MSFC - 596 - Abstract

Environment Challenges for Exploration of the Moon

Joseph I. Minow[1], William C. Blackwell, Jr.[2], Victoria N. Coffey[1], William B. Cooke[1], James W. Howard[2], Jr., Linda N. Parker[2], John Sharp[1], Greg Schunck[1], Robert W. Suggs[1], and Joseph W. Wang[3]

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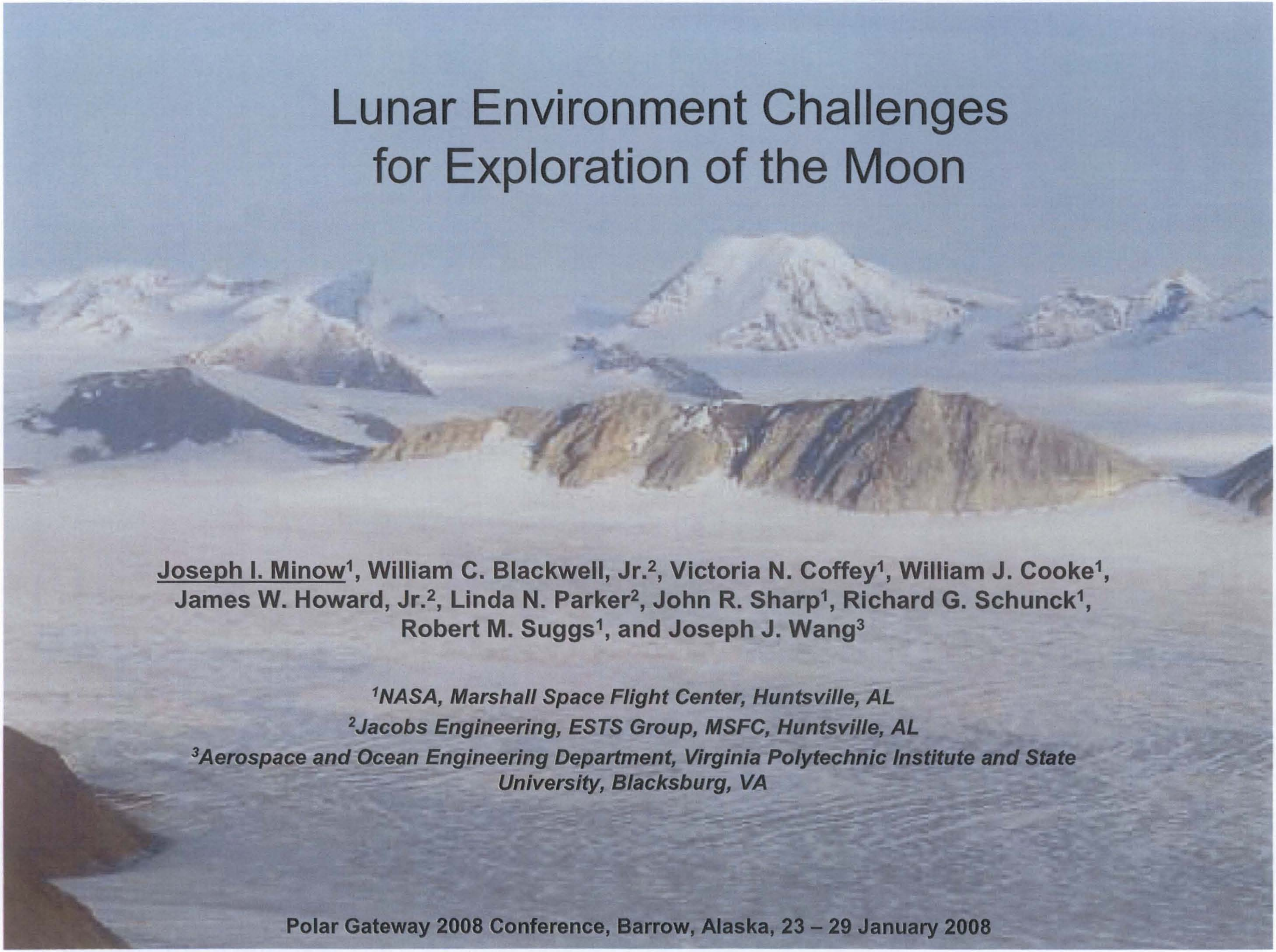
NASA's Constellation Program is designing a new generation of human rated launch and space transportation vehicles to first replace the Space Shuttle fleet, then support develop of a permanent human habitat on the Moon, and ultimately prepare for human exploration of Mars. The ambitious first step beyond low Earth orbit is to develop the infrastructure required for conducting missions to a variety of locations on the lunar surface for periods of a week and establishment of a permanent settlement at one of the lunar poles where crews will serve for periods on the order of ~200 days. We present an overview of the most challenging aspects of the lunar environment that will need to be addressed when developing transport and habitat infrastructure for long term human presence on the Moon including low temperatures and dusty regolith surfaces, radiation environments due to galactic cosmic rays and solar energetic particles, charging of lunar infrastructure when exposed to lunar plasma environments, and secondary meteor environments generated by primary impacts on the lunar surface.

MSFC-596-Presentation



Lunar Environment Challenges for Exploration of the Moon

Joseph I. Minow[1], **William C. Blackwell, Jr.**[2], **Victoria N. Coffey**[1], **William J. Cooke**[1], **James W. Howard, Jr.**[2], **Linda N. Parker**[2], **John R. Sharp**[1], **Richard G. Schunck**[1], **Robert M. Suggs**[1], and **Joseph J. Wang**[3]

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Introduction

- The Moon is an airless, dusty world of extremes in temperature exposed to the space plasma and radiation environments

- This presentation will:
  - Provide an overview of lunar environments of importance to development of infrastructure for human exploration of the Moon
  - Describe a variety of activities in progress to characterize lunar environments including use of
    - Historical data
    - New observations
    - Future spacecraft missions

- Overview
  - NASA's Constellation Program
  - Lunar atmosphere and dust
  - Illumination and thermal environments
  - Meteor impacts
  - Radiation
  - Plasma
  - Summary

- **Constellation**
- Lunar atmosphere and dust
- Illumination and Thermal Environments
- Meteor impacts
- Radiation
- Plasma
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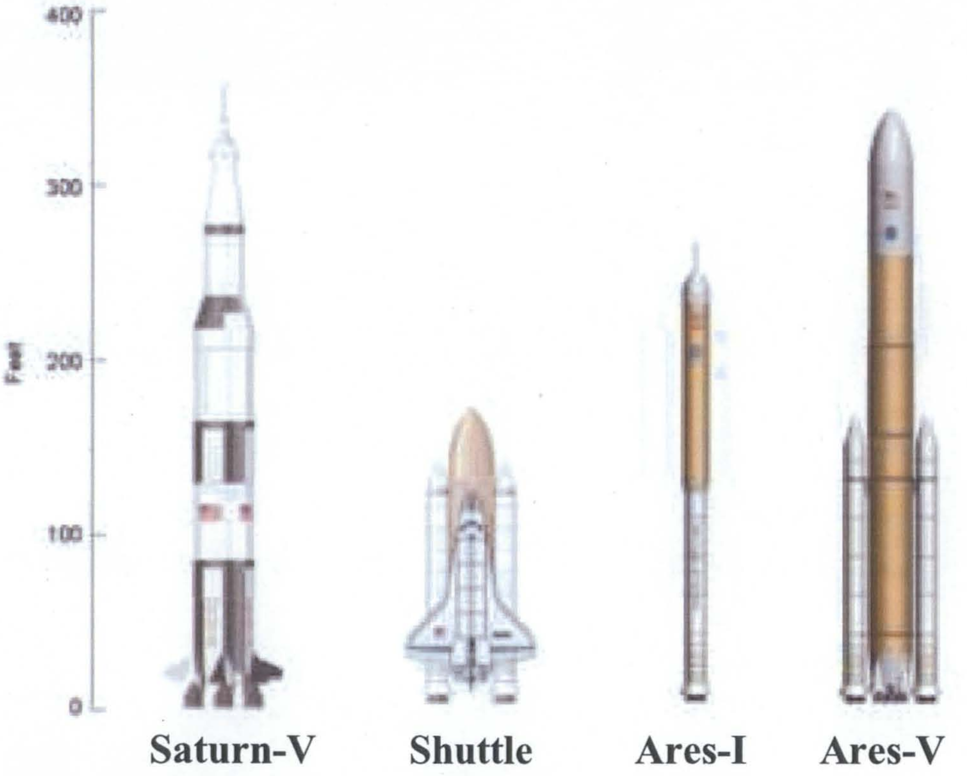
Constellation Program

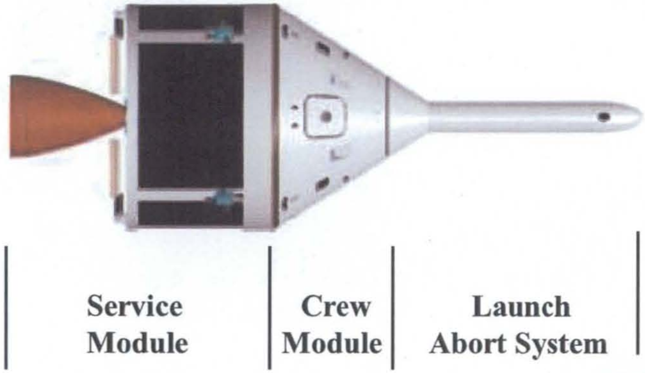
- Human-rated space transportation system to replace Space Transportation System (Shuttle)
  - ISS support ~2014
  - Lunar exploration ~2020
  - Mars exploration TBD

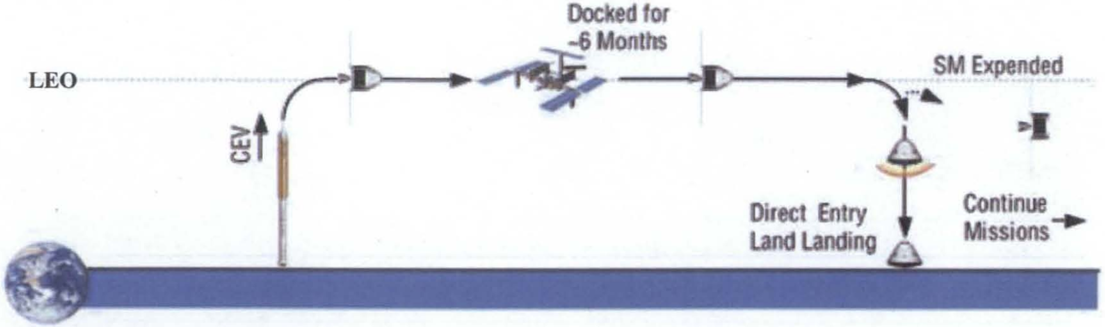


[NASA's Exploration Systems Architecture Study—Final Report, Nov 2006]

ISS Support

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





Lunar Exploration Architecture

Composite Shroud

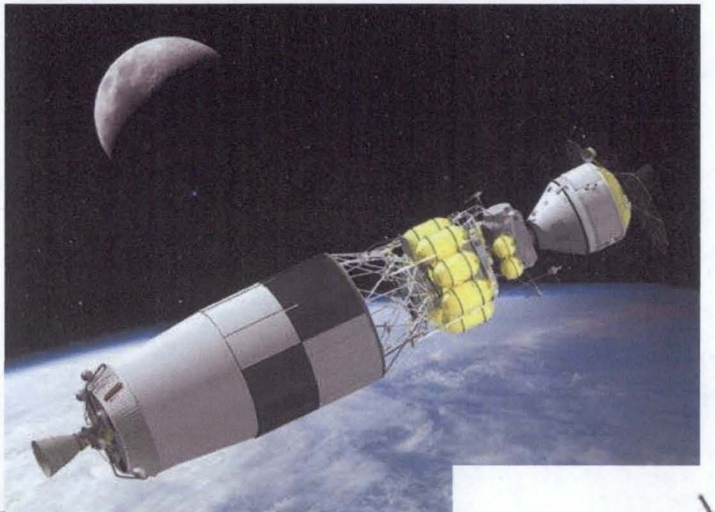
Lunar Surface Access Module (LSAM)

<u>Earth Departure Stage</u>
LOx/LH$_2$
1 J-2X Engine
Al-Li Tanks/Structures

Interstage

<u>Core Stage</u>
LOx/LH$_2$
5 RS-68 Engines
Al-Li Tanks/Structures

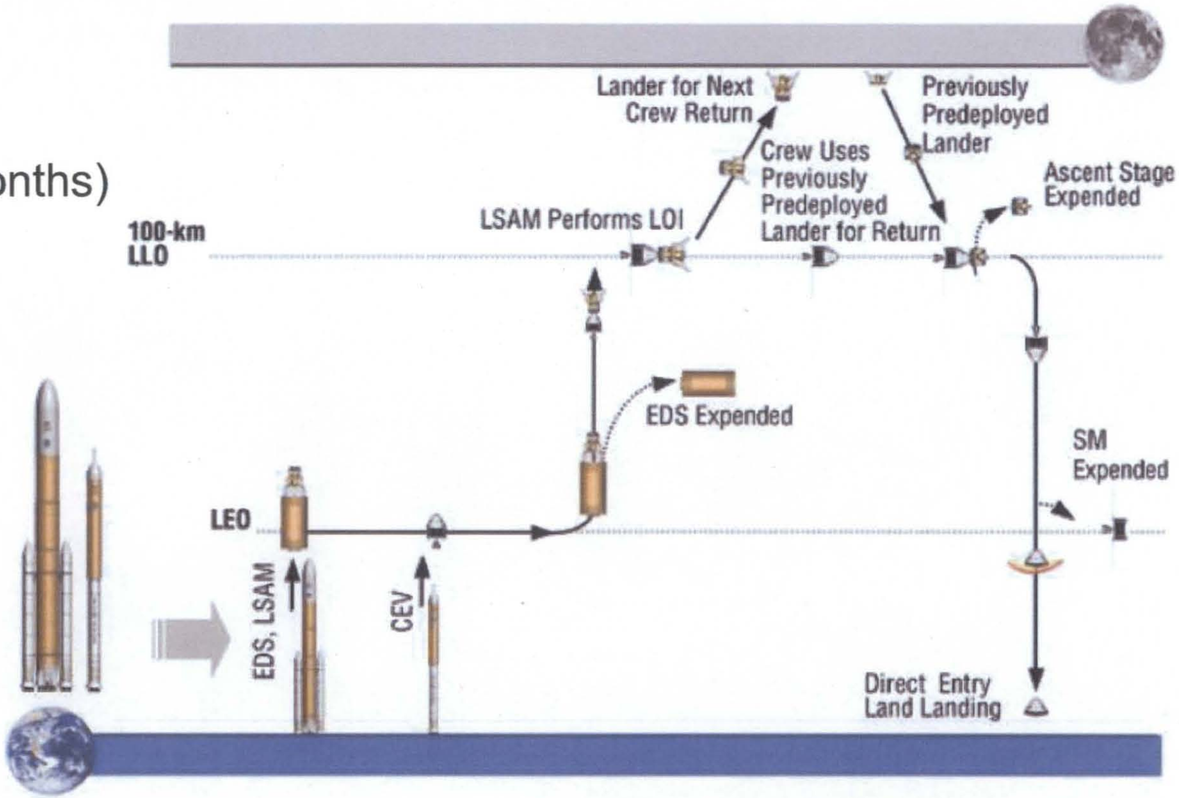
5-Segment
2 RSRB's



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

Example Lunar Mission

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



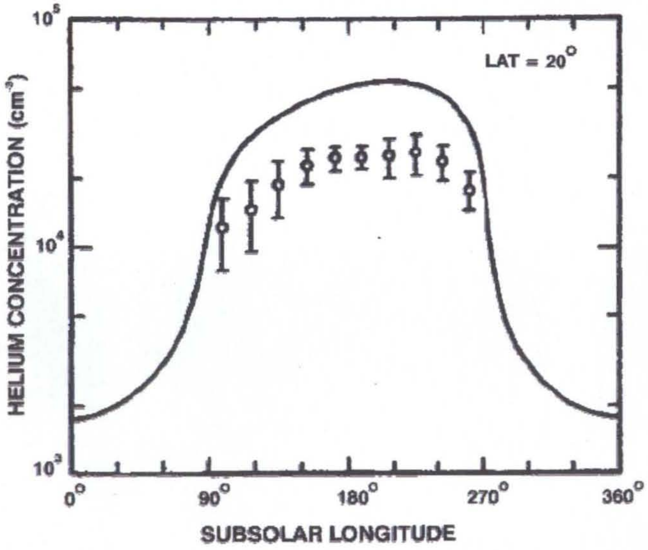
[NASA's Exploration Systems Architecture Study—Final Report, Nov 2006]

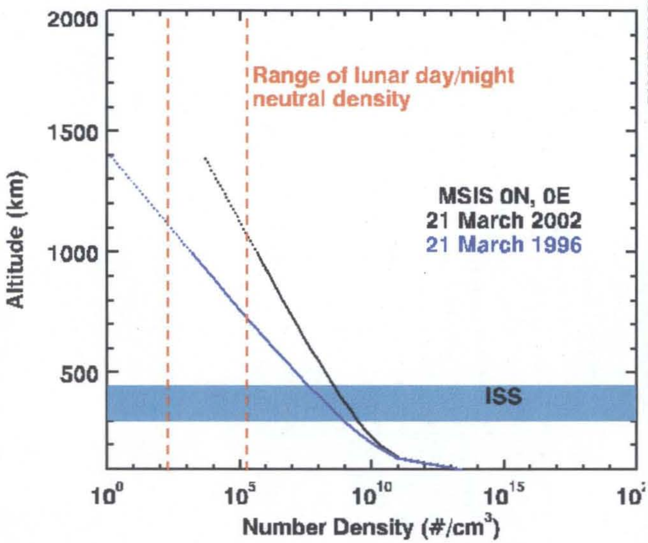
- Current program focus is on developing an outpost at one of the lunar poles with access to other locations on lunar surface
- Designing long term habitats for the lunar poles requires an understanding of the environments in the lunar polar regions.

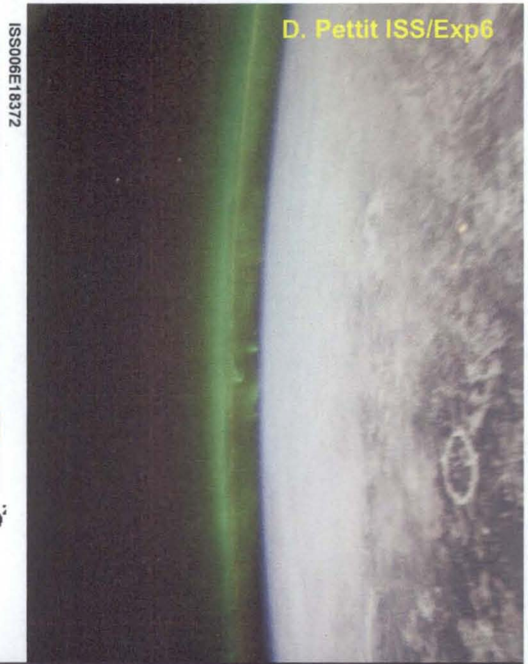
- Constellation
- **Lunar atmosphere and dust**
- Illumination and Thermal Environments
- Meteor impacts
- Radiation
- Plasma
- Summary

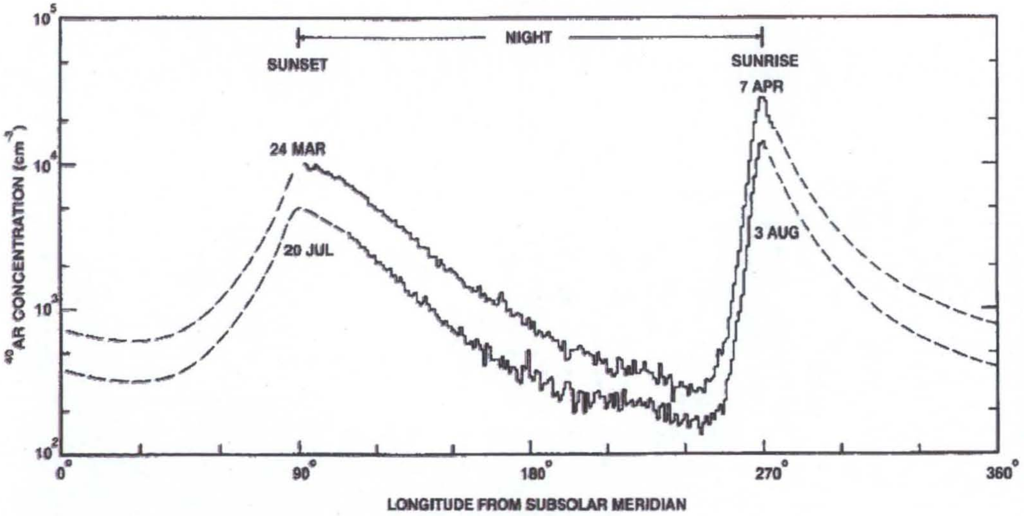
Lunar Atmosphere

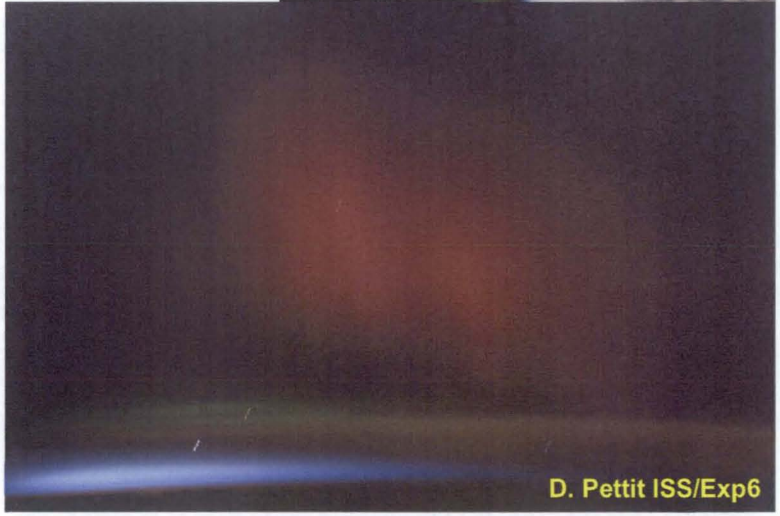
Moon's tenuous atmosphere (exosphere) dominated by ^{40}Ar, He



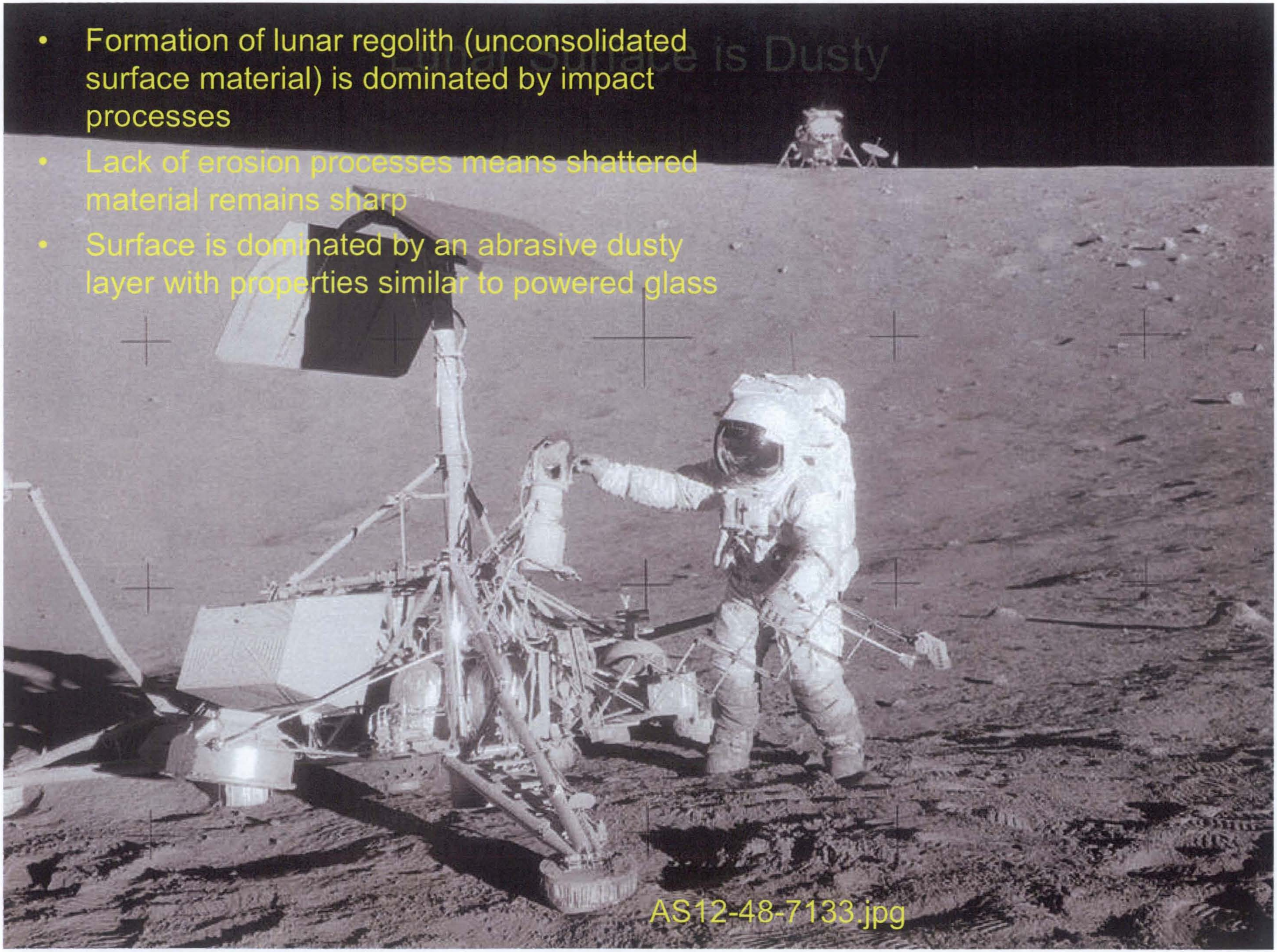








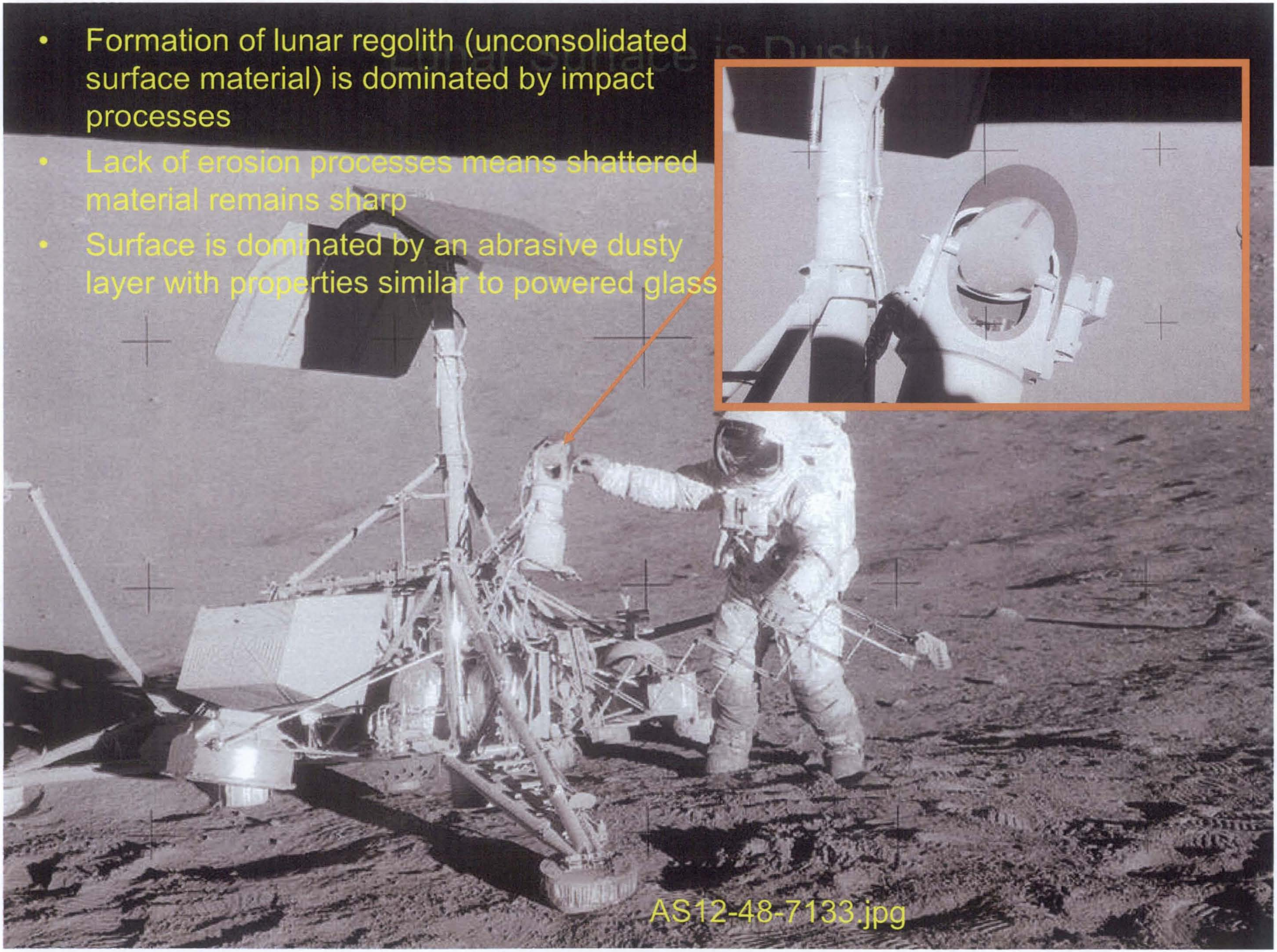
Lunar Surface is Dusty



- Formation of lunar regolith (unconsolidated surface material) is dominated by impact processes
- Lack of erosion processes means shattered material remains sharp
- Surface is dominated by an abrasive dusty layer with properties similar to powered glass

AS12-48-7133.jpg

Lunar Surface is Dusty



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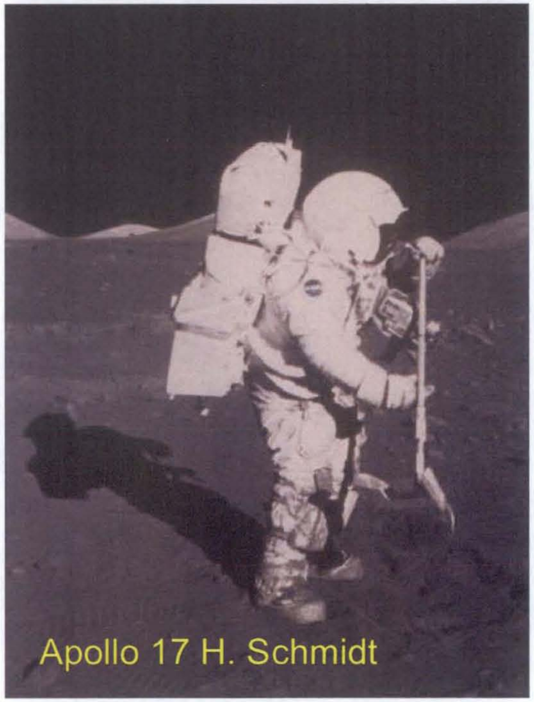
AS12-48-7133.jpg

Lunar Dust

Surveyor III footpad
Apollo 12
AS12-48-7110 (OF300)

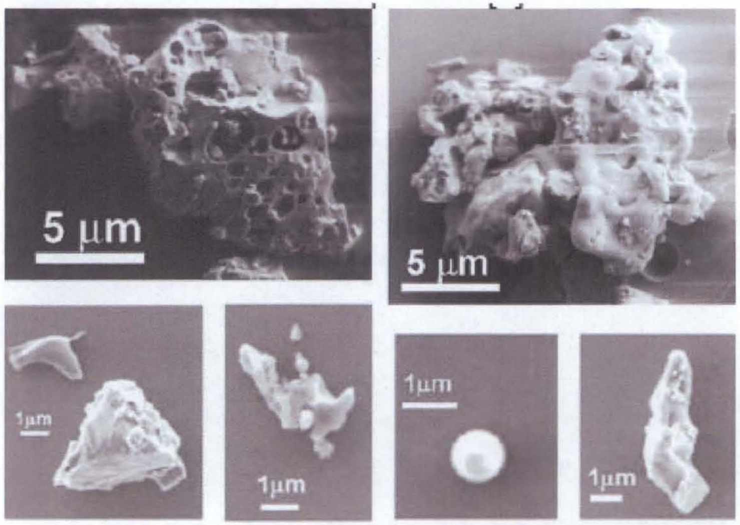
Apollo 17



Apollo 17 H. Schmidt

Lunar Dust Properties

- Lunar dust is a serious issue for engineering in lunar environments
  - Sharp, abrasive particles
  - Abrasion of EVA suits, seals, bearings
  - Human health including



[Park et al., 2006]

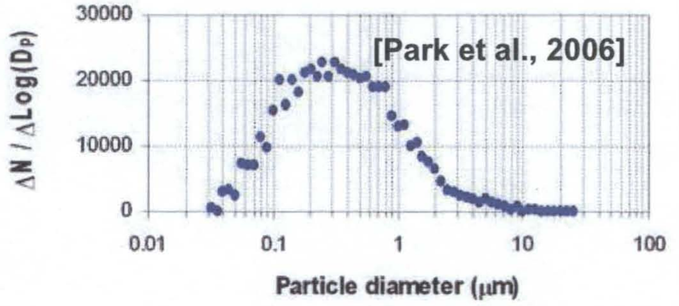


Figure 2. Particle size distribution of Apollo 17 lunar dust 70051

[Park et al., 2006]

- Constellation
- Lunar atmosphere and dust
- **Illumination and Thermal Environments**
- Meteor impacts
- Radiation
- Plasma
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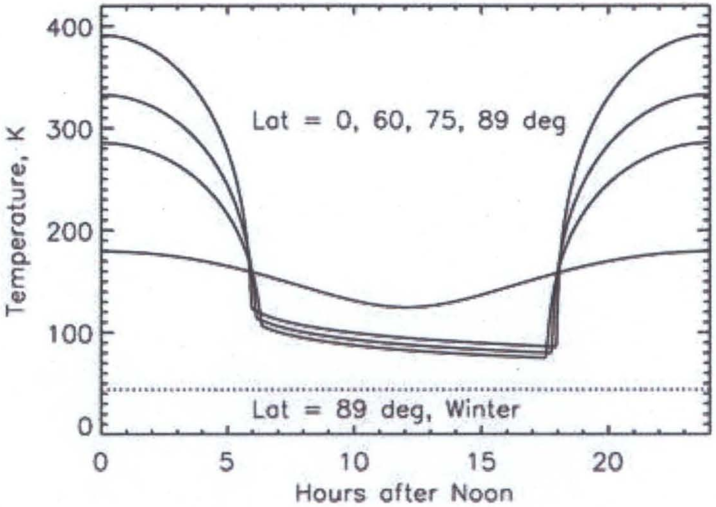
Lunar Temperature Extremes

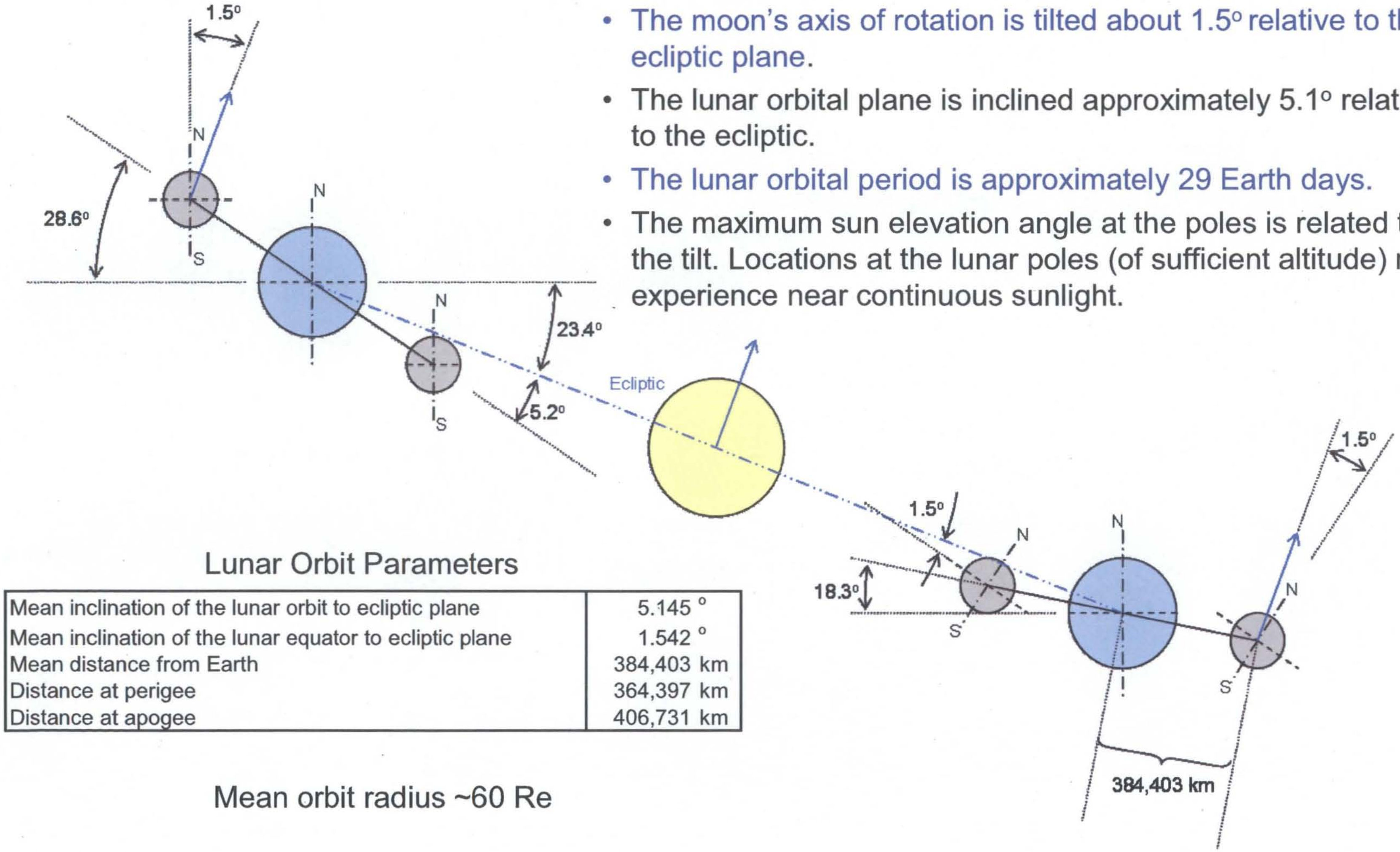
- Moon has greatest temperature variation of any body in the solar system except Mercury
  - Equator: 400K at day to less than 100K at night
  - Polar regions: 120K to 180K during day
  - Shadowed regions at poles: 40K to 60K



- Compare to terrestrial temperatures:
  - Barrow

Lunar Orbit and Solar Elevation Angle

- The moon's axis of rotation is tilted about 1.5° relative to the ecliptic plane.
- The lunar orbital plane is inclined approximately 5.1° relative to the ecliptic.
- The lunar orbital period is approximately 29 Earth days.
- The maximum sun elevation angle at the poles is related to the tilt. Locations at the lunar poles (of sufficient altitude) may experience near continuous sunlight.



Lunar Orbit Parameters

Mean inclination of the lunar orbit to ecliptic plane	5.145 °
Mean inclination of the lunar equator to ecliptic plane	1.542 °
Mean distance from Earth	384,403 km
Distance at perigee	364,397 km
Distance at apogee	406,731 km

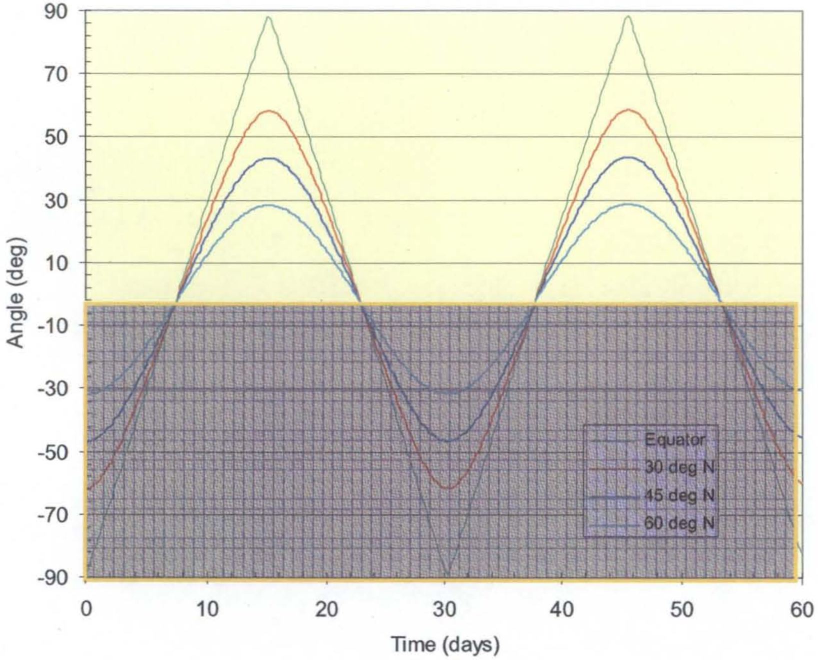
Mean orbit radius ~60 Re

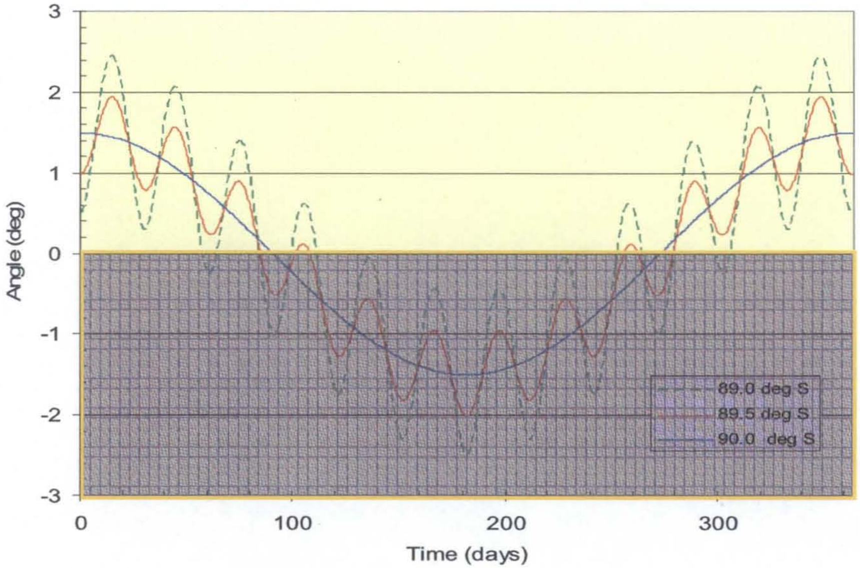
[*Sharp and Schunk*, 2007]

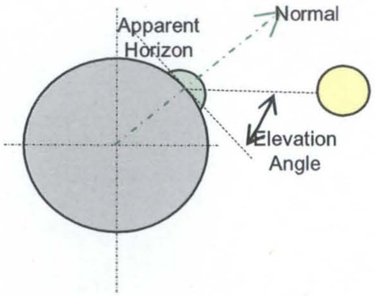
Polar Illumination

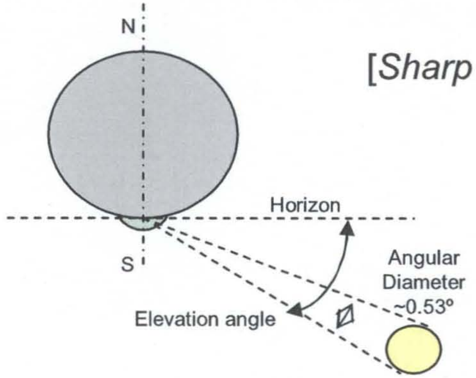
Solar Elevation Angles (Typical Solar Elevation for Lunar South Pole)

Solar angular diameter (~0.53° from lunar surface) i s important for considering illumination in polar regions





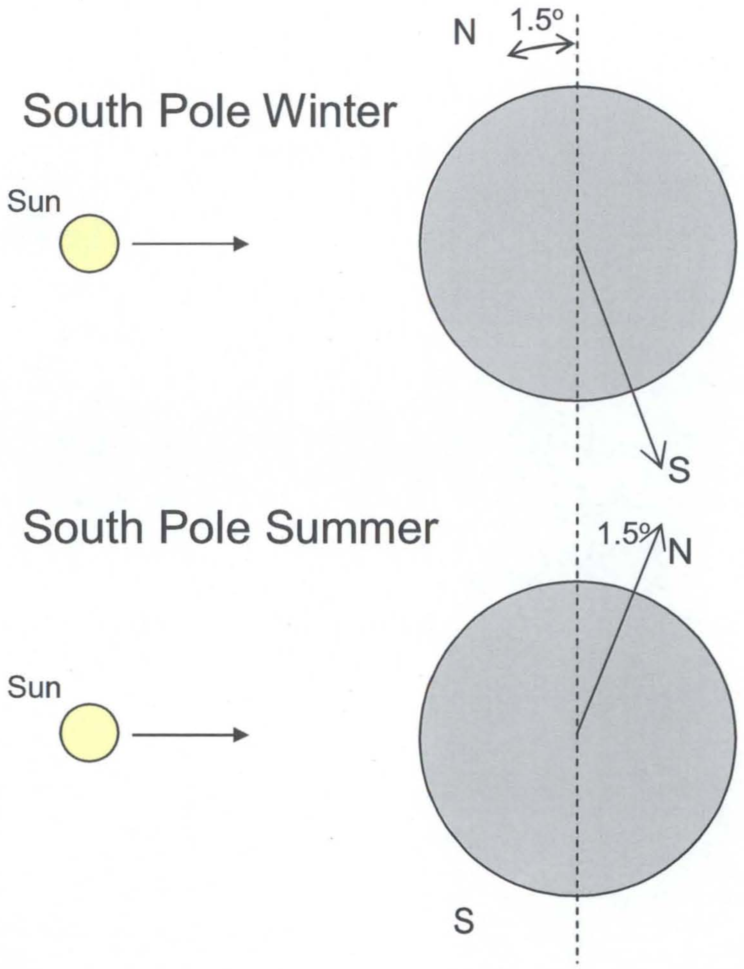




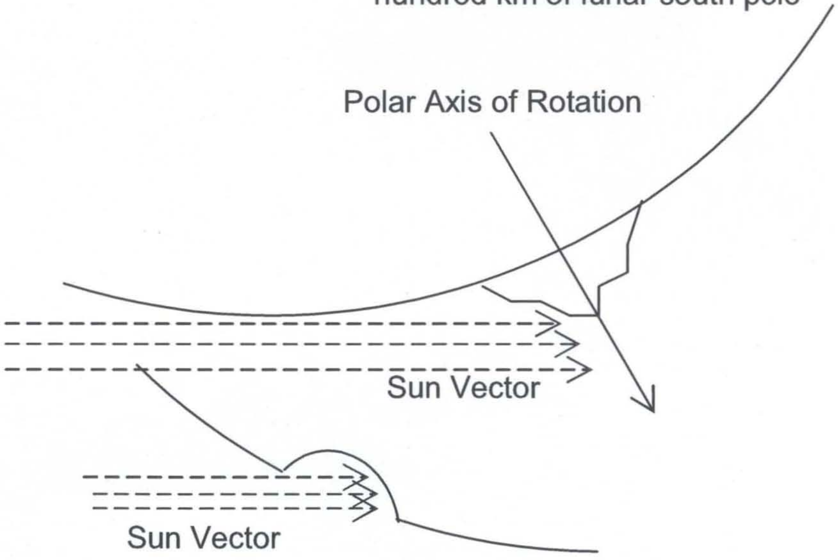
[*Sharp and Schunk*, 2007]

Eternal Light and Dark

- Depending on altitude, lunar polar regions may have continuous (or near continuous) sunlight or darkness



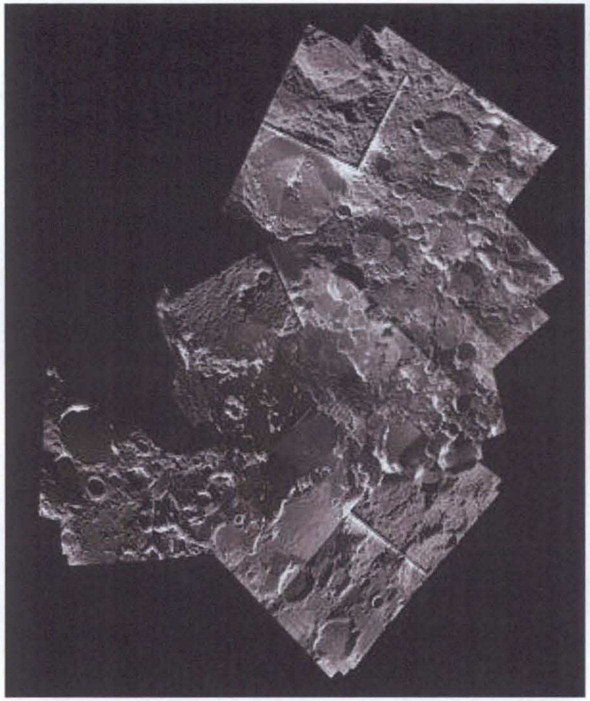
- Local topography is important
  - Moon is nearly spherical
  - Local variations are greater than figure of the Moon
    - Earth: +/- 10 km from geoid
      ~9 km max/??? Min altitudes
    - Moon: +/- ~0 from geoid
      ~10 km altitude variation within few hundred km of lunar south pole



[*Sharp and Schunk*, 2007]

Light and Dark of the Lunar Poles

- North pole

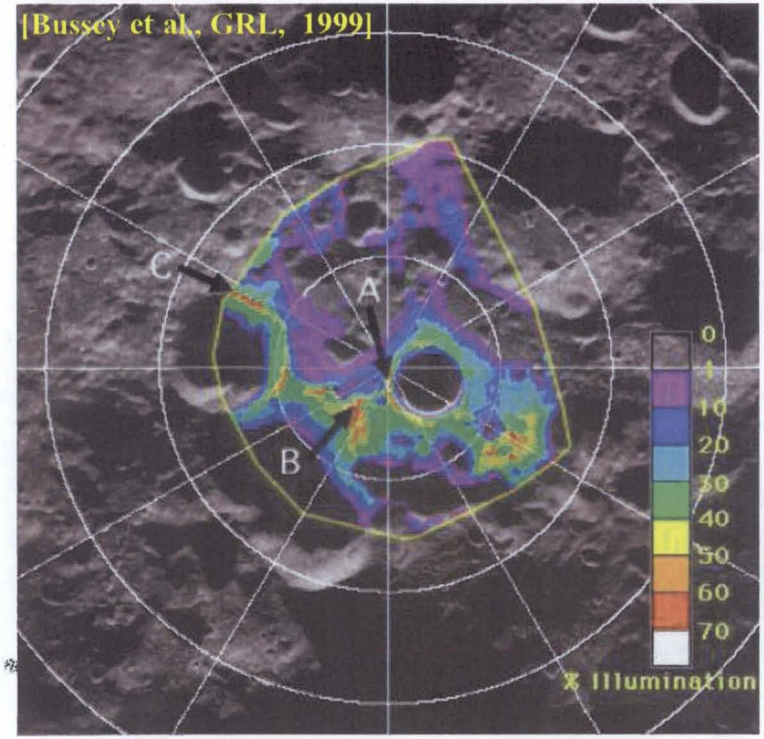


This mosaic of the lunar north pole was obtained with images taken by the Advanced Moon Imaging Experiment (AMIE) on board ESA's SMART-1. The mosaic, composed of about 30 images, covers an area of about 800 by 600 km. (Credit: ESA/Space-X (Space Exploration Institute))

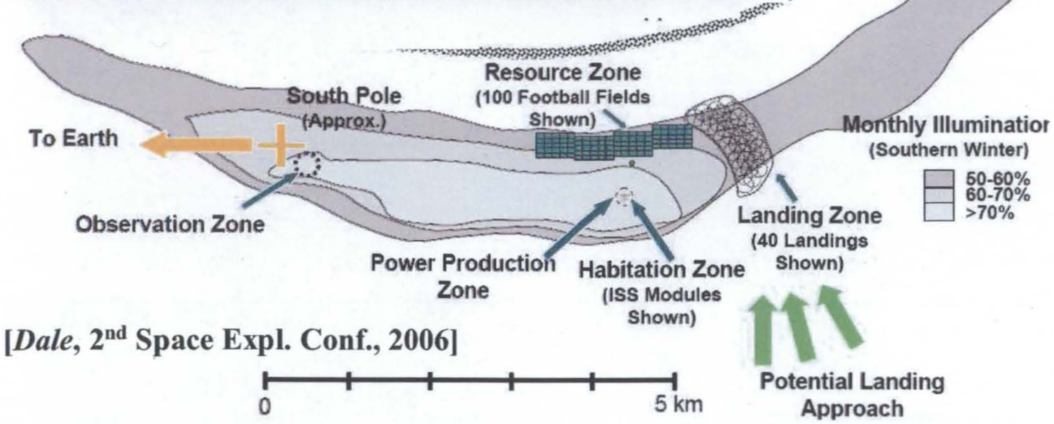
Image of a 275 km area close to the North pole (upper left corner) observed by ESA's SMART-1 on 29 Dec 2004 from 5500 km distance. This shows a heavily cratered highland terrain, and is used to monitor illumination of polar areas, and long shadows cast by large crater rims. (Credits: ESA/SMART-1/SPACE-X Space Exploration Institute)

Lunar South Pole

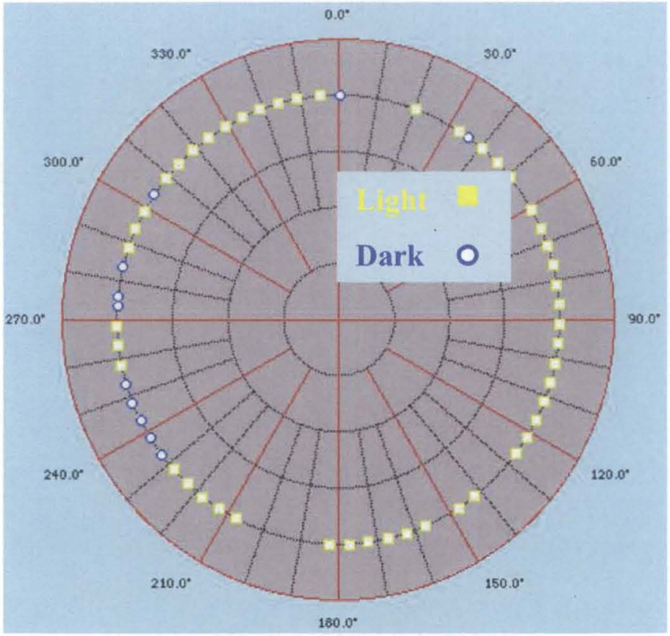
- >70% illumination on rim of Shakelton Crater
- T ~ 220±10 K…relatively benign!
  - Compare with terrestrial extreme of 146 K (-127°C) at Vostok, Antarctica
- Night temperatures near equator are T~ 100K
- T~40K to 50K in permanently dark craters



[Bussey et al., GRL, 1999]



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

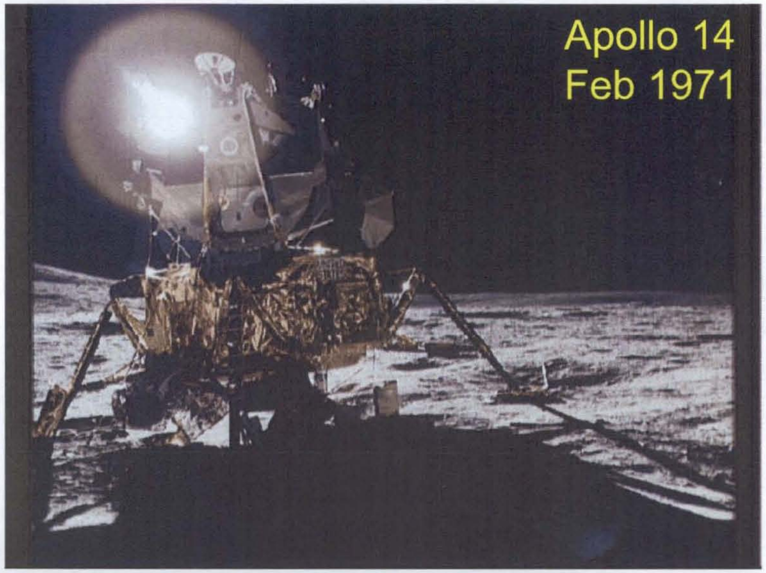


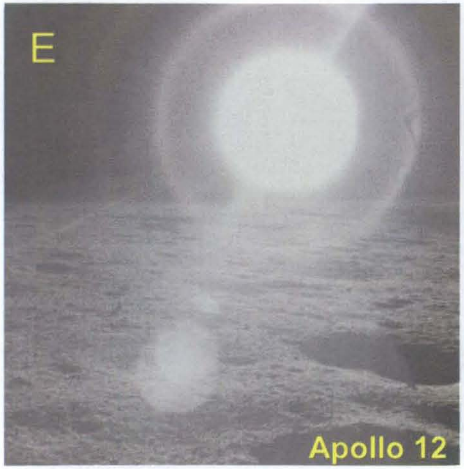
[adapted from *Bussey et al.*, LPSC 1999]

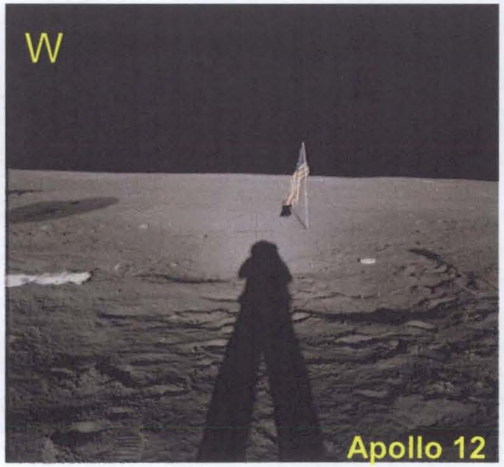
Longest period of shadow ~49 hours based on ~29.5day/Sol or 12.2 deg/day

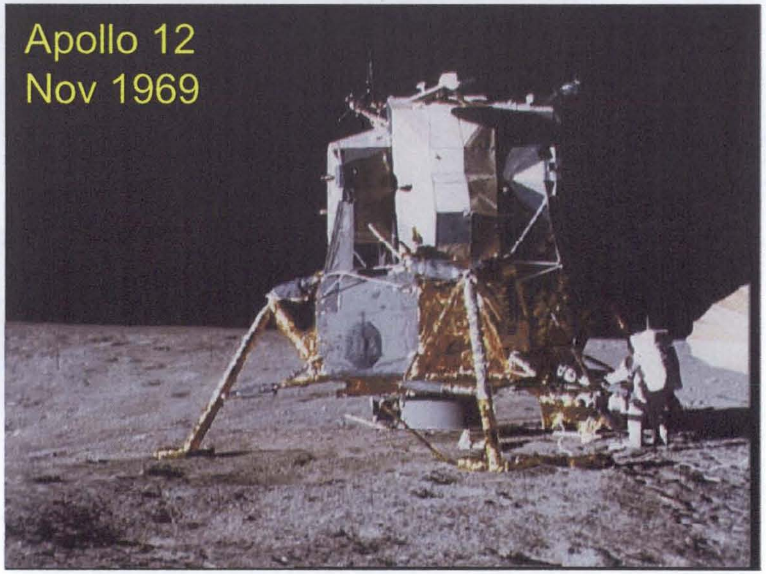
Apollo Illumination Experience

- Apollo 14….10.3° solar elevation angle
- Apollo 12…. 5.1° solar elevation angle





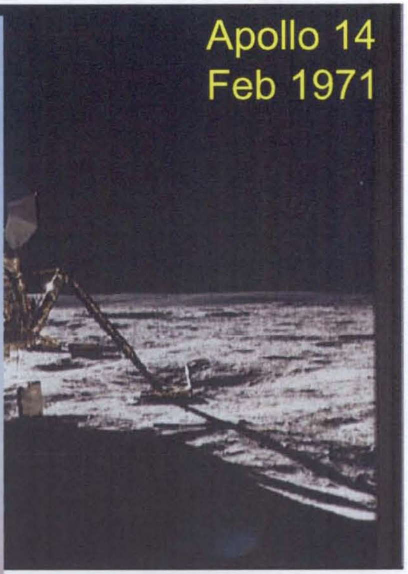


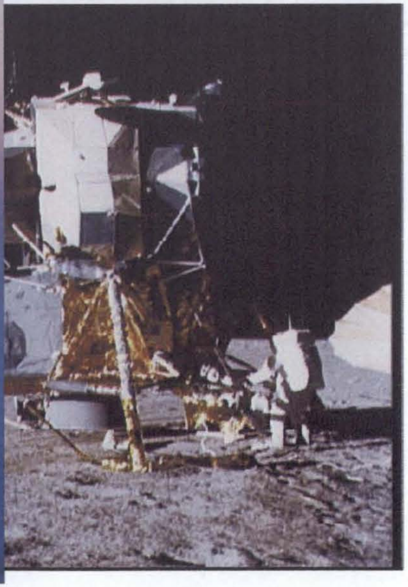


Apollo Illumination Experience

- A
- A


Barrow, 23 Jan 2008

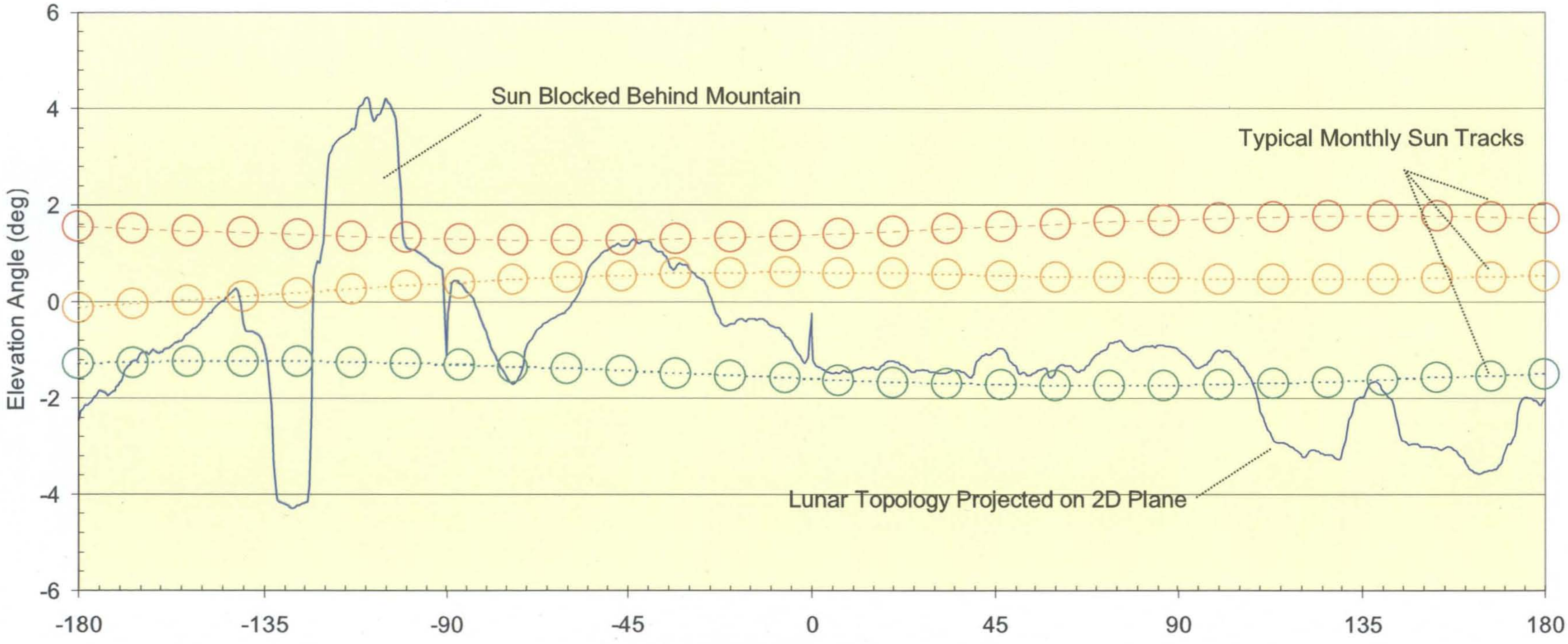

Apollo 14
Feb 1971



Local Terrain Shadowing

- South pole

(Reference point is Lunar South Pole at 0 meter elevation relative to mean Lunar radius)

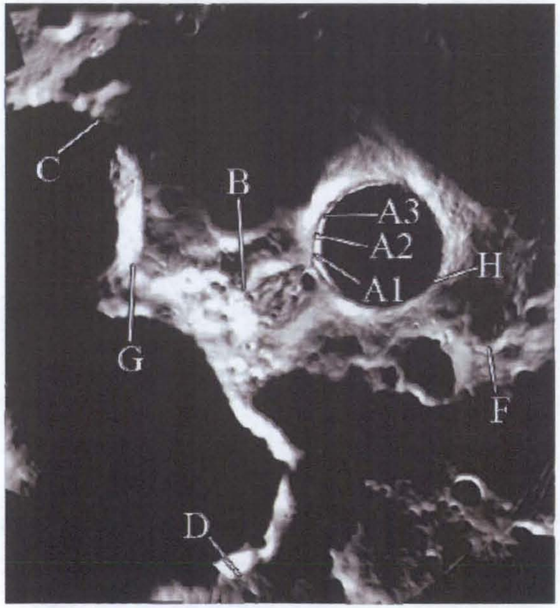


[*Sharp and Schunk*, 2007]

Note: Solar track is approximately one lunar day (29 earth days) in duration. There are approximately 13 lunar days per year. The sun will traverse across the entire sky (360°) in one lunar day.

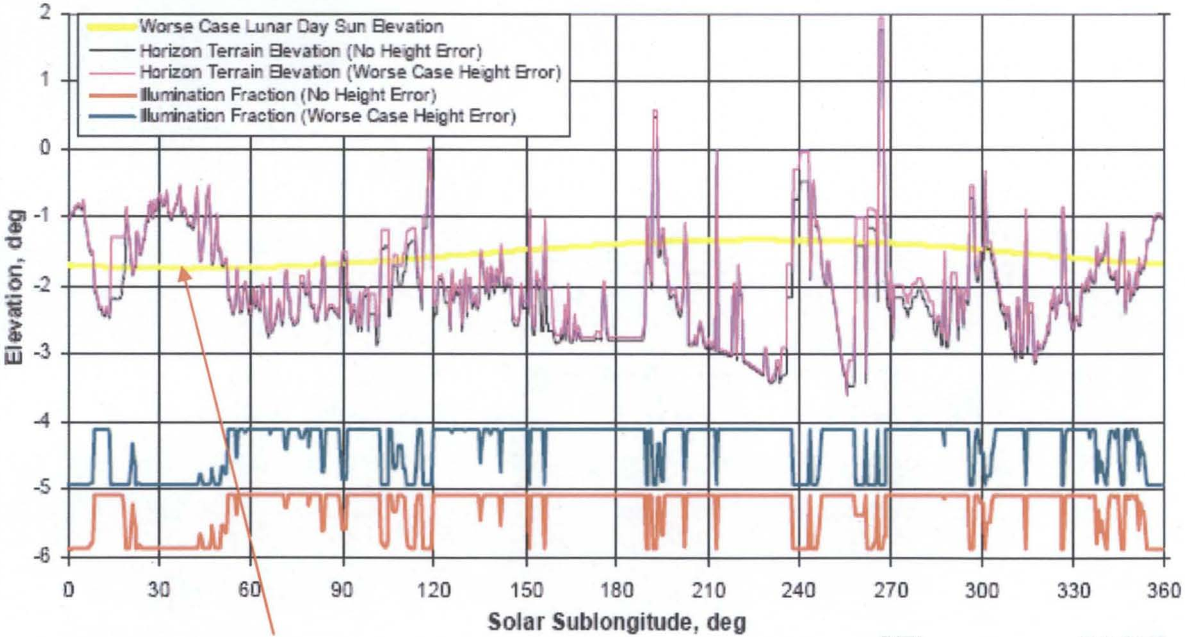
Terrain Shadowing at Shackleton Crater Rim

- Specification of operational environments for landing, EVA worksites
  - Models need to include horizon dependent illumination
  - Solar disk/umbral effects
- Characterization of photoelectron emission processes involved in spacecraft charging, wake charging in shadows



[*Fincannon*, 2007]

Site A1, Shackleton Rim

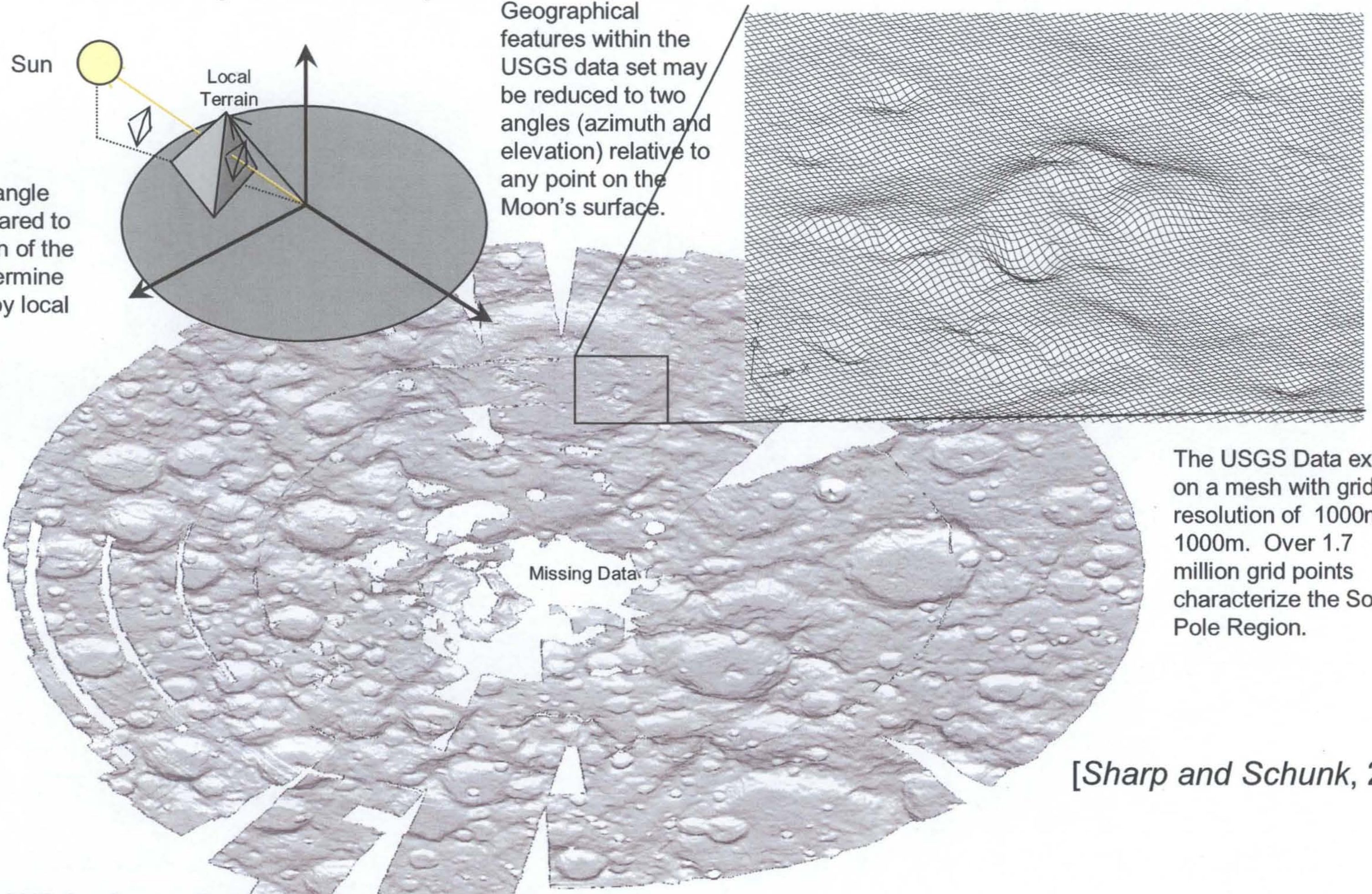


[*Fincannon*, 2007]

Plasma wake ~2.3 day duration

Lunar Terrain Modeling

- Digital U.S. Geological Survey topographical maps are currently being used to study illumination characteristics of lunar poles
- New data from Lunar Reconnaissance Orbiter, Selene probes will fill in holes near poles that are currently under sampled



Elevation angle may compared to the position of the sun to determine blockage by local terrain.

Geographical features within the USGS data set may be reduced to two angles (azimuth and elevation) relative to any point on the Moon's surface.

The USGS Data exists on a mesh with grid resolution of 1000m x 1000m. Over 1.7 million grid points characterize the South Pole Region.

[*Sharp and Schunk*, 2007]

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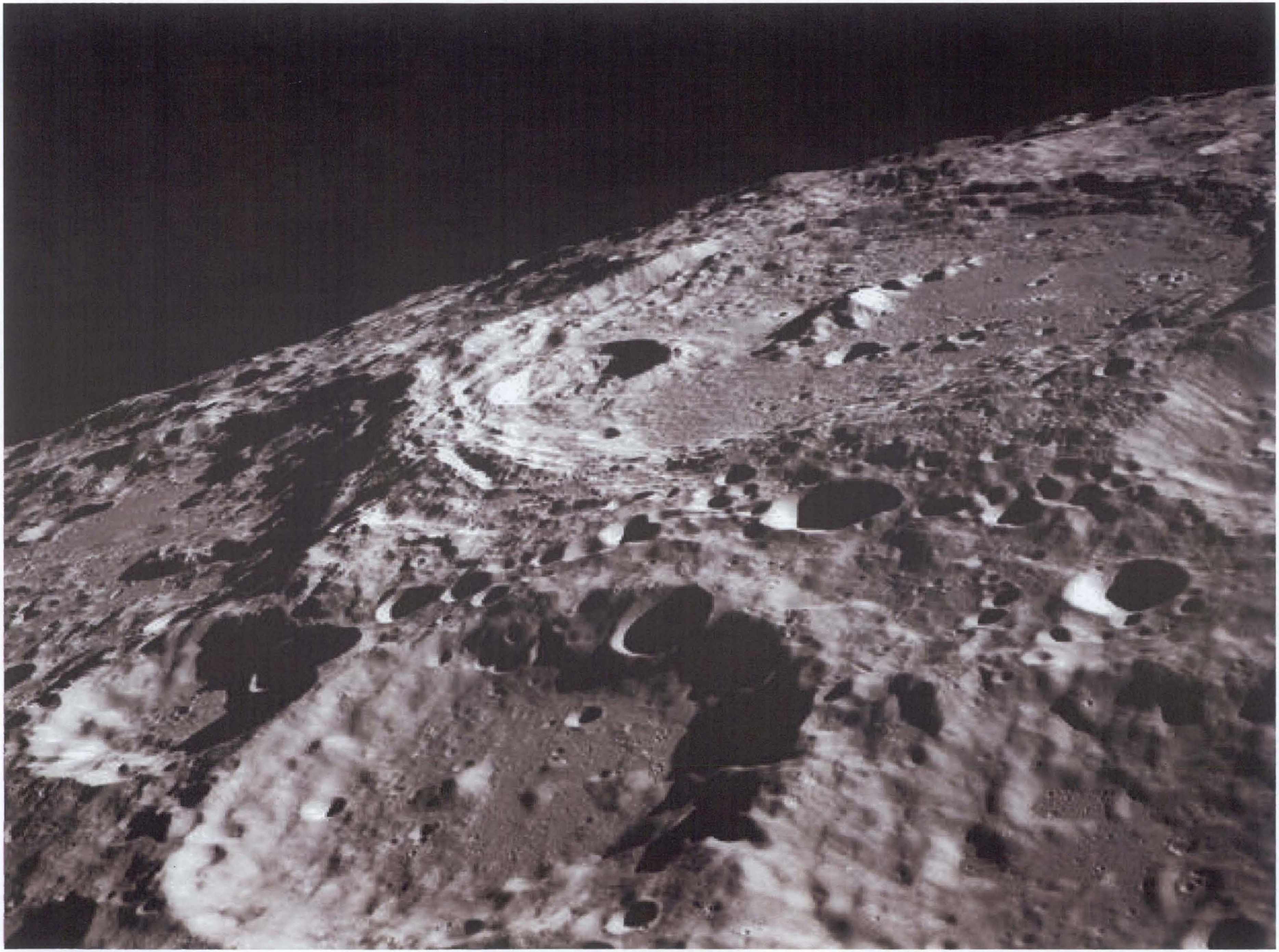
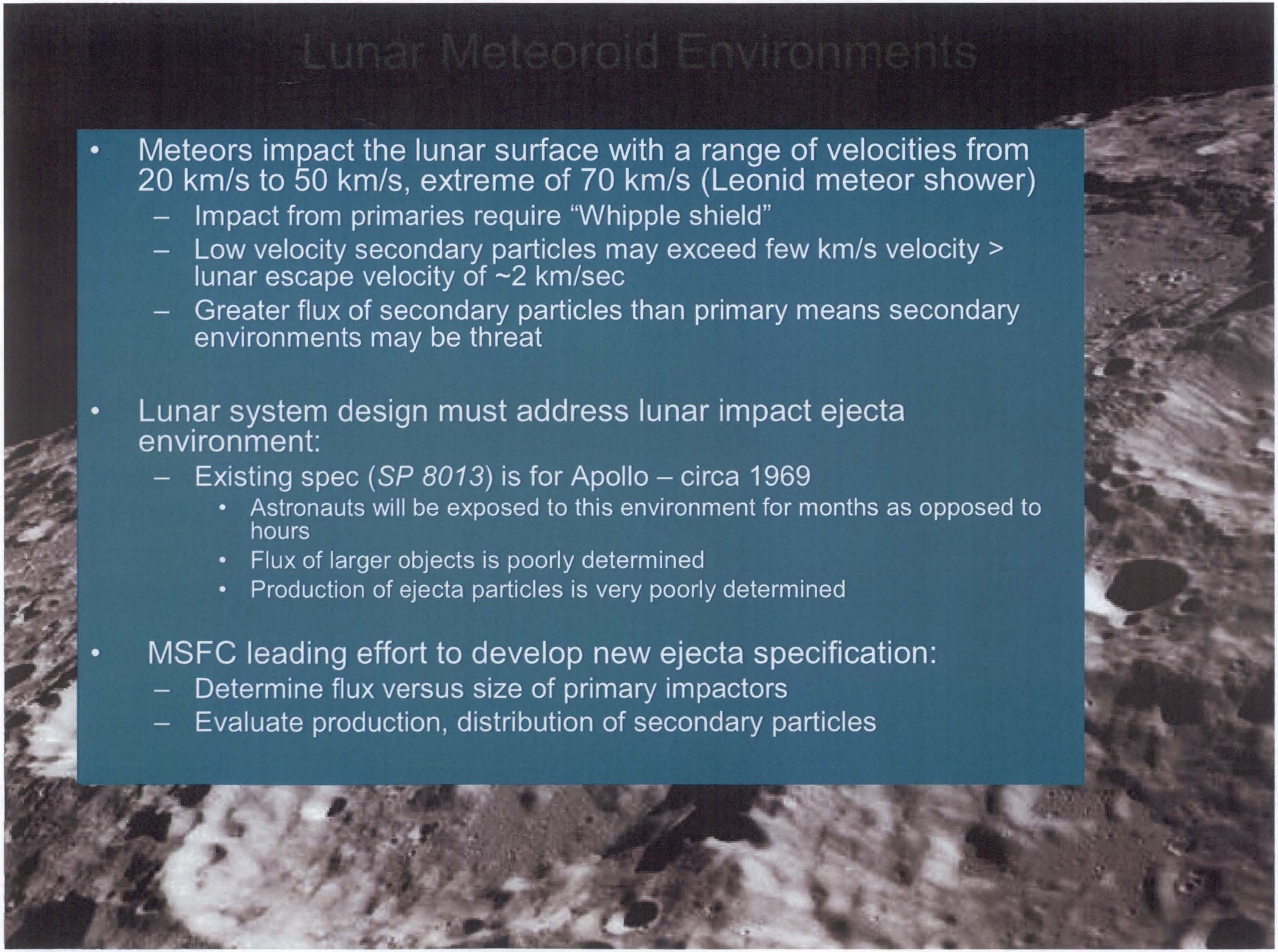




Lunar Meteoroid Environments

- Meteors impact the lunar surface with a range of velocities from 20 km/s to 50 km/s, extreme of 70 km/s (Leonid meteor shower)
  - Impact from primaries require “Whipple shield”
  - Low velocity secondary particles may exceed few km/s velocity > lunar escape velocity of ~2 km/sec
  - Greater flux of secondary particles than primary means secondary environments may be threat

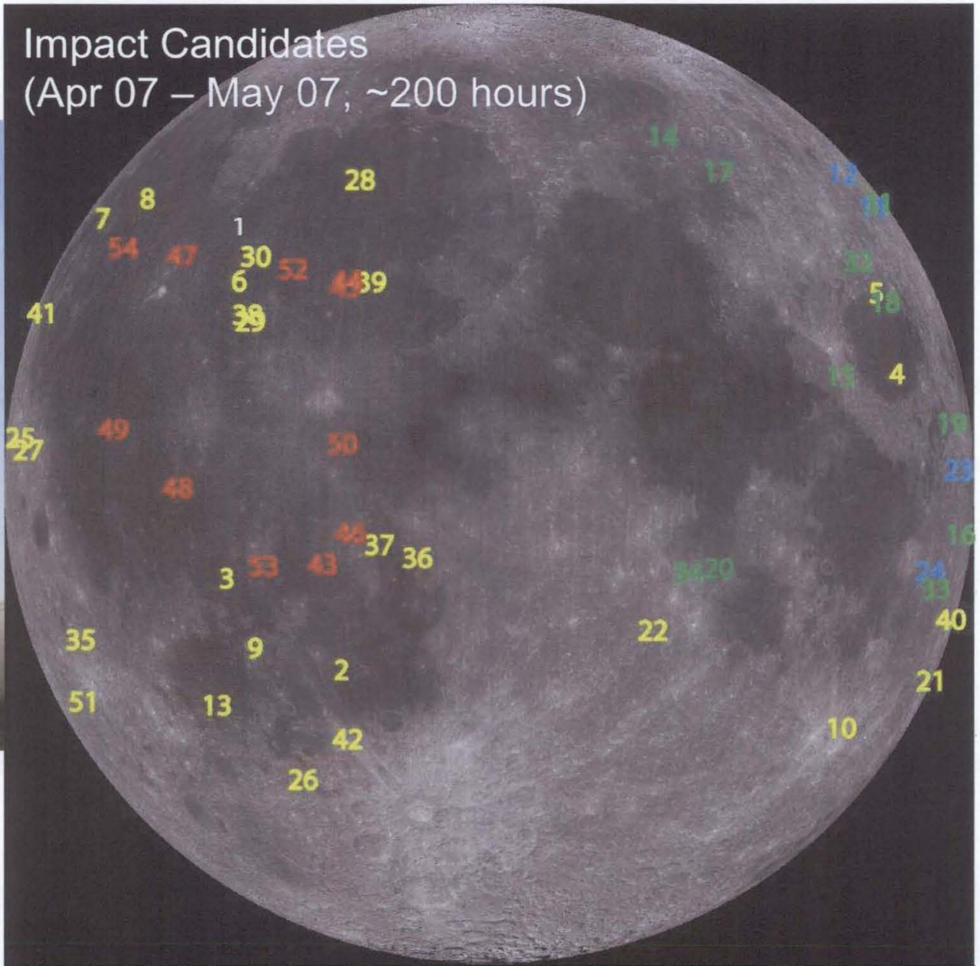
- Lunar system design must address lunar impact ejecta environment:
  - Existing spec (*SP 8013*) is for Apollo – circa 1969
    - Astronauts will be exposed to this environment for months as opposed to hours
    - Flux of larger objects is poorly determined
    - Production of ejecta particles is very poorly determined

- MSFC leading effort to develop new ejecta specification:
  - Determine flux versus size of primary impactors
  - Evaluate production, distribution of secondary particles

Characterizing Primary Impactors

Automated Lunar and Meteor Observatory (ALAMO) Facility

- Telescopes
  - 2 Meade RCX400 14”
- Recording Devices
  - Astrovid Stellacam EX
  - Sony Digital 8 recorder as digitizer
  - Firewire to PC harddisk



Impact Candidates
(Apr 07 – May 07, ~200 hours)

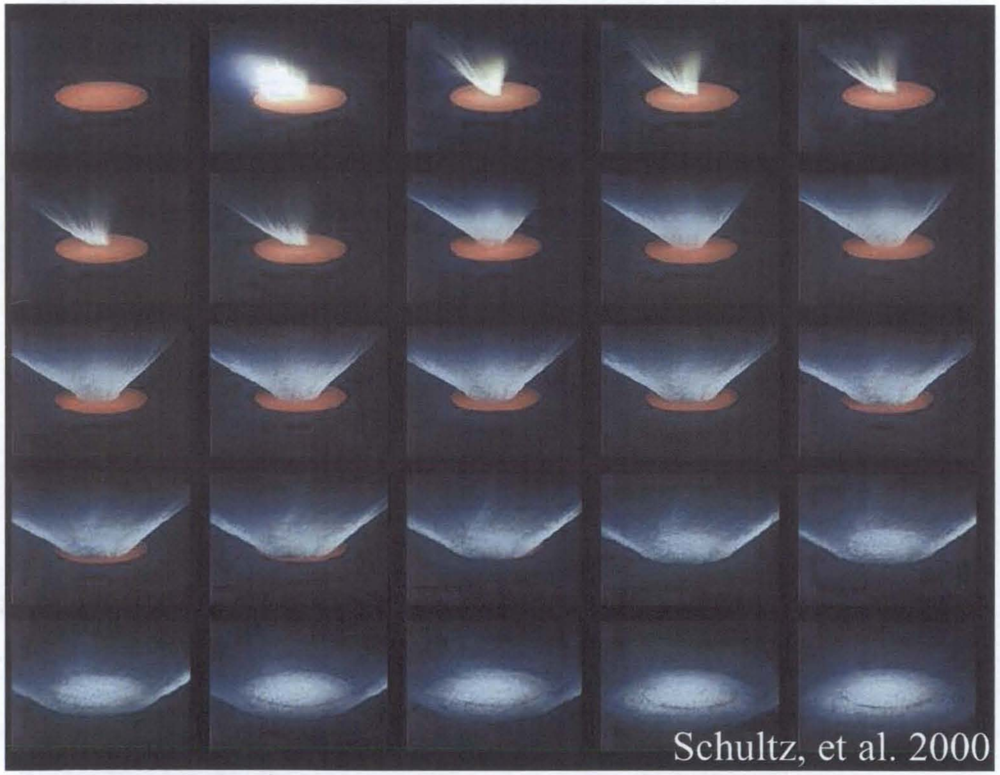
Likely meteoroid sources:

Sporadic background

Taurids Geminids Leonids Lyrids

Secondary Meteors

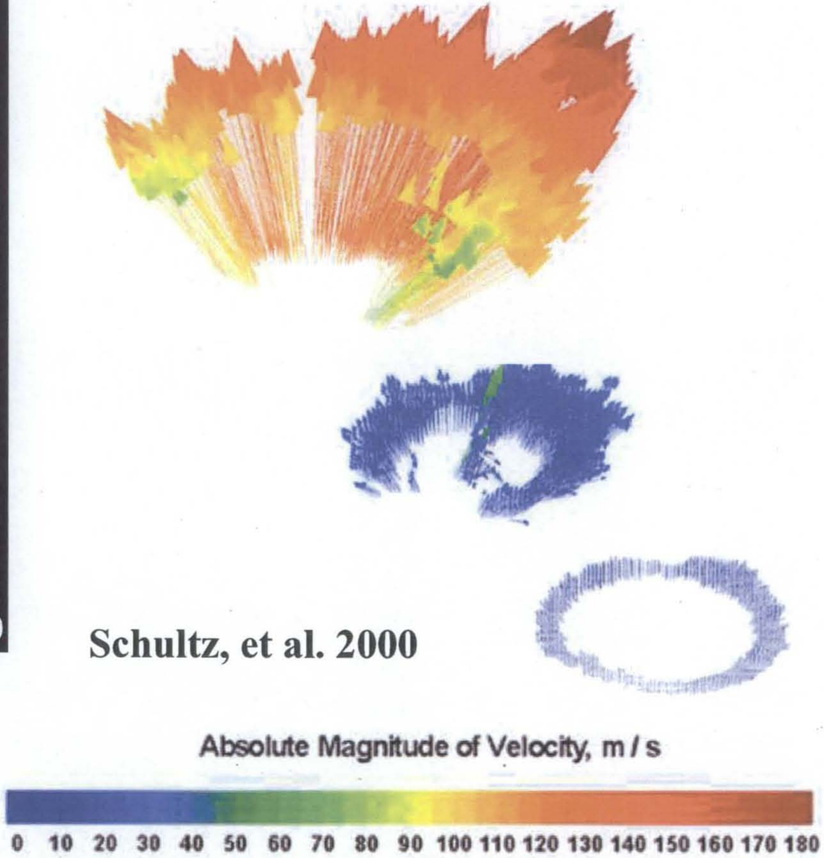
Crater development (high speed photography)
170 millionths of second/frame



Schultz, et al. 2000

NASA/AMES Vertical Gun Range (AVGR)

- Oblique Views of 3-component vector plots
- Oblique impact captured at three different times, vector colors indicate ejecta speed



Schultz, et al. 2000

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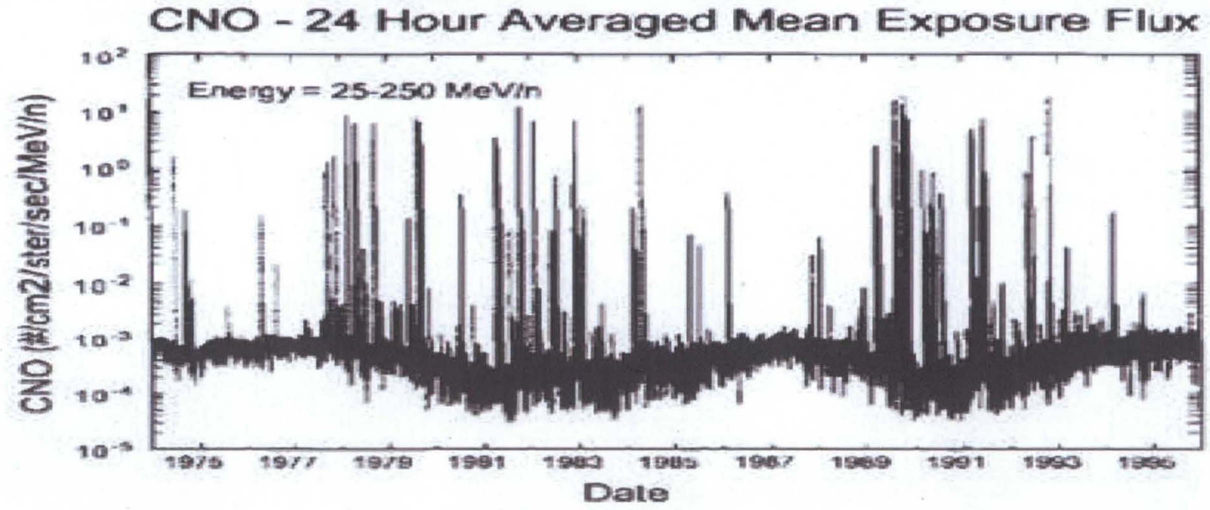
Galactic Cosmic Rays, Solar Energetic Particles

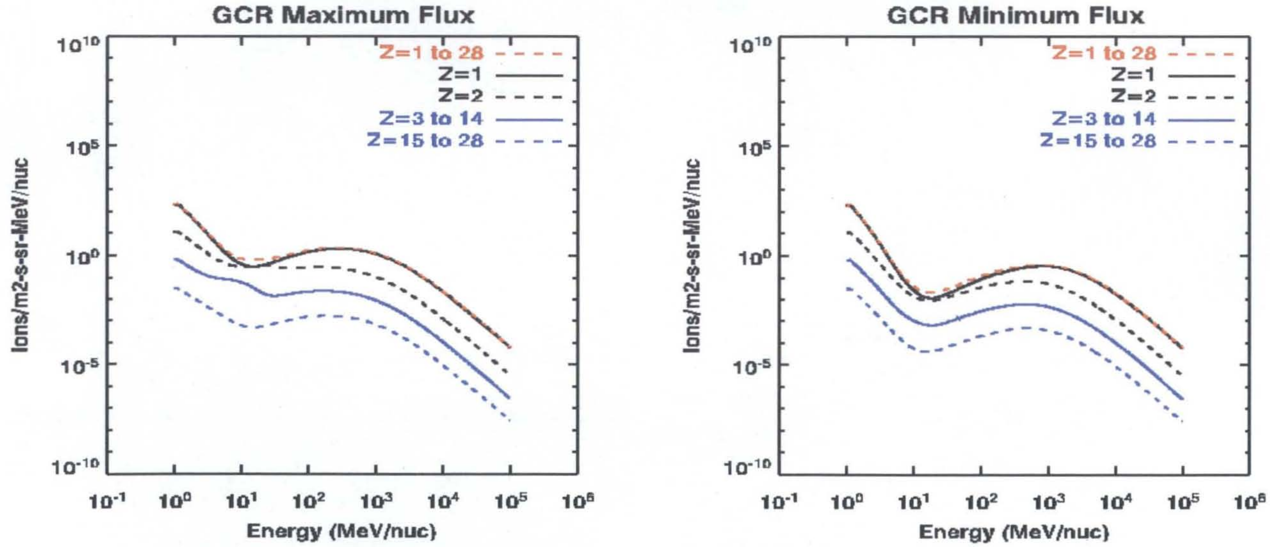


CNO - 24 Hour Averaged Mean Exposure Flux

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



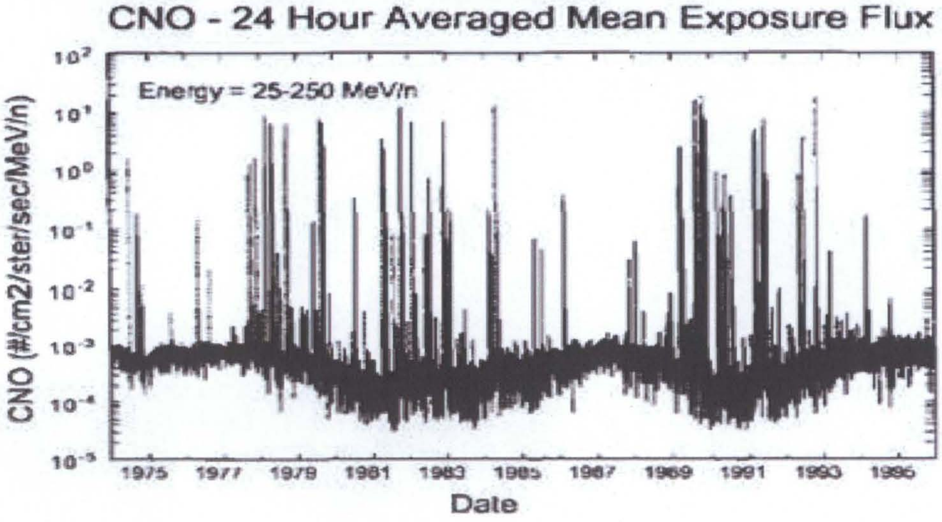
GCR Maximum Flux

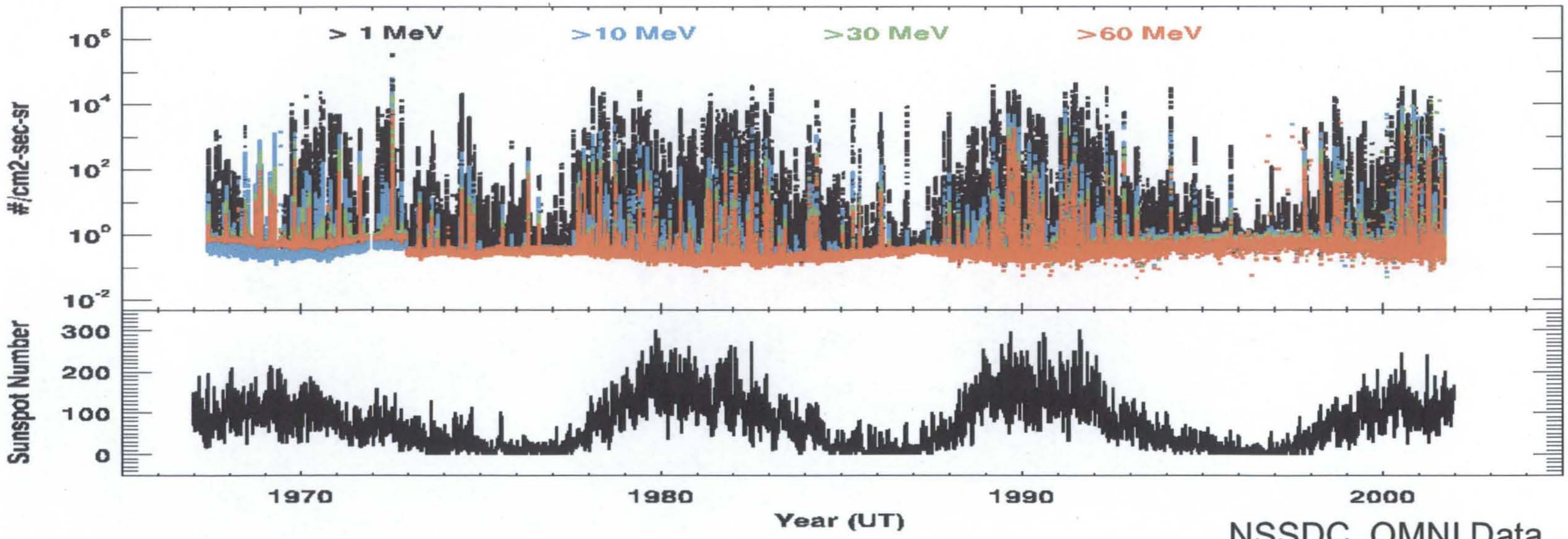
GCR Minimum Flux

CREME 1996 [*Tylka et al.*, 1997]

Solar Cycle Variation

- GCR
  - Anti-correlated with solar cycle
  - Small variation
- SEP
  - Correlated with solar cycle
  - Large variation



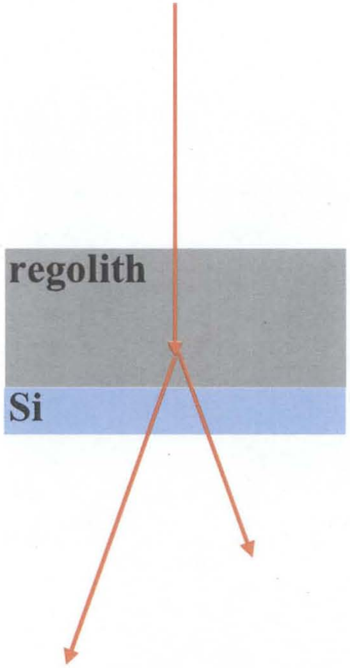


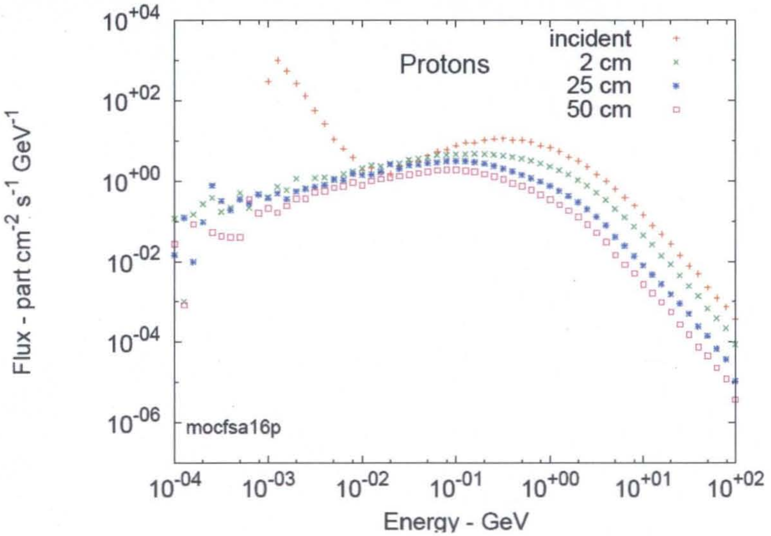
NSSDC, OMNI Data
Monthly mean SSN

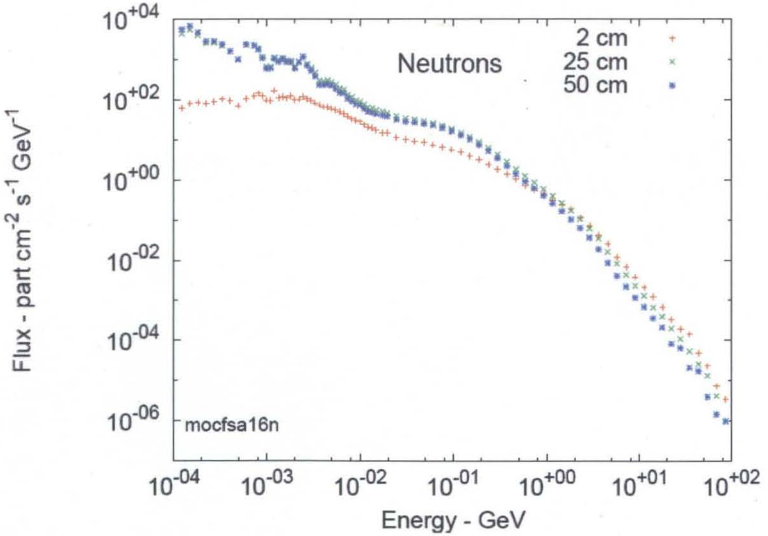
Regolith Shielding Properties for GCR

- **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

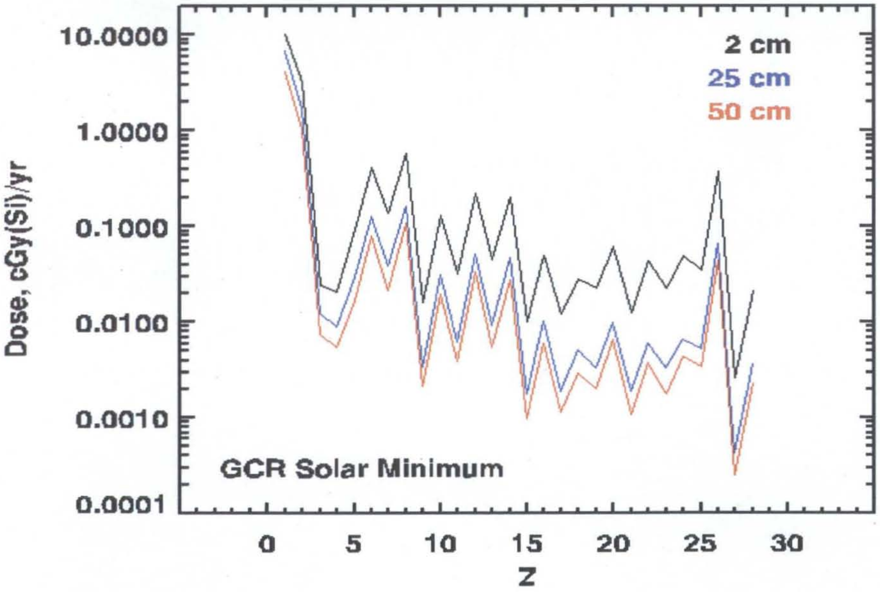






GCR, Flare Dose

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



1 Gy = 100 rad = 1 J/kg

Sv = RBE*Gy

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)

GCR Dose

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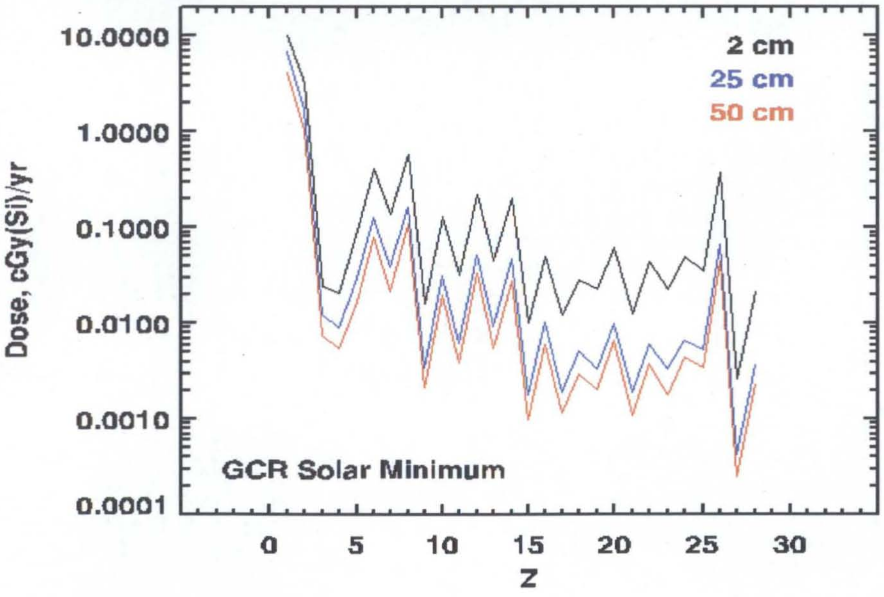

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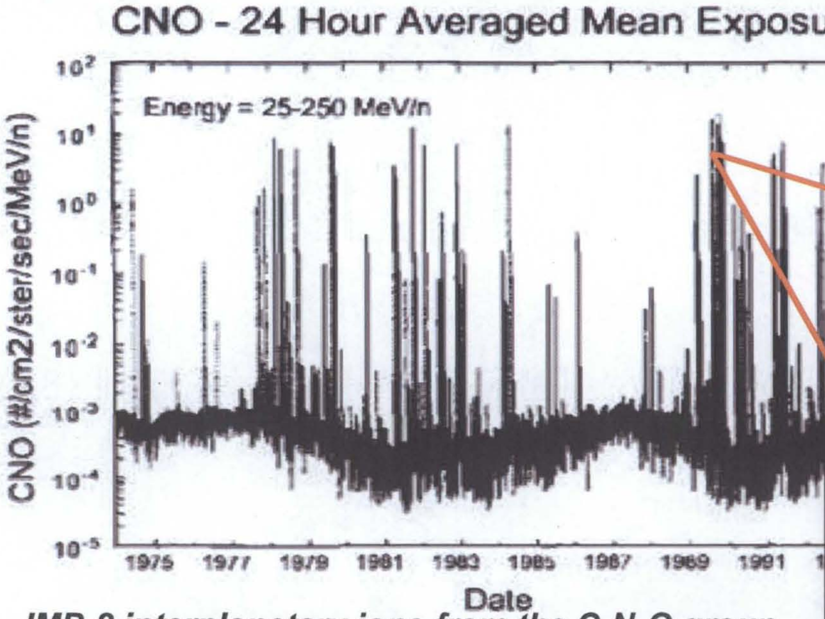
(from *Simonson et al.*, 1997)

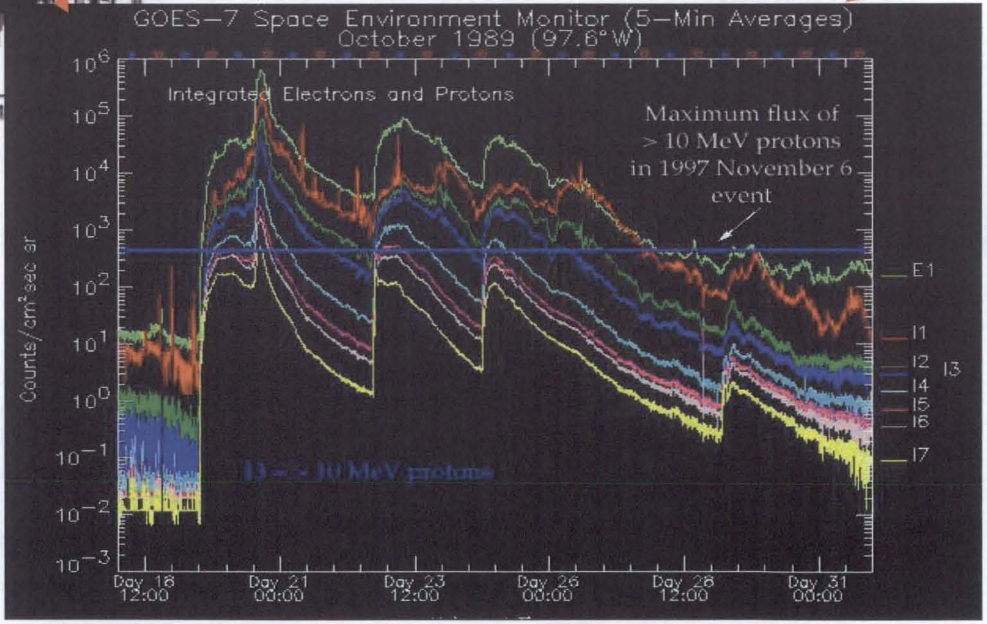
Evaluating stochastic human dose risk requires more detailed analysis!

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

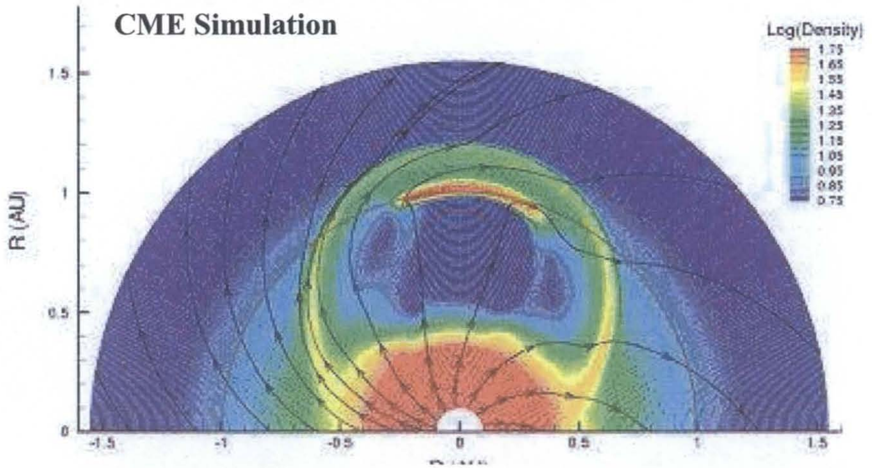
Example flux and duration of large proton solar particle event in October 1989



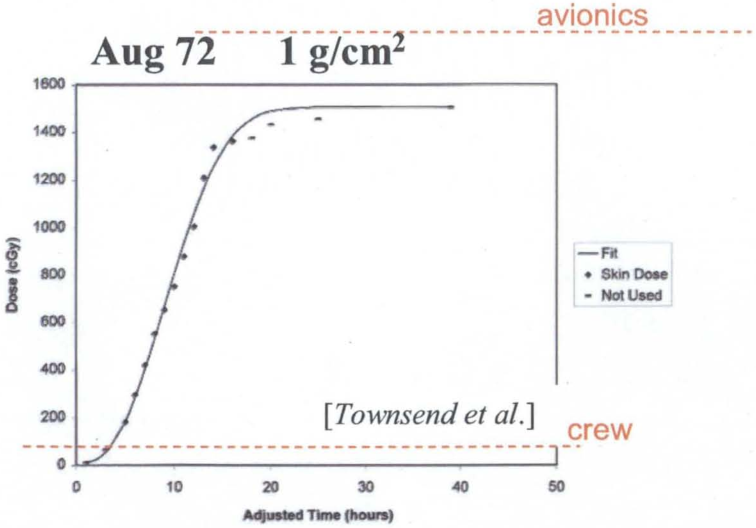
Frequency and magnitude of solar particle events demonstrates that Shuttle exposure to a high flux solar energetic particle event (or an equivalent fluence due to a number of smaller events) is a credible event during Shuttle life

Flares, CME's

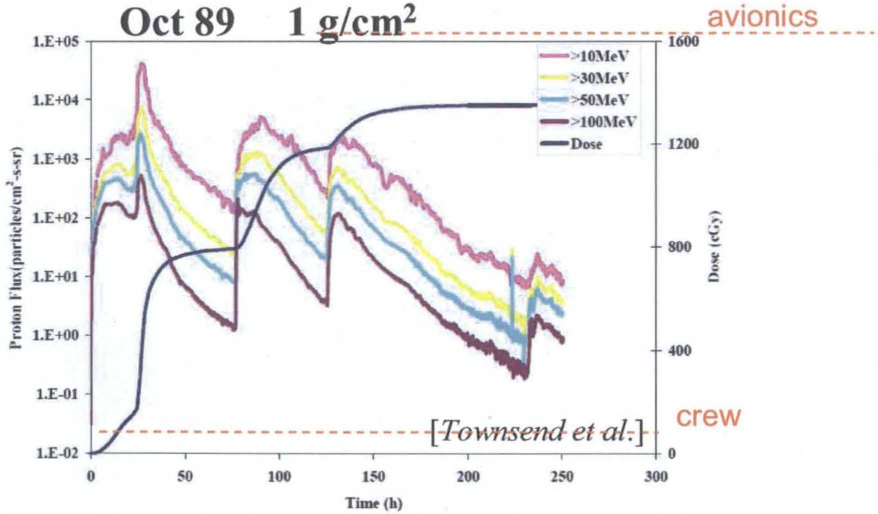
- Impulsive events
  - Minutes to hours
  - Electron rich
  - ~1000/yr at solar max
- Gradual events
  - Days
  - Proton rich
  - ~100/year



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



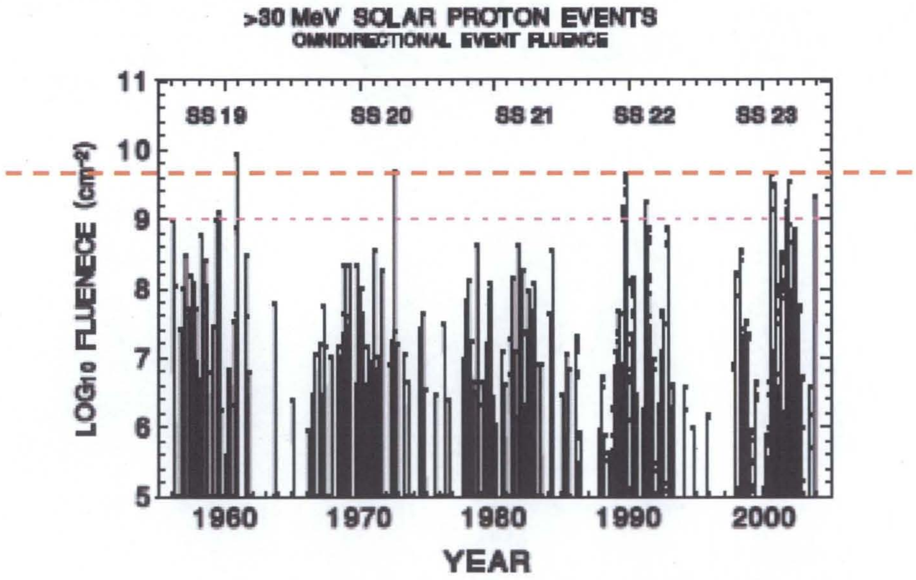
[*Townsend et al.*]

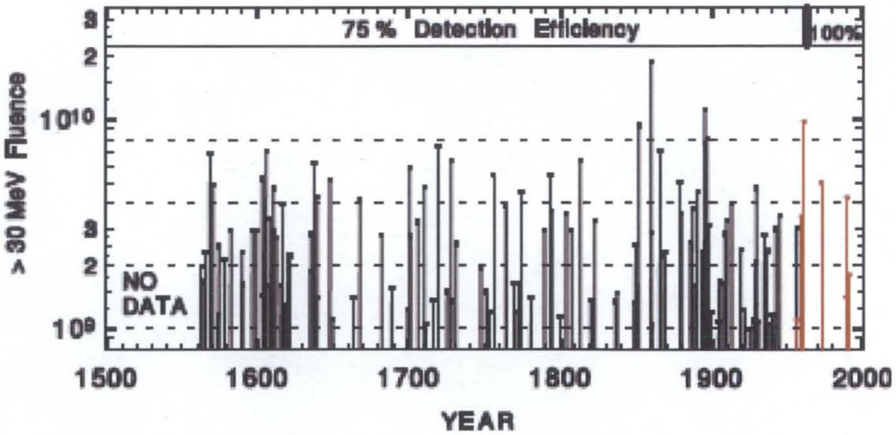


[*Townsend et al.*]

Large SPE Events are Real

- SPE events with >30 MeV fluence exceeding 10^9 p/cm2 are major hazards and occur
- NOx proxy for >30 MeV proton fluence provides extreme event history over multiple solar cycles for period ~400 years
- Ice core data shows 1859 Carrington event to be the largest in ~400 years
  - 4x 1989 event
  - 2x Constellation radiation design environment
  - Carrington event is also consistent with Emission of Solar Proton (ESP) model worst case event
- Long time series of historical records and ice core proxy have been important in establishing design environments for Constellation program





[*Shea et al.*, 2005]

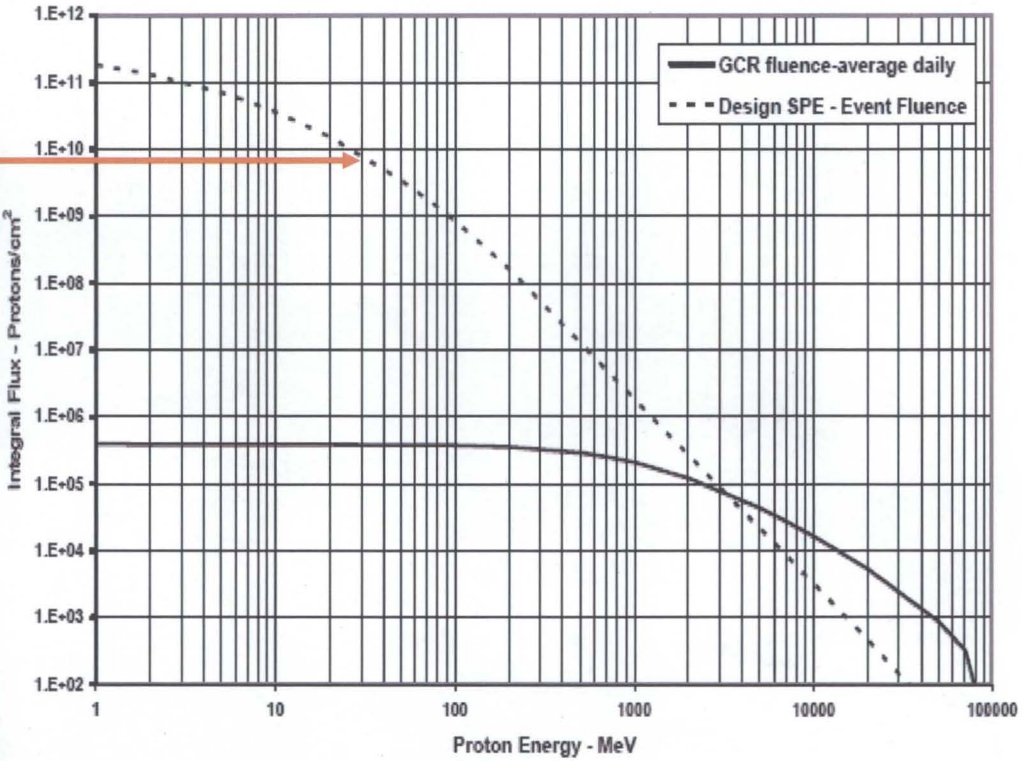
Constellation Design Environments

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

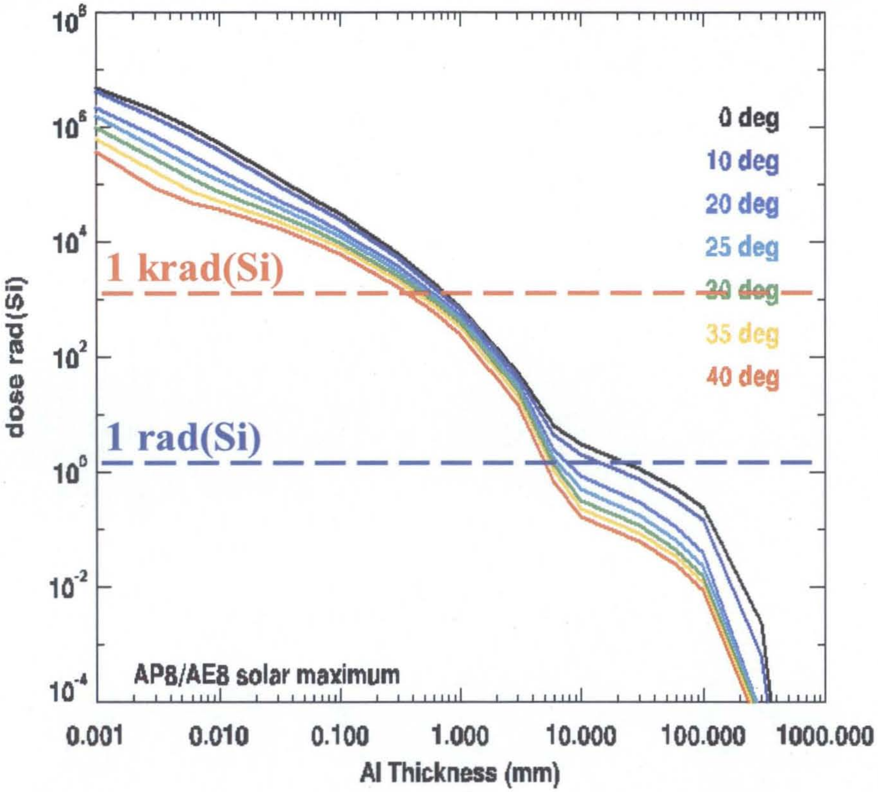
Event	Max >30 MeV flux (#/cm2-s-sr)	>30 MeV fluence (#/cm2)
1859/09/01	5 x 10^4	19 x 10^9
	hardware	
1960/11/15	-------	9 x 10^9
1946/07/25	-------	6 x 10^9
	crew dose	
1972/08/04	2 x 10^4	5 x 10^9
2000/07/12	--------	4.3 x 10^9
1989/10/19	--------	4.2 x 10^9
2001/11/04	--------	3.4 x 10^9
2003/10/28	4.5x10^3	3.4 x 10^9
2000/08/00	--------	3.2 x 10^9
1959/07/14	-------	2.3 x 10^9
1991/03/22	--------	1.8 x 10^9
1989/08/12	--------	1.4 x 10^9
1989/09/29	--------	1.4 x 10^9
2001/09/24	--------	1.2 x 10^9
2005/01/15	---------	1.0 x 10^9

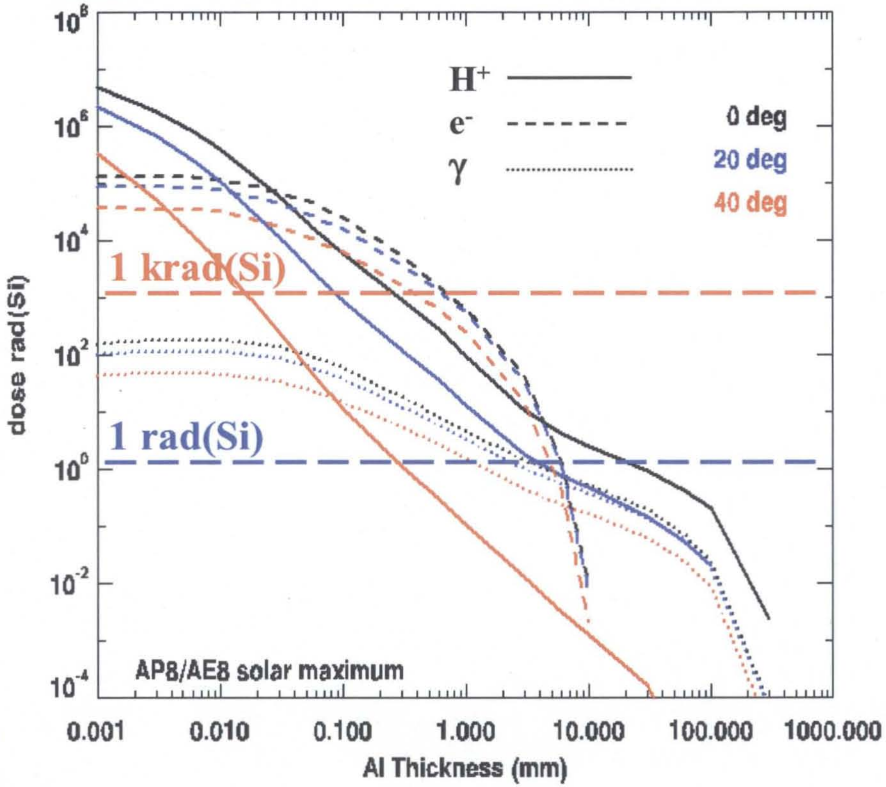
Sources: *Smart and Shea*, 2002; *Reedy*, 2006;

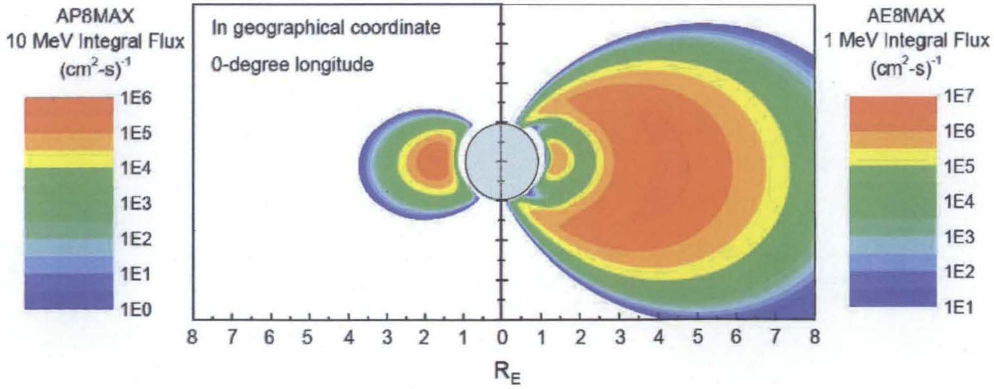
Smart et al., 2005



Inclination and Dose







Single TLI orbit

perigee = 300 km

apogee = 379,867 km

Polar [illegible]

Energetic Particle Access to Magnetotail

ACE

Protons

107-227 keV

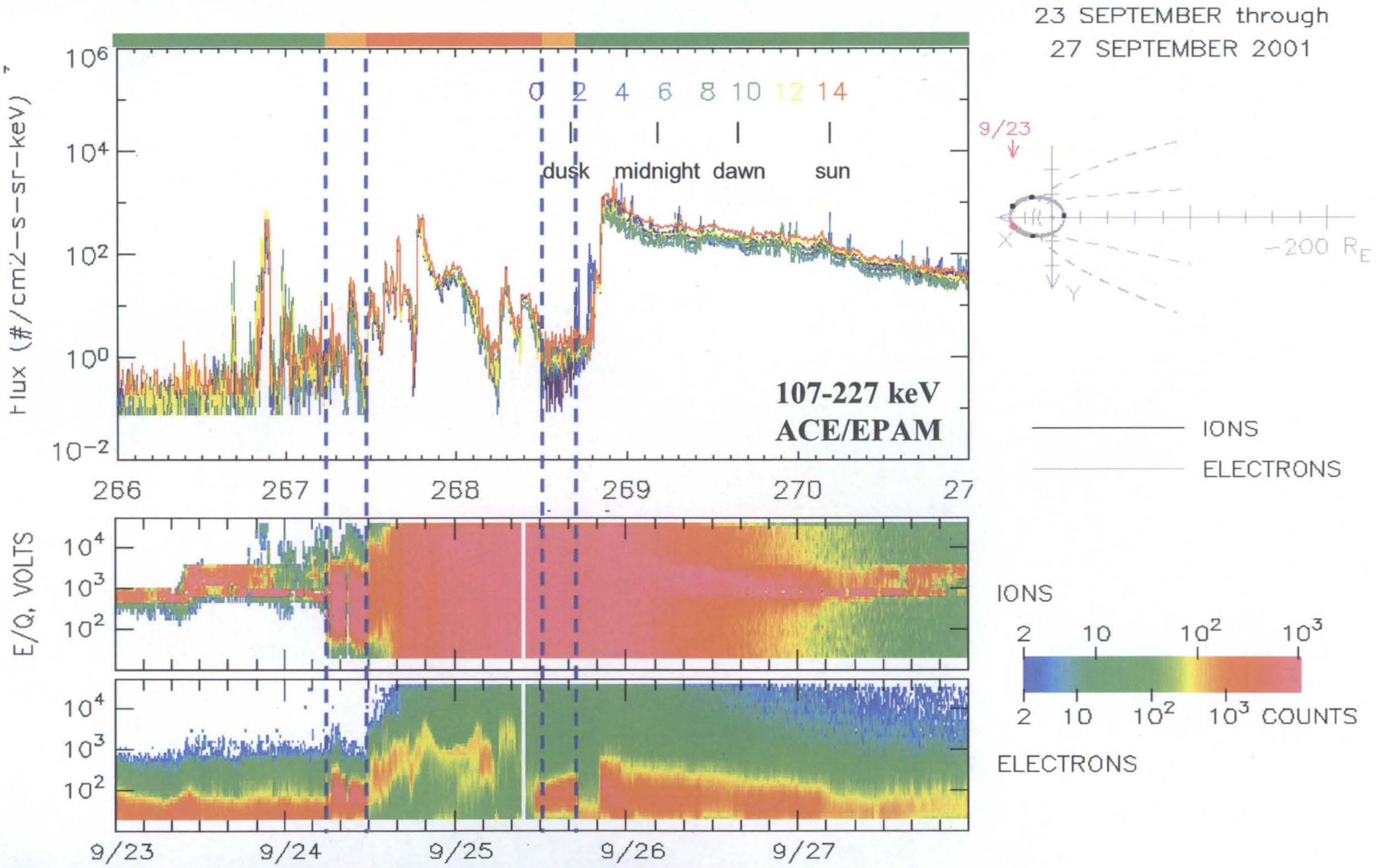
Geotail

Ions

0.03-30 keV

Electrons

0.03-30 keV



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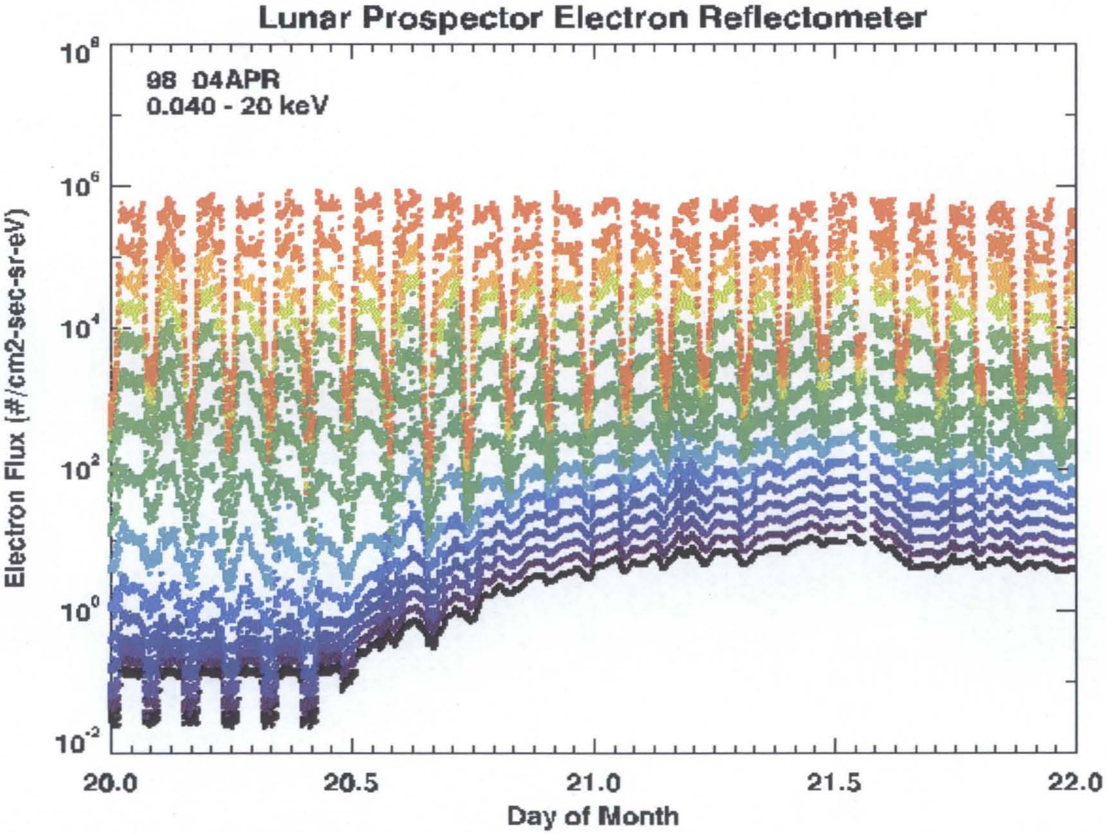
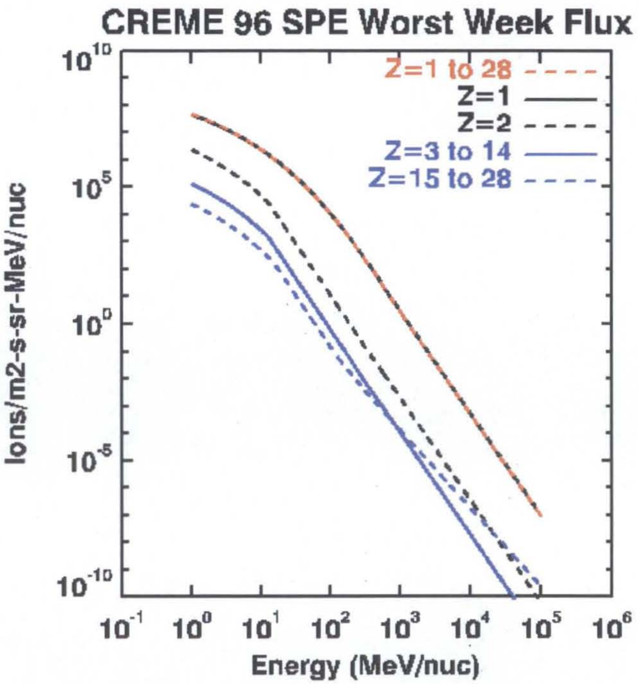
Solar energetic particles have nearly free access to outer magnetosphere and magnetotail—no protection for Moon when in magnetotail

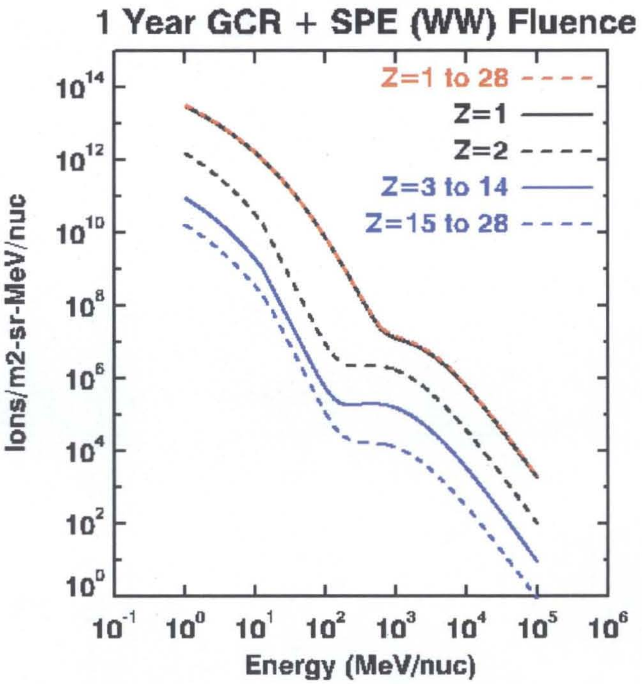
Lunar Radiation Environments

- **Lunar Prospector Electron Reflectometer**
  - **Spin average electron flux**
  - **~40 eV to ~20 keV**
- **4-5April 1998**
  - **Moon in solar wind**
  - **Plasma wake behind Moon**
  - **Solar particle event penetrates wake**
  - **No hiding "behind" the Moon from high energy particle events**



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**

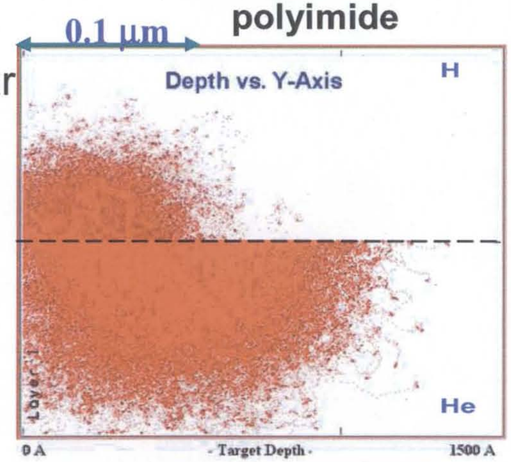
Solar Wind as Radiation Environment

- 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
  - ~10^2 MGy/yr dose rates within the thin 0.1 µm coating
  - Important for optical (and therefore thermal) properties of materials

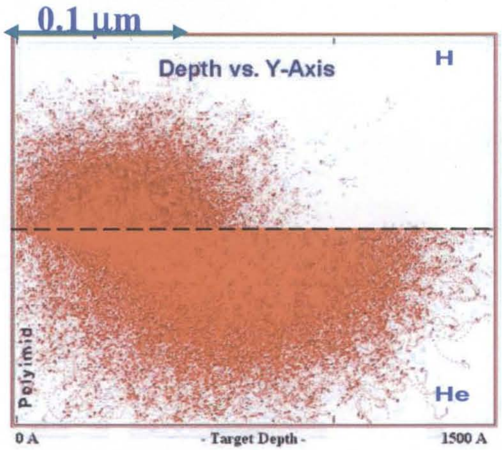
TRIM Analyses

H, He on Al

polyimide



H, He on



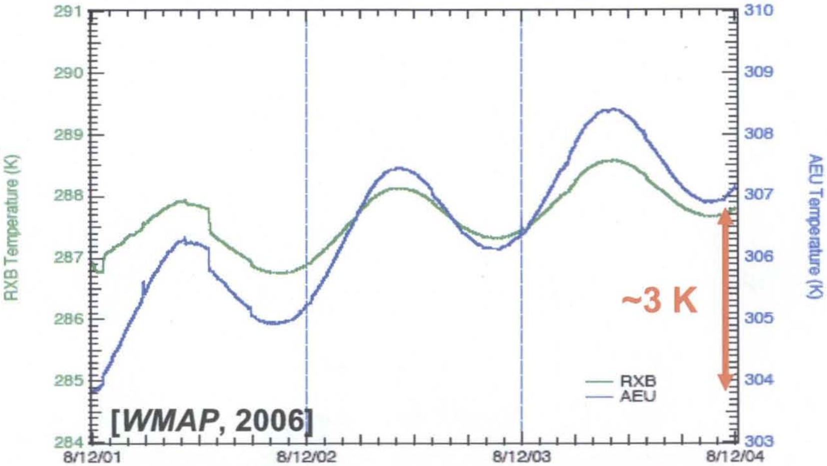
[*Minow et al.*, 2007]

10,000 1.22 keV H^+
10,000 5.27 keV He^{++}

Material Surfaces Modified by Space Environment

- Surface properties of materials degrade when exposed to space environments
  - Changes in optical properties are important for thermal behavior of materials exposed to solar wind for long periods
  - UV, out gassing are important as well…

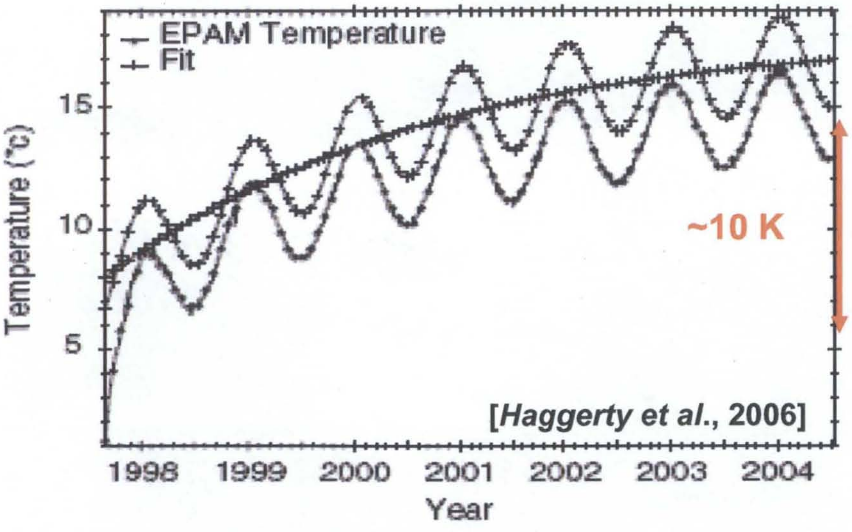
Wilkerson Microwave Anisotropy Probe Sun-Earth L2



~3 K

[*WMAP*, 2006]

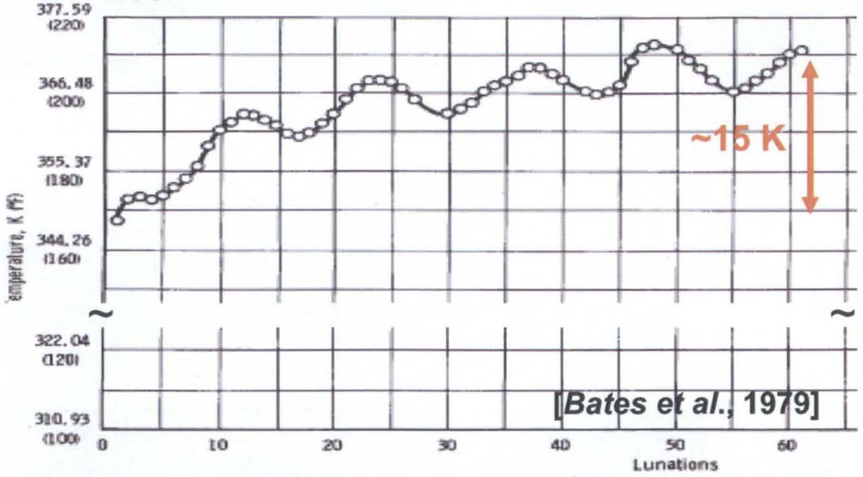
Advanced Composition Explorer (ACE) Sun-Earth L1



~10 K

[*Haggerty et al.*, 2006]

Apollo Lunar Surface Experiment Package (ALSEP) Moon



~15 K

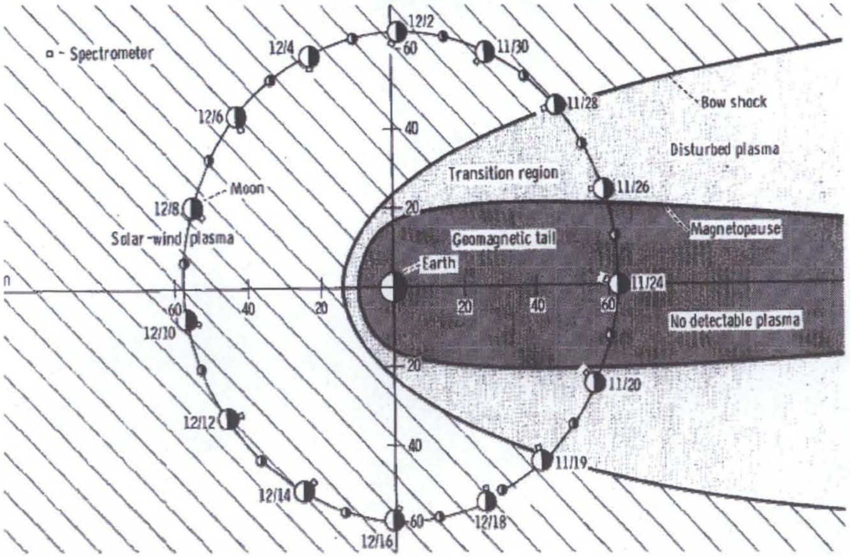
[*Bates et al.*, 1979]

Temperature profile for Apollo 14 ALSEP central station (normalized to 90° Sun angle)

- Constellation
- Lunar atmosphere and dust
- Illumination and Thermal Environments
- Meteor impacts
- Radiation
- **Plasma**
- Summary

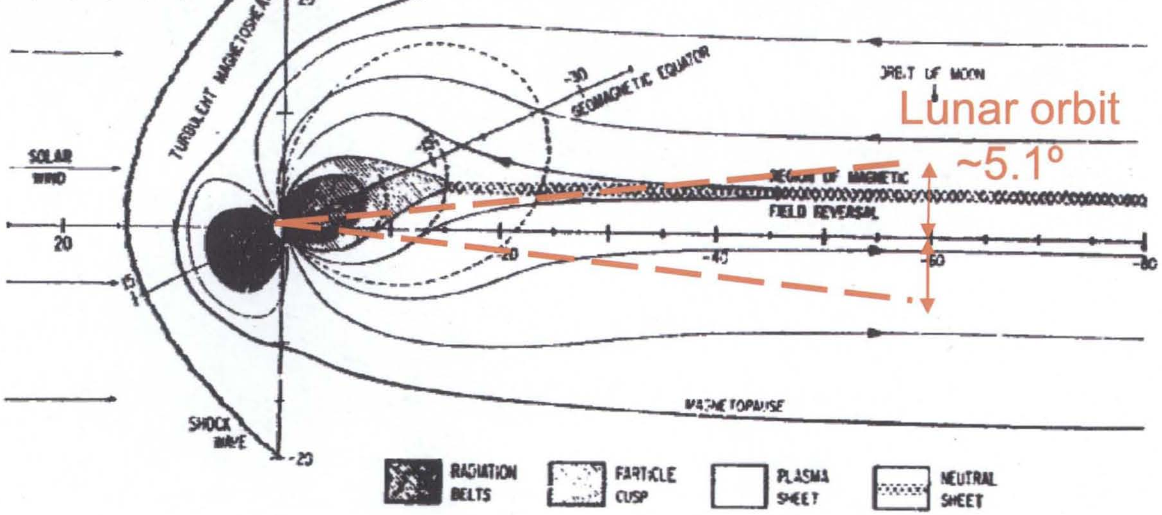
Magnetosphere and Lunar Orbit

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



Moon passes through magnetotail and magnetosheath plasma environments every month

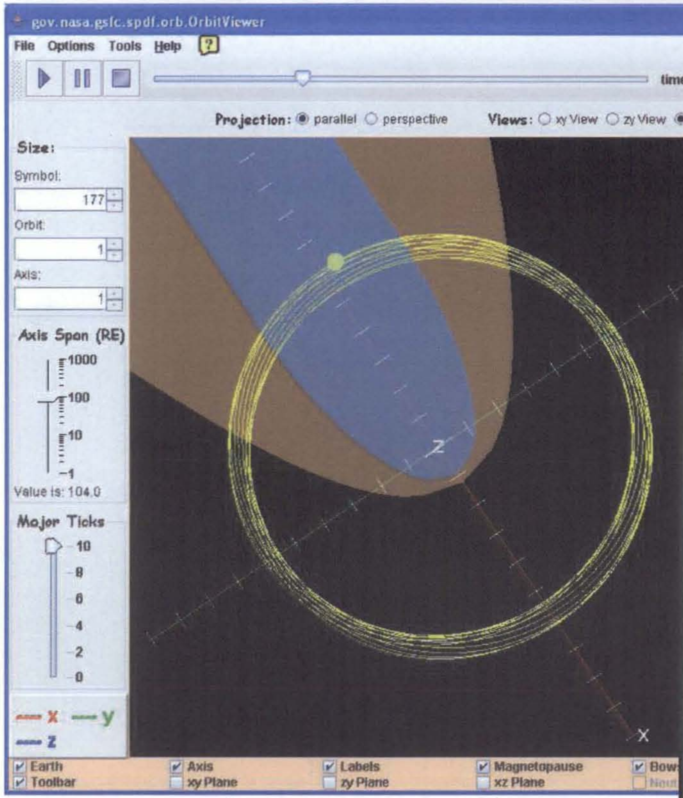
Adams et al., 1981



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

Magnetotail

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



gov.nasa.gsfc.spdf.orb.OrbitViewer

time: 1998-04-11 13:48 speed: 10

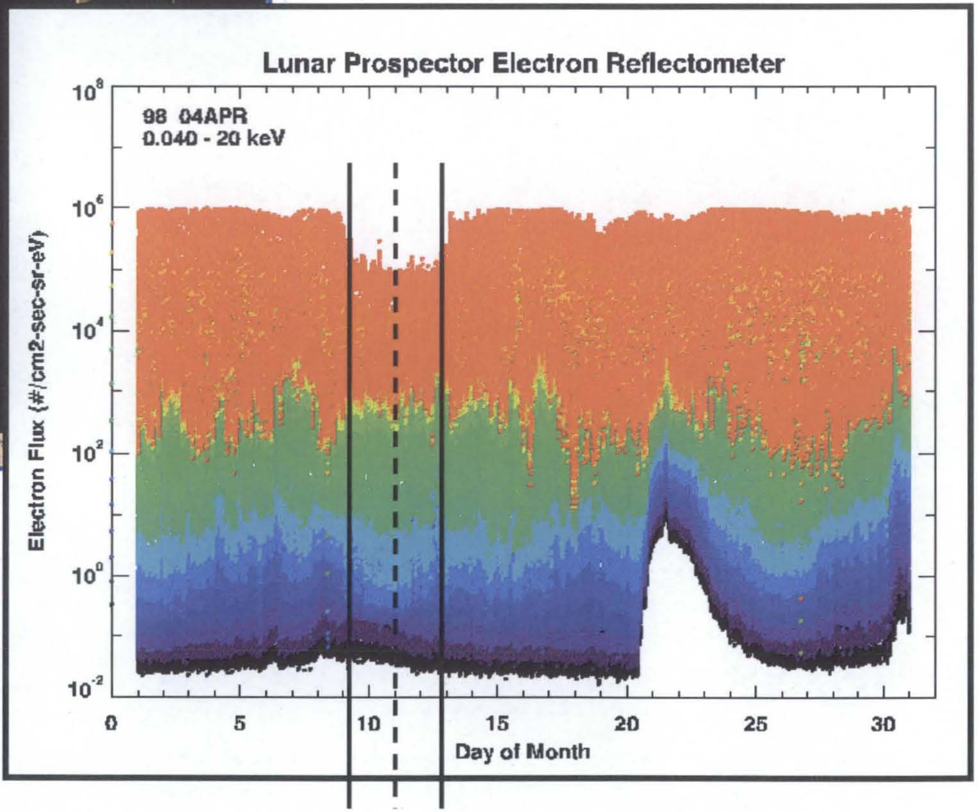
Projection: ● parallel ○ perspective Views: ○ xy View ○ zy View ● xz View

Size:
Symbol: 177
Orbit: 1
Axis: 1

Axis Span (RE)
Value is: 104.0

Major Ticks

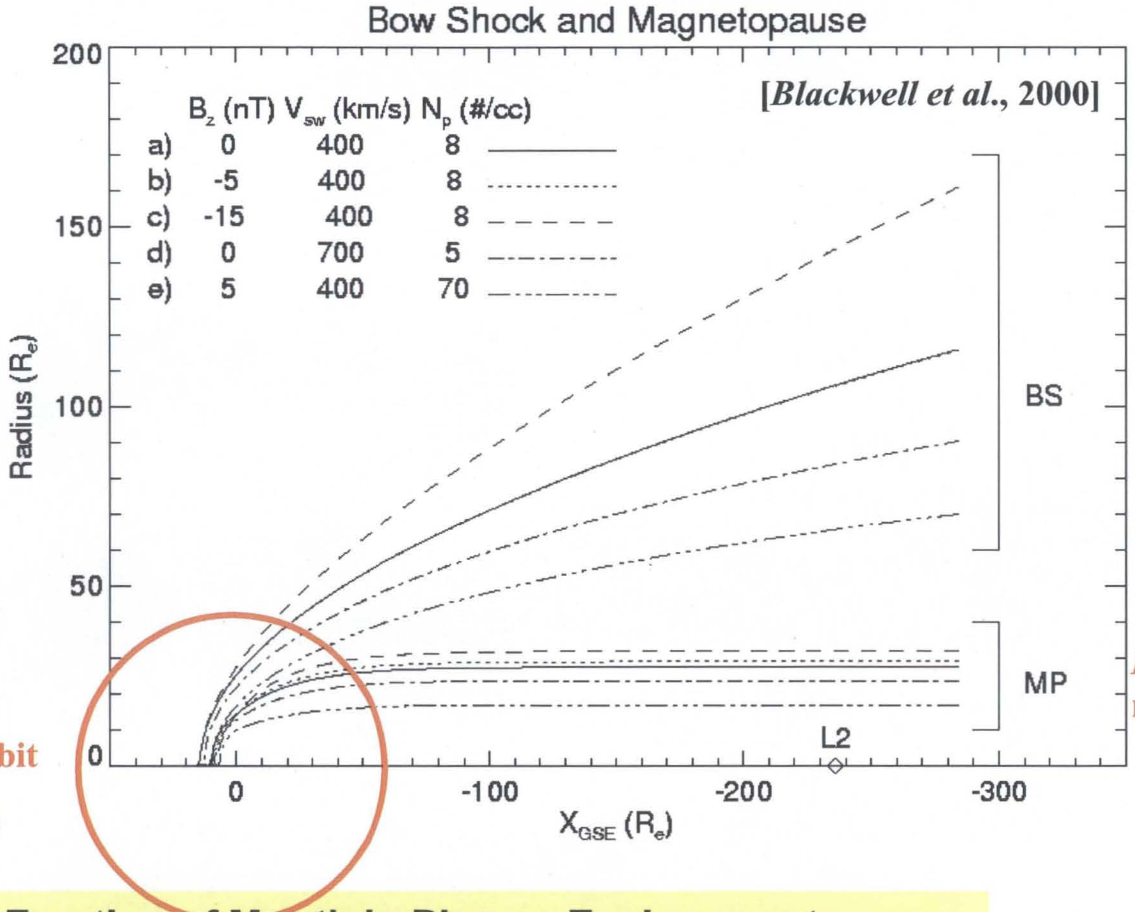
☑ Earth ☑ Axis ☑ Labels ☑ Magnetopause ☑ Bow
☑ Toolbar ☐ xy Plane ☐ zy Plane ☐ xz Plane ☐ Neut



Lunar Prospector Electron Reflectometer

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

Bow Shock and Magnetopause Variability


Bow Shock and Magnetopause

[*Blackwell et al.*, 2000]

Bennett et al. [1997]
bow shock

Petrinic and Russell [1993, 1996]
magnetopause

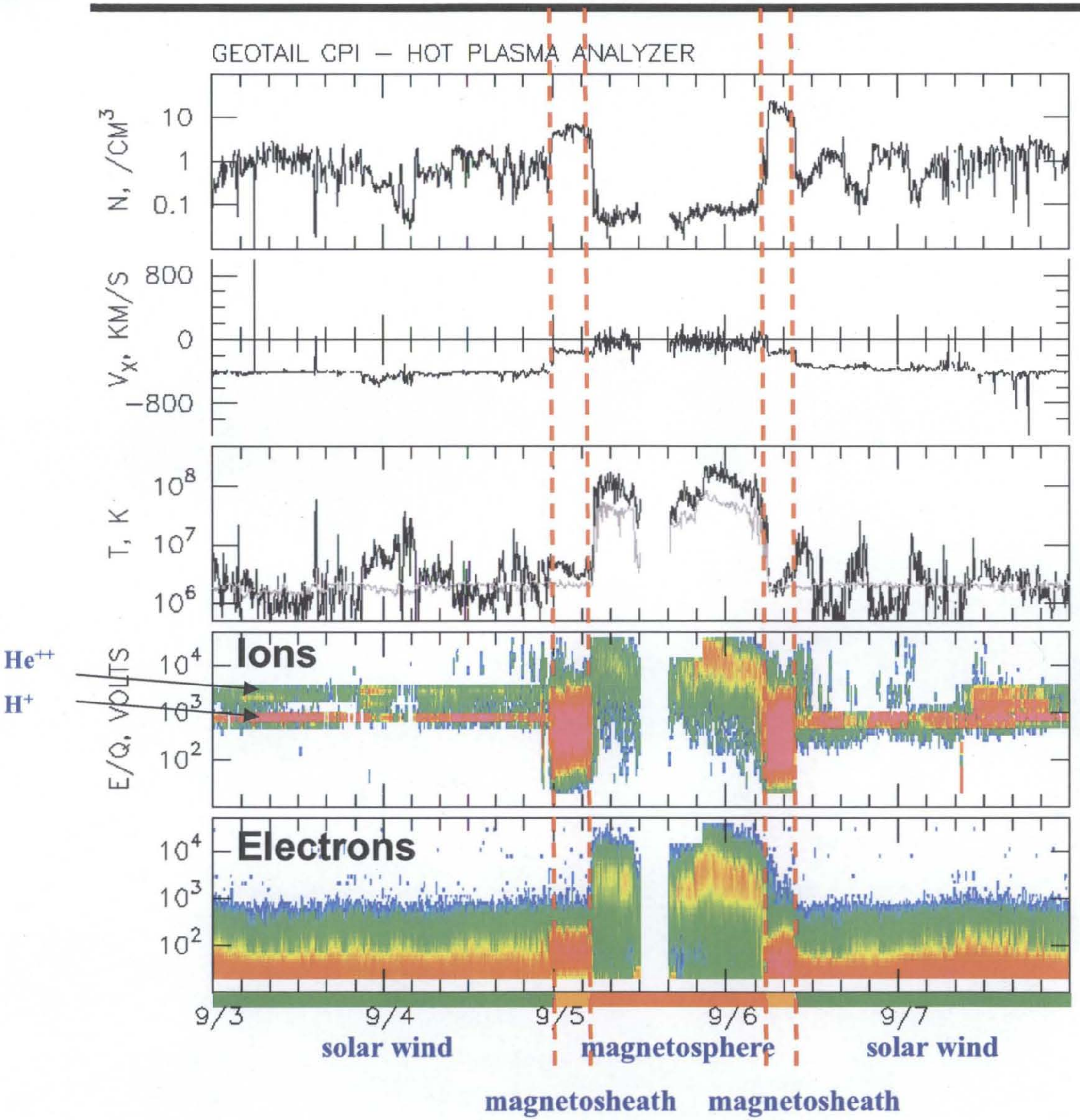
Lunar orbit

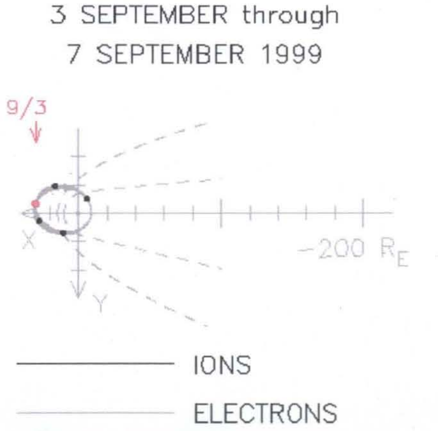
~60 Re

Fraction of Month in Plasma Environments

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

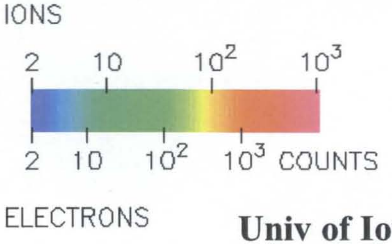
Near Earth Plasma Regimes





Near Earth plasma regimes are well ordered at low energies

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



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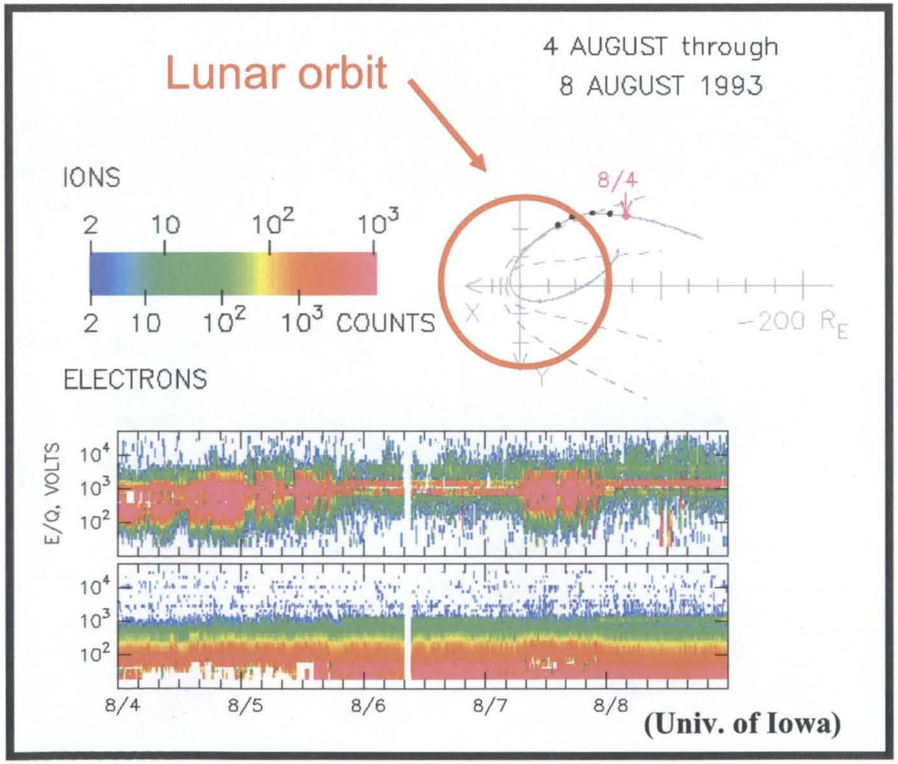
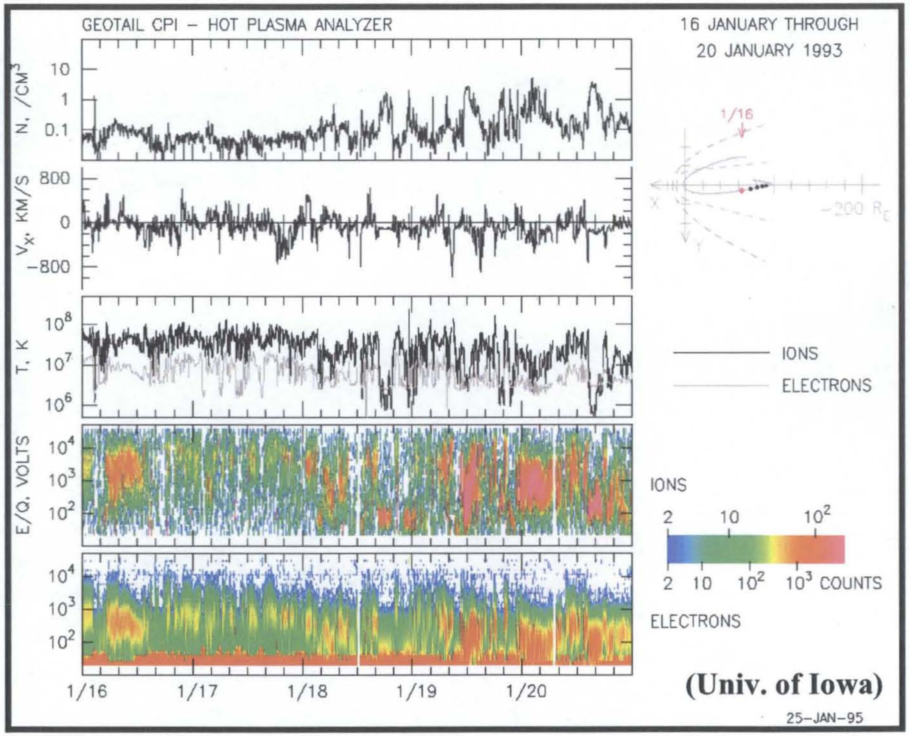
Magnetotail Plasma at Lunar Distances

- 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


Lunar orbit

4 AUGUST through 8 AUGUST 1993

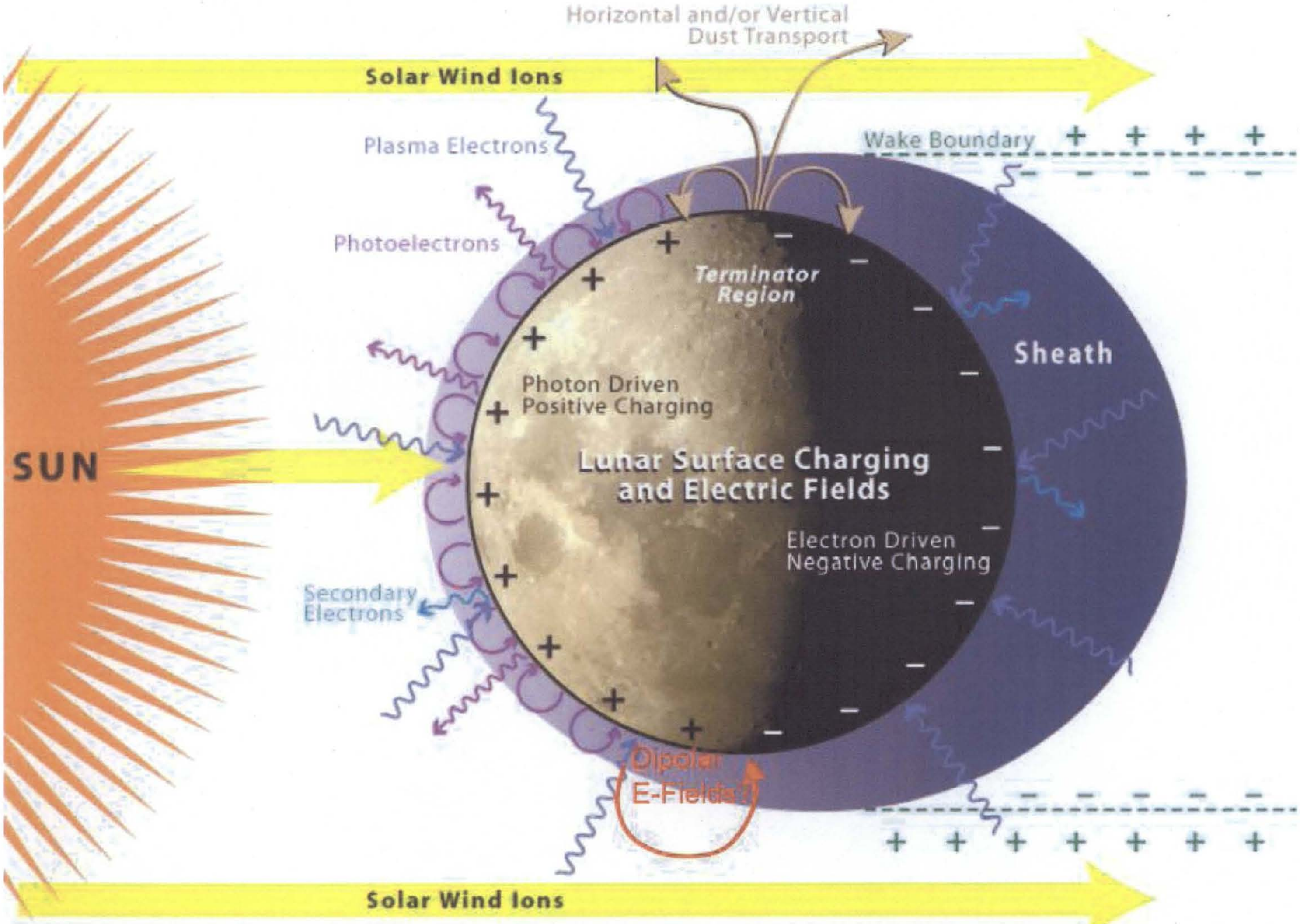
(Univ. of Iowa)


GEOTAIL CPI – HOT PLASMA ANALYZER

16 JANUARY THROUGH 20 JANUARY 1993

(Univ. of Iowa)

Lunar Plasma Environments/Interactions



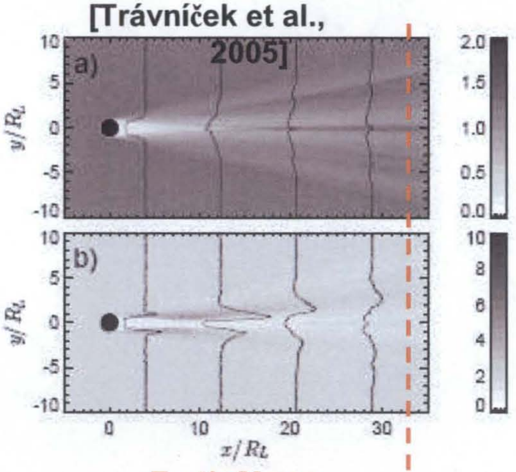
[*Lin et al.*, 2007; *Halekas et al.*, 2007]

Lunar Wake

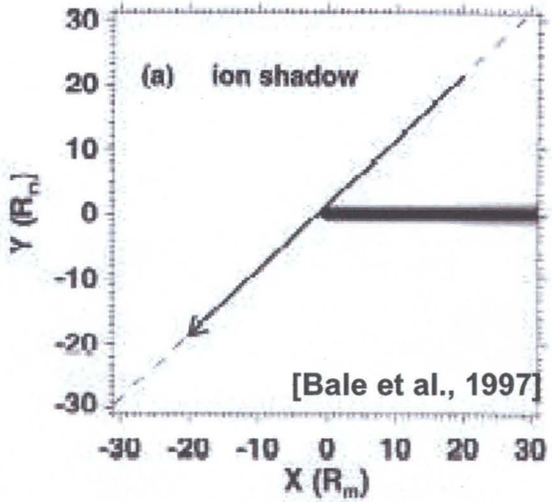
$\theta_{sw} \sim 45$ deg

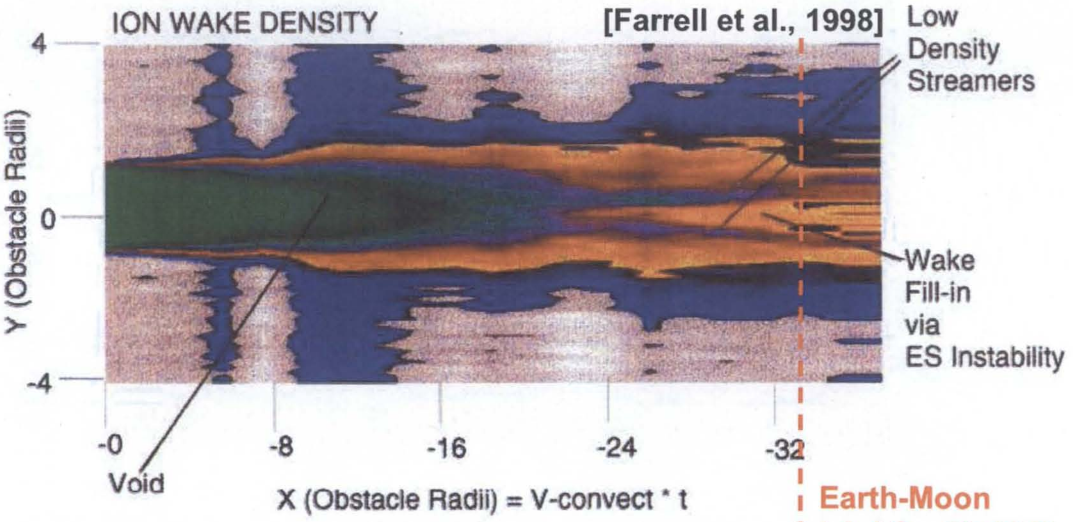
a) Density

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


[Trávníček et al., 2005]

Earth-Moon L1, L2 ~ 33.12 R_l


[Bale et al., 1997]

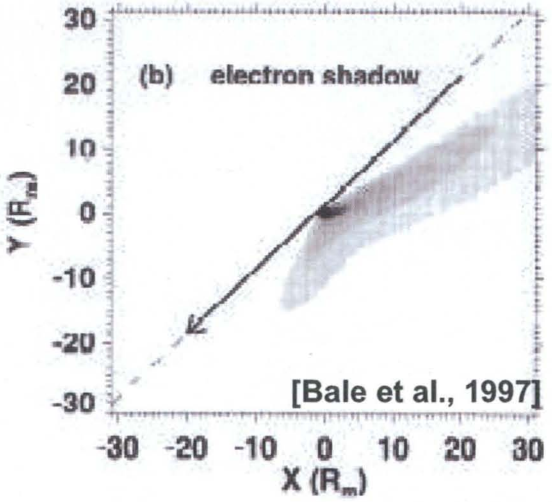

[Farrell et al., 1998]

Low Density Streamers

Wake Fill-in via ES Instability

Void

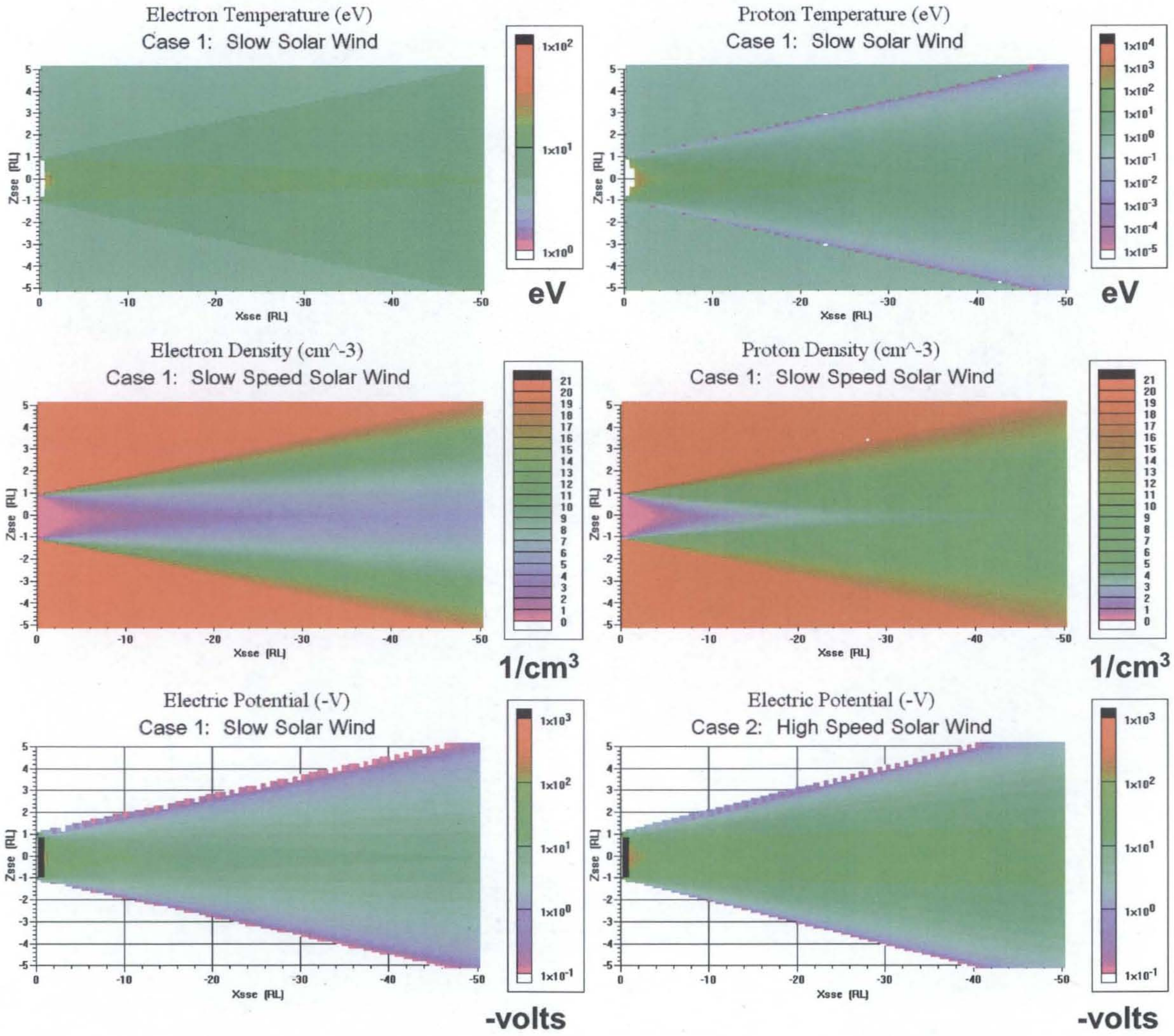
Earth-Moon L1, L2 ~ 33.12 R_L


[Bale et al., 1997]

Analytical Lunar Wake Model

- Analytical models useful for first order estimate of wake plasma environments
  - Electrons [*Halekas et al.*, 2005]
  - Ions [*Samir et al.*, 1983]

- Numerical electrostatic codes required to evaluate details of wake including
  - Particle distribution functions
  - Energetic solar particle events
  - Backflow from distant magnetotail


Electron Temperature (eV) Case 1: Slow Solar Wind

Proton Temperature (eV) Case 1: Slow Solar Wind

Electron Density (cm^-3) Case 1: Slow Speed Solar Wind

Proton Density (cm^-3) Case 1: Slow Speed Solar Wind

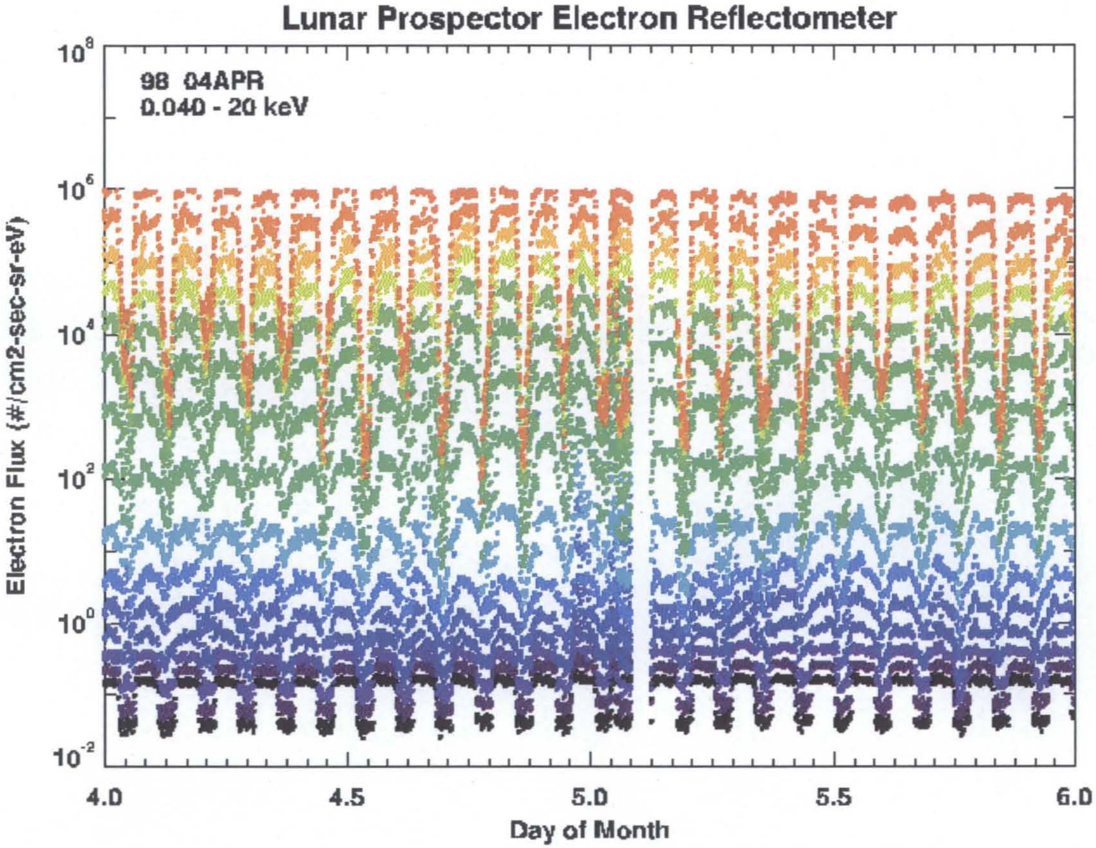
Electric Potential (-V) Case 1: Slow Solar Wind

Electric Potential (-V) Case 2: High Speed Solar Wind

[Blackwell et al., 2007]

Lunar Plasma Environments

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



Surface Charging

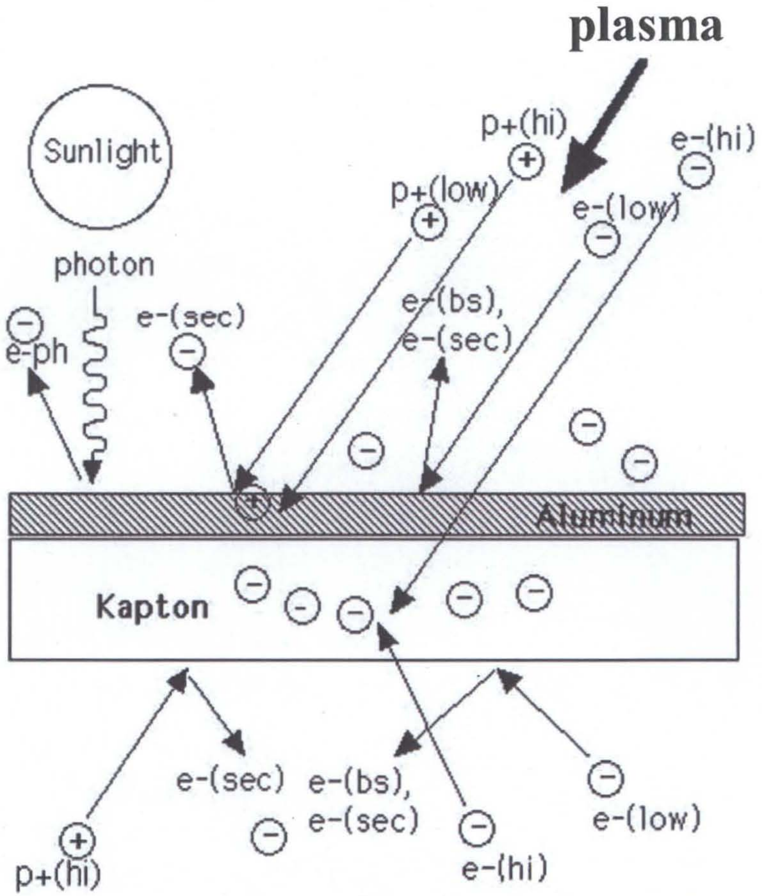
- Time dependent current balance on surfaces

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

$$\sum_k I_k =$$

$+ I_i(V)$	**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]

Charging in Lunar Wake

Lunar Prospector

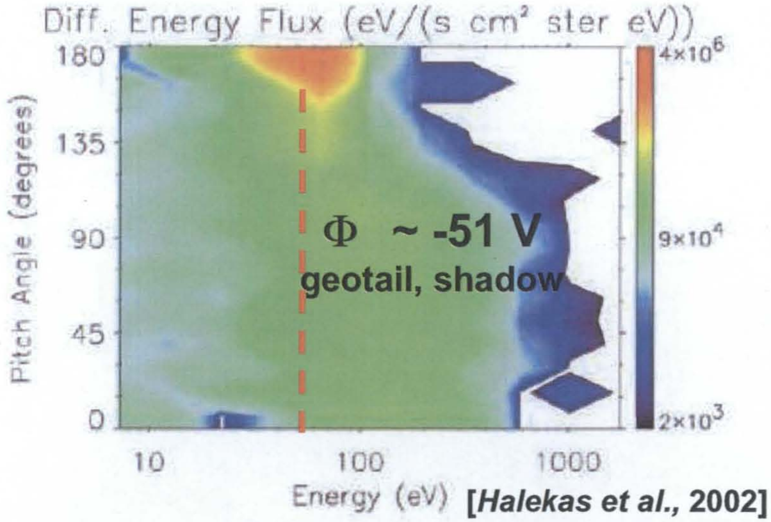
20-115 km

Wake properties relative to ambient solar wind

Spacecraft potentials

day +10 V to +50V

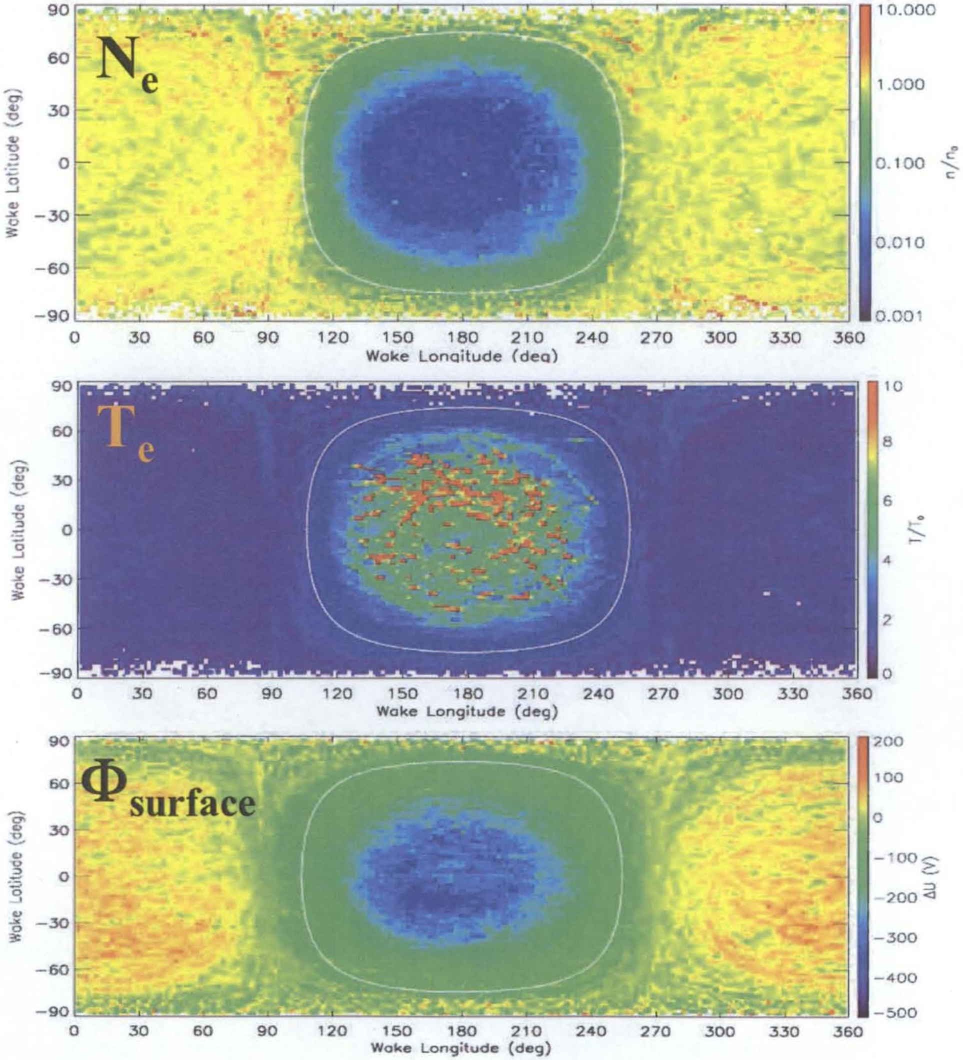
night -100 V to -300 V



Φ ~ -51 V

geotail, shadow

[*Halekas et al.*, 2002]

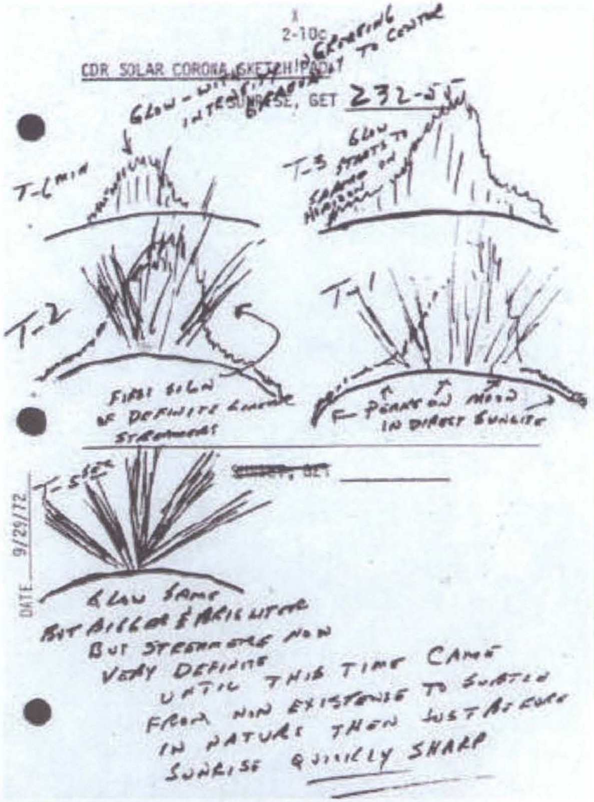


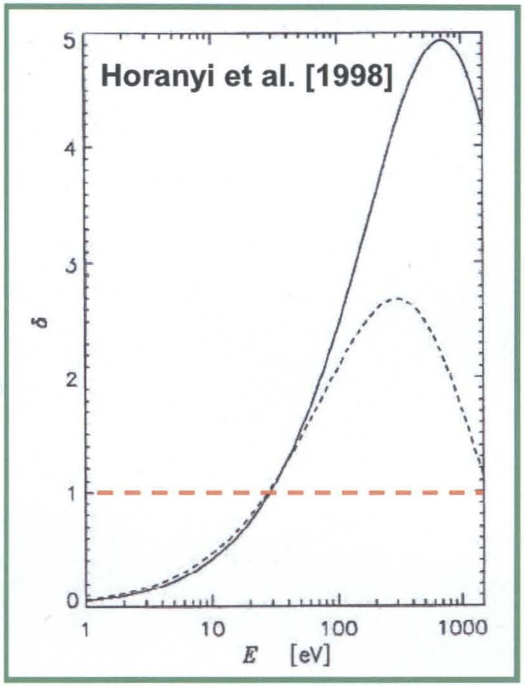
[*Halekas et al.* 2005]

Lunar Dust Charging

Evidence for charged lunar dust

- Apollo 17 astronaut observations (scattered light)
- Surveyor 5,6,7 images of transient horizon glows (scattered light)
- Clementine images (scattered light)
- Apollo 17 Lunar Ejecta and Meteorite Experiment (temperature anomaly)



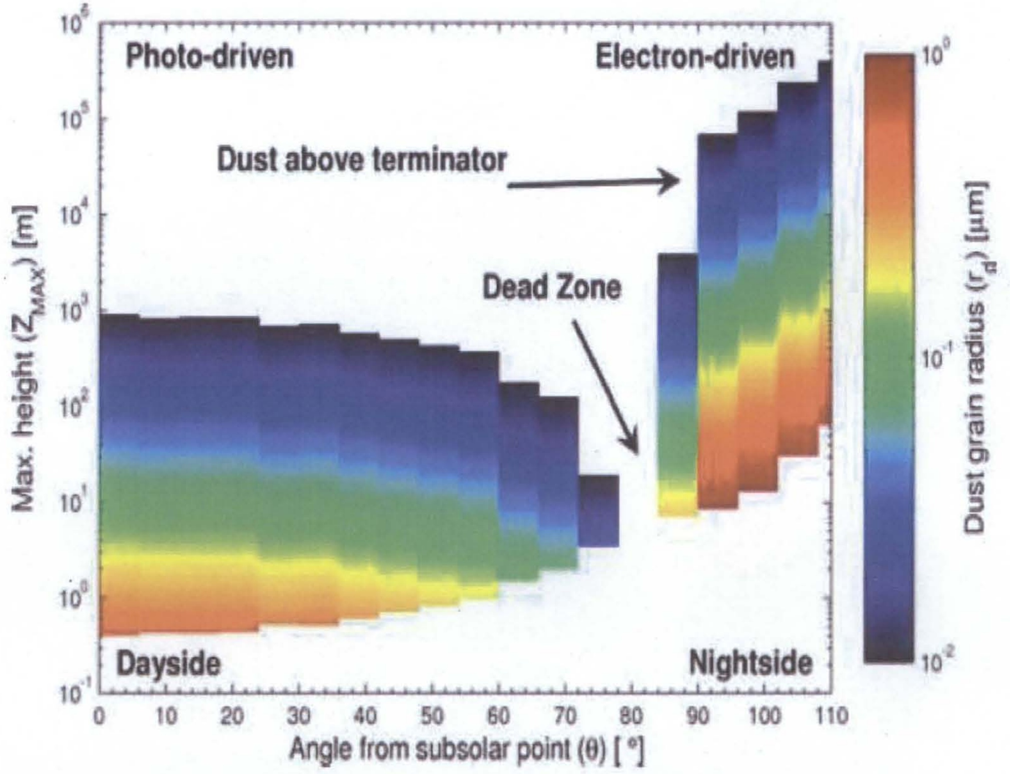


Surveyor 7
Sunset view looking west

- Large secondary yield of lunar dust may reduce dust charging in lunar night (T_e hotter in lunar wake)

Lunar Dust Charging Models

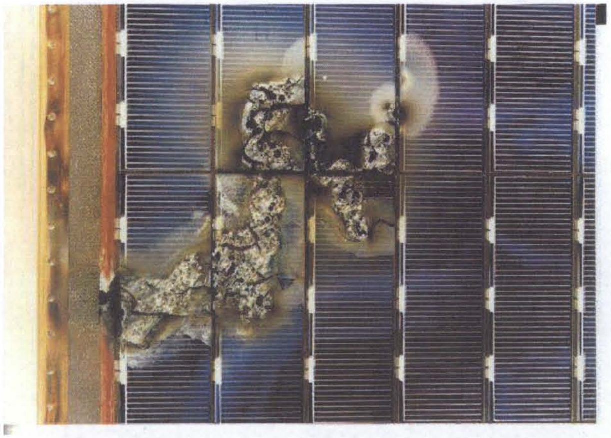
- *Stubbs et al.*, 2005
  - Dynamic fountain model
  - Current collection dominated by photoelectron currents in sunlight and plasma currents in darkness
  - But secondary electron currents are neglected in the current model
- *Sickafoose et al.* 1998 argue SEY for lunar dust are too small to be significant in the charging process for solar wind plasma electrons with T_e~10's eV
  - Dust exposure to magnetotail plasma in eclipse condition (lunar darkside) with T_e ~ 100's eV may predict excessive charging when secondary electron yields are not included in the analysis



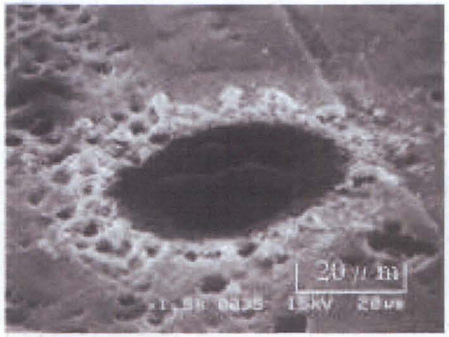
Reference	Material	$\delta_{e,m}$	E_m
Willis et al., 1973	lunar fines	1.5±0.1	300-700 eV
Horanyi et al. 1998	Apollo 17 soil	3.2	400 eV
	JSC-1	3.4	400 eV
	MLS-1	3.1	400 eV

Charging Damage

- Excess charge in localized regions can fail catastrophically producing electrostatic discharge (ESD) arcs



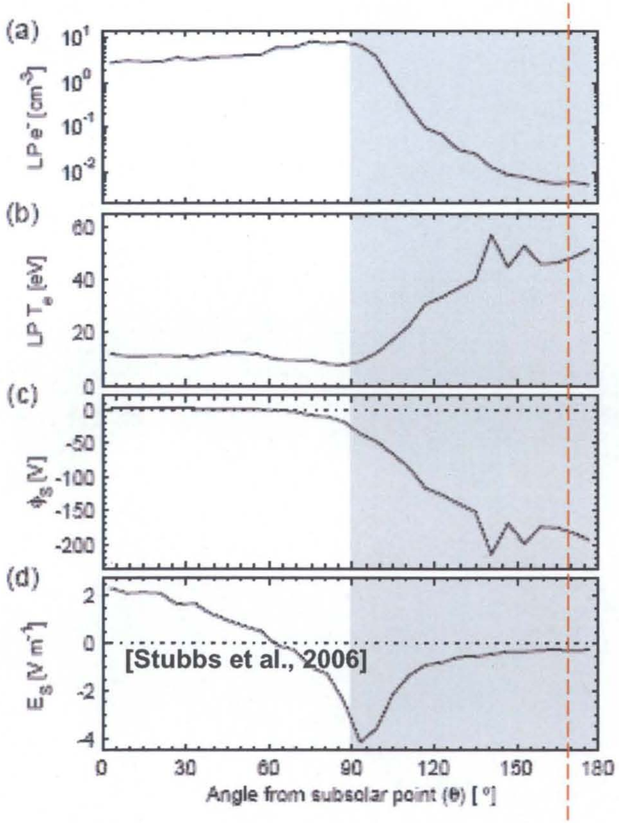
[Source: D. *Ferguson*]

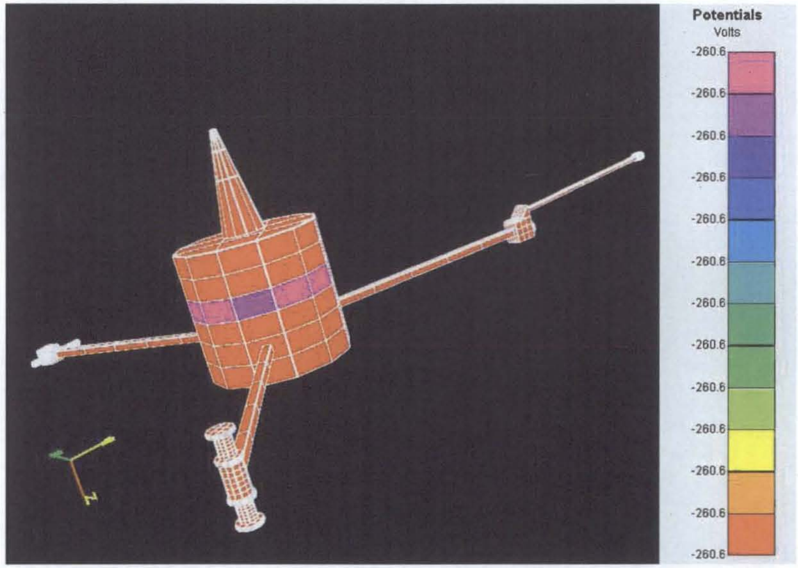


Kawakita et al., 2005

Lunar Surface, Low Lunar Orbit Wake Charging

- Environment from Stubbs et al., 2006
  - Ne ~ 0.01 #/cm3
  - Te ~ 50 eV
- Assume
  - Ni ~ 0.001 Ne (wake)
  - Ti ~ Te





Ni	LP Potentials (volts)	
	Min	Max
0.001 Ne	-260.6	-260.6
0.01 Ne	-233.7	-233.8
0.1 Ne	-149.3	-149.4

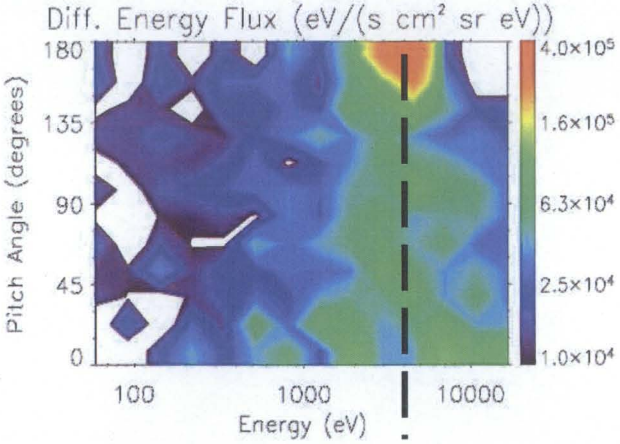
Suggests LP results are ~50% of the true lunar surface potential!

Charging in Lunar Environments

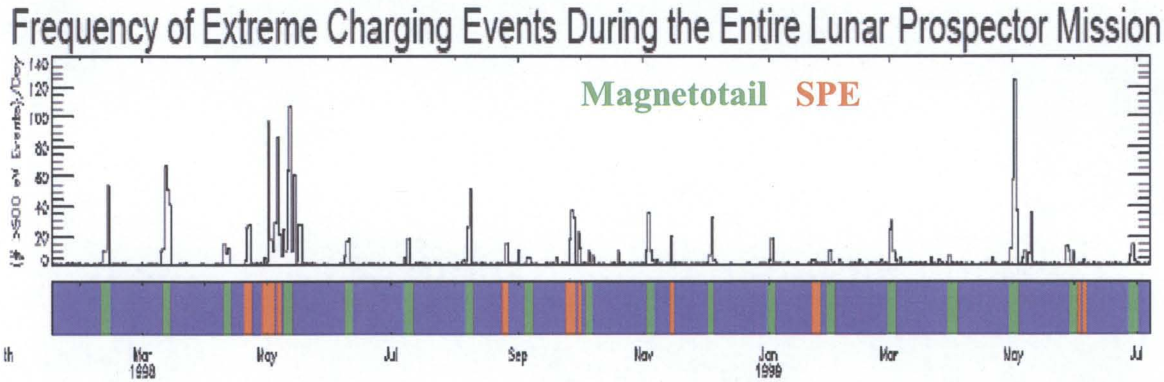
- Solar wind
  - Quiet solar wind T_{eo} ~ 12.15 ± 3.27 eV [*Newbury, 1996*; *Newbury et al.*, 1998]
    N_{eo} ~ 5.87 ± 5.25 #/cm^3 [3 years Genesis L1 ion moments]
    - Wake 6x to 10x T_e enhancements yield ~72 to ~122 eV
    - Surface charging rule of thumb

		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 may occur for extreme conditions

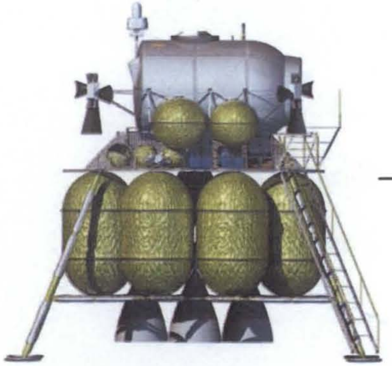


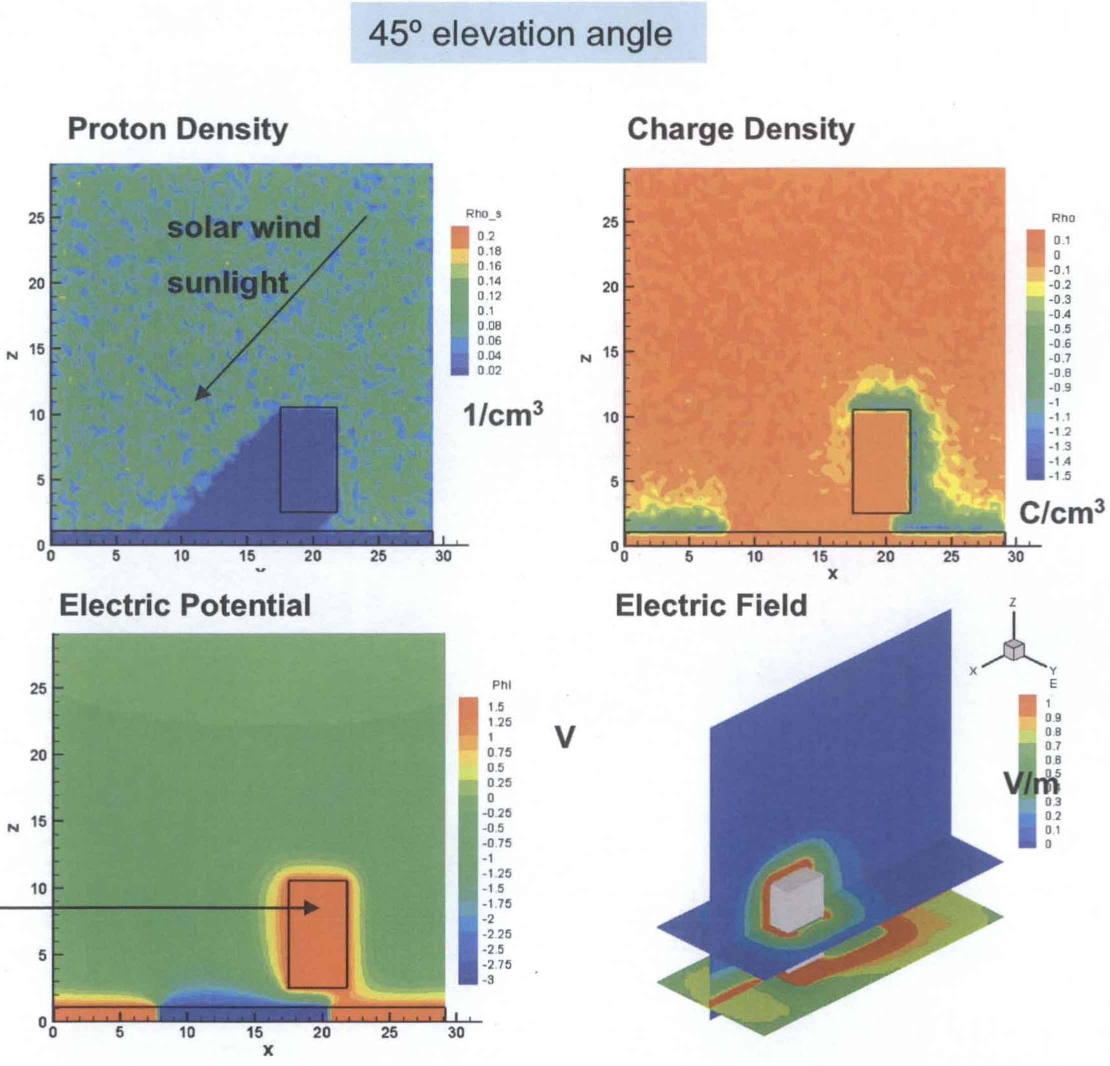
~4.5 kV


Frequency of Extreme Charging Events During the Entire Lunar Prospector Mission

Lunar Plasma Interaction Models

- PIC plasma models [*Wang et al.*, 2006, 2007] used to evaluate charging of coupled lunar surface, infrastructure systems
  - Full particle PIC: particle representation for both ions and electrons
  - Real ion to electron mass ratio (mi/me=1836)
  - ~Typical 10x10^6 particles
- Tool for evaluating plasma environment due to local geometry of habitat, EVA sites




45° elevation angle

Proton Density

Charge Density

Electric Potential

Electric Field

[*Wang et al.*, 2007]

Apollo Experience

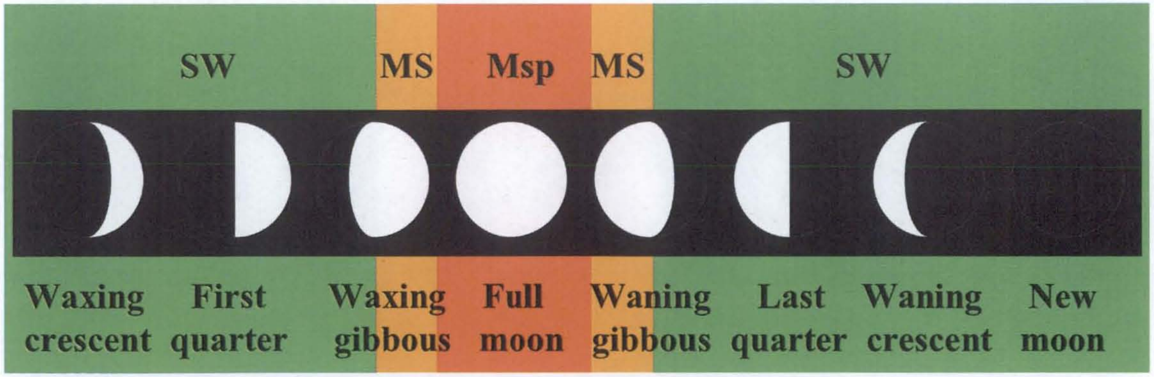
Mission	Landing Date (GMT)	SEA[a] (deg)	Lunar[c] Phase
Apollo 11	20 Jul 69	10.8	WxC, 31%
Apollo 12	19 Nov 69	5.1	WxG, 81%
Apollo 13	----	18.5[b]	----
Apollo 14	5 Feb 71	10.3	WxG, 81%
Apollo 15	30 Jul 71	12.2	1Qtr, 50%
Apollo 16	21 Apr 72	11.9	WxG, 62%
Apollo 17	11 Dec 72	13.0	WxC, 29%

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

[b] Planned

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

John Young at Shadow Rock
Apollo 16 EVA-3
AS16-106-17413



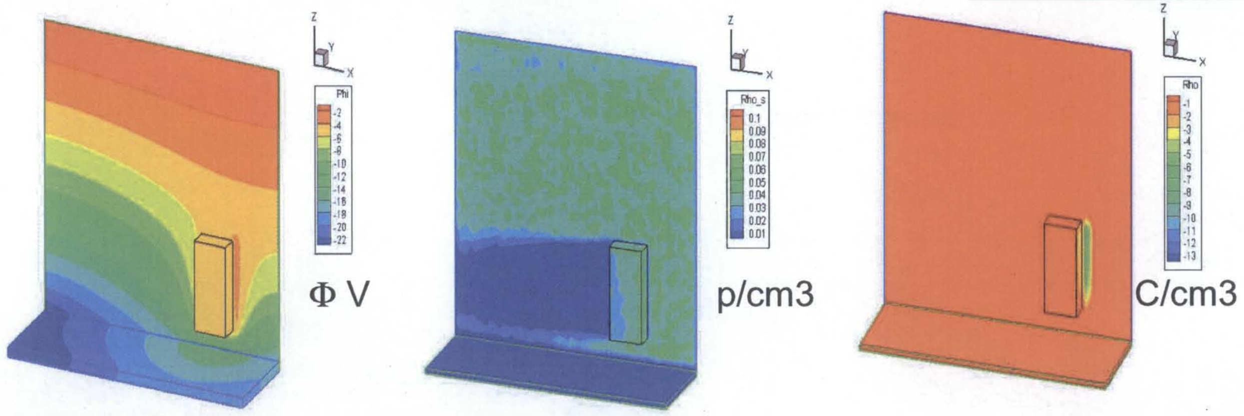
SW **MS** **Msp** **MS** **SW**

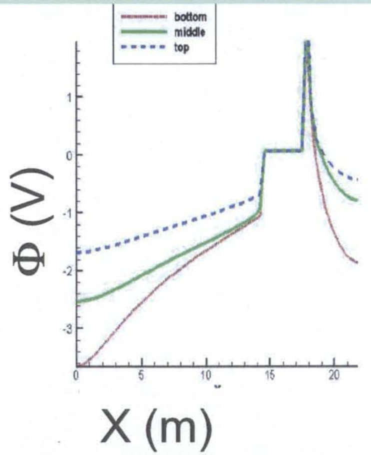
Waxing crescent **First quarter** **Waxing gibbous** **Full moon** **Waning gibbous** **Last quarter** **Waning crescent** **New moon**

Charging and Solar Elevation Angle

5º Solar elevation angle

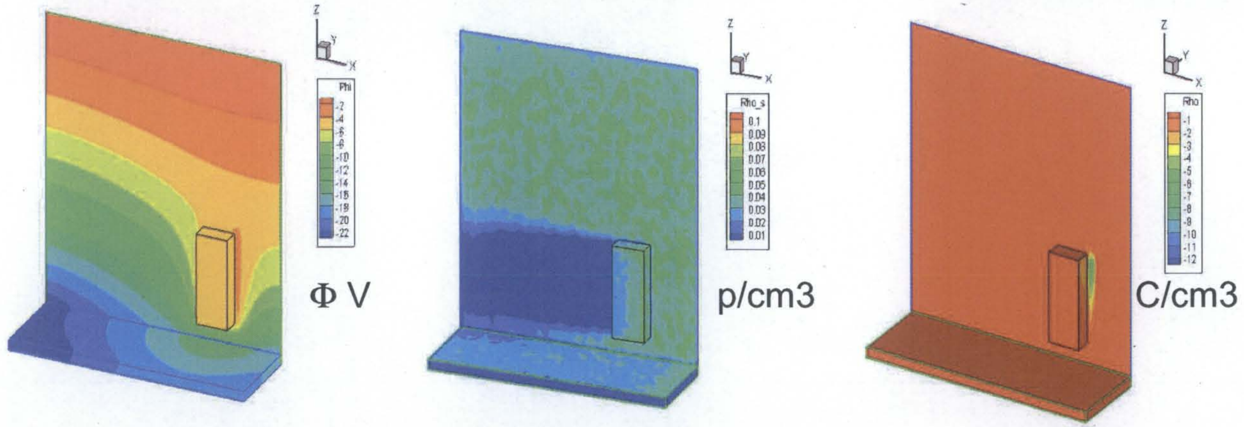
$\Phi_{s/c} \sim 0$ V $\Phi_{wake} \sim -3$ V

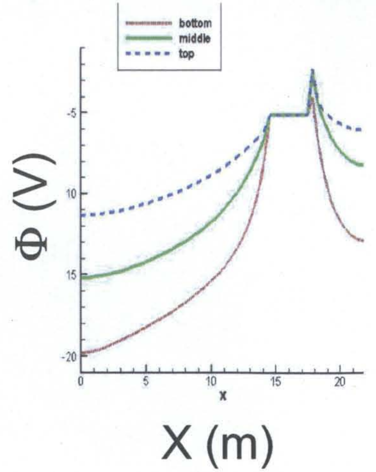




0º Solar elevation angle

$\Phi_{s/c} \sim -5$ V $\Phi_{wake} \sim -15$ V





[*Wang et al.*, 2007]

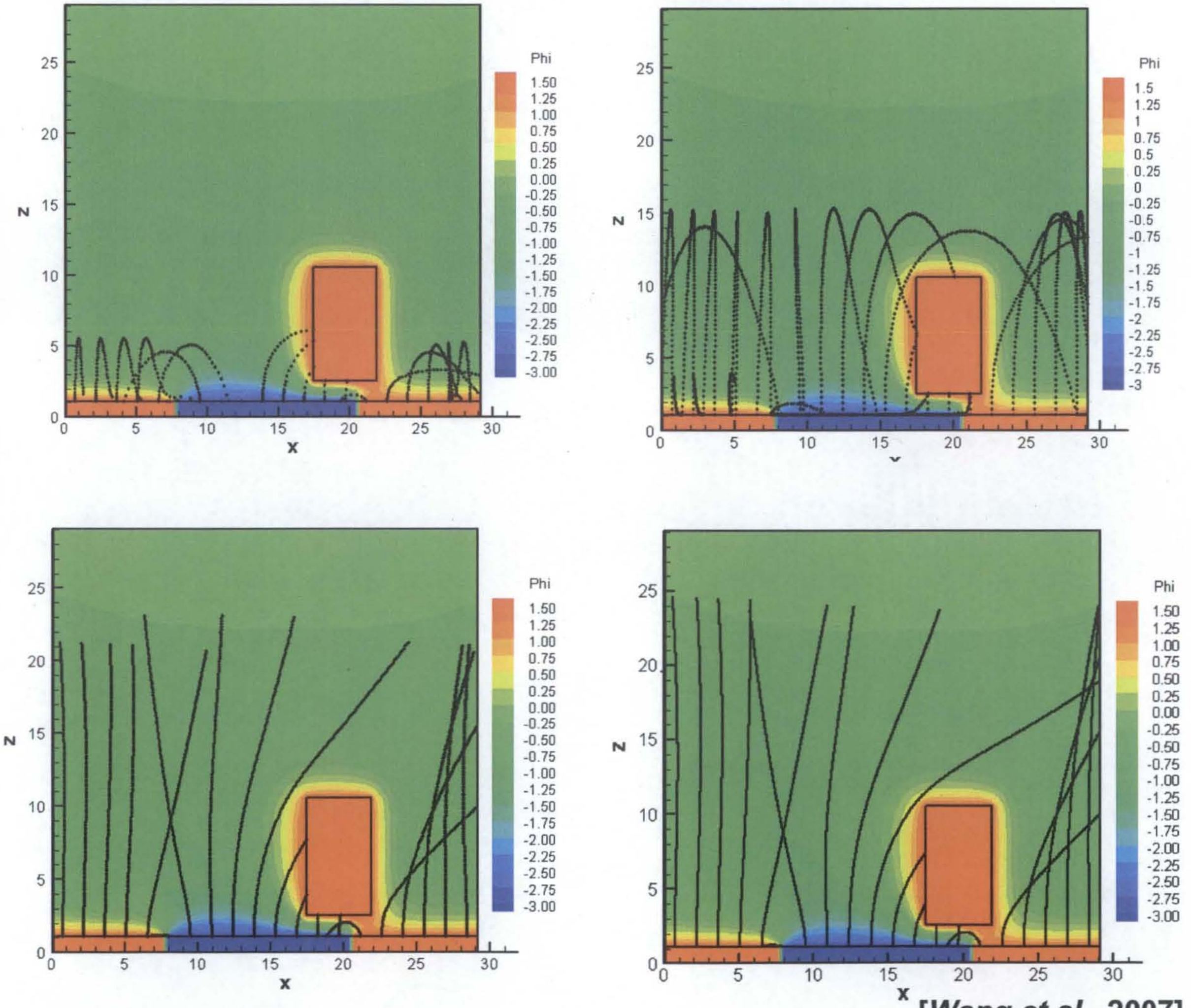
Charged Dust, Lander Simulations

Dust initial condition:

Vz = 0 m/s **Vz = 1 m/s**

Dust radius: 1 µm

Dust radius: 0.1 µm



[Wang et al., 2007]

Bulk (Deep Dielectric) Charging

- Radiation charging of insulators, isolated conductors

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

$$D = \varepsilon E$$

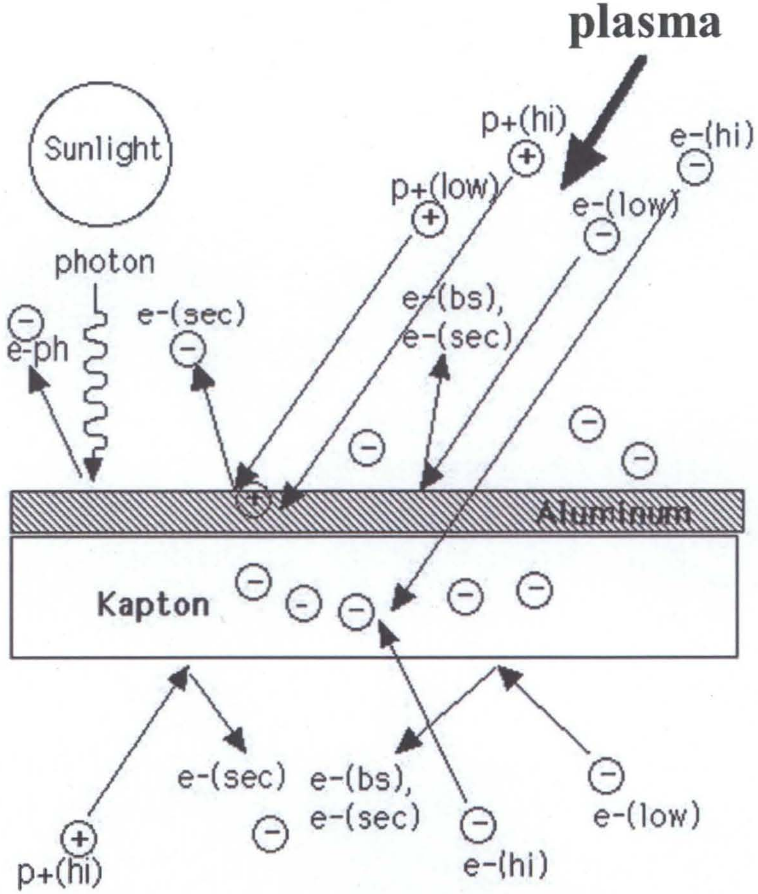
$$\varepsilon = \kappa \varepsilon_0$$

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

$$J = J_0 + J_C$$

$$J = \sigma E$$
$$= \left(\sigma_{dark} + \sigma_{radiation}\right) E$$

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



(Garrett and Minow, 2004)

Charging in Cold Environments

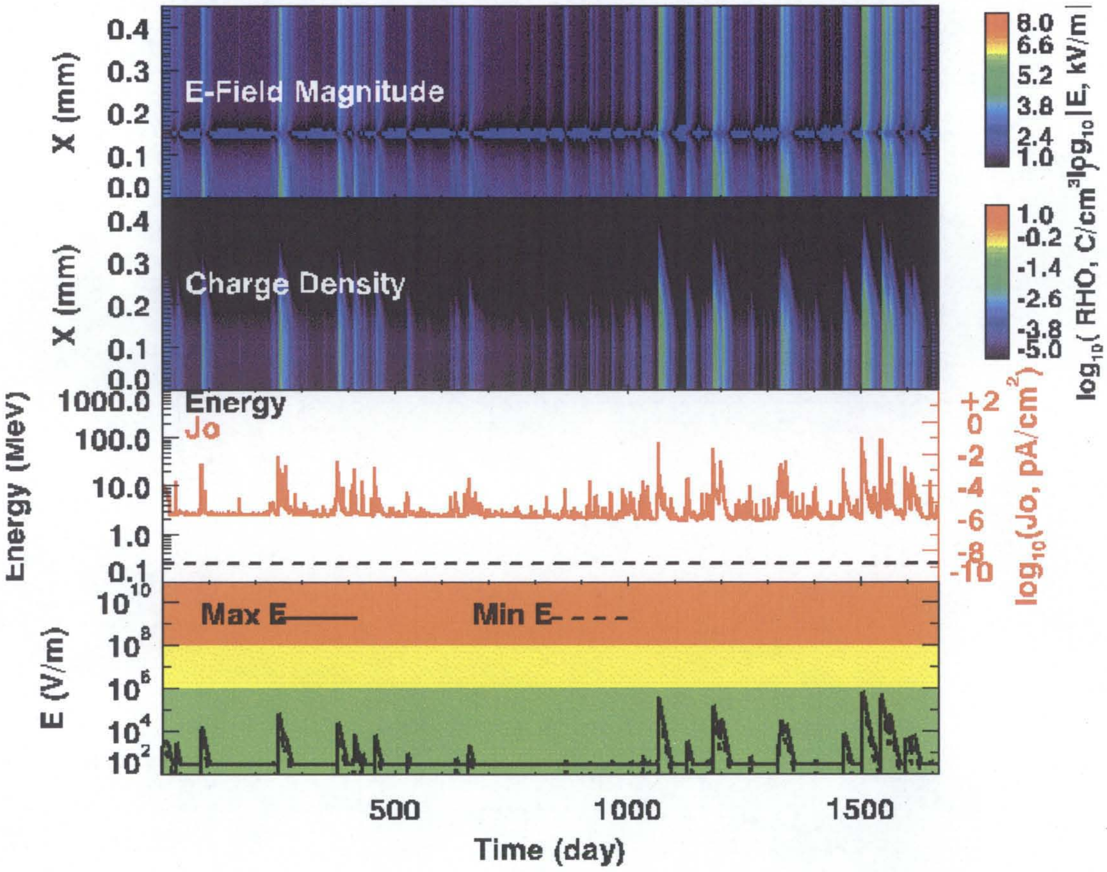
- Lunar environments can be very cold
  - ~85K in night just before sunrise
  - ~40K to 50K in permanently dark polar craters
- Insulator charging in these environments will integrate charge for extended periods of time

$T \sim 300\text{K}$

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

$\kappa \sim 3.706$

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



Minow et al., 2007

Charging in Cold Environments

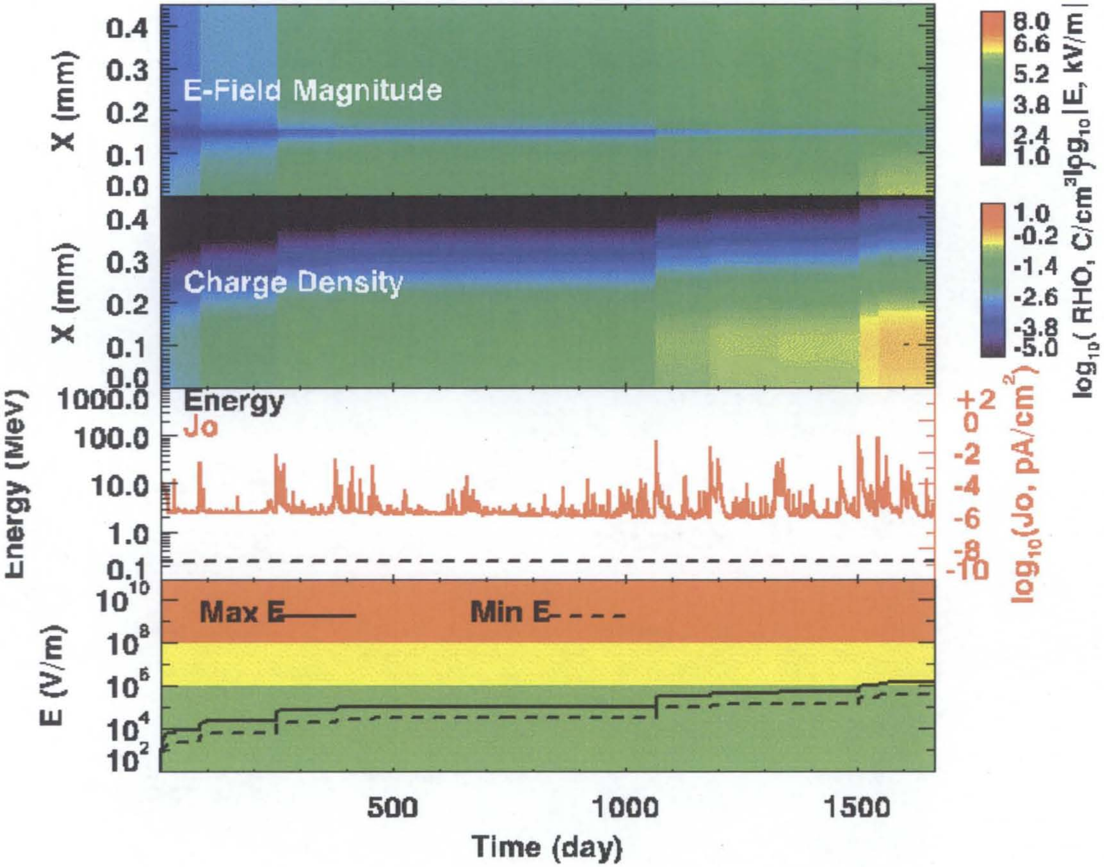
- Lunar environments can be very cold
  - ~85K in night just before sunrise
  - ~40K to 50K in permanently dark polar craters
- Insulator charging in these environments will integrate charge for extended periods of time

$T \sim 100K$

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

$\kappa \sim 7.412$

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



Minow et al., 2007

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

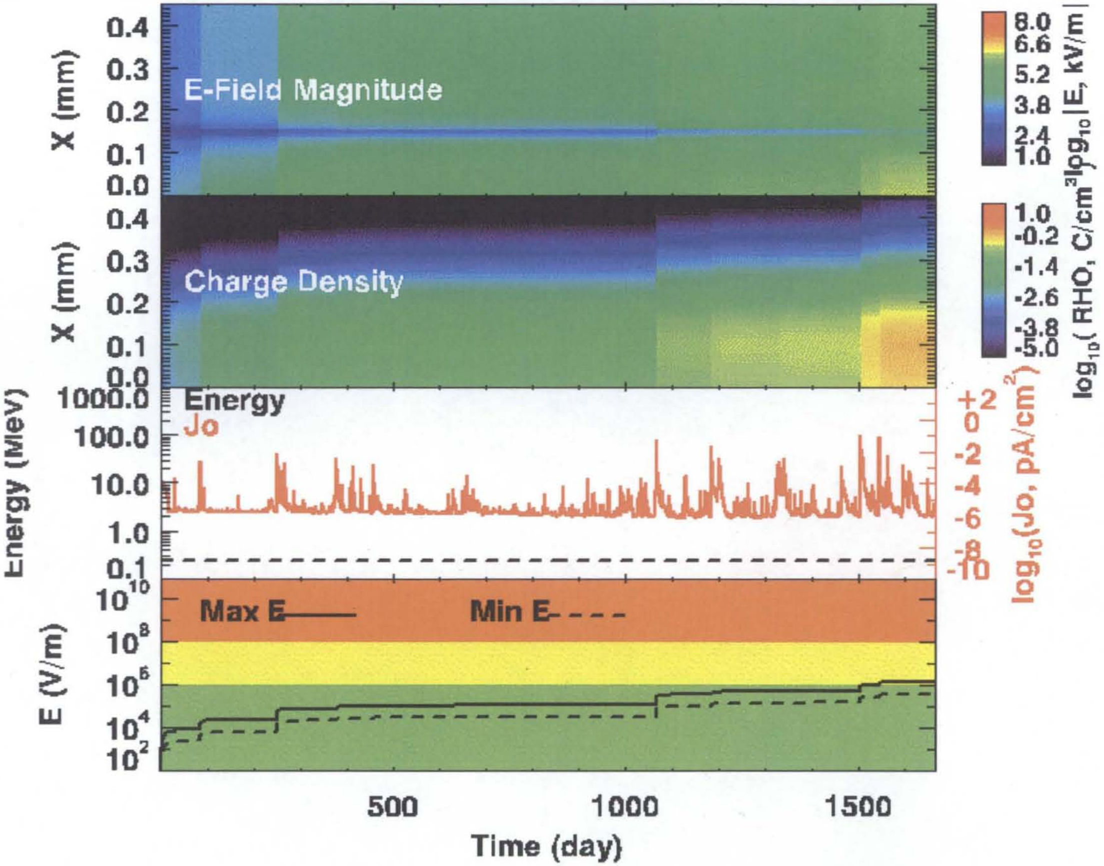
$T < 50K$

$\sigma \sim 10^{-25}$ 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"



Minow et al., 2007

Summary

- Lunar environments represent numerous engineering challenges for establishing a long term human presence on the Moon
- Apollo experience tells us that landing and operating on lunar surface can successfully be done over 2-3 day periods
- Construction of robust lunar infrastructure will require careful attention to lunar environments