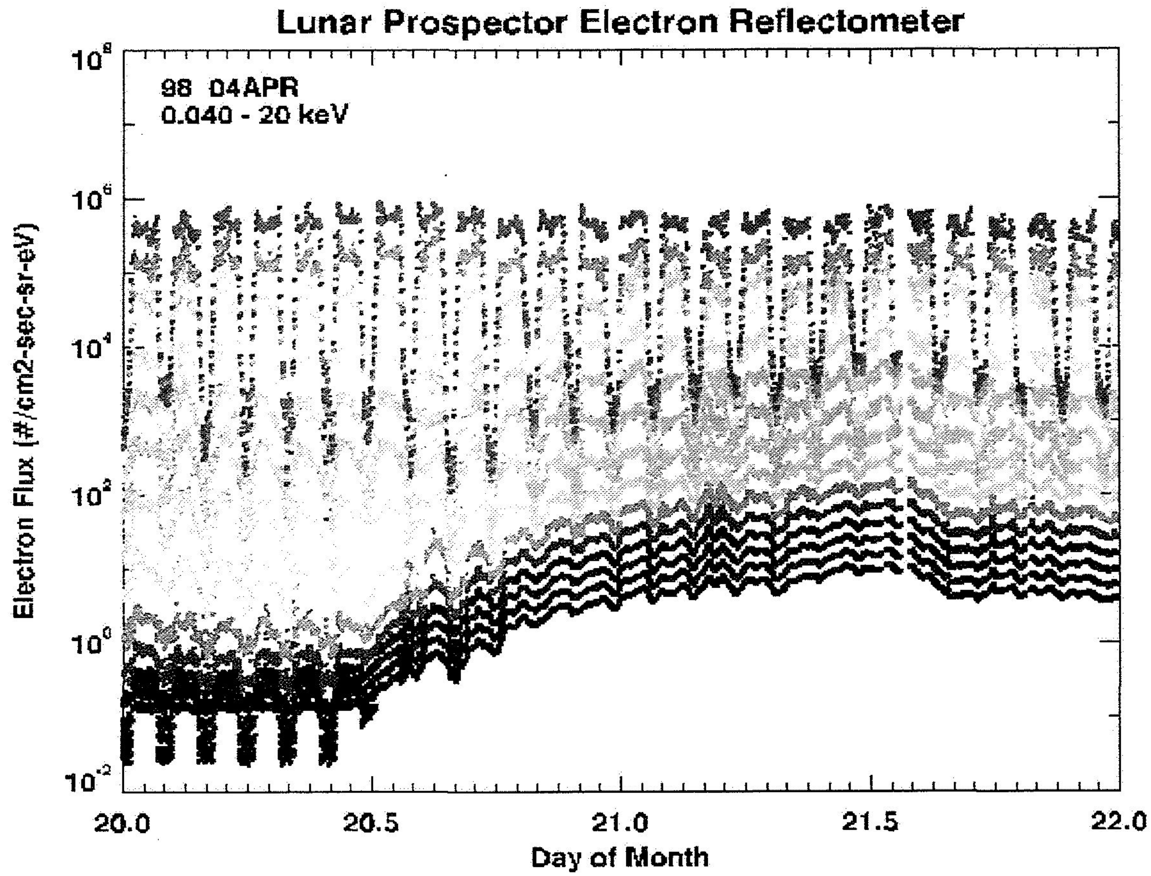
- Lunar Prospector Electron Reflectometer
  - Spin average electron flux
  - ~40 eV to ~20 keV
- 4-5April 1998
  - Moon in solar wind
  - Plasma wake



Lunar Plasma 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**

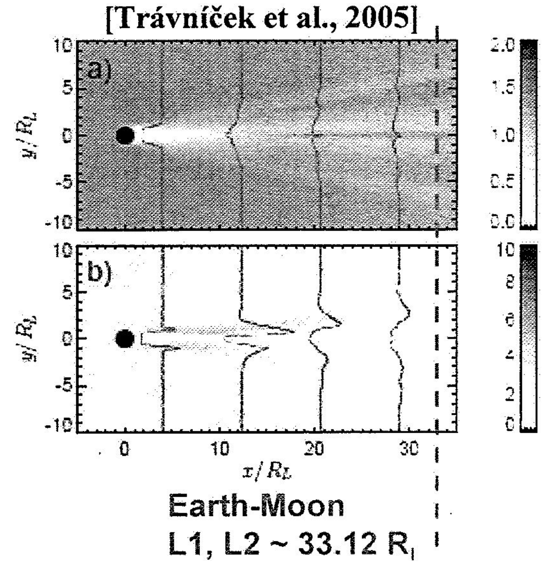


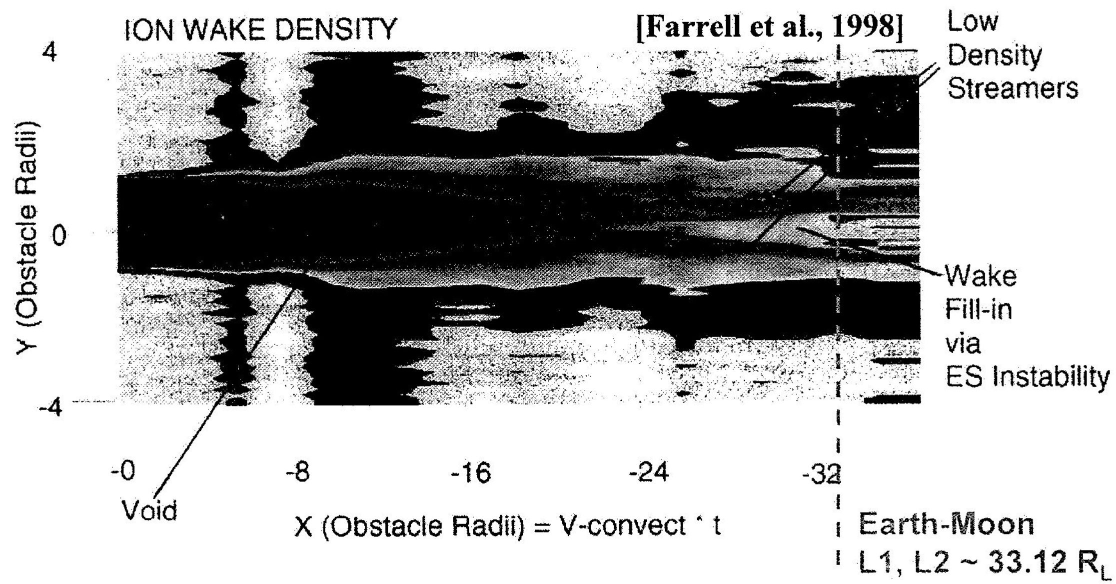
Lunar Wake

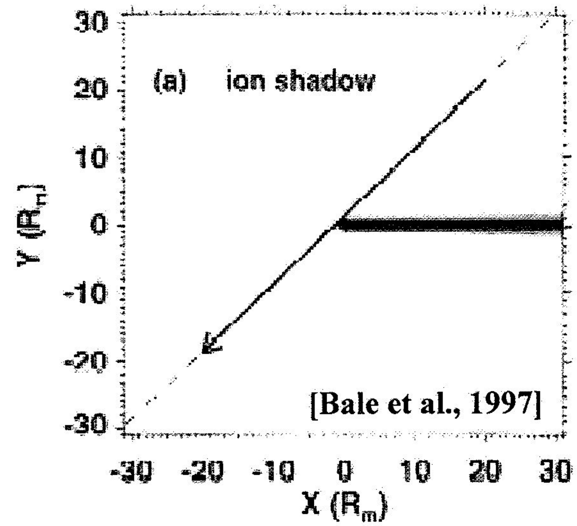
$\theta_{sw} \sim 45$ deg

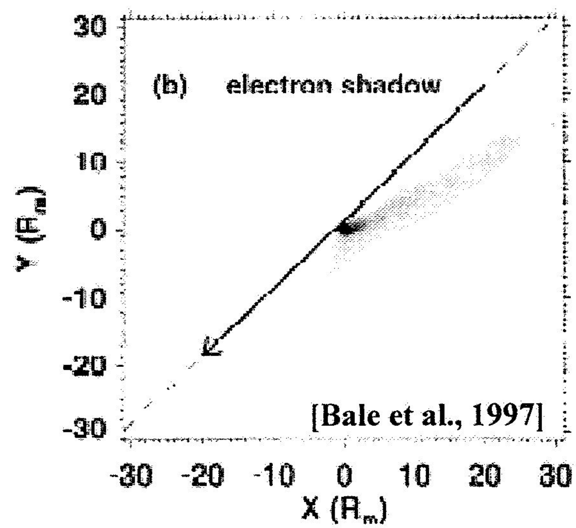
a) Density

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









Charging in Lunar Wake

Lunar Prospector

20-115 km

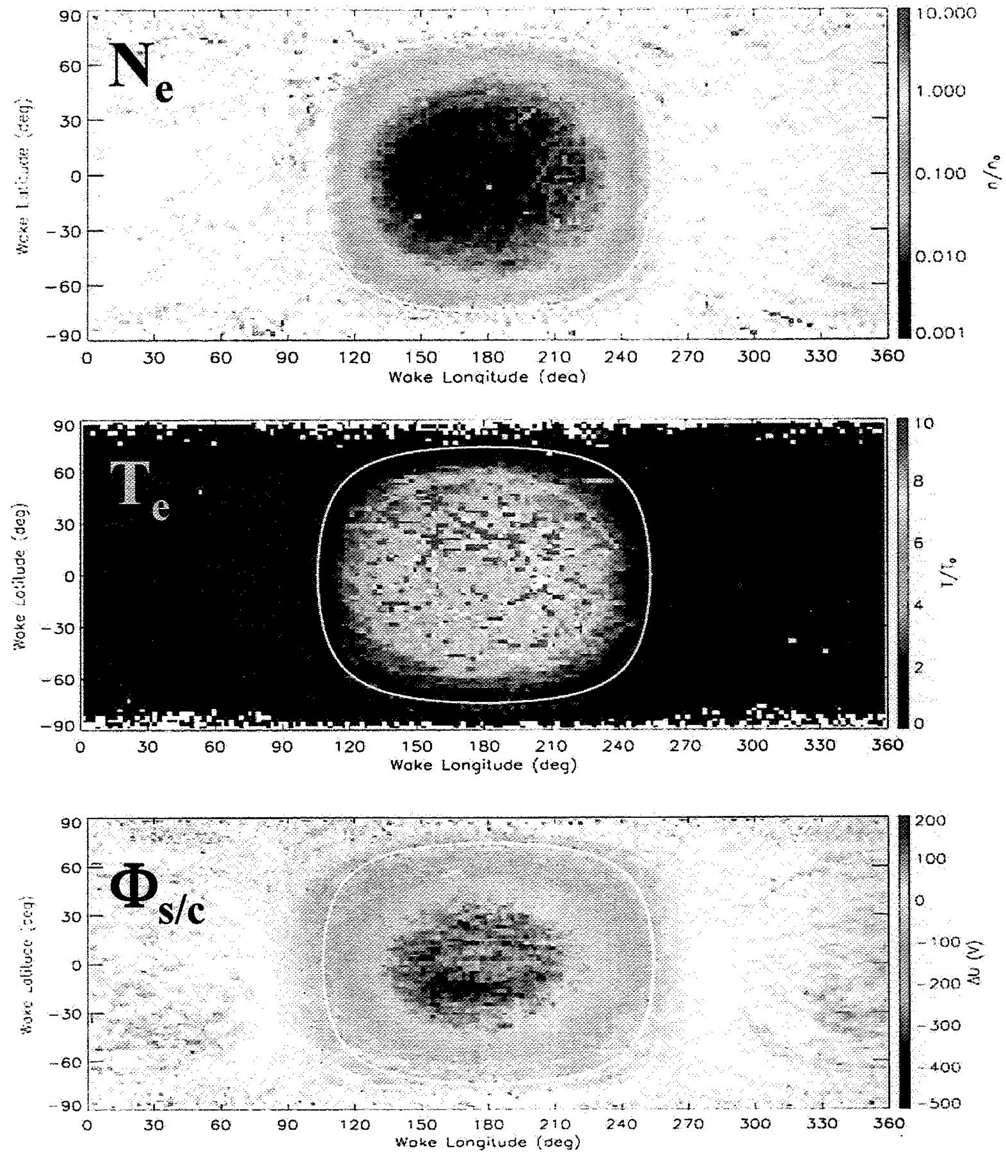
Wake properties relative to ambient solar wind

[Halekas et al. 2005]

Spacecraft potentials

day +10 V to +50V

night -100 V to -300 V

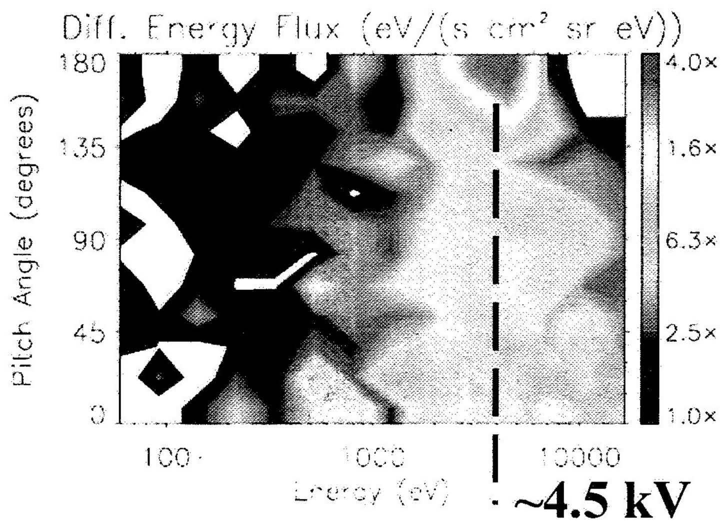


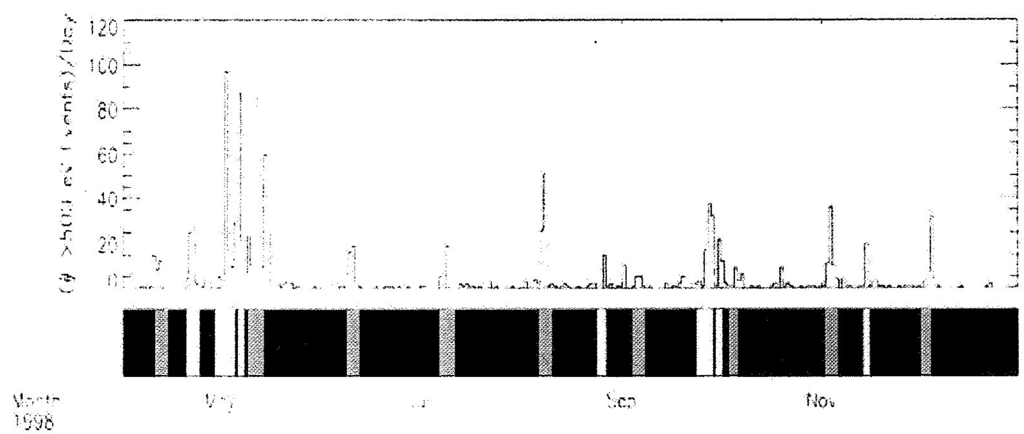
Charging in Lunar Environments

- 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 Te enhancements yield 72 to 122 eV (means)
    - Surface charging rule of thumb

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

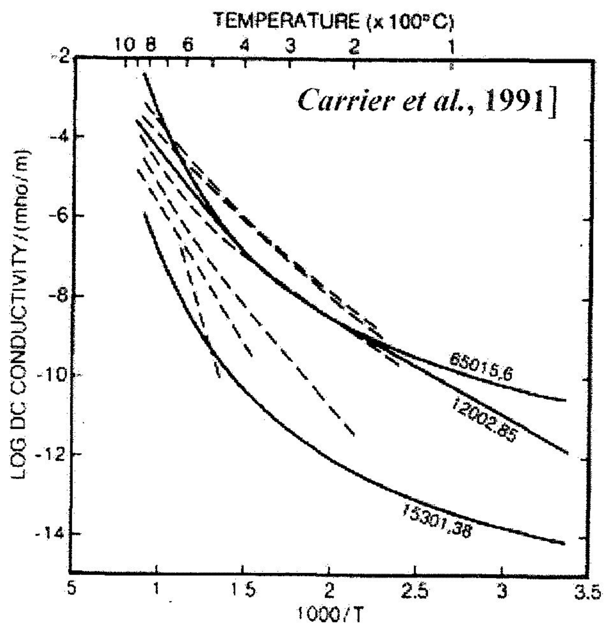
- Recent analysis of Lunar Prospector records [*Halekas et al.*, 2007] suggest lunar surface potentials ~ 4.5 kV

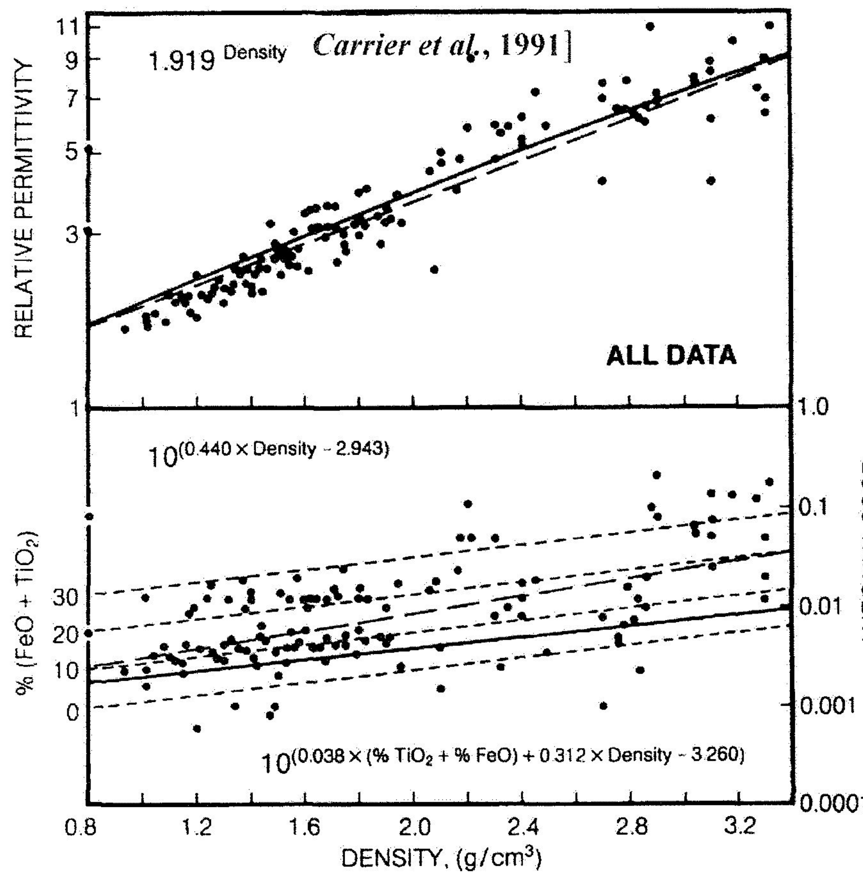




Electrical Properties of Lunar Regolith

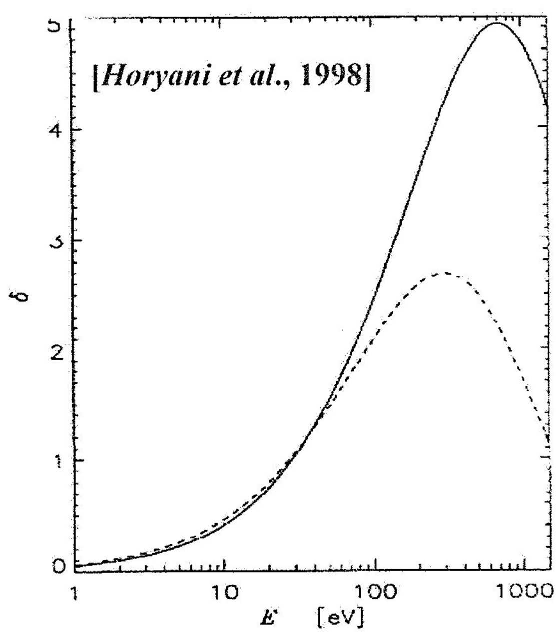
- Charging analyses require electrical properties of materials
  - $\sigma(T)$ conductivity
  - κ dielectric constant
  - Radiation induced conductivity parameters k_p, Δ
  - Secondary electron yields
- Terrestrial material properties meası
- Some information is available for lu





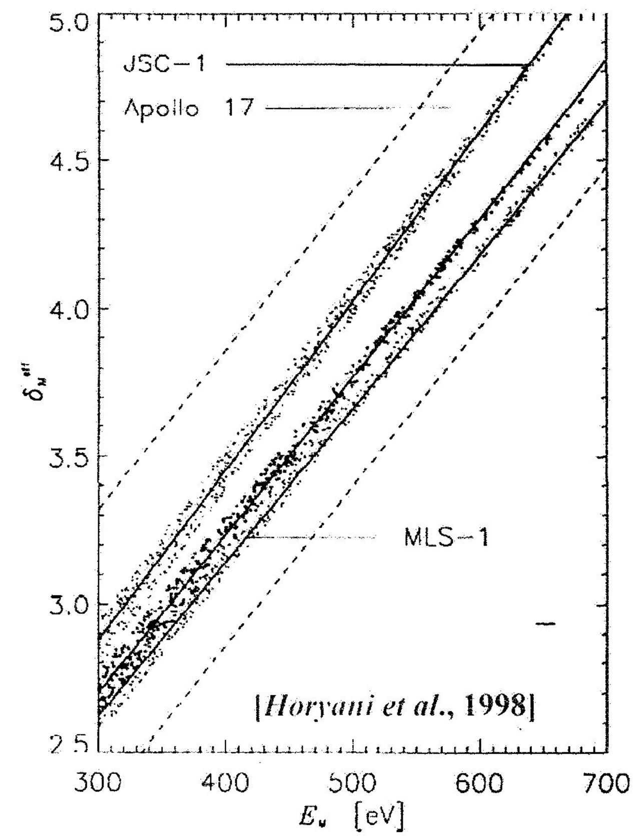
Electrical Properties of Lunar Regolith

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



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

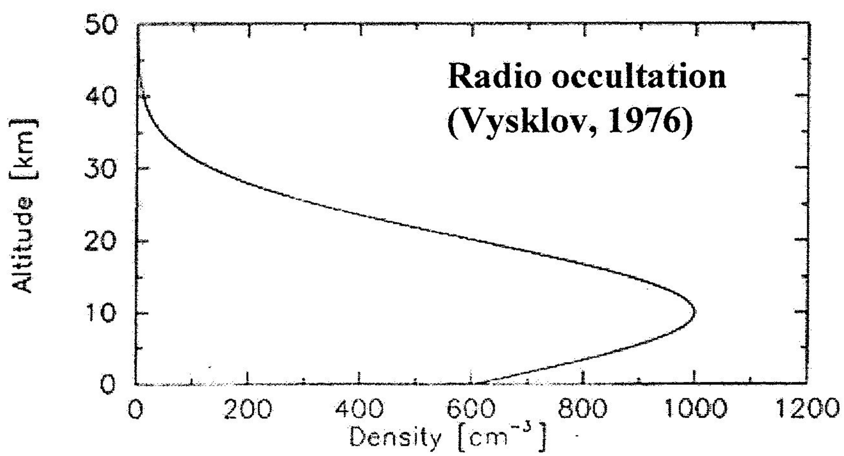
[*Sternglass*, 1954]



Lunar Secondary Electron Environments

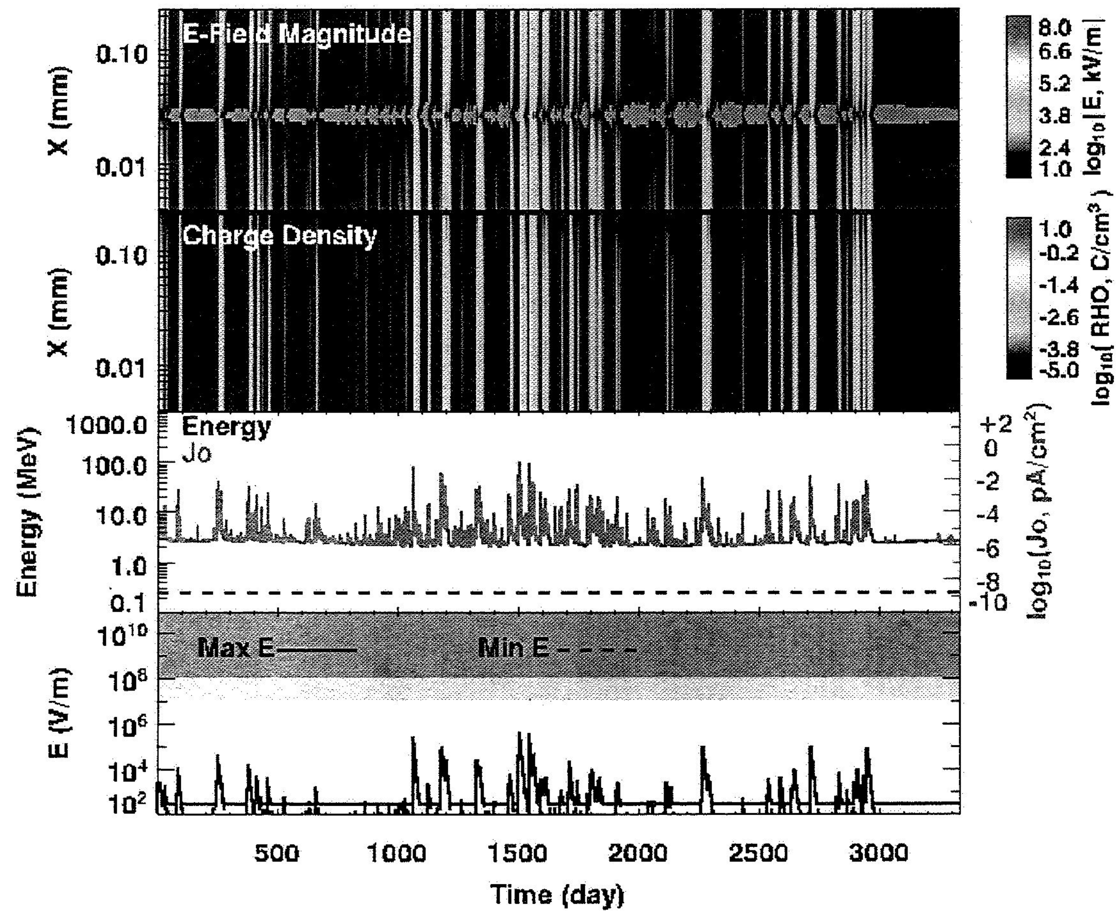
- Lunar photoelectron sheath
  - Vysklov (1976) reported lunar "ionosphere" using radio occultation technique from Luna 22 with peak electron densities of 500-1000 $\#/cm^3$ at altitudes of 5-10 km above sunlit lunar surface
  - In-situ measurements from Apollo 12, 15, 15 Suprathermal Ion Detector Experiment (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



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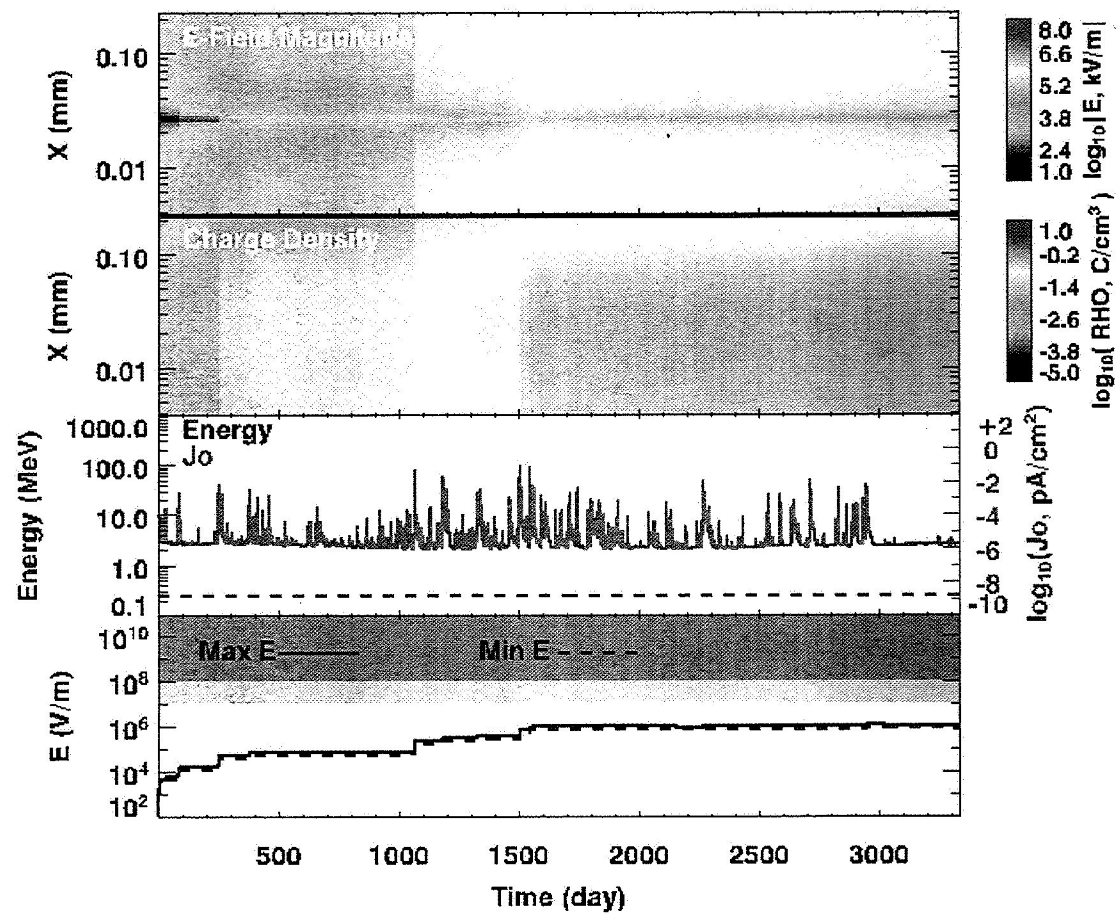
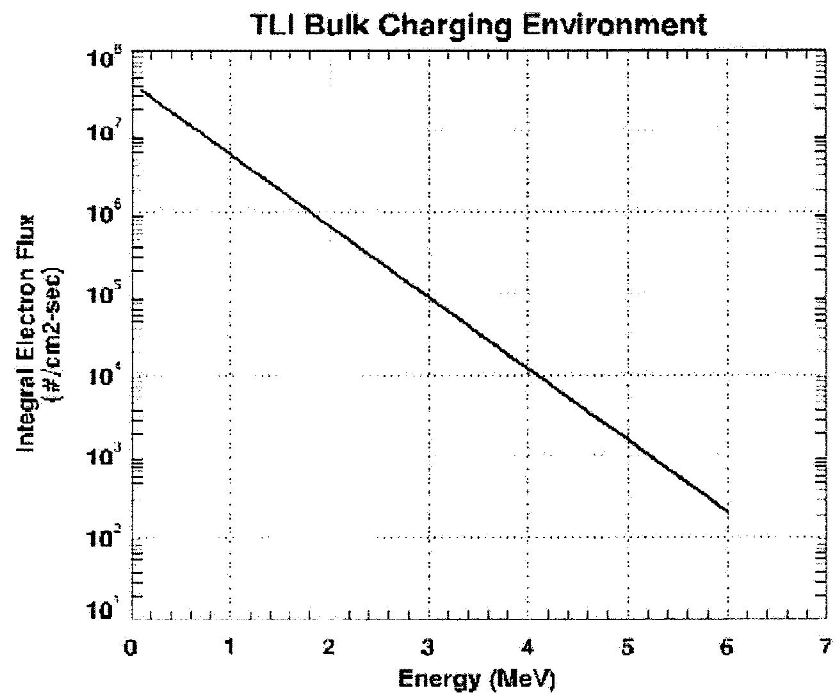


Constellation Design Environments

- 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**