Impacts of the Space Environment on Lunar Exploration

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AIAA SciTech Forum
23 – 27 January 2023, National Harbor, MD

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Image: NASA

Introduction

- "Cis-lunar" space including lunar orbit and the lunar surface is once again a strong focus as a destination for both robotic and human space exploration

- Multiple nations are now pursuing both robotic exploration programs with spacecraft in lunar orbit and landers on the lunar surface.

- In addition to these purely robotic exploration programs, NASA has started construction of the Gateway space station for operations in lunar orbit and development work has begun on the Human Landing System infrastructure which promises to return humans to the lunar surface for the first time since the last Apollo missions in the 1970's.

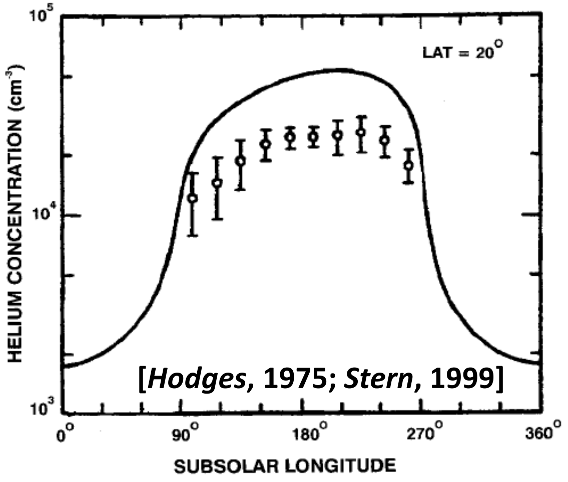
- Because the Moon has very little atmosphere and no strong intrinsic magnetic field to protect the surface from meteoroid impacts and charge particles, respectively, the space environments that need to be considered when designing and operating lunar exploration missions are essentially the free-field environments used in design of interplanetary missions

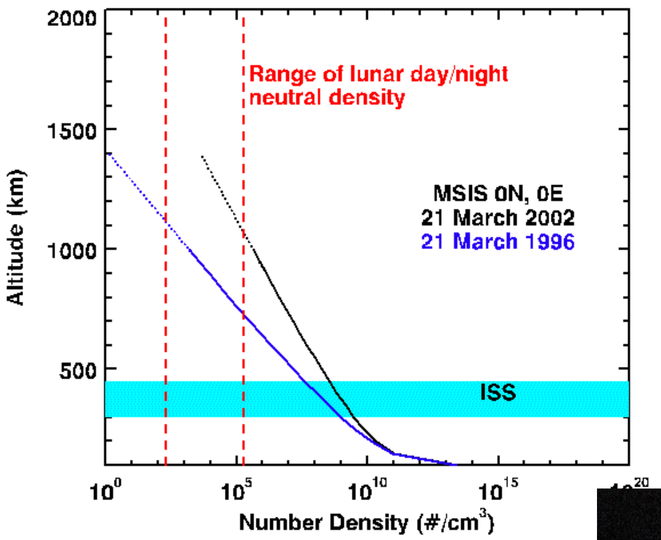
Outline

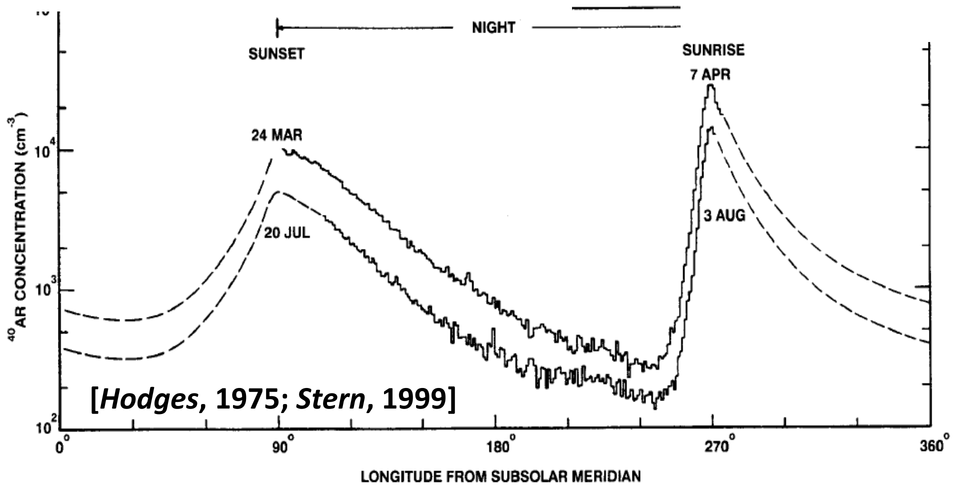
- Atmosphere
- Lunar regolith and dust
- Illumination and thermal
- Solar UV/EUV
- Ionizing radiation
  - GCR
  - SPE
  - Albedo neutrons
- Space plasma and charging
- Meteoroid environments
  - Primary impacts
  - Ejecta
- DSNE Lunar Environments

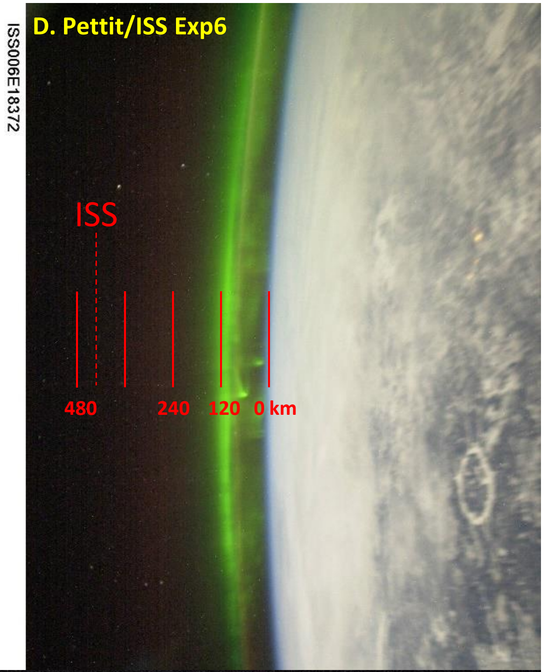
Lunar Atmosphere

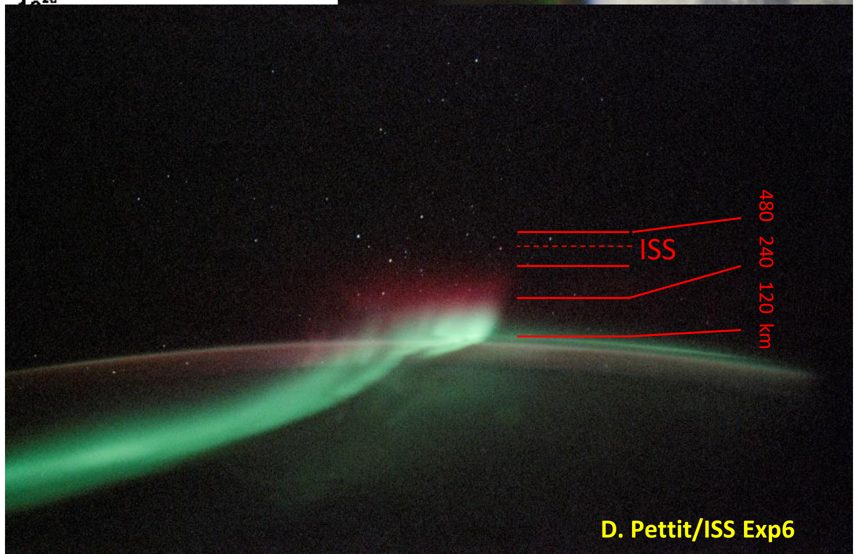
- Moon’s tenuous atmosphere (exosphere) is dominated by ^{40}Ar, He
- Peak density occurs during the lunar day
- Peak density lunar atmospheric density is similar to thermosphere density in LEO at altitudes >1000 km (better vacuum than ISS environment around 400 km)!





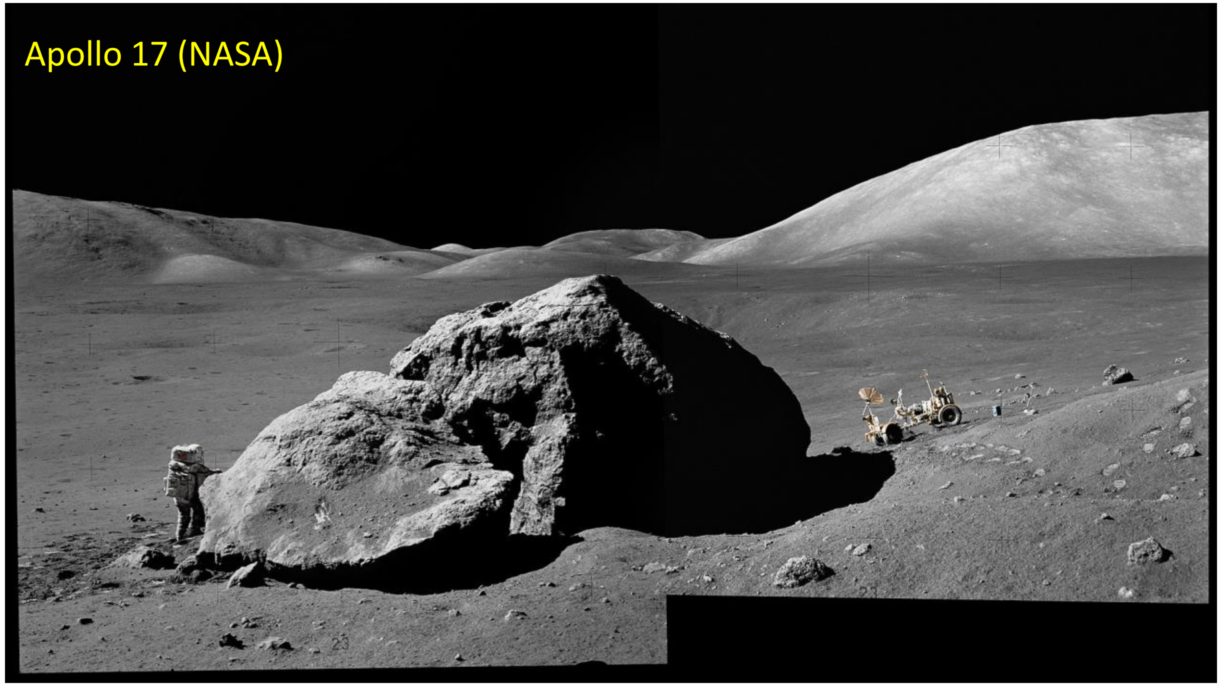


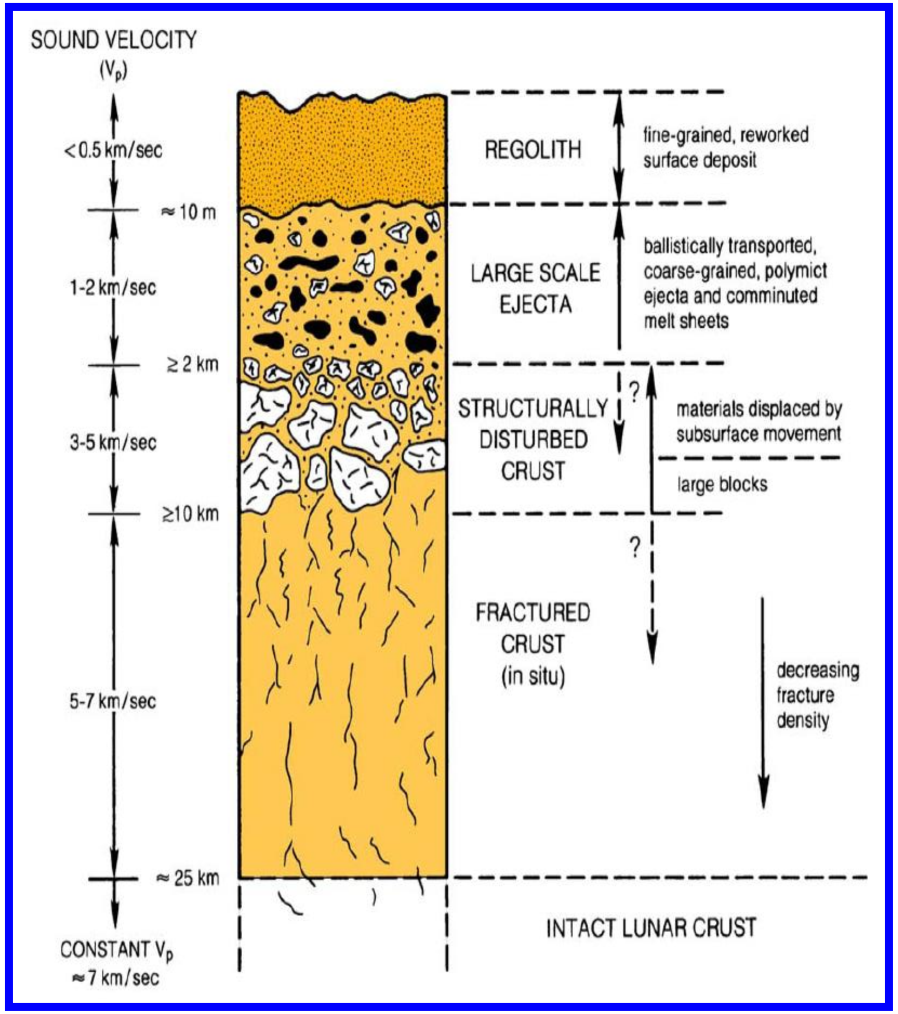




Dusty Regolith

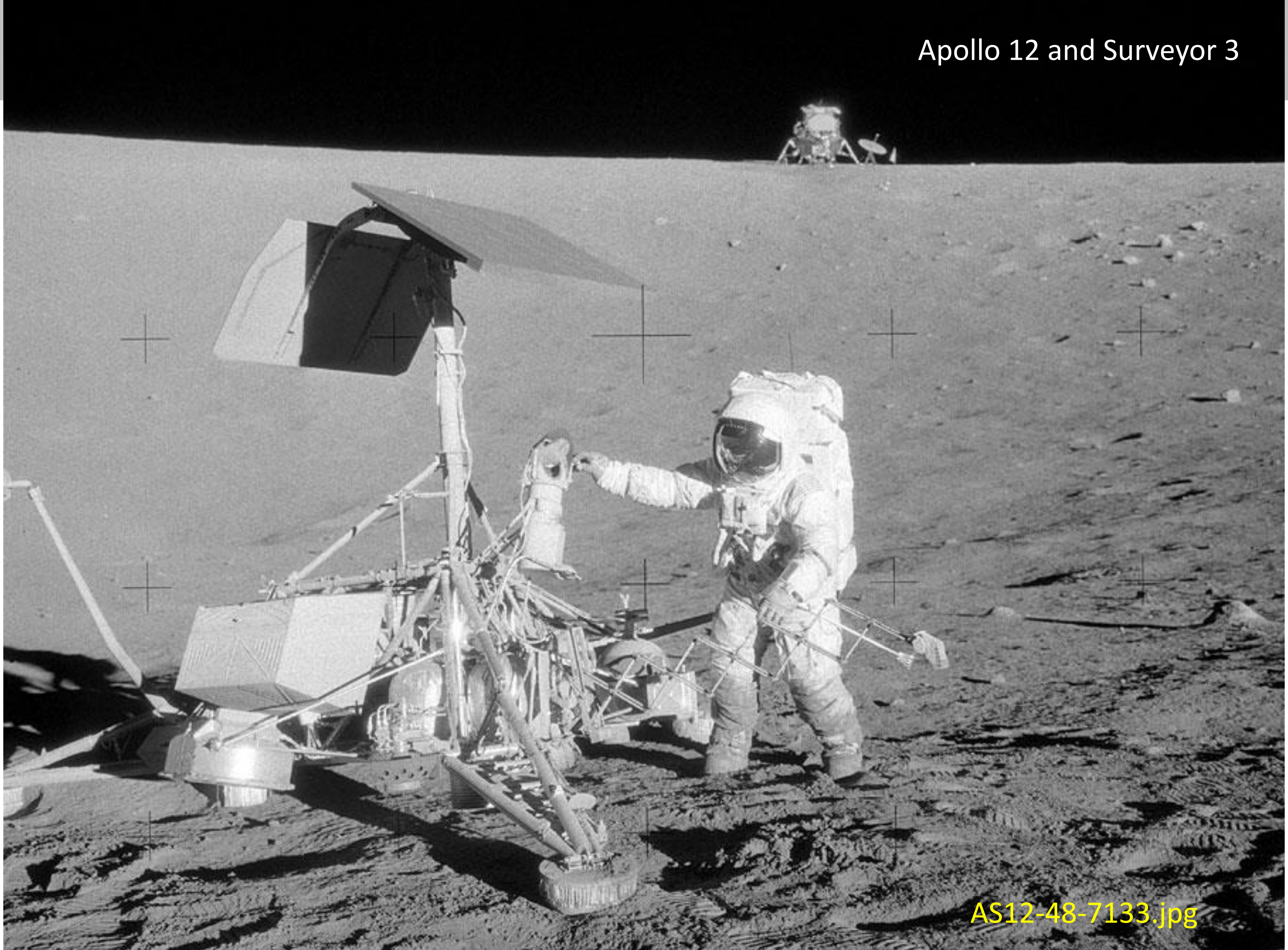
- Formation of lunar regolith (unconsolidated surface material) is dominated by impact processes
- Shattered material remains sharp due to lack of erosion processes
- Surface layer of loose, unconsolidated material <1 cm thick overlays ~10 m of dense, packed regolith
- Surface is covered by an abrasive dusty layer with properties similar to powdered glass
- Lunar regolith covers the lunar surface with bedrock visible only on the walls of steep craters



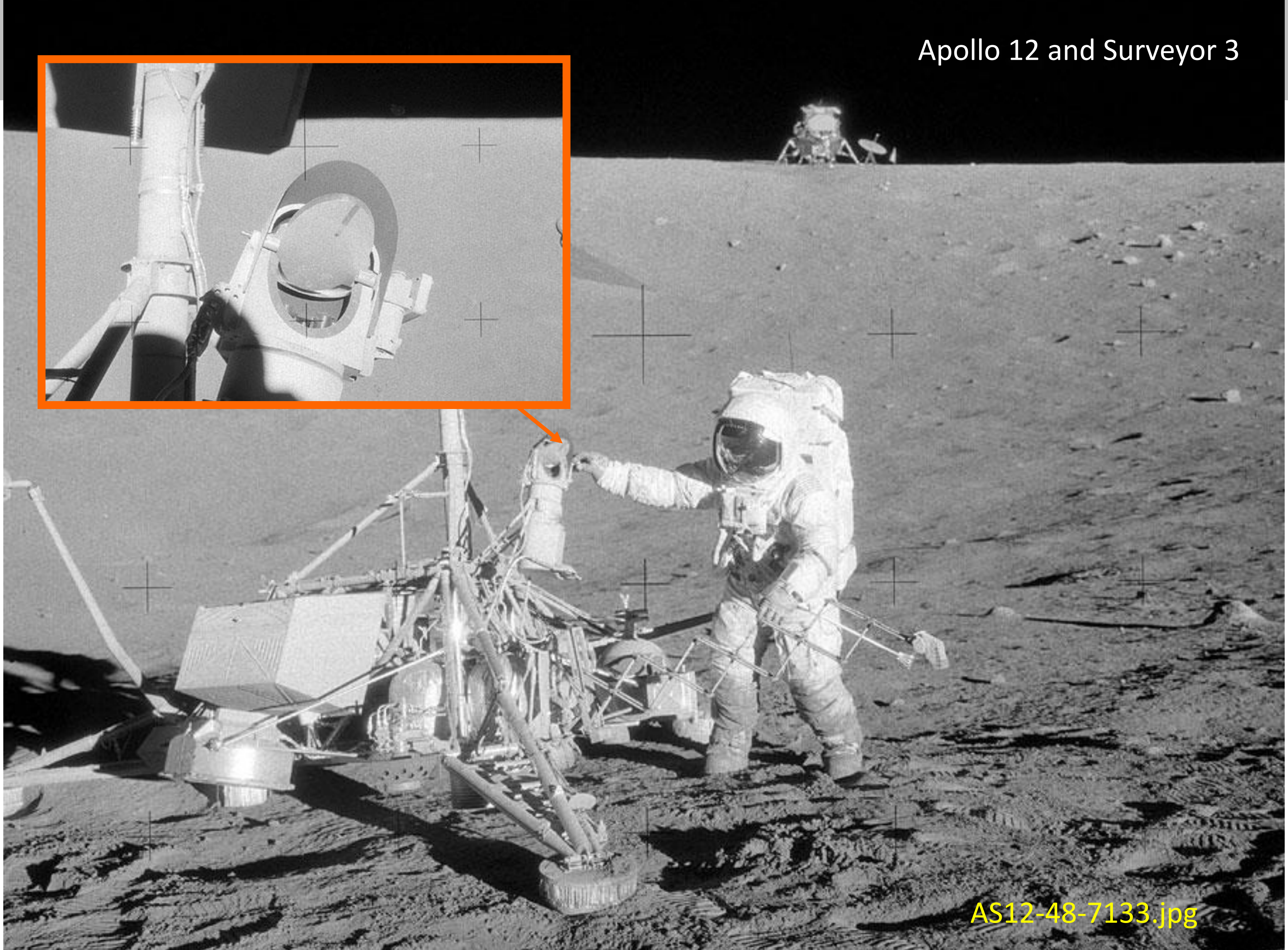


[*Hörz et al.* 1991; *Kring*, 2006]

Apollo 12 and Surveyor 3

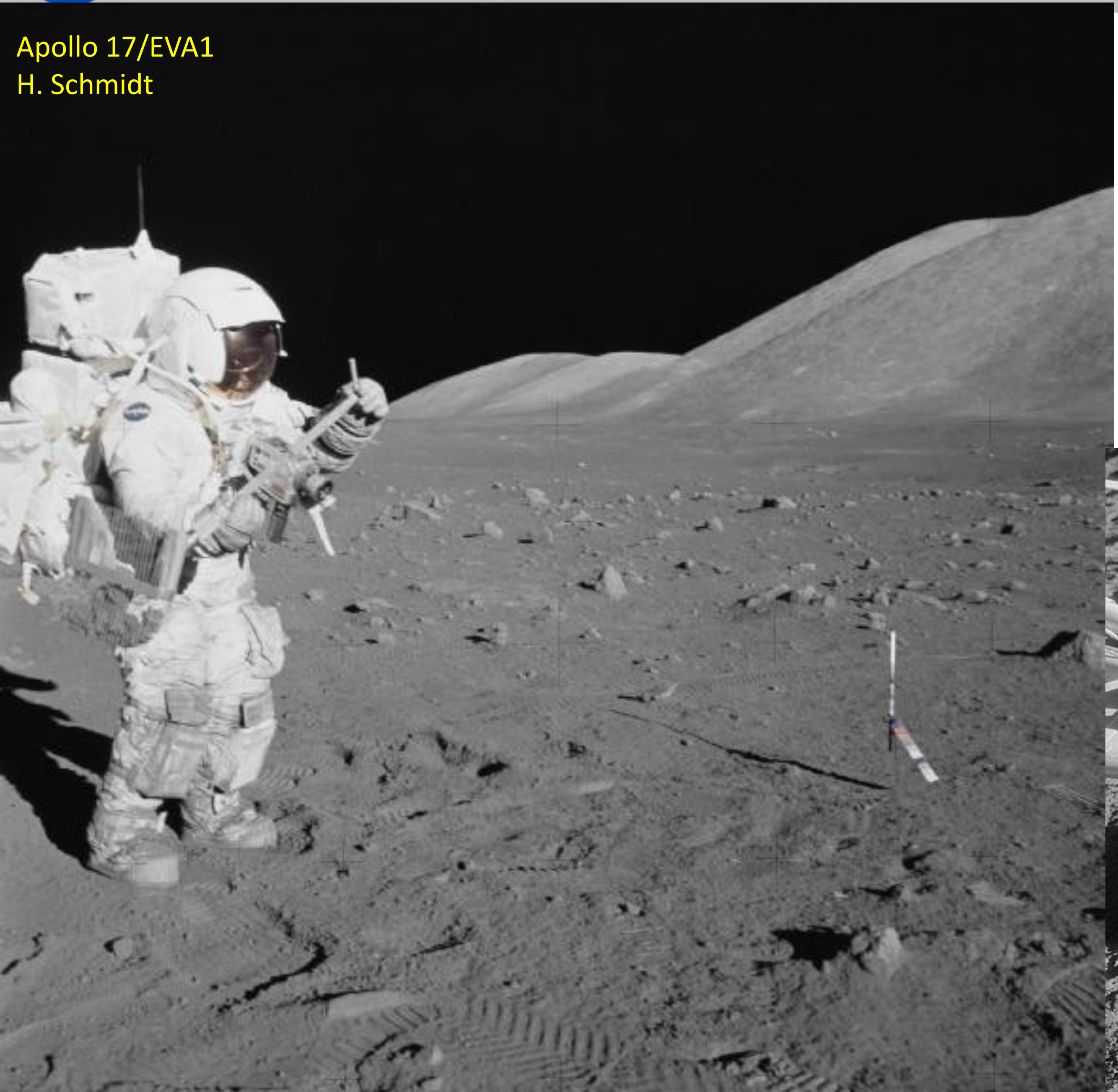


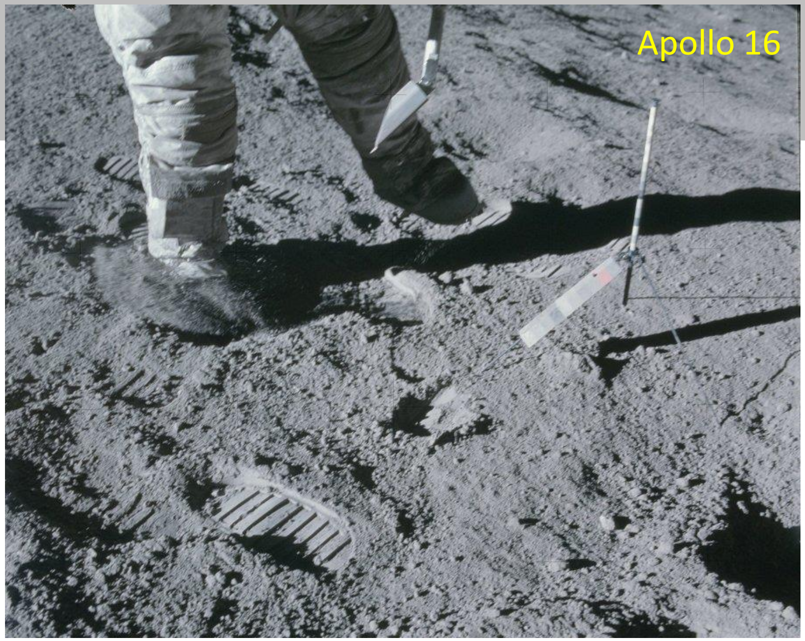
Apollo 12 and Surveyor 3

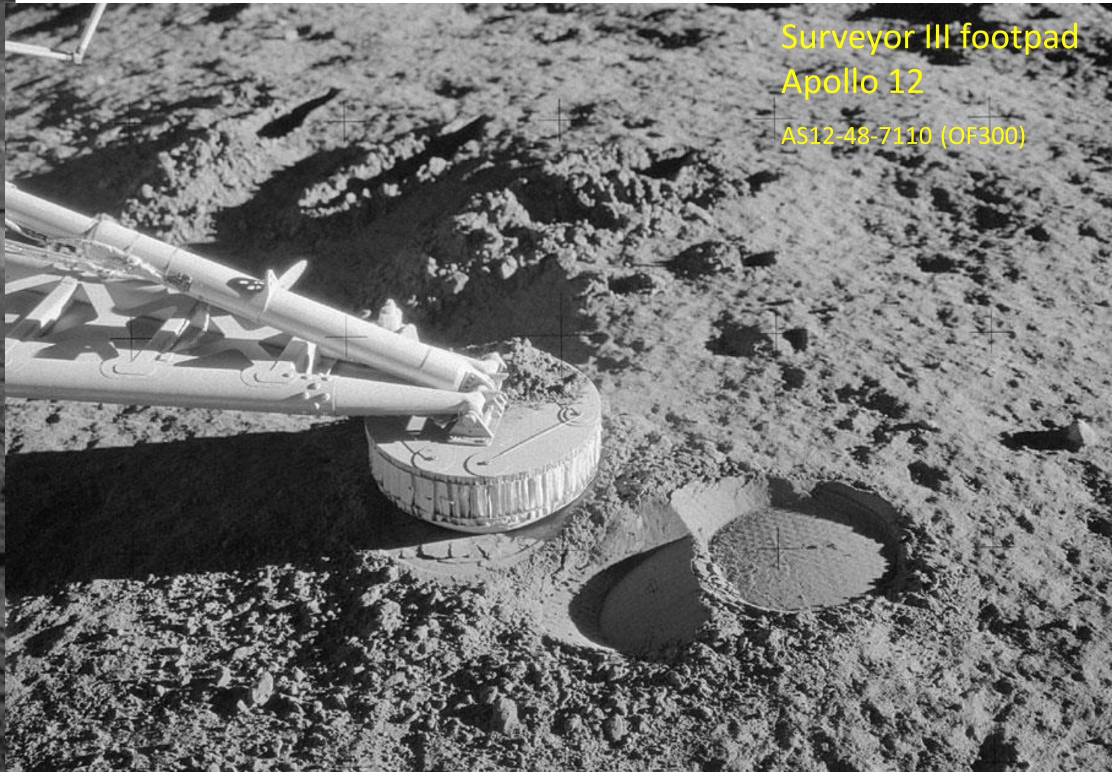


AS12-48-7133.jpg

Lunar Dust

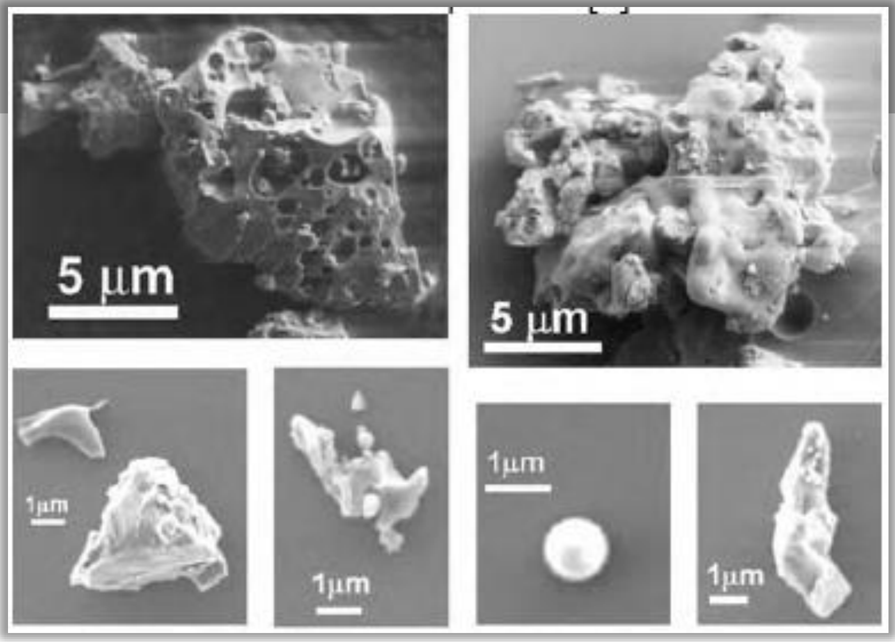

Apollo 17/EVA1
H. Schmidt


Apollo 16


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

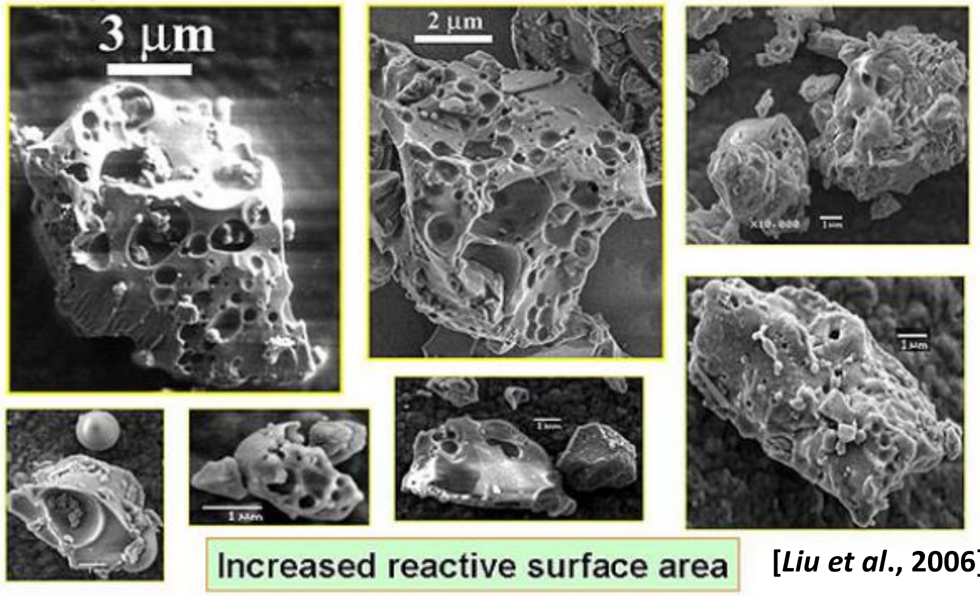
Lunar Dust Properties

- Lunar dust is an issue for engineering systems for lunar environments
  - Sharp, abrasive particles
  - Abrasion of EVA suits, seals, and bearings
- Human health issues
  - Toxic? Lung irritation, damage?
- <20 µm particles represent ~20 wt% of lunar soil
  - Challenge to design systems to reduce, eliminate the <10 µm particles in crew habitat

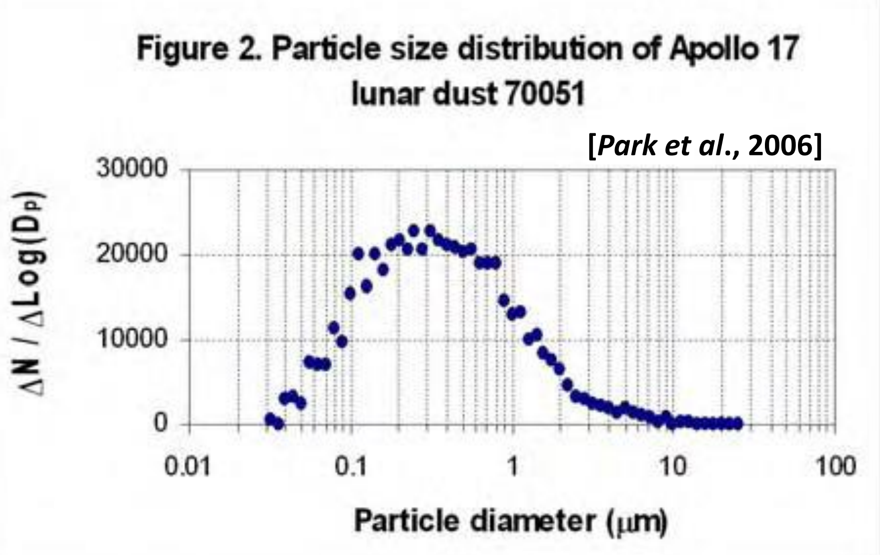


[*Park et al.*, 2006]

Vesicular Grains **Apollo 17 70051**



[*Liu et al.*, 2006]



Dust Impacts

- Lunar dust is a challenge for long term exploration of the Moon
- EVA operations will necessarily be conducted within the dusty surface environment
- Abrasive, glass-like material sticks to suits, irritates throat and lungs, and can damage mechanical systems
- Dust transfer from lunar surface is spacecraft and orbital systems will need to be mitigated

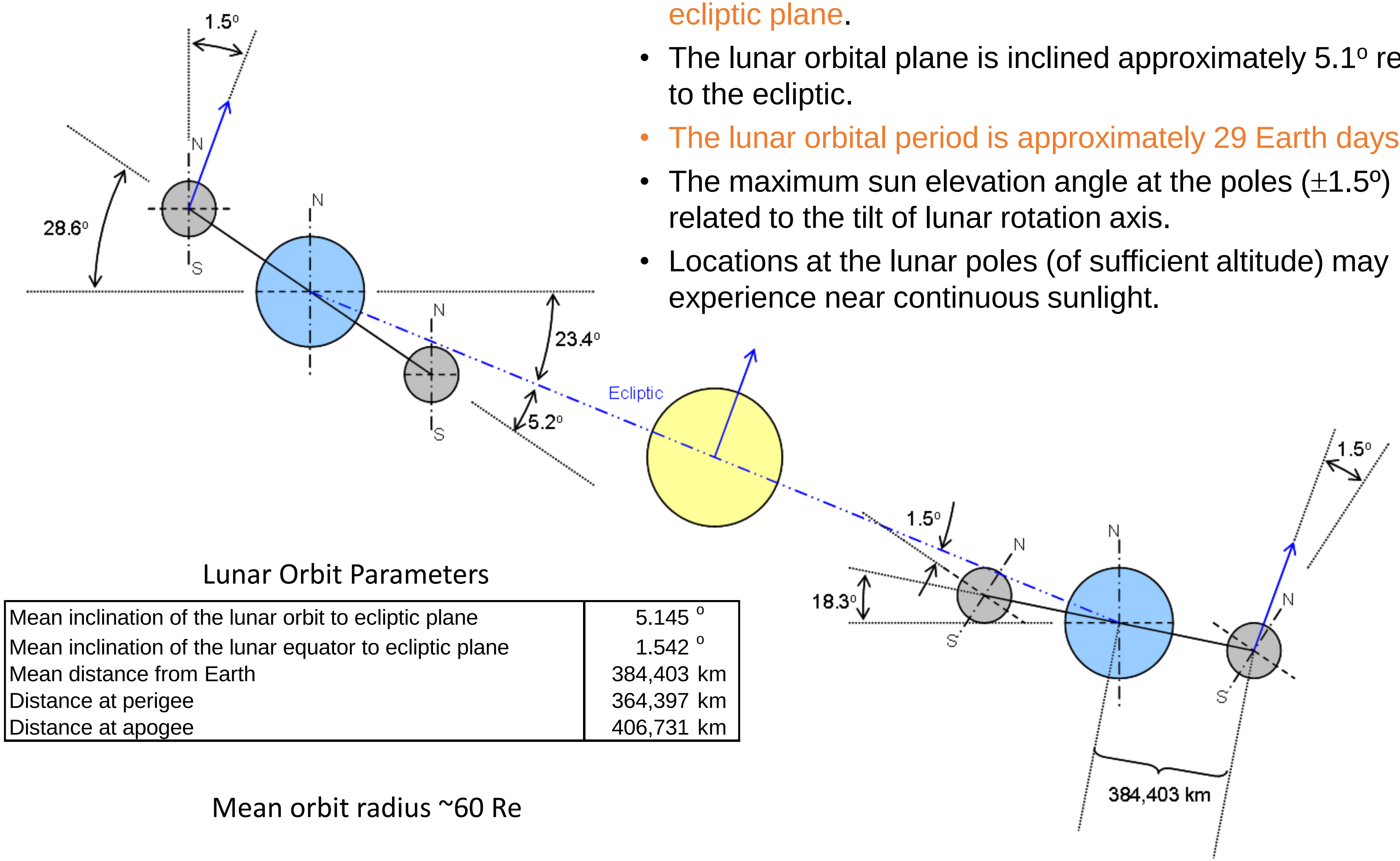

Apollo 16 (NASA)


Apollo 16 (NASA)


Apollo 17
E. Cernan in LEM
following EVA (NASA

Lunar Orbit and Solar Elevation Angle

- The moon's axis of rotation is tilted about 1.5º relative to the ecliptic plane.
- The lunar orbital plane is inclined approximately 5.1º relative to the ecliptic.
- The lunar orbital period is approximately 29 Earth days.
- The maximum sun elevation angle at the poles (±1.5º) is related to the tilt of lunar rotation axis.
- 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 º
Mean inclination of the lunar equator to ecliptic plane	1.542 º
Mean distance from Earth	384,403 km
Distance at perigee	364,397 km
Distance at apogee	406,731 km

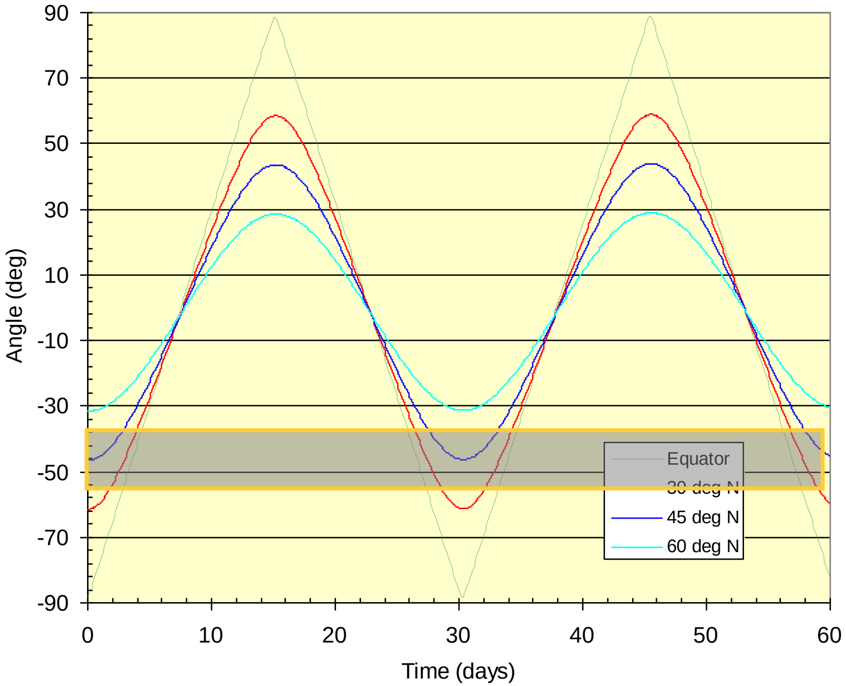
Mean orbit radius ~60 Re

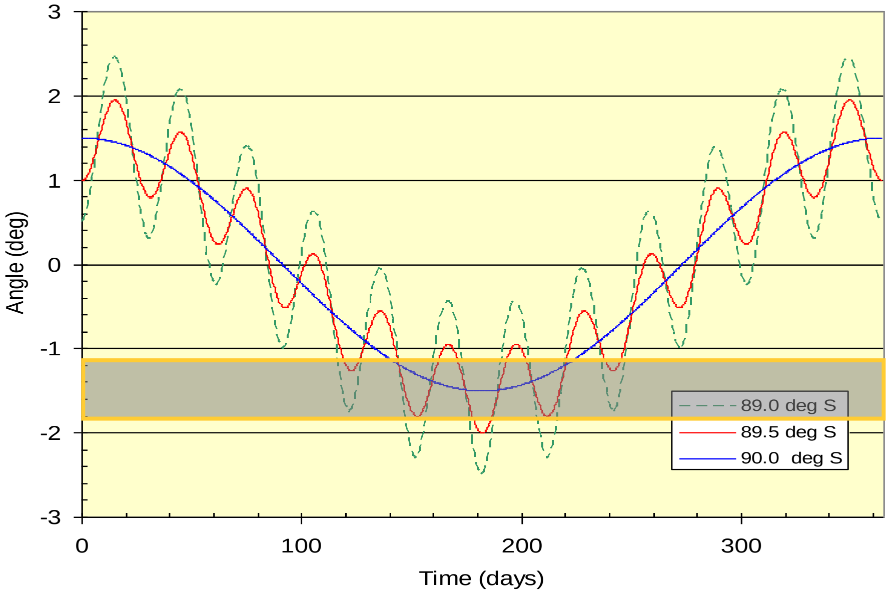
[*Sharp and Schunk*, 2007]

Polar Illumination

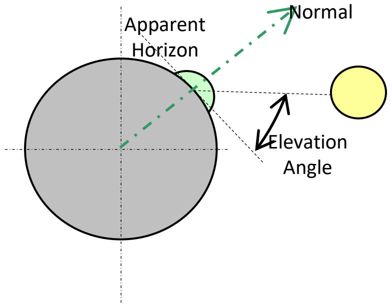
Solar Elevation Angles (Typical Solar Elevation for Lunar South Pole)

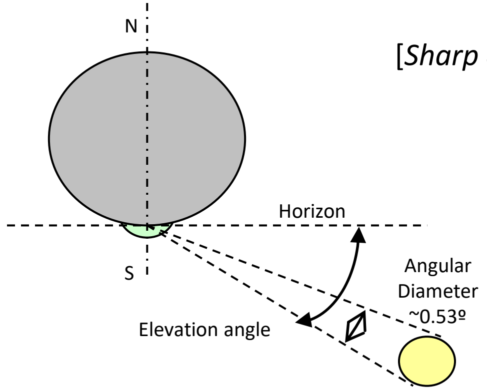
Solar angular diameter (~0.53° from lunar surface) is important for considering illumination in polar regions





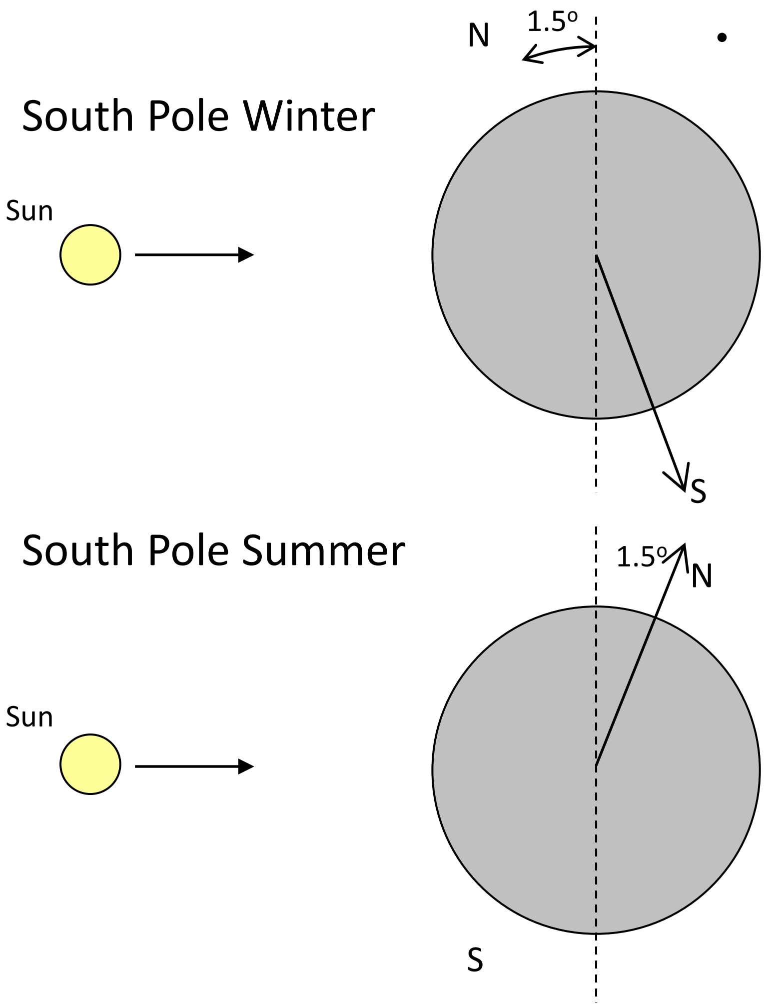
[*Sharp and Schunk*, 2007]





Eternal Light and Dark

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

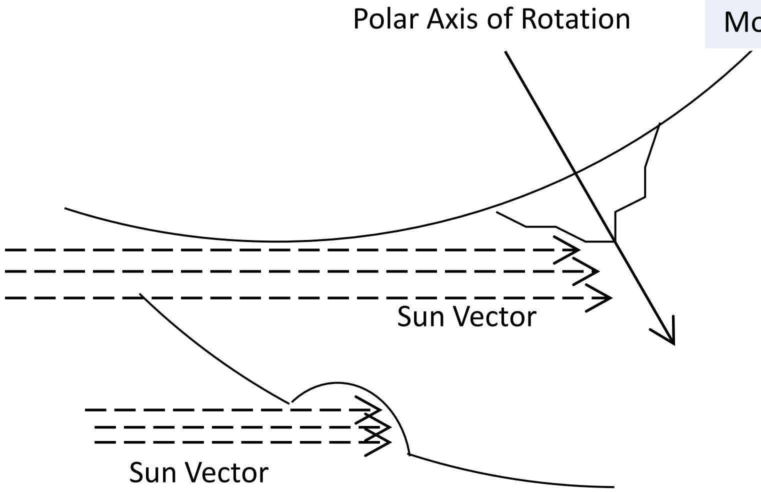


- Local topography is important on the Moon
- Moon is nearly spherical
- Local variation in topography are great than the figure of the Moon
  - Earth: geoid +/- ~10 km from sphere
  - Moon: geoid +/- ~0 km from sphere

    Altitude variations of ~10 km occur within few hundred km of lunar south pole

Peak	Prom-inence	Height
Everest	8.85 km	8.85 km
Aconcagua	6.96 km	6.96 km
Denali	6.14 km	6.19 km
Mount Kilimanjaro	5.86 km	5.90 km
Pico Cristobal Colon	5.51 km	5.70 km
Mount Logan	5.25 km	5.96 km
Pico de Orizaba	4.92 km	5.64 km
Vinson Massif	4.89 km	4.89 km
Puncak Jaya	4.88 km	4.88 km
Mount Elbrus	4.74 km	5.64 km

https://en.wikipedia.org/wiki/List_of_mountain_peaks_by_prominence



[*Sharp and Schunk*, 2007]

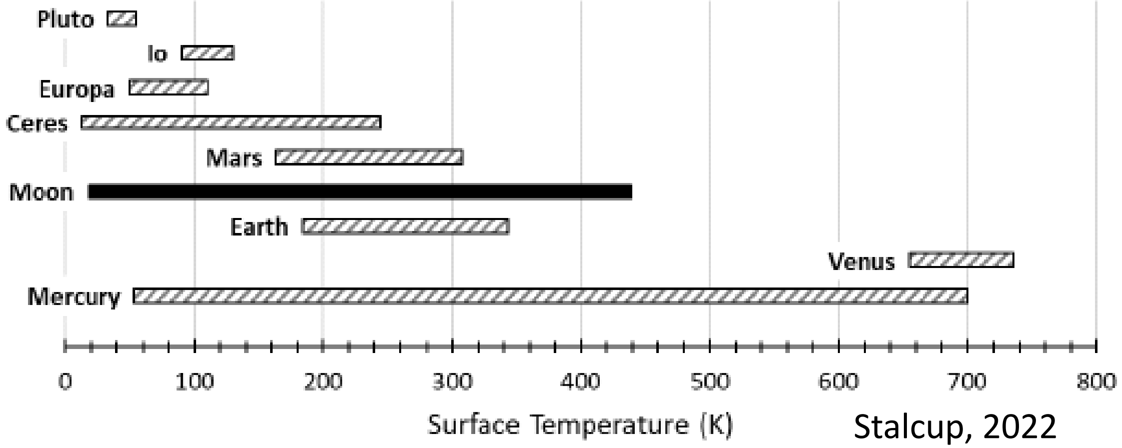
Thermal

- Extreme lunar surface temperatures due to the lack of an appreciable atmosphere and the long period of cooling during the lunar night

- Mean equatorial temperatures
  - Daytime maximum ~387 – 397 K
  - Daytime minimum ~ 95K

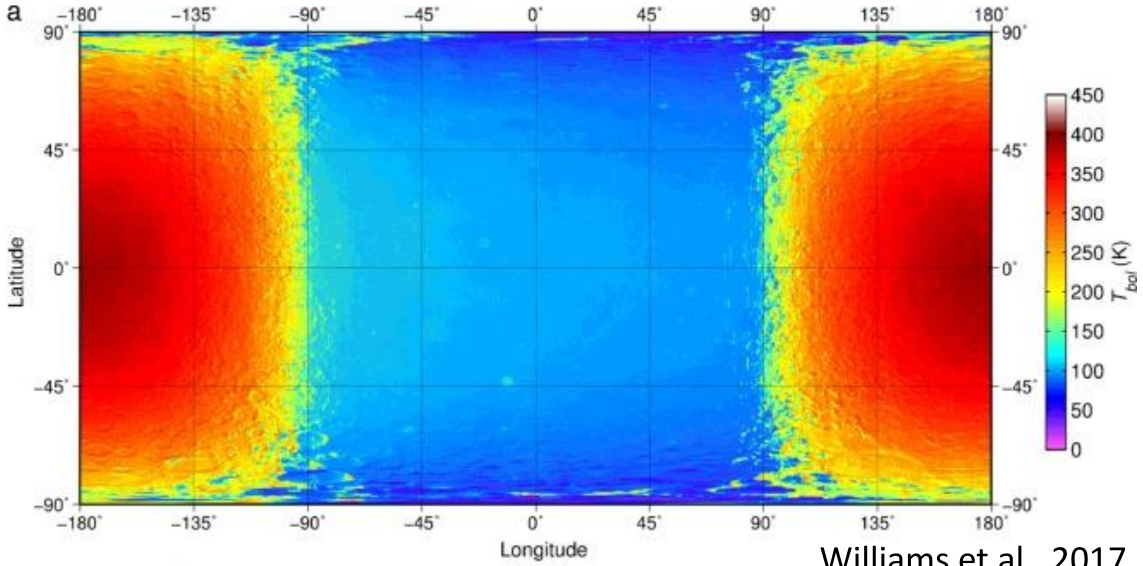
- Mean polar temperatures
  - Maximum 202K
  - Minimum 50K

- Extreme cold in permanently shadowed regions within craters at the lunar poles
  - Minimum ~ 18 K to 20 K



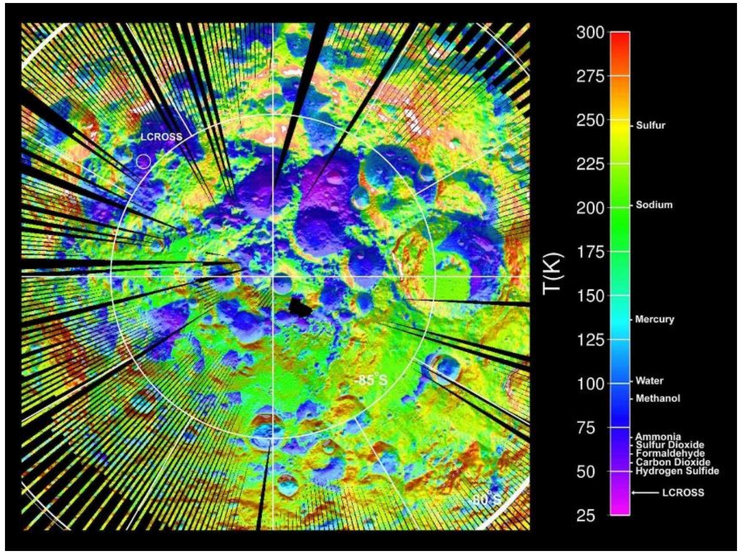
Stalcup, 2022

LRO/Diviner Global Instantaneous Lunar Surface Temperatures



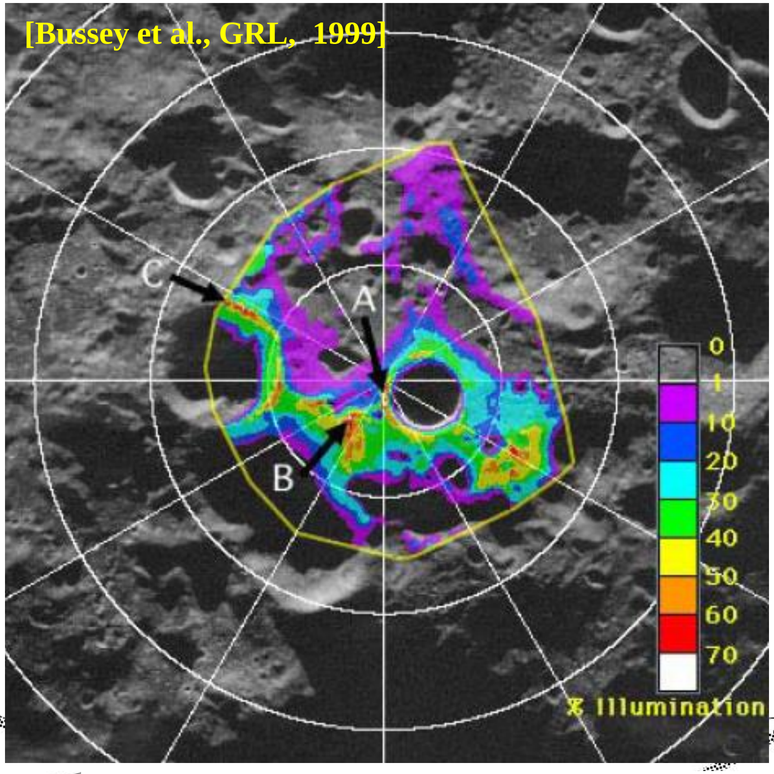
Williams et al., 2017

LRO/Diviner Lunar South Pole Temperature Map

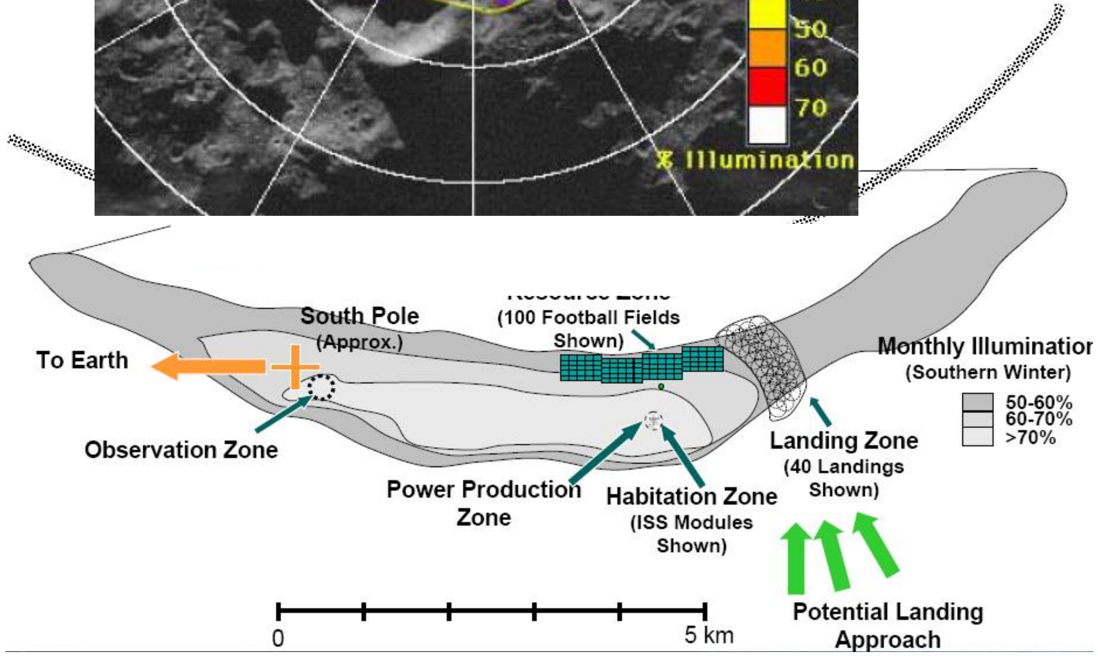


UCLA/NASA/JPL/GSFC

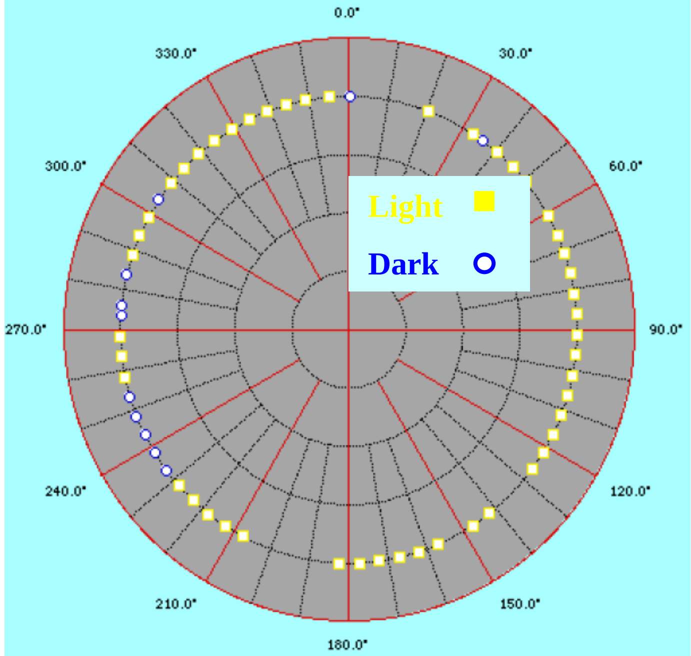
Lunar South Pole



- >70% illumination on rim of Shackleton Crater
- T ~ 220±10 K (-53±10ºC)…relatively benign!
  - Compare with terrestrial extreme of 146 K (-127ºC) at Vostok, Antarctica
- Night temperatures near equator are T~ 100K
- T~40K to 50K in permanently dark craters (more recent LRO data shows extreme low temperatures to ~18 to 20K)



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

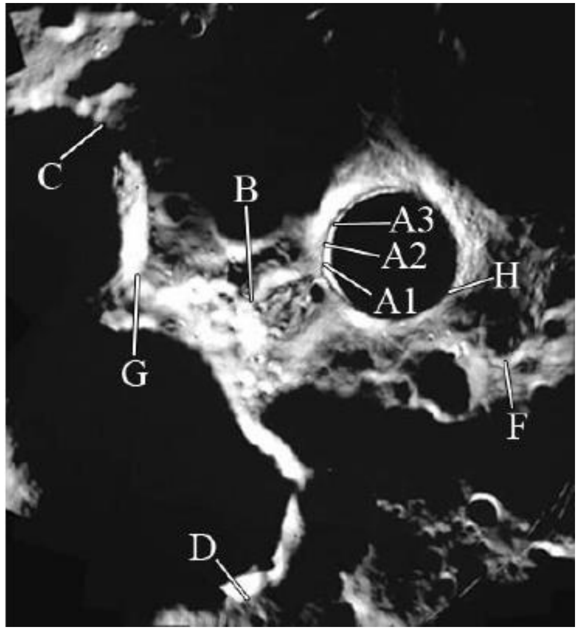


[adapted from *Bussey et al.*, LPSC 1999]

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

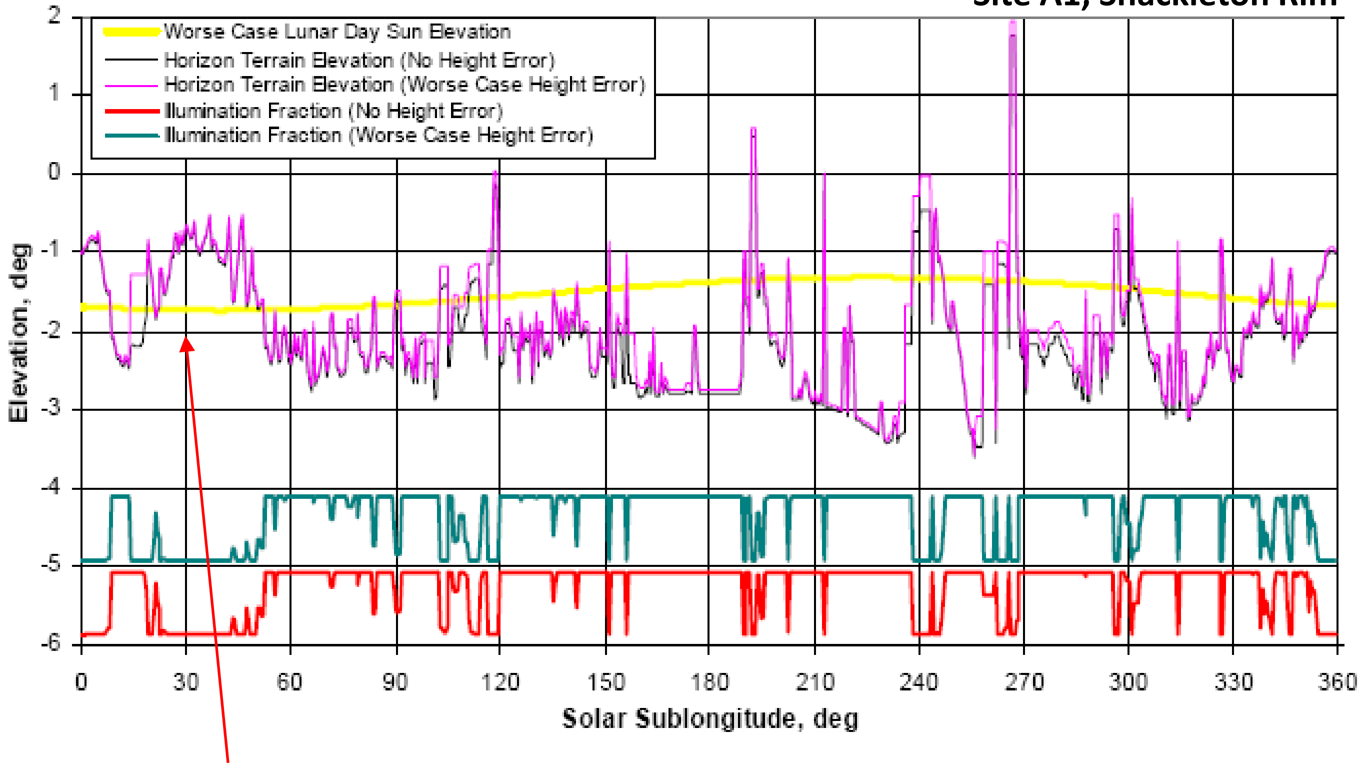
Terrain Shadowing at Shackleton Crater Rim

- Mapping required for evaluation of processes involving illumination that impact exploration operations
  - Illumination conditions for landing operations
  - EVA worksite illumination
  - Photovoltaic power system designs (power production and storage requirements)
  - Photoelectron emission processes involved in spacecraft charging
  - Wake charging of vehicles, habitats, and EVA systems



[*Fincannon*, 2007]

Site A1, Shackleton Rim

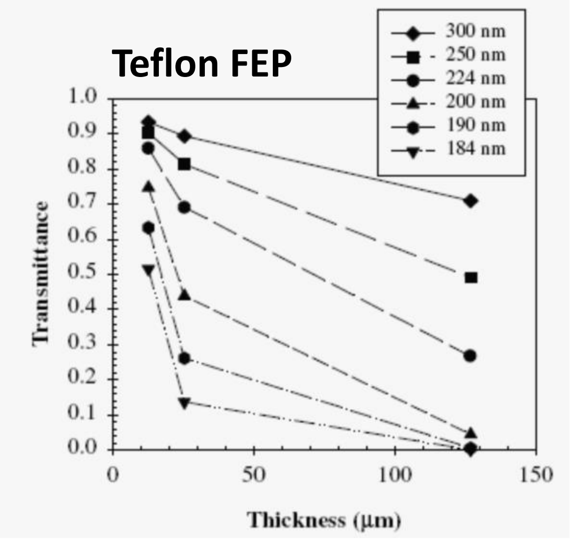


Plasma wake ~2.3 day duration

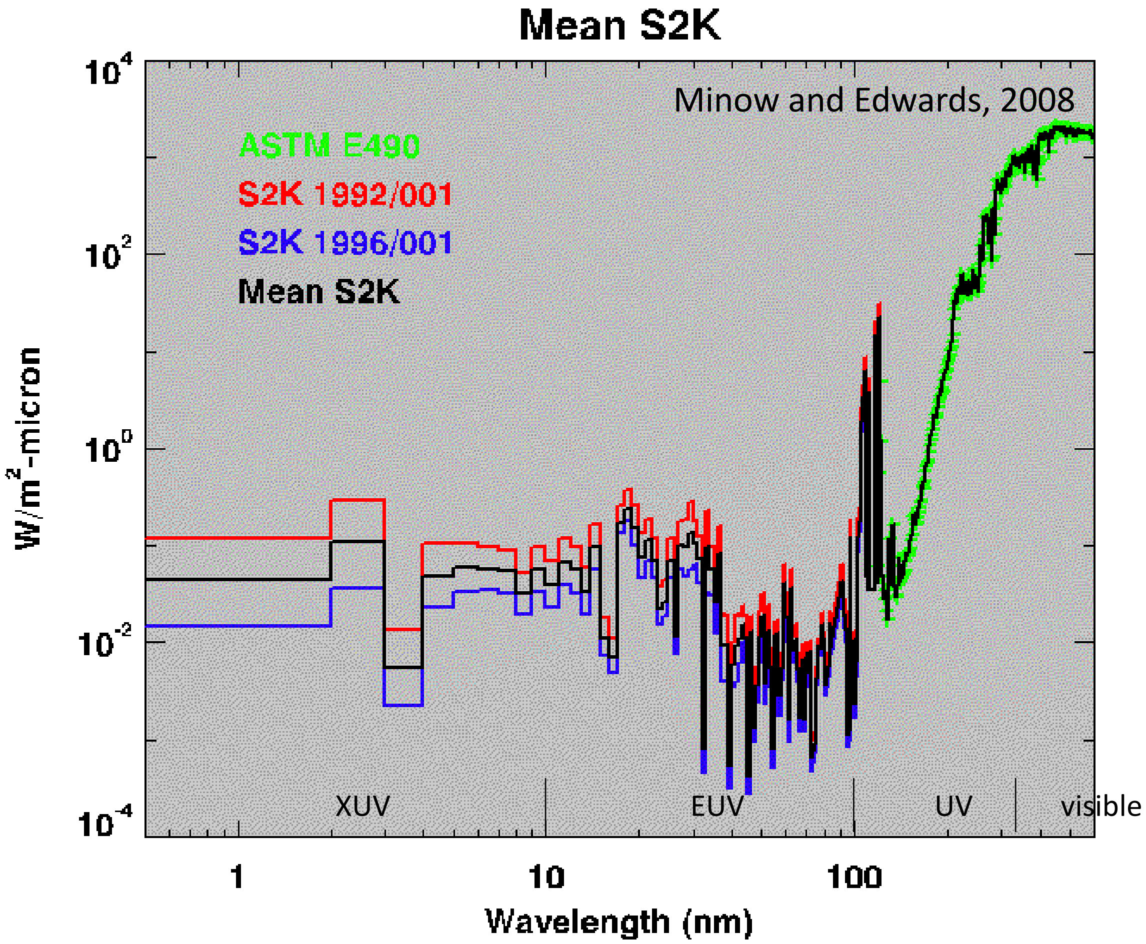
[*Fincannon*, 2007]

Solar UV/EUV/XUV Spectrum

- Lunar surface exposed to the Sun is exposed to the full flux of solar photons without an atmosphere to absorb the photons at ultraviolet wavelengths
- Short wavelength UV/EUV/XUV photons with sufficient energy to damage materials exhibit solar cycle variations
- Short wavelength photons do not penetrate deeply into materials, UV light is primarily an issue for material surfaces and thin materials
- Materials used in lunar orbit or on the lunar surface will need to be UV-resistant or shielded from UV photons



Dever et al., 2002



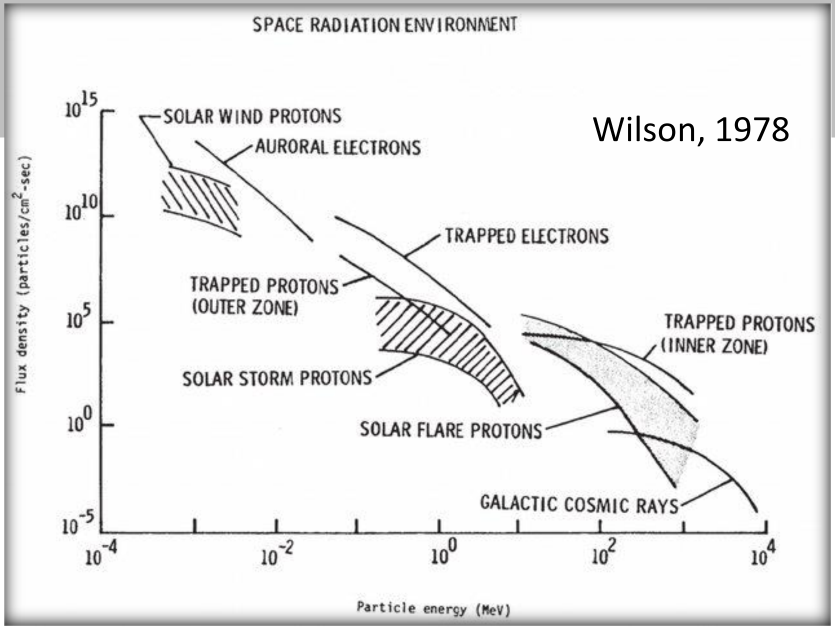
Solar2000 (S2K) Model*

- Static ASTM E490 visible spectrum
- Variable XUV/EUV/UV spectrum

*Tobiska, 2000

Ionizing Radiation Environments

- Radiation environments relevant to lunar missions in approximate order of decreasing energy and increasing flux:
  - Galactic cosmic rays 100's MeV to GeV
  - Solar particle events 10's MeV to 100's MeV
  - Earth radiation belts (transit) 10's keV to 100's MeV
  - Solar wind, magnetosheath, and magnetotail 10's eV to 1 MeV
- Moon has no intrinsic magnetic field or appreciable atmosphere
- Radiation environment on the Moon is about 50% of the interplanetary environment due to shielding by the Moon
- Albedo neutrons are an additional radiation environment in spacecraft and on the lunar surface
- Operating in lunar orbit and on the lunar surface is essentially the same as operating in interplanetary space with respect to the space radiation environment



Wilson, 1978

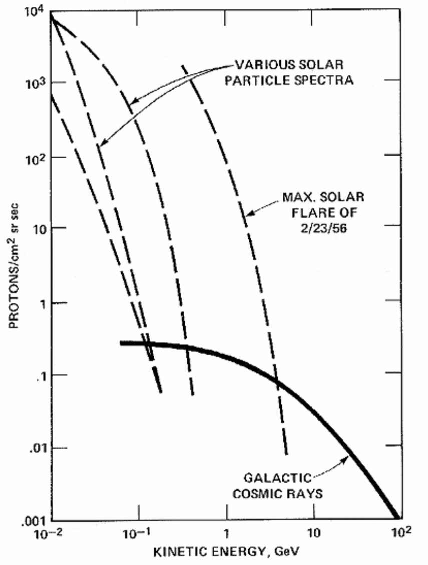


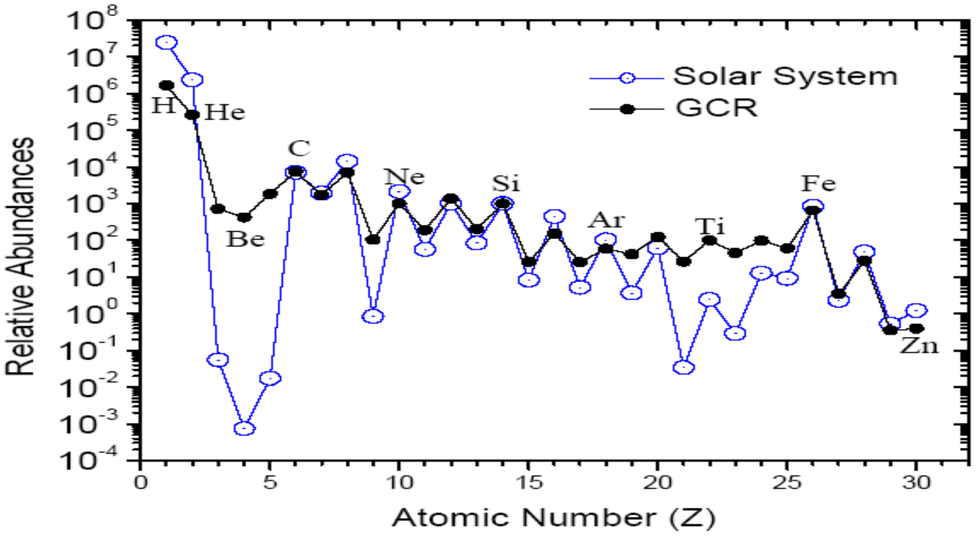
Figure 2-6.– *Energy spectra from several moderate size solar flares (dotted curves) compared with galactic cosmic ray spectrum.*

https://space.nss.org/settlement/nasa/75SummerStudy/Chapt.2.html

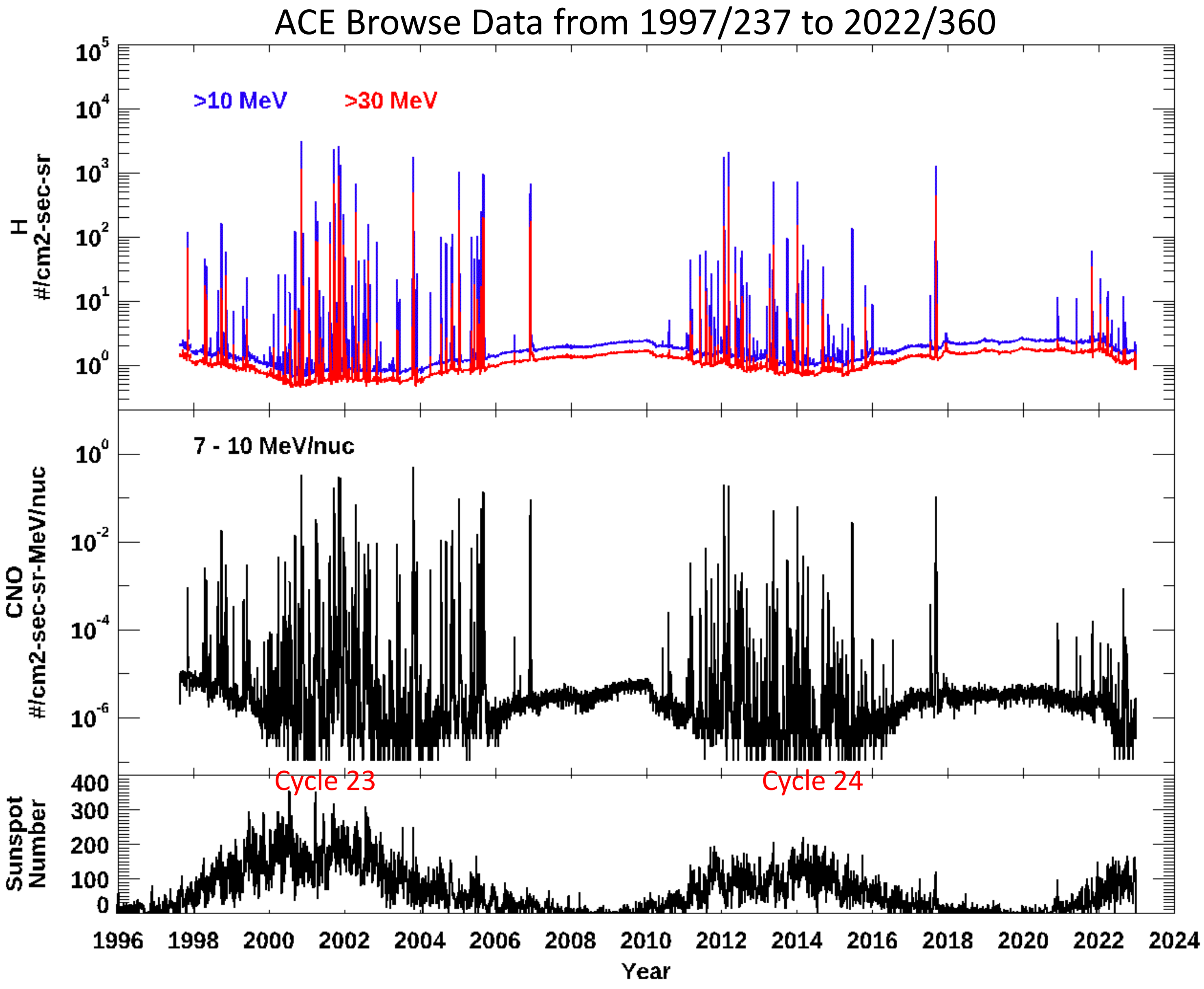
Solar Cycle Variation in GCR and SPE Flux

- Galactic Cosmic Rays
  - 0.1 - >10 GeV
  - Anti-correlated with solar cycle
  - Small variation in flux

- Solar Energetic Particles
  - 1-100 MeV
  - Correlated with solar cycle
  - Large variation in flux



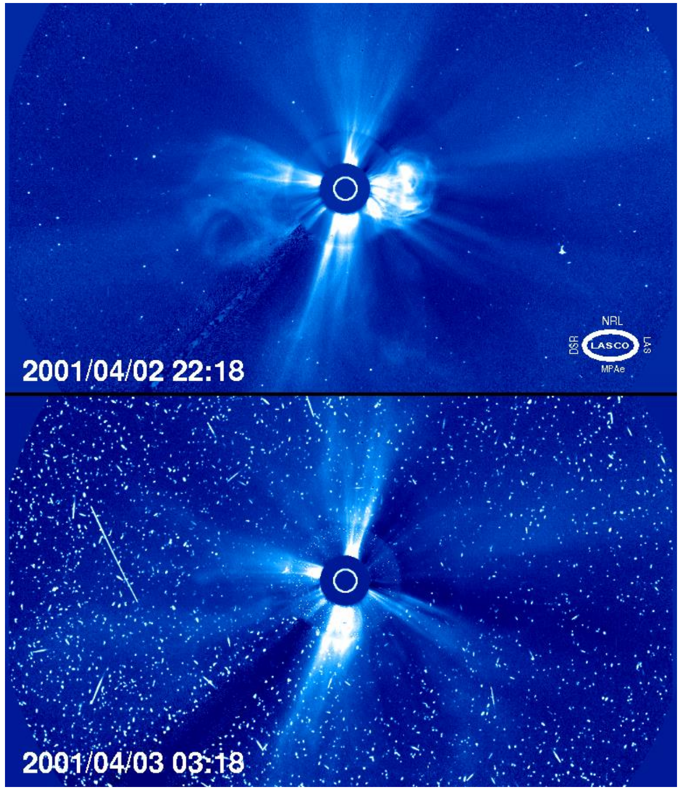
https://izw1.caltech.edu/ACE/ACENews/ACENews83.html



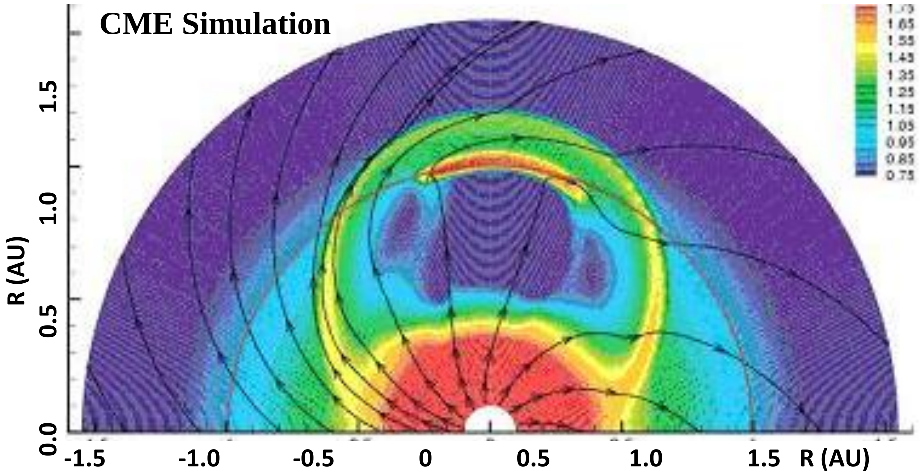
https://izw1.caltech.edu/ACE/ASC/browse/view_browse_data.html

Coronal Mass Ejections

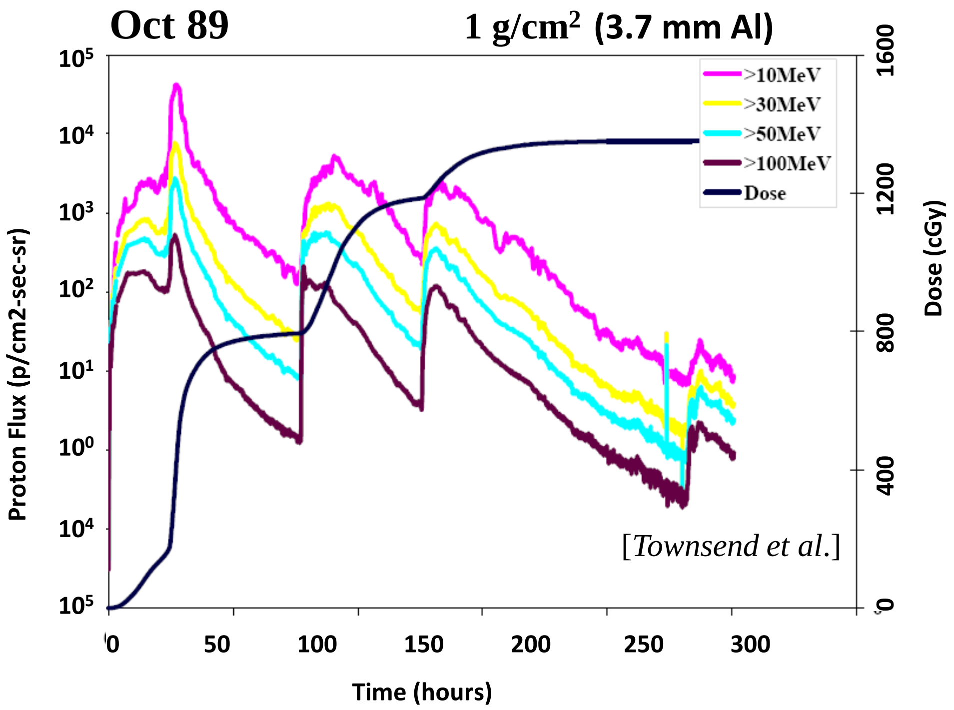
- Impulsive events
  - Minutes to hours
  - Electron rich
  - ~1000/yr at solar max
- Gradual events: significant impact on exploration!
  - Days
  - Proton rich
  - ~100/year



SOHO, LASCO



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



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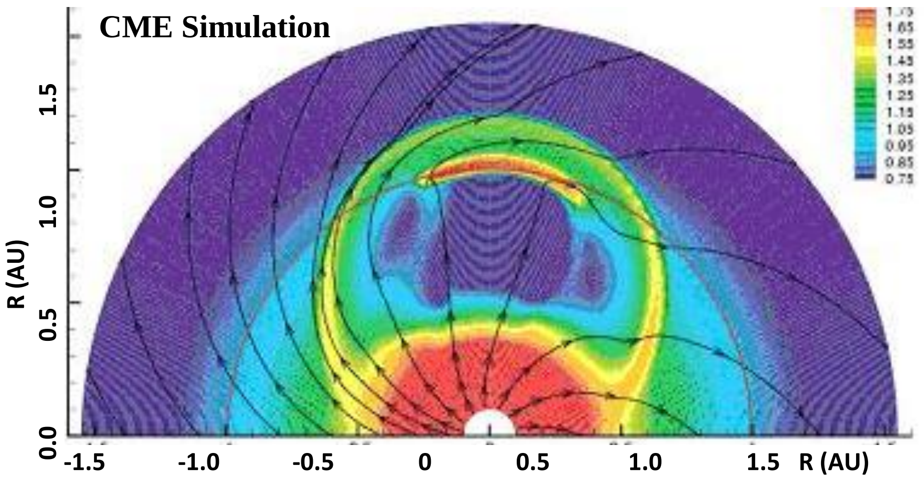

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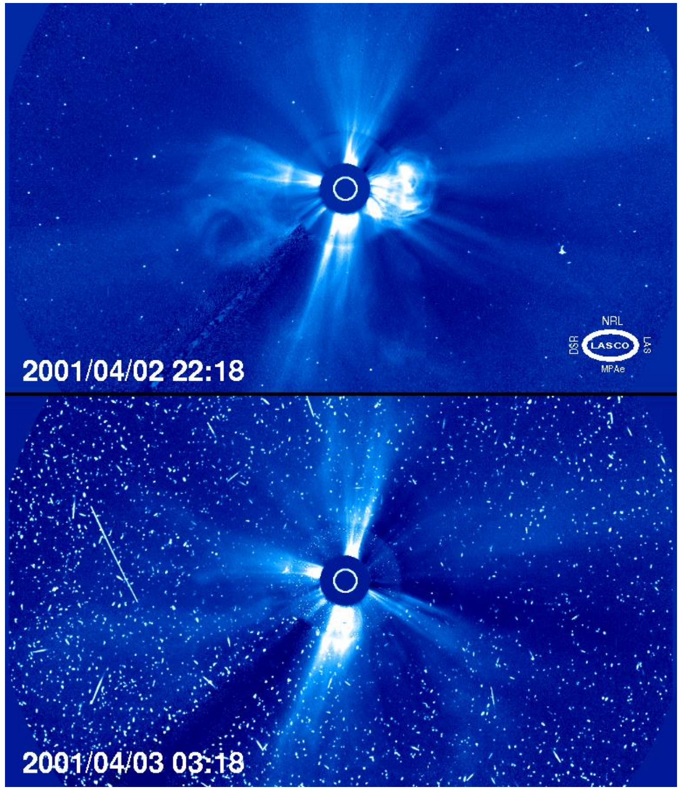

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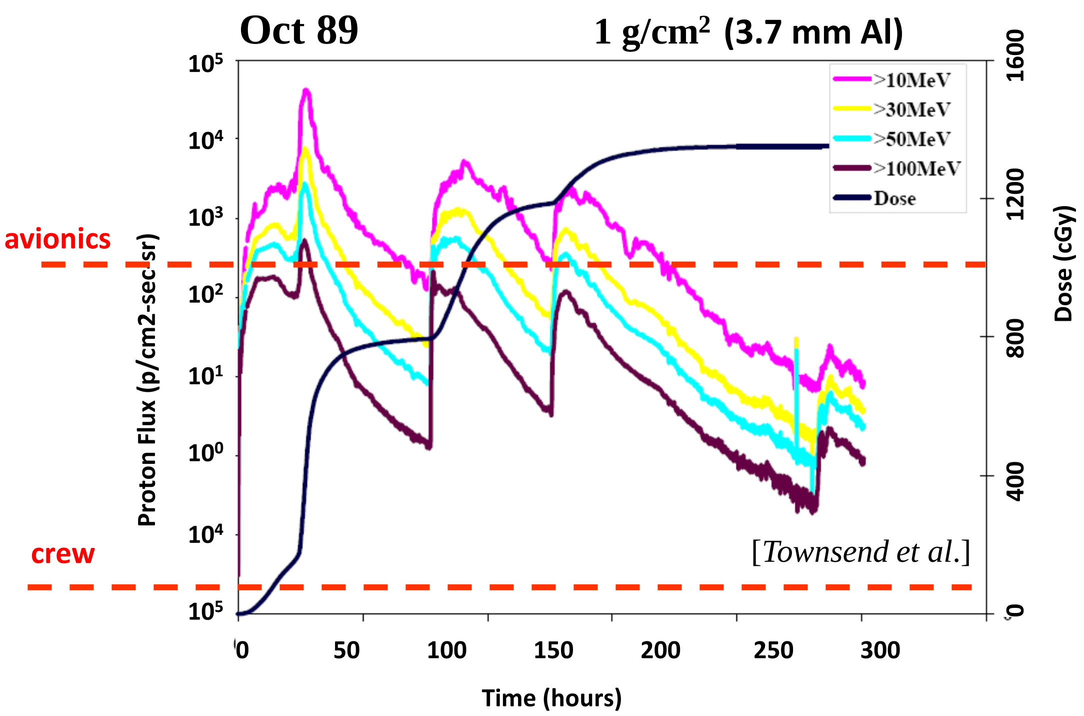
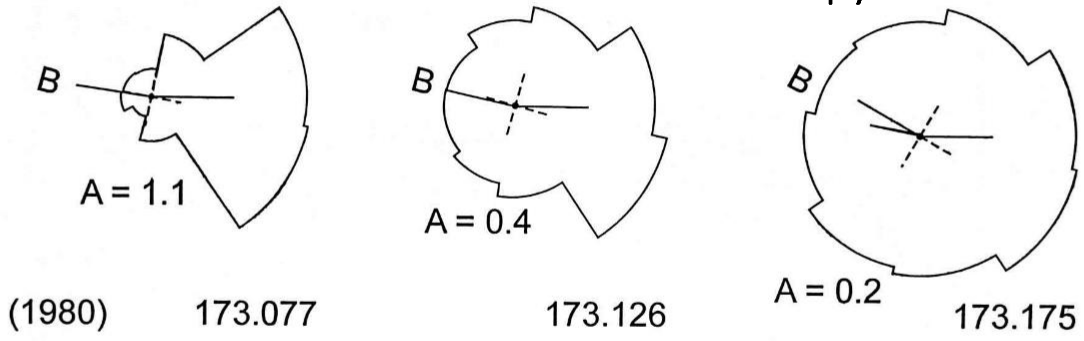


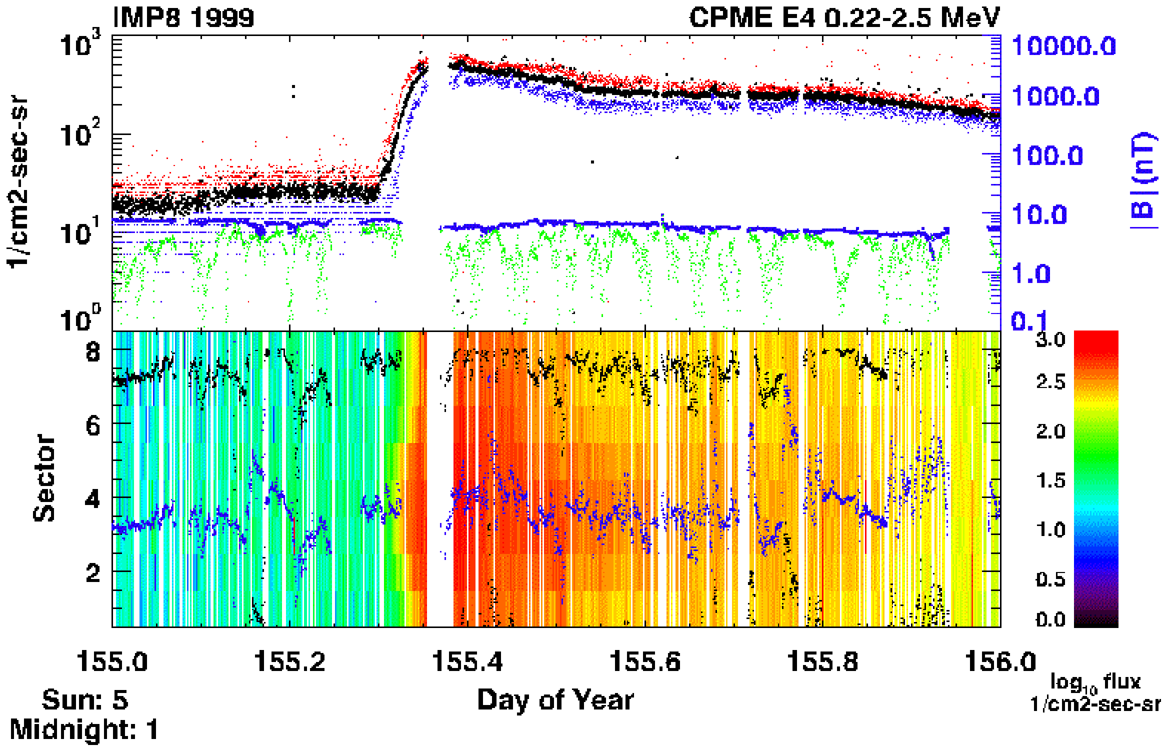
Angular Variations in SPE Flux

- SPE particles initially exhibit anisotropic angular distributions at SPE onset with the particles arriving in a narrow range of angles about the interplanetary (solar) magnetic field direction
- The angular distributions evolve into isotropic angular distributions with a few hours due to pitch angle scattering
- Impact on SPE shielding
  - Topography such as mountain, crater wall, or berm provides some protection for crew by reducing the flux
  - Once the SPE is isotropic near the peak flux there is radiation arriving from all directions not blocked by the Moon itselt
  - Radiation shielding needs to factor in the isotropic nature of SPEs

Evolution of Proton Anisotropy



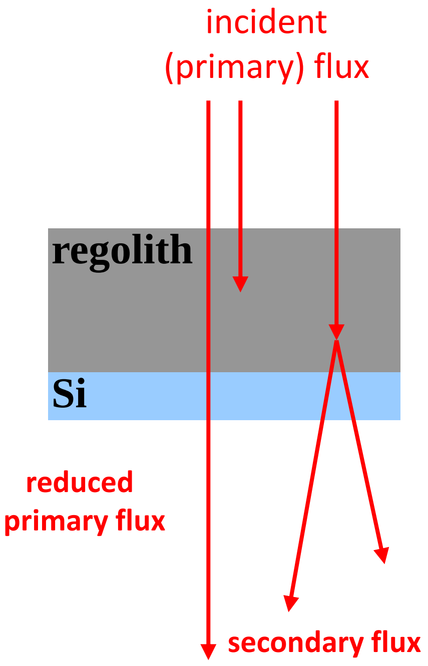
Smart and Shea, 2015

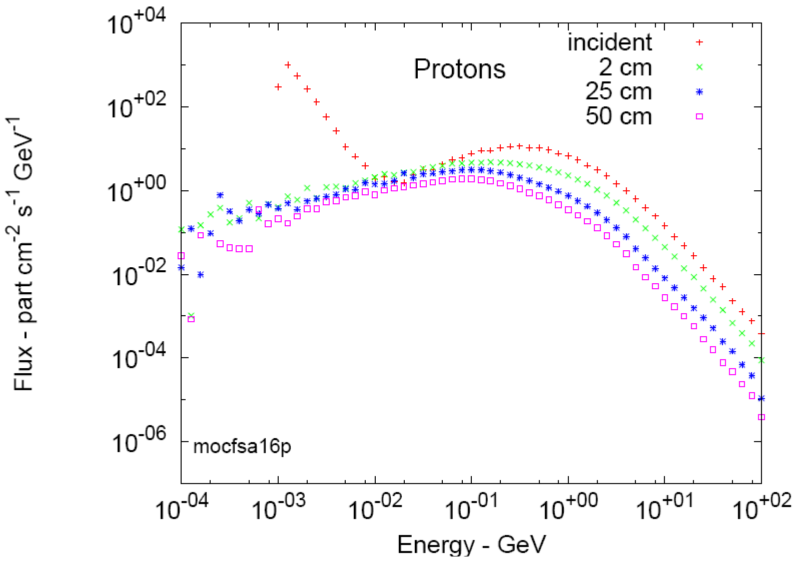


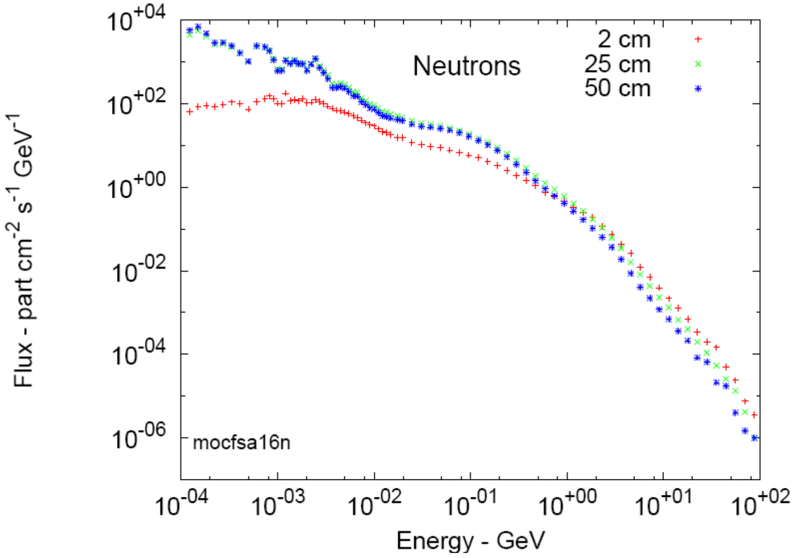
Regolith Shielding Properties for GCR

- **FLUKA transport code**
- **Apollo-16 lunar soil shield**
- **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

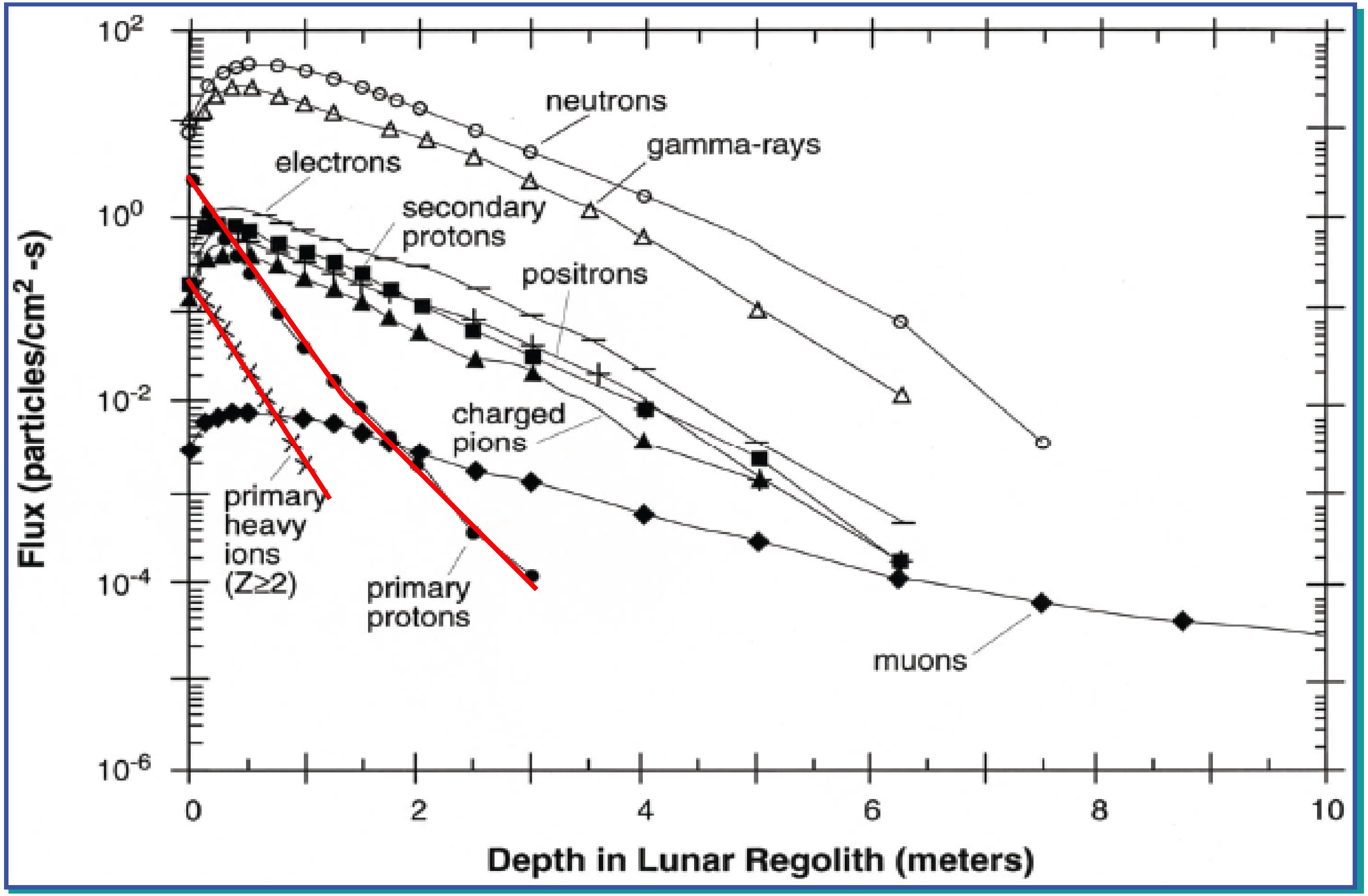






Harine, 2006; *Minow et al.*, 2007

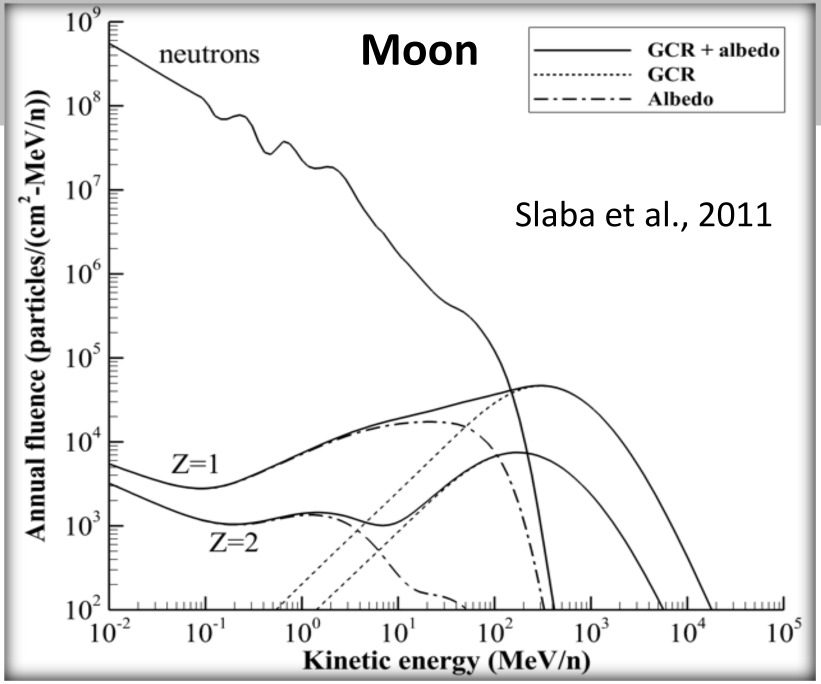
Regolith Shielding Properties for GCR



Parnell et al., 1998

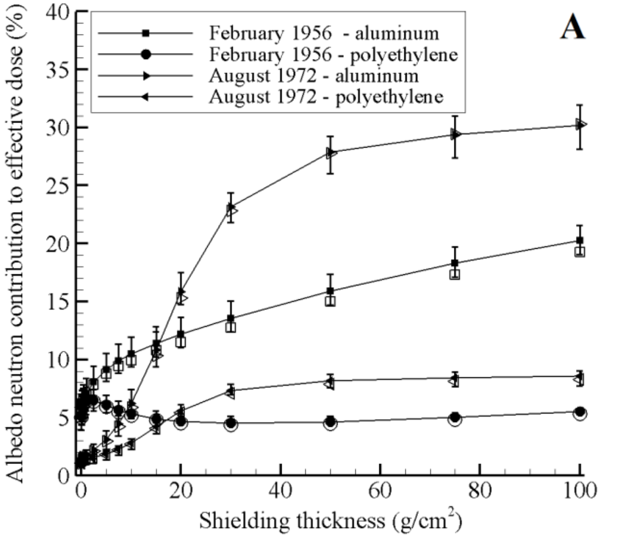
Lunar Neutron Environments

- Albedo neutrons are generated by nuclear interactions of GCR and SPE ions with lunar regolith
- Modeling shows neutrons to be a significant contribution on the order of 10% to 30% for total effective dose for large shielding thickness
- Long term exploration will benefit from a better understanding of the albedo neutron environment
  - Past efforts to measure lunar albedo neutrons have only extended to energies of 15 or 20 MeV
  - In-situ measurements of the secondary neutron environment on the lunar surface extending beyond tens to hundreds of MeV to GeV energies are needed to support dose estimates for long-term lunar exploration
- A single mission is adequate to characterize the albedo environment since the goal is primarily to validate the nuclear interaction models used to simulate the production of neutrons from the GCR source and GCR flux varies slowly over time
- Lunar albedo neutron measurements are not required for the near-term missions to Gateway and the lunar surface since the current plan is to keep the mission durations sufficiently short such that GCRs and any albedo neutron contributions to crew dose are small compared with the NASA lifetime radiation exposure limit of 600mSv

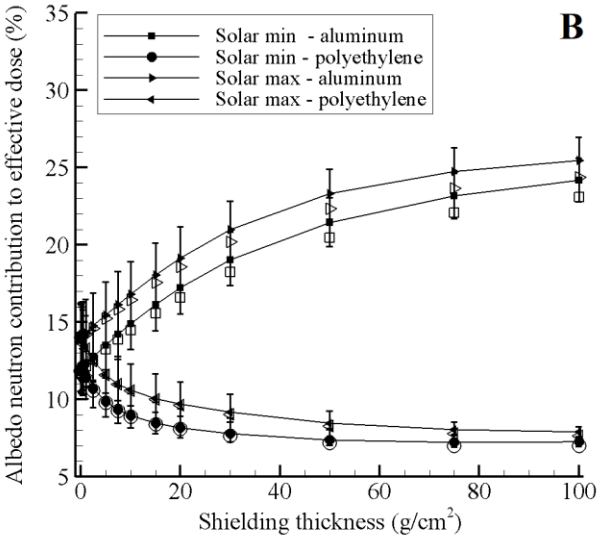


2009 Solar Minimum GCR Environments

Moon - SPE



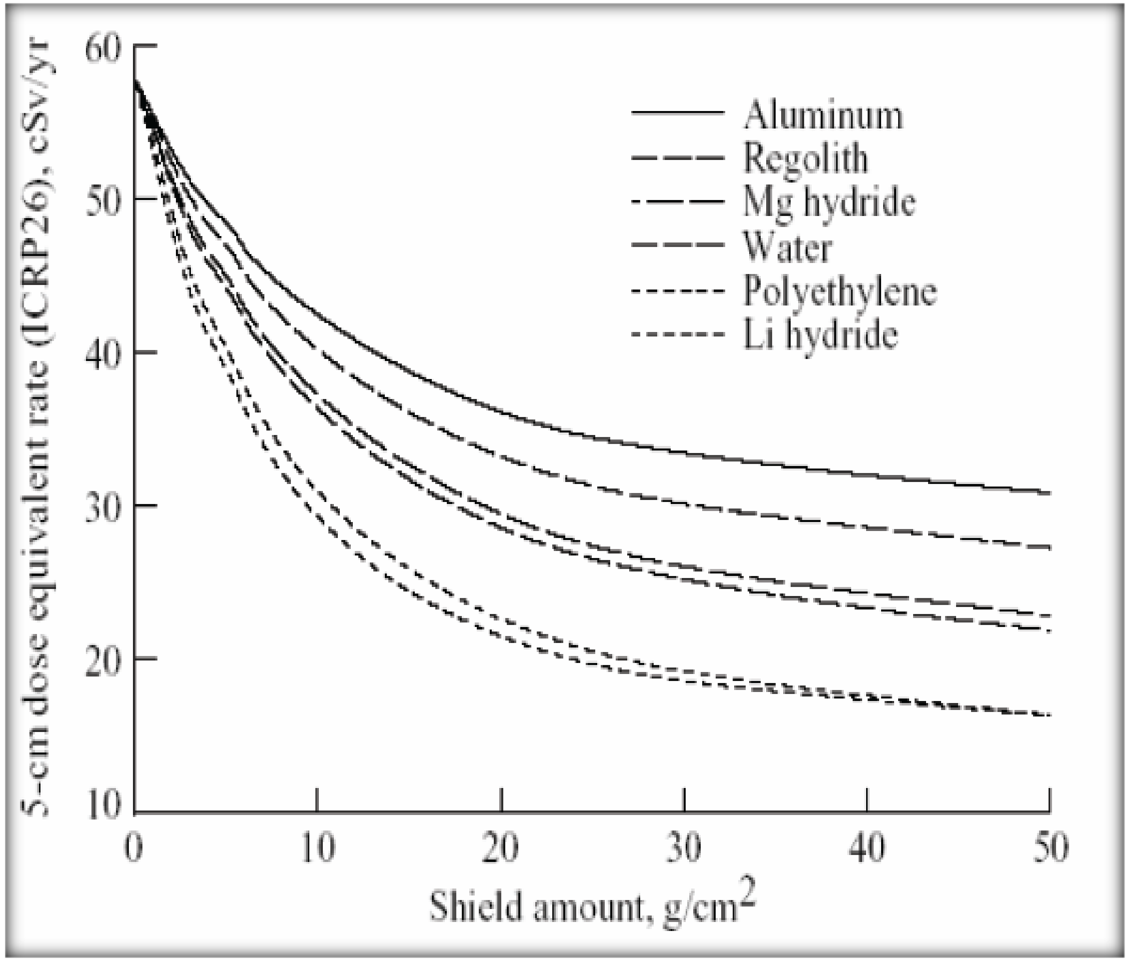
Moon - GCR



Slaba et al., 2011

Regolith Shielding Properties for GCR

- **GCR shielding strategy**
  - Break up incident heavy nuclei
  - Minimize neutron generation
- **SEP shielding strategy**
  - Stop light ions in shield
  - Minimize neutron generation
- **Low Z materials are best**
  - Fewest protons, neutrons in target nuclei
  - Pure hydrogen, lithium provide best GCR shielding of all elements…difficult to engineer
  - Practical shielding materials include high hydrogen content compounds



Wilson et al., 1998; *Adams*, 2005

Mission GCR Radiation Exposures

NASA-STD-3001, Rev B., Vol. 1, Section 4.8.2: Career Space Permissible Exposure Limit for Space Flight Radiation

An individual astronaut's total career effective radiation dose due to space flight radiation exposure shall be less than 600 mSv. This limit is universal for all ages and sexes.

Shielding:
0, 20, 40 g/cm^2
spherical Al shield

GCR environment:
Solar min 2009
Solar max 2001

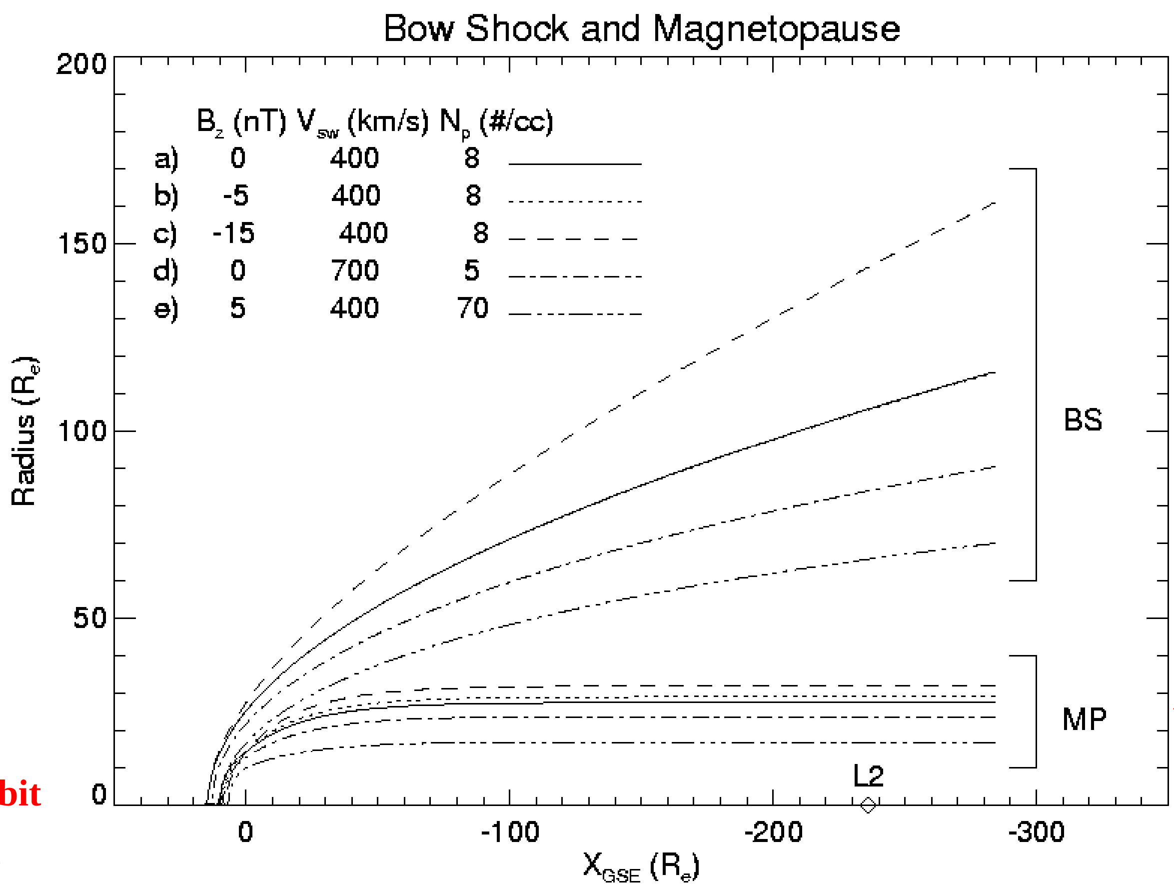
X/Y duration format:
X days in free space
Y days on surface

Effective dose ≥600 mSv

	Mission	Duration (days)	Dose (mGy)			Dose equivalent (mSv)			Effective dose (mSv)		
			0	20	40	0	20	40	0	20	40
solar maximum	Artemis II	10	1.5	2.1	2.5	10.2	6.9	5.9	6.3	5.1	5.3
	Artemis III	30	4.6	6.4	7.6	30.5	20.7	17.6	19.0	15.4	15.8
	Artemis III (surface)	23.5/6.5	4.2	5.8	6.9	27.7	18.7	16.0	17.4	14.1	14.4
	Gateway – 6 month	183	28	39	46	186	126	108	116	94	96
	Gateway – 12 month	365	56	78	92	372	252	215	232	188	192
	Mars DRM	621/40	99	137	163	644	440	377	405	331	339
	Mars DRM	840	128	178	213	855	580	494	533	432	442
solar minimum	Artemis II	10	4.6	5.2	5.6	28.5	15.0	12.2	14.6	10.9	10.7
	Artemis III	30	13.8	15.5	16.7	85.5	44.9	36.5	43.8	32.8	32.1
	Artemis III (surface)	23.5/6.5	12.6	14.0	15.0	77.1	40.5	33.0	39.8	29.9	29.2
	Gateway – 6 month	183	84	95	102	522	274	223	267	200	196
	Gateway – 12 month	365	168	189	203	1040	546	445	533	399	391
	Mars DRM	621/40	295	332	356	1795	950	779	929	702	688
	Mars DRM	840	386	434	466	2395	1256	1023	1228	918	899

Valinia et al., 2022

Plasma Environments



Lunar orbit

~60 Re

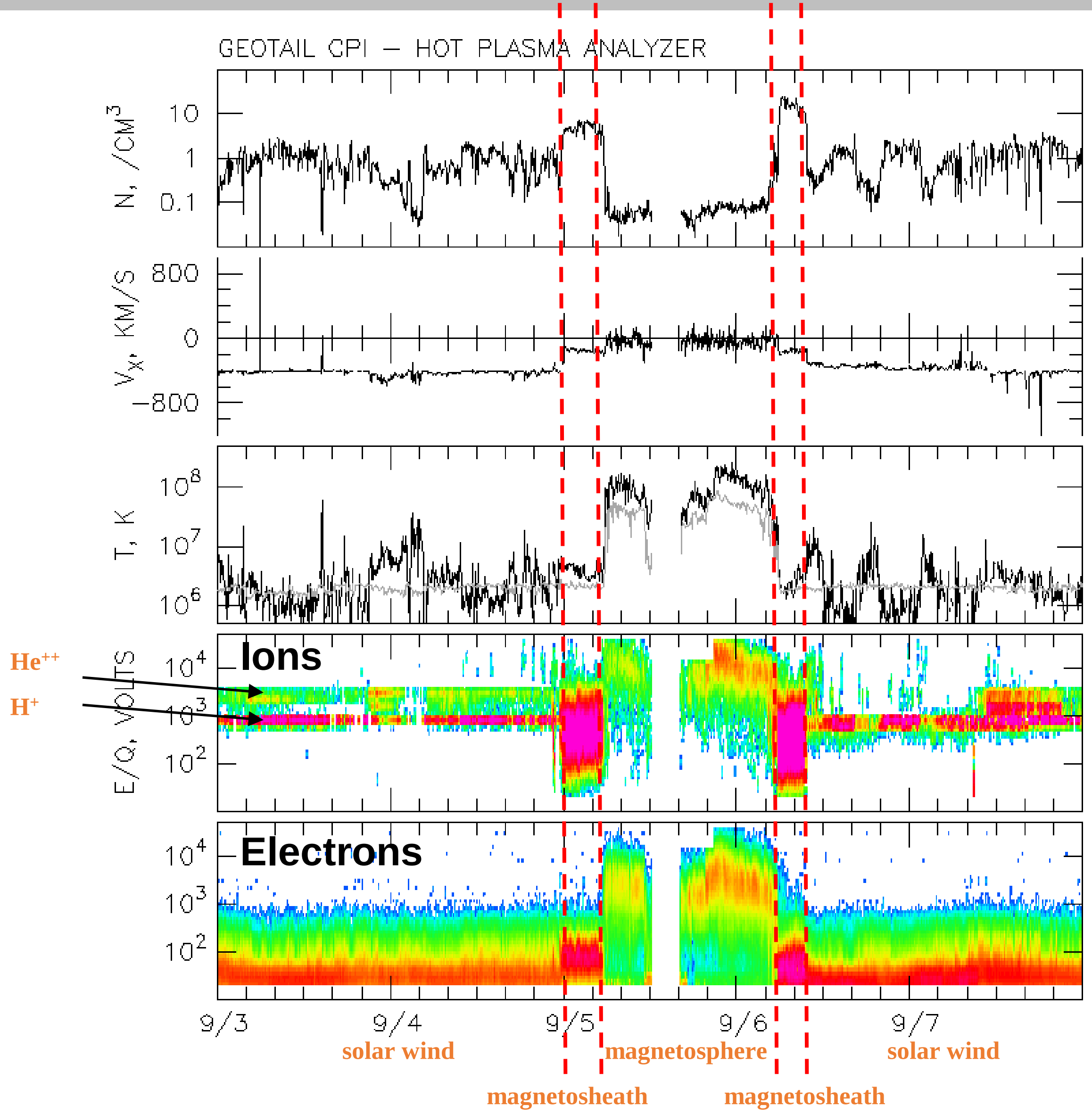
Bennett et al. [1997]
bow shock

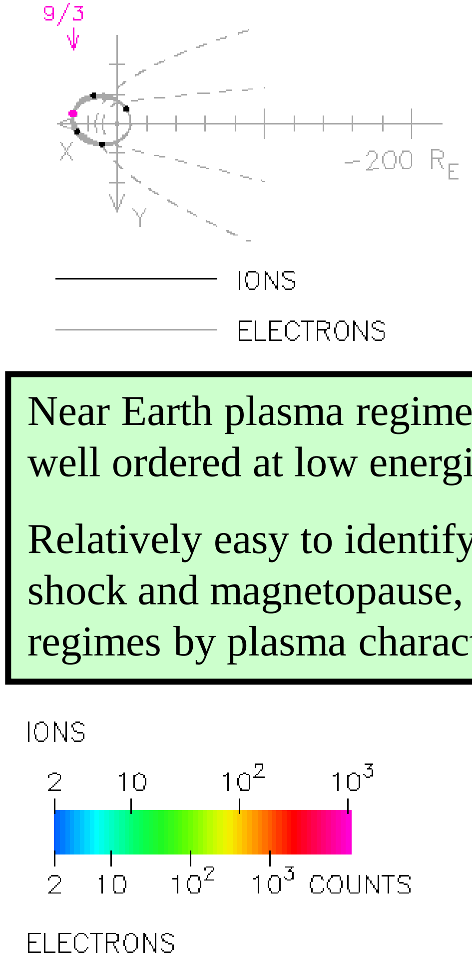
Petrinic and Russell [1993, 1996]
magnetopause

Fraction of Month in Plasma Environments

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

Plasma Regime Identification





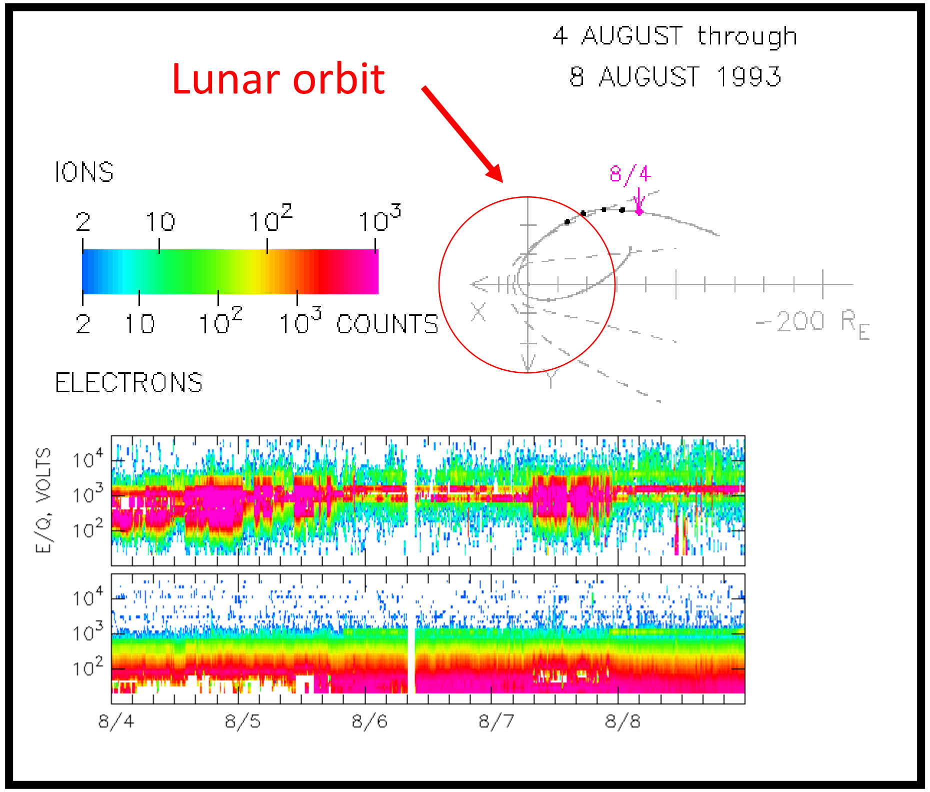
Near Earth plasma regimes are well ordered at low energies

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

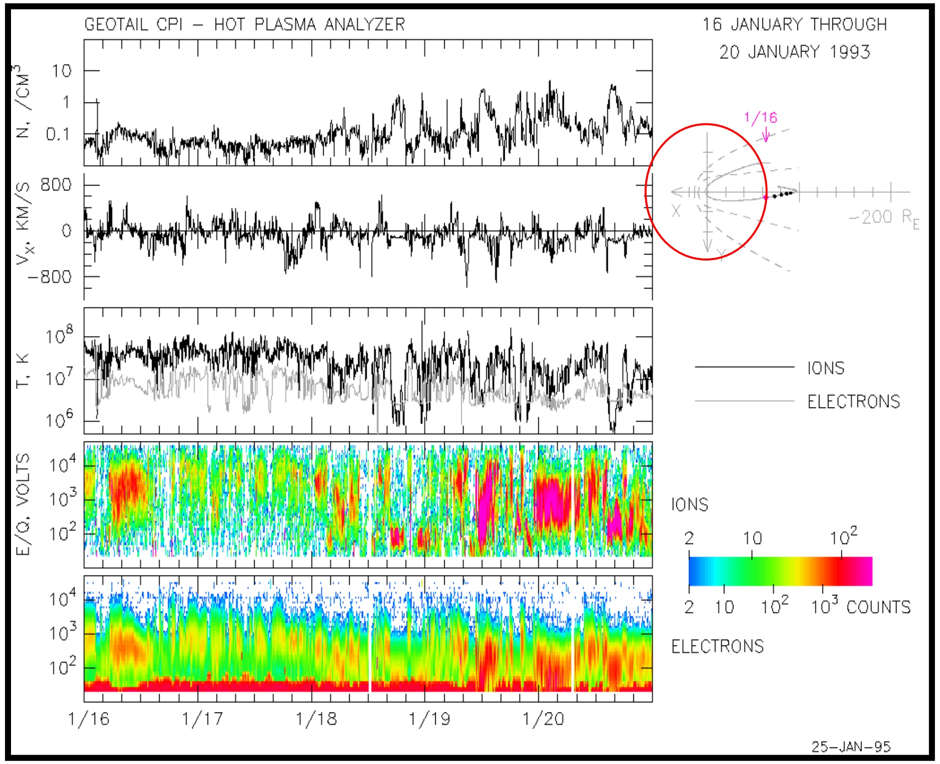
Geotail/CPI:
http://www-pi.physics.uiowa.edu/cpi/

Magnetosheath and Magnetotail Plasma at Lunar Distances

- Lunar plasma environment includes encounters with magnetotail and magnetosheath once a month (around full Moon)
- High temperature, low density plasma environments in magnetotail



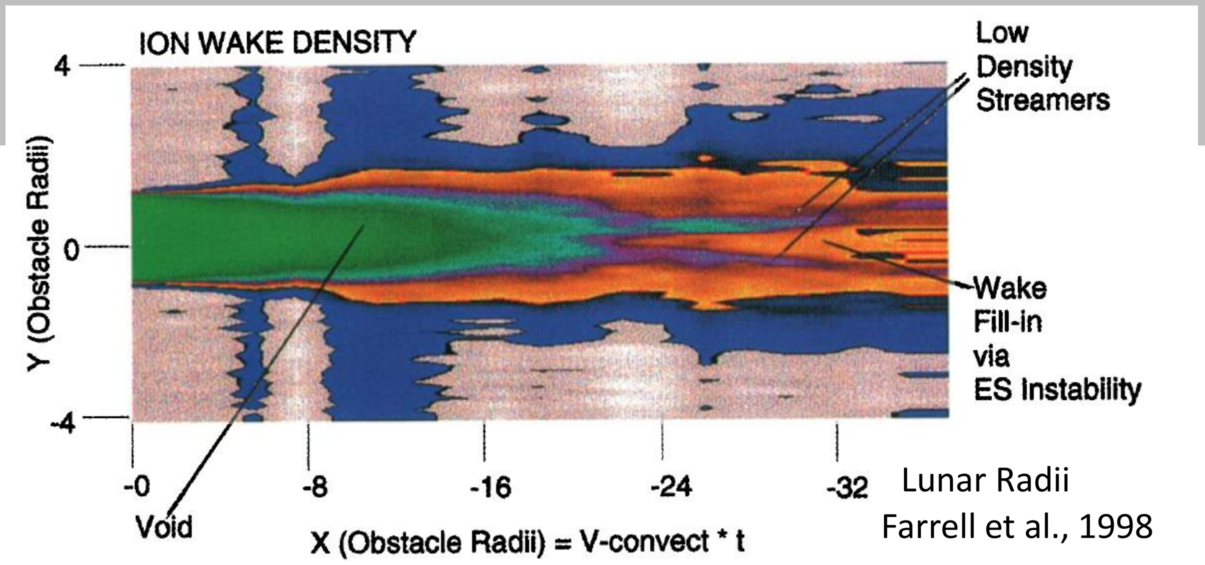
(Univ. of Iowa)



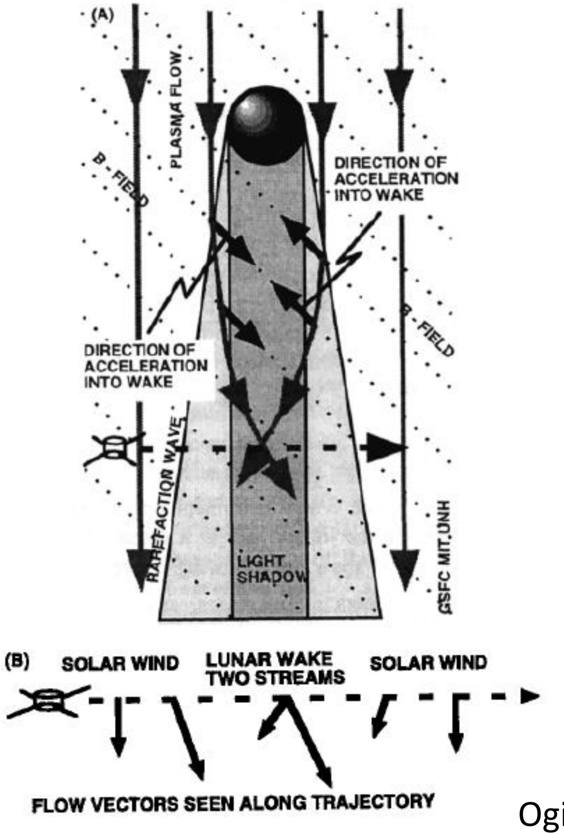
Geotail/CPI:
http://www-pi.physics.uiowa.edu/cpi/

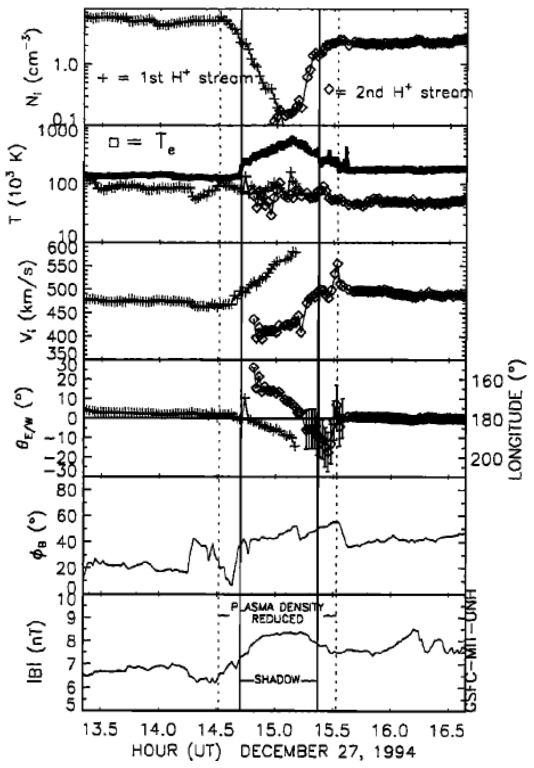
Lunar Wake

- Moon is a dielectric body that absorbs plasma flowing onto the surface
- Plasma void with very low density forms in anti-sunward direction: lunar wake
- High energy electrons can penetrate the wake establishing ambipolar electric fields that pull ions into the wake
- Wake eventually fills through complicated plasma interaction process that is still being studied



Farrell et al., 1998



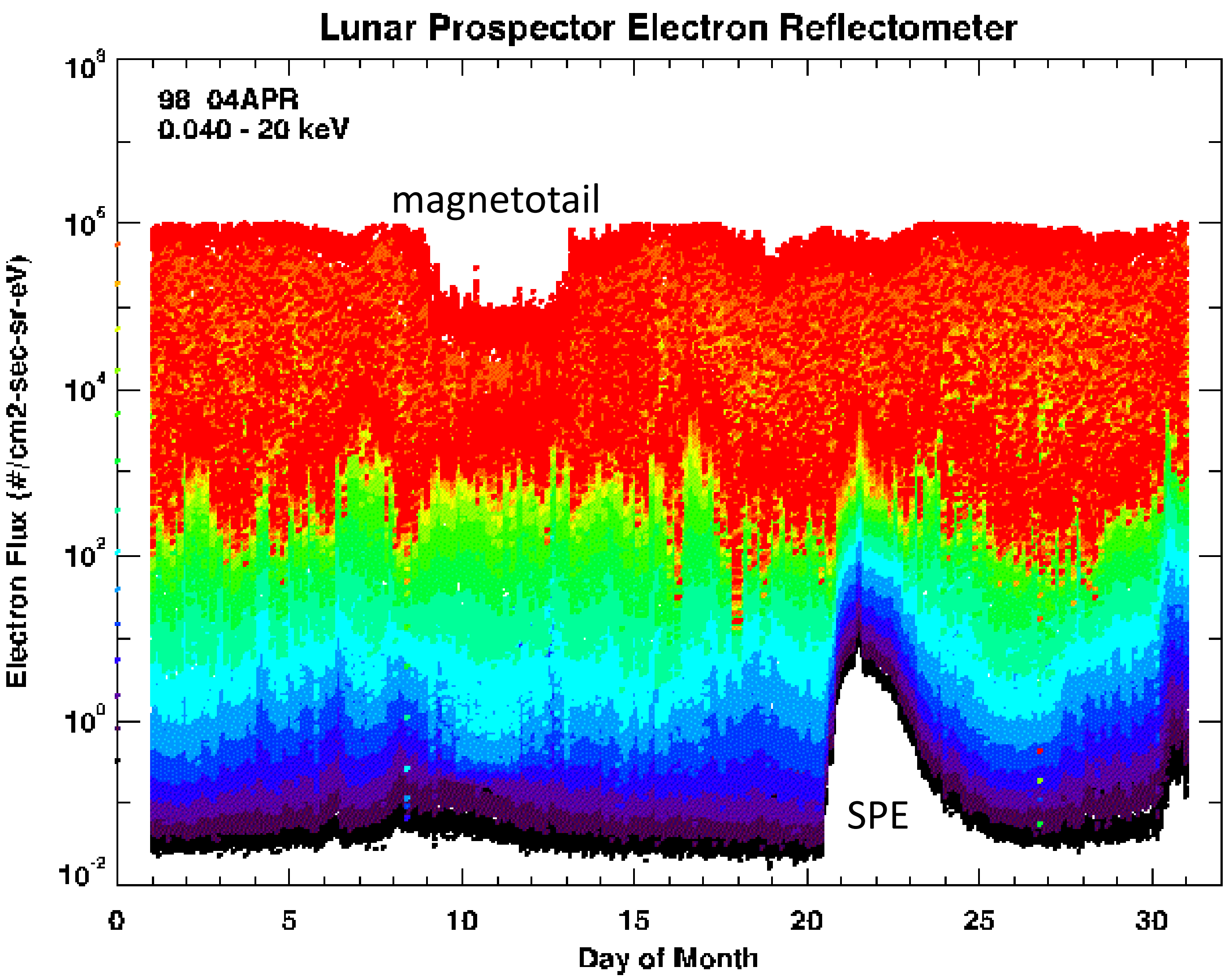


Ogilvie et al., 1996

Lunar Plasma Environments

- Lunar Prospector Electron Reflectometer
  - Spin average electron flux
  - ~40 eV (red) to ~20 keV (black)

- April 1998
  - Moon in magnetotail exhibits reduced plasma flux at low energies, little or no impact on energetic electrons
  - Solar energetic particle event



Lunar Plasma Environments

- Lunar Prospector Electron Reflectometer
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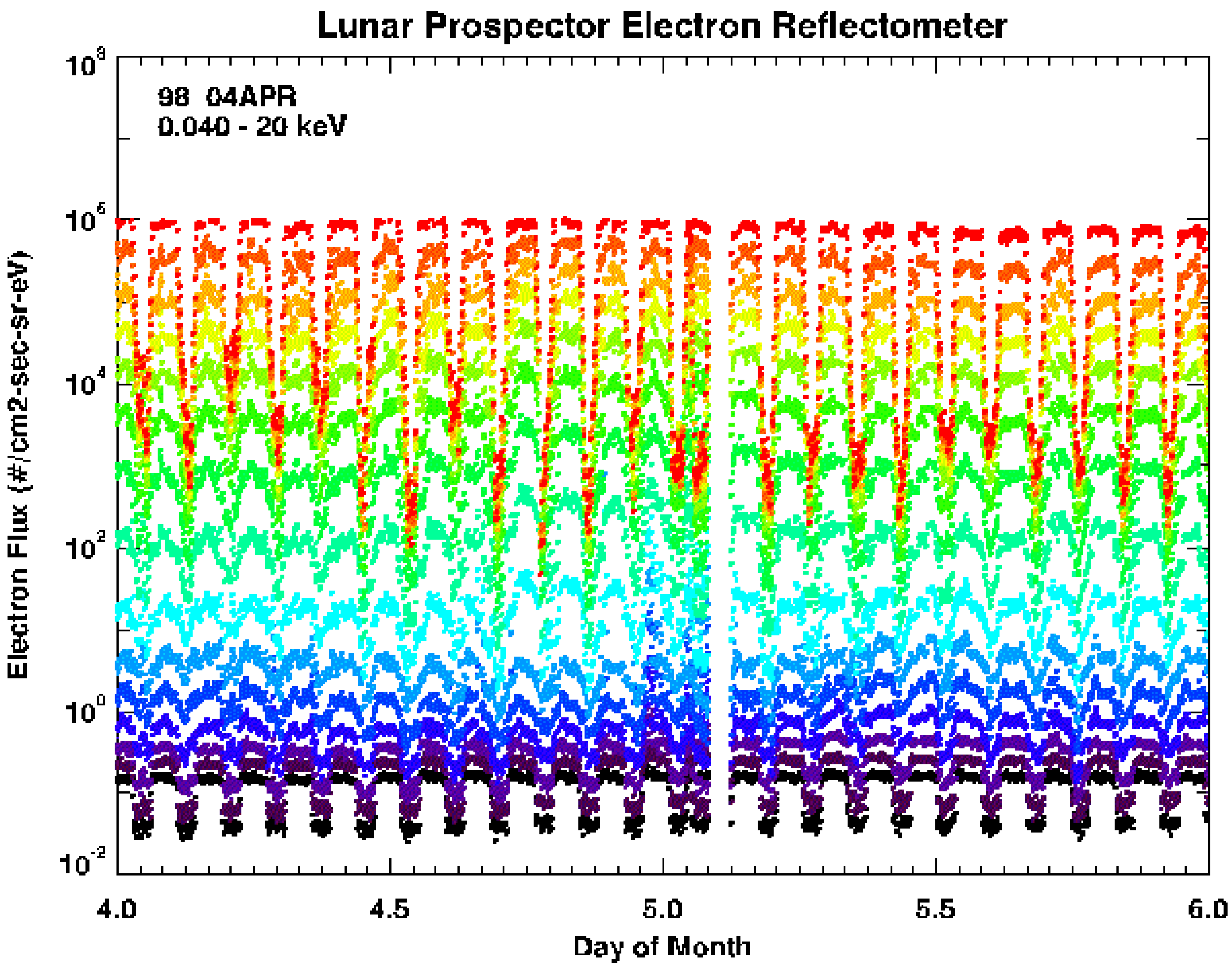
- 4-5 April 1998
  - Moon in solar wind
  - Plasma wake electron depletions

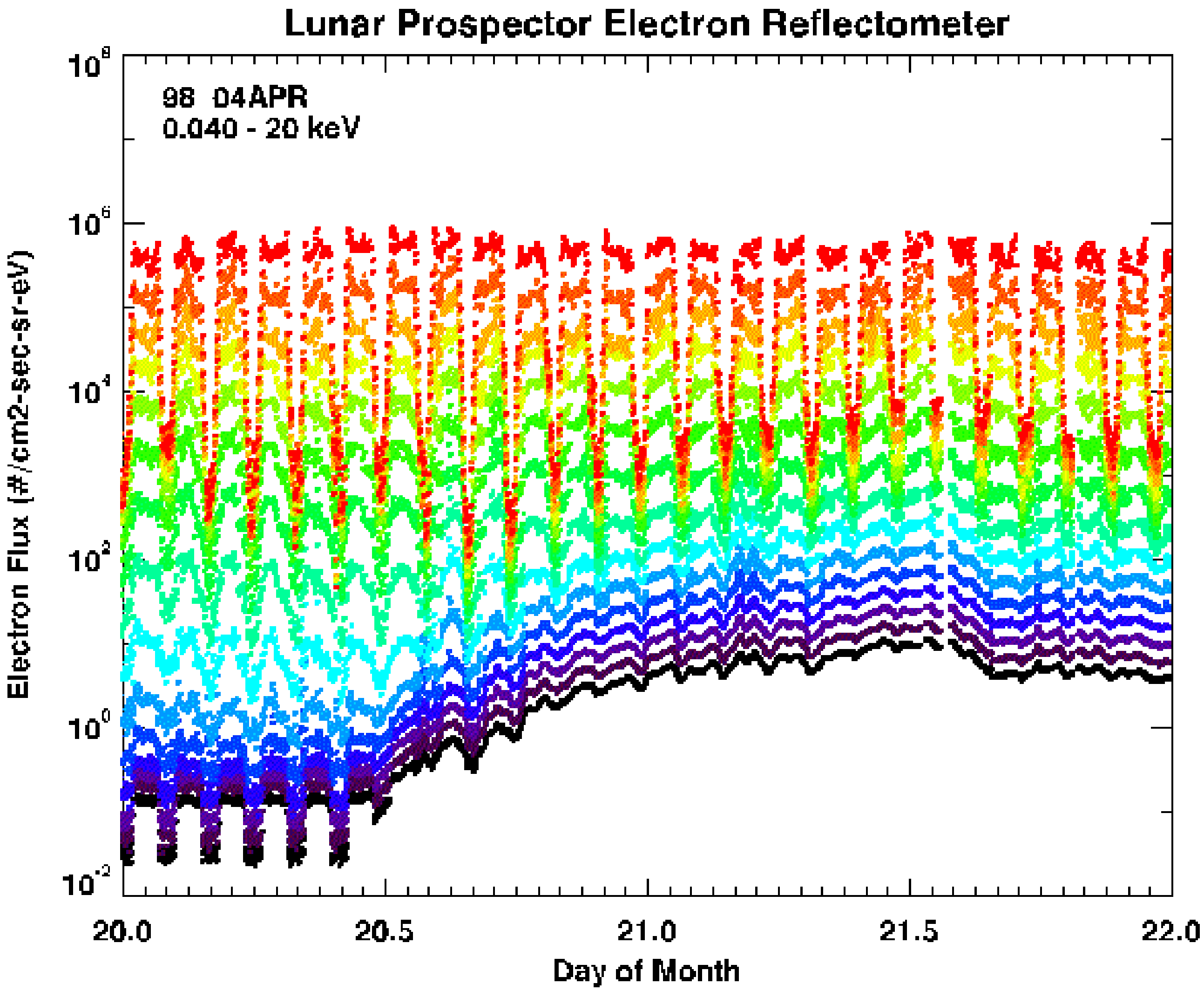


Lunar Plasma Environments

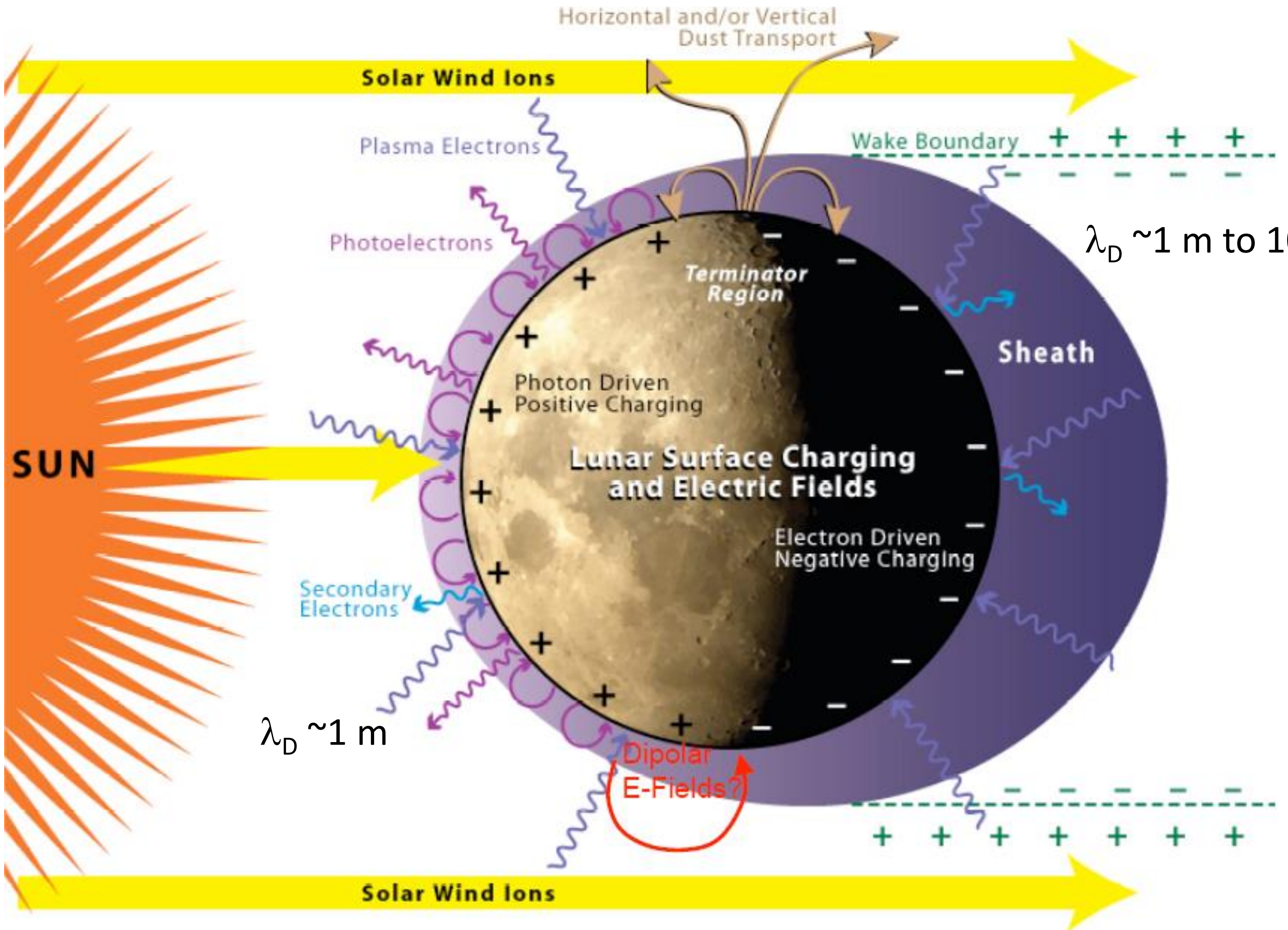
- Lunar Prospector Electron Reflectometer
  - Spin average electron flux
  - ~40 eV (red) to ~20 keV (black)

- 4-5 April 1998
  - Moon in solar wind
  - Plasma wake electron depletions

- SPE particles have free access to wake environments with little modulation



Lunar Plasma Environments/Interactions



λ_D ~1 m to 1000 m

λ_D ~1 m

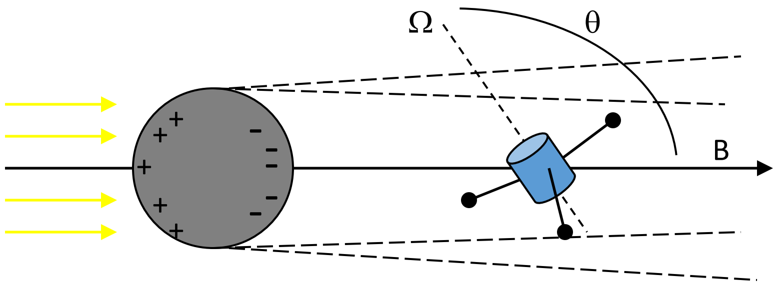
[*Lin et al.*, 2007; *Halekas et al.*, 2007]

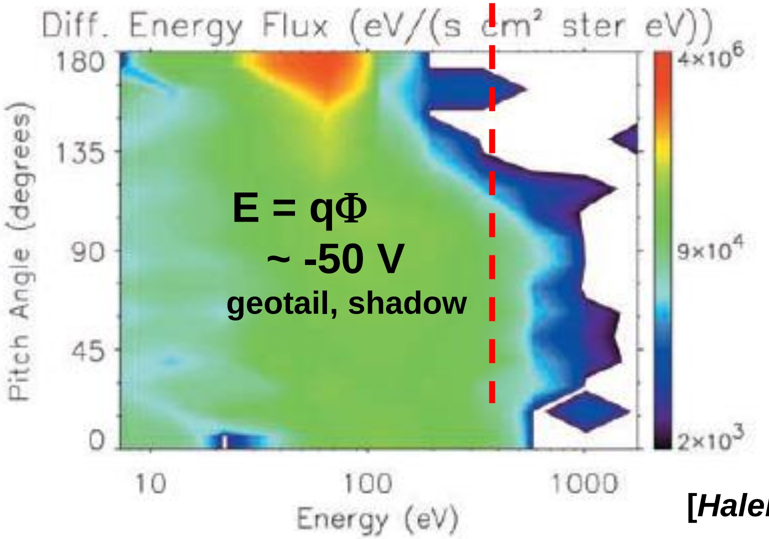
Charging in Lunar Wake

- Lunar Prospector 20-115 km
  - Wake properties relative to ambient solar wind
  - Spacecraft potentials

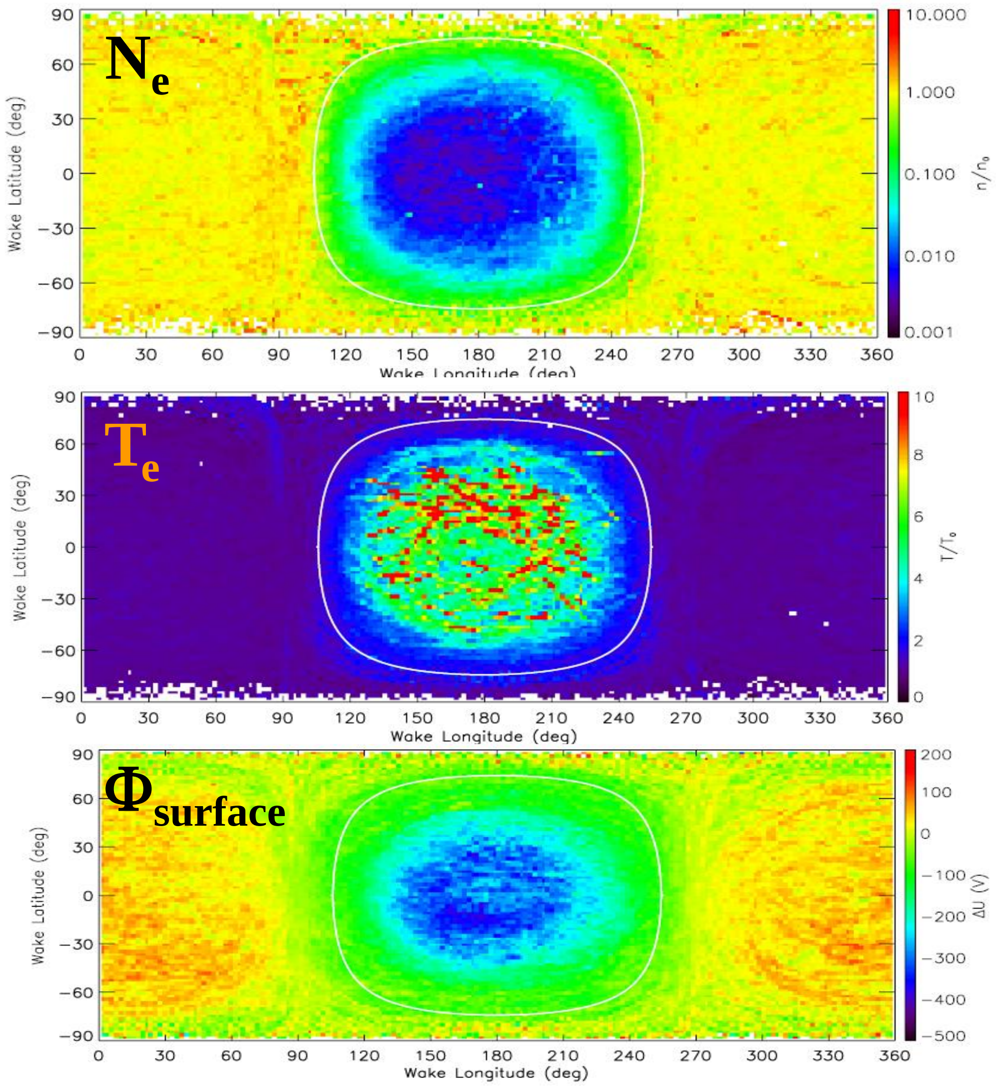
    day +10 V to +50V

    night -100 V to -300 V



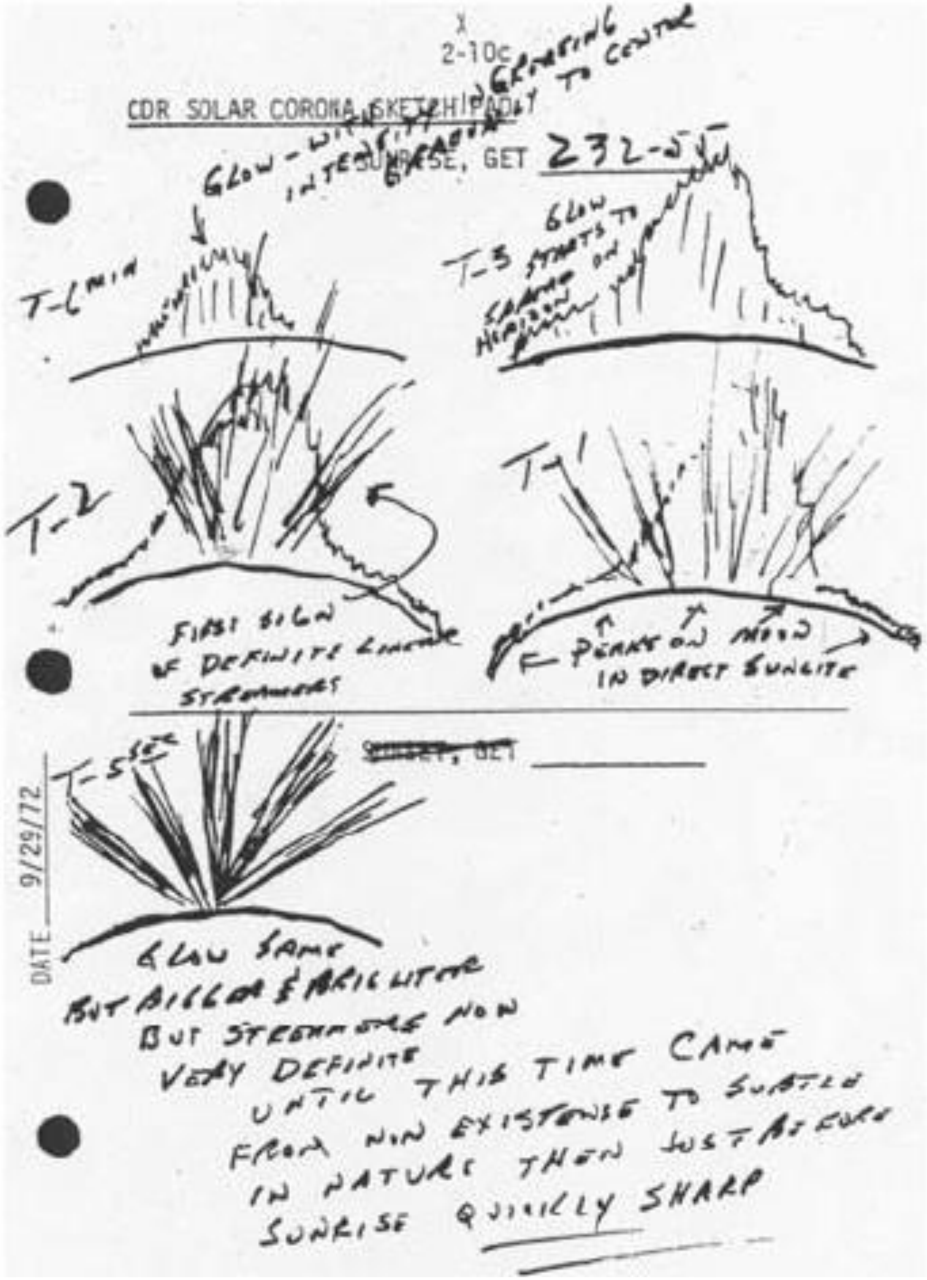


[*Halekas et al.*, 2002]



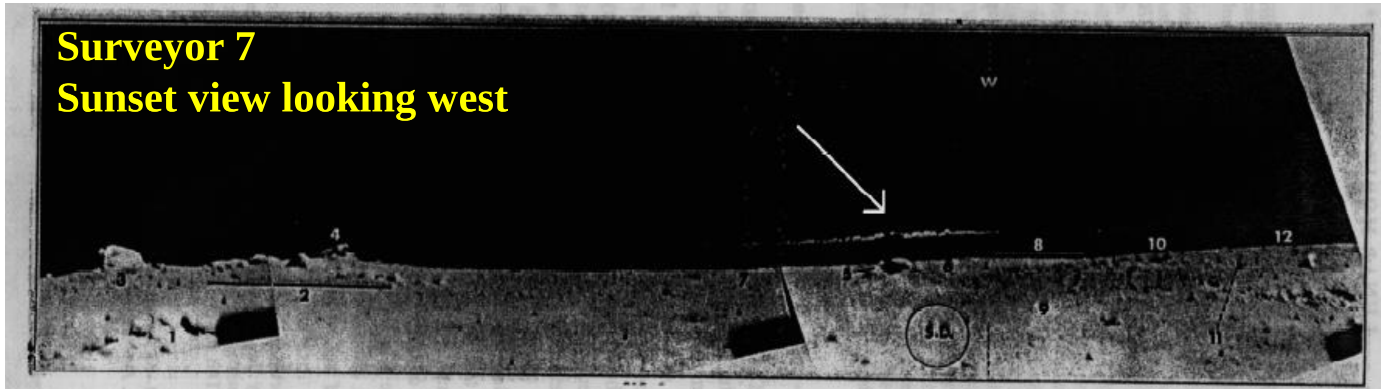
[*Halekas et al*. 2005]

Lunar Dust Charging



Evidence for charged lunar dust

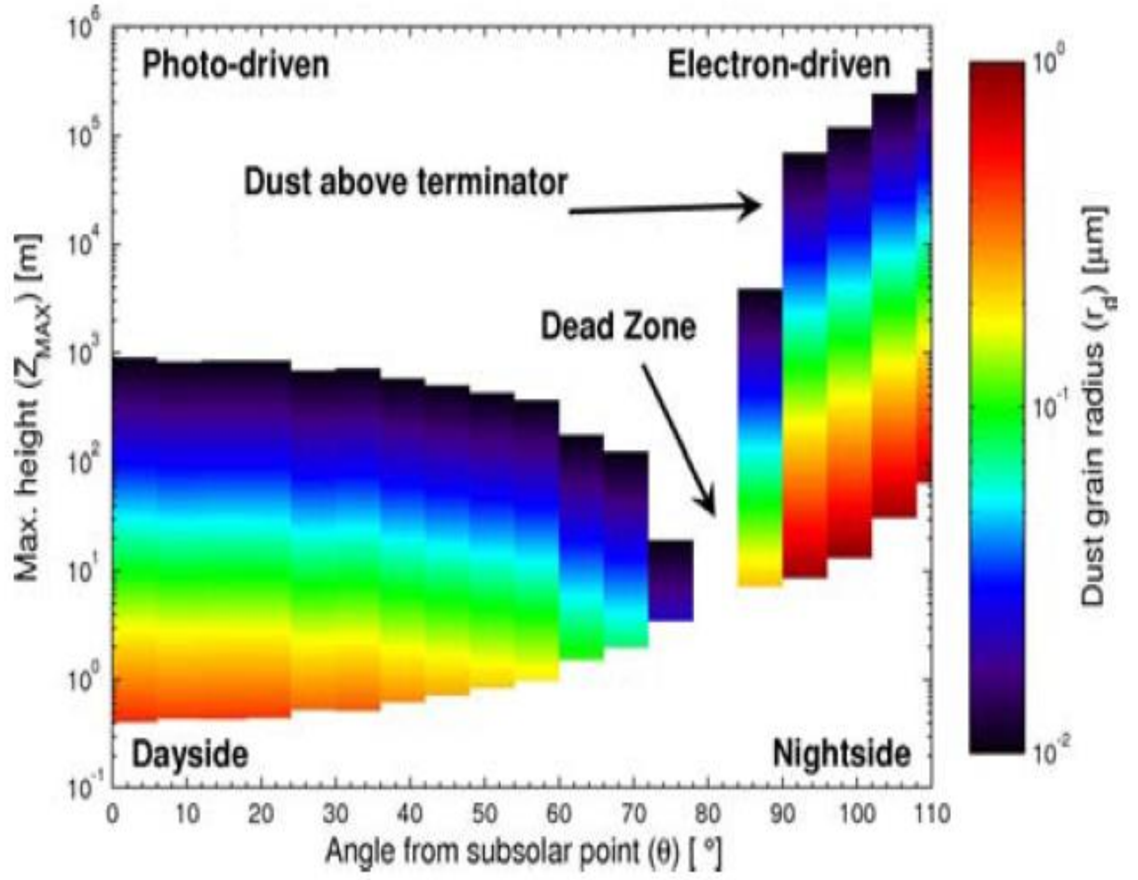
- Apollo 17 astronaut observations (scattered light)
- Surveyor 5,6,7 images of transient horizon glows (scattered light)
- Clementine images (scattered light)
- Apollo 17 Lunar Ejecta and Meteorite Experiment (temperature anomaly)

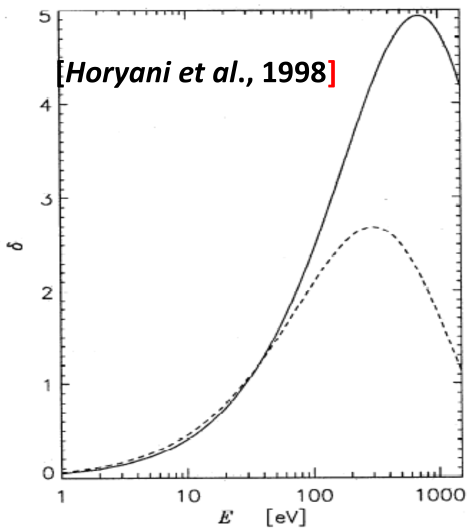


Lunar Dust Charging Models

- *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



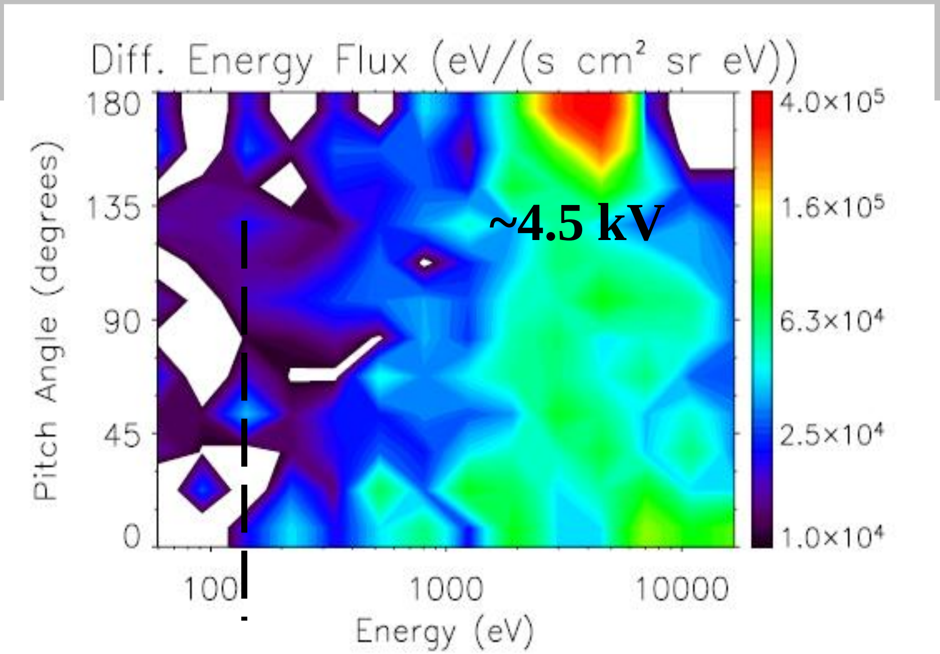


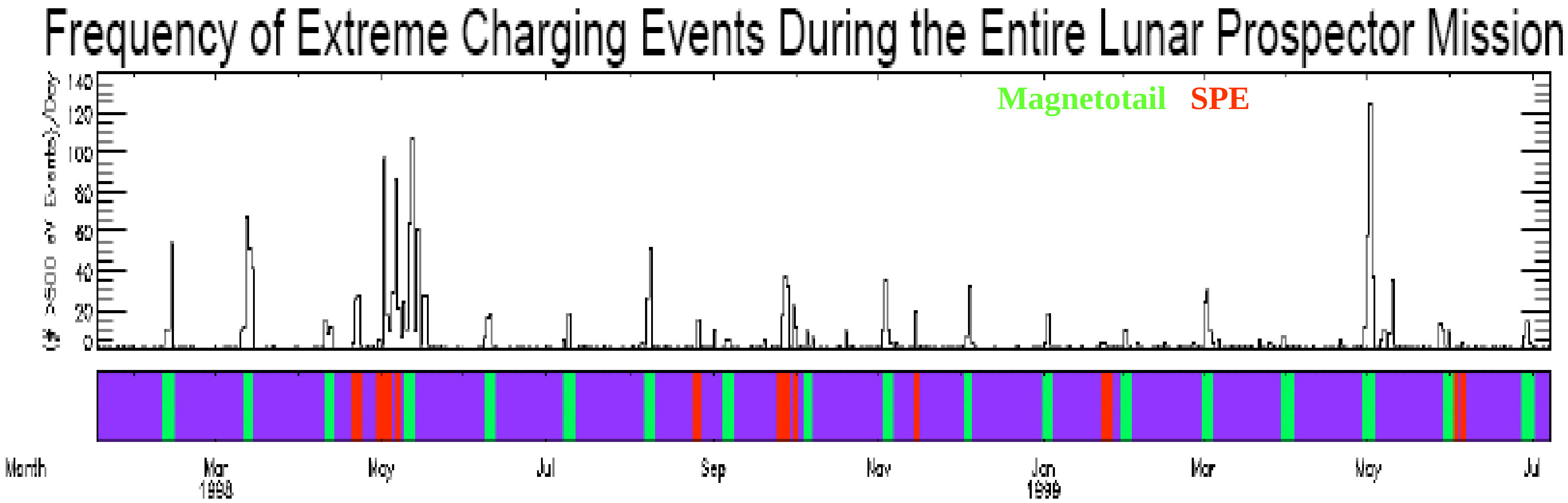
SEY

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

Extreme Charging in Lunar Environments

- Analysis of Lunar Prospector records suggest lunar surface potentials ~ 4.5 kV may occur for extreme conditions [*Halekas et al.*, 2007]
- Lower bound to lunar negative surface potential only since spacecraft potential is unknown

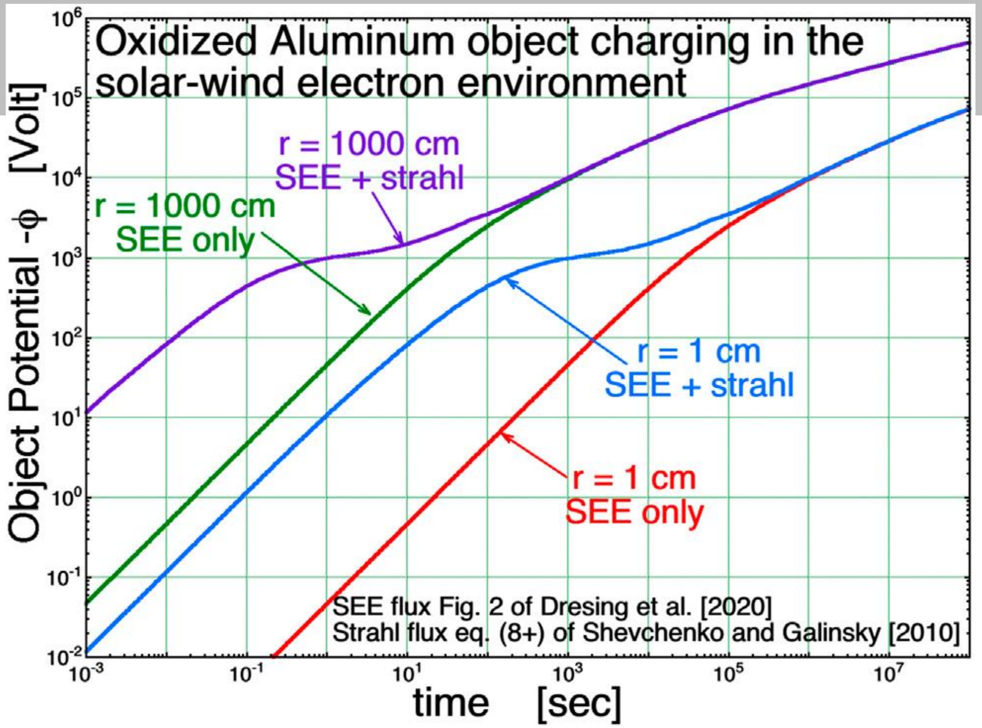




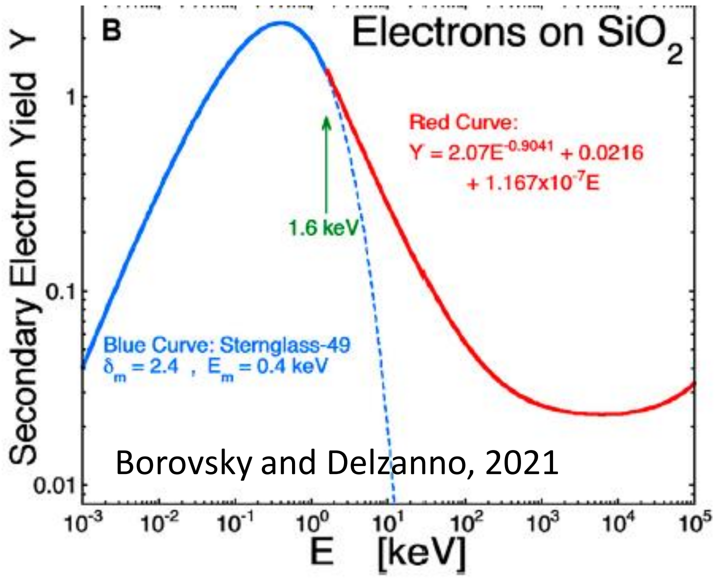
Extreme Charging in Lunar Environments

- Recent work by Borovsky and Delzanno (2021) suggest that impulsive solar energetic electron (SEE) events will provide an high energy environment within the lunar wake that drives strong charging
  - SEE events are rich in 100’s keV electrons
  - Occur about 20 times a year
- SEY yields for lunar analog materials
  - Oxidized aluminum and SiO2 exhibit maximum yields in the 01 – 1 keV range
  - Second crossover (where yields ~ 1) occur at E < 10 keV:
  - High flux of 100’s keV rich electron environment will drive strong charging
- Modeling results suggest lunar surface potentials in the wake can reach extremely high voltages if the electron exposure is long

Charging Time (sec)	(day)	Negative Potential (kilovolt)
10		~ 1
100		~ 3
1,000	0.01	~ 10
10,000	0.12	~ 30
100,000	1.16	~ 80
1,000,000	11.6	~100
10,000,000	116	~200



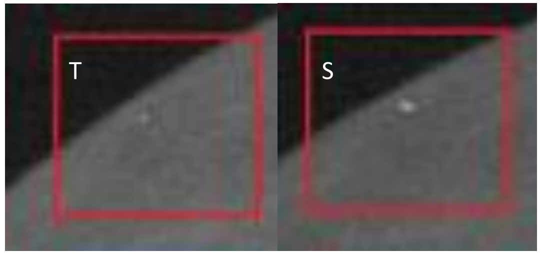
Borovsky and Delzanno, 2021



Borovsky and Delzanno, 2021

Lunar Meteoroid Primary Impactors

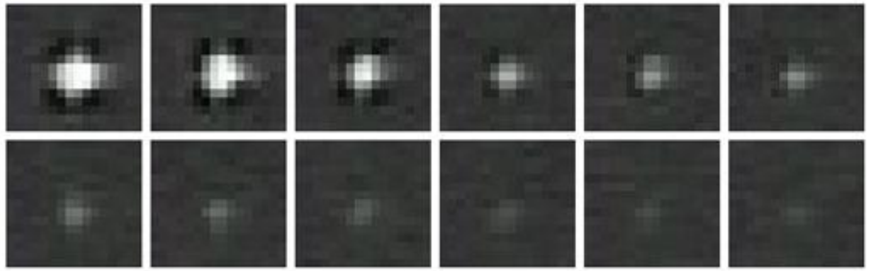
- Meteoroids impact the lunar surface, range in velocity from 10’s km/s to over 70 km/s
- No atmosphere to reduce the meteoroid energy and flux
- Impact risk is primarily for long term exploration infrastructure including development of lunar habitats, power systems, and other hardware on the surface for extended periods of time
- Regular monitoring of lunar meteoroid impacts by NASA MSFC over a period from 2005 to 2020 yielded over 400 candidate lunar impacts, demonstrating the Moon is subject to regular bombardment by meteoroids with masses in the 10’s g range

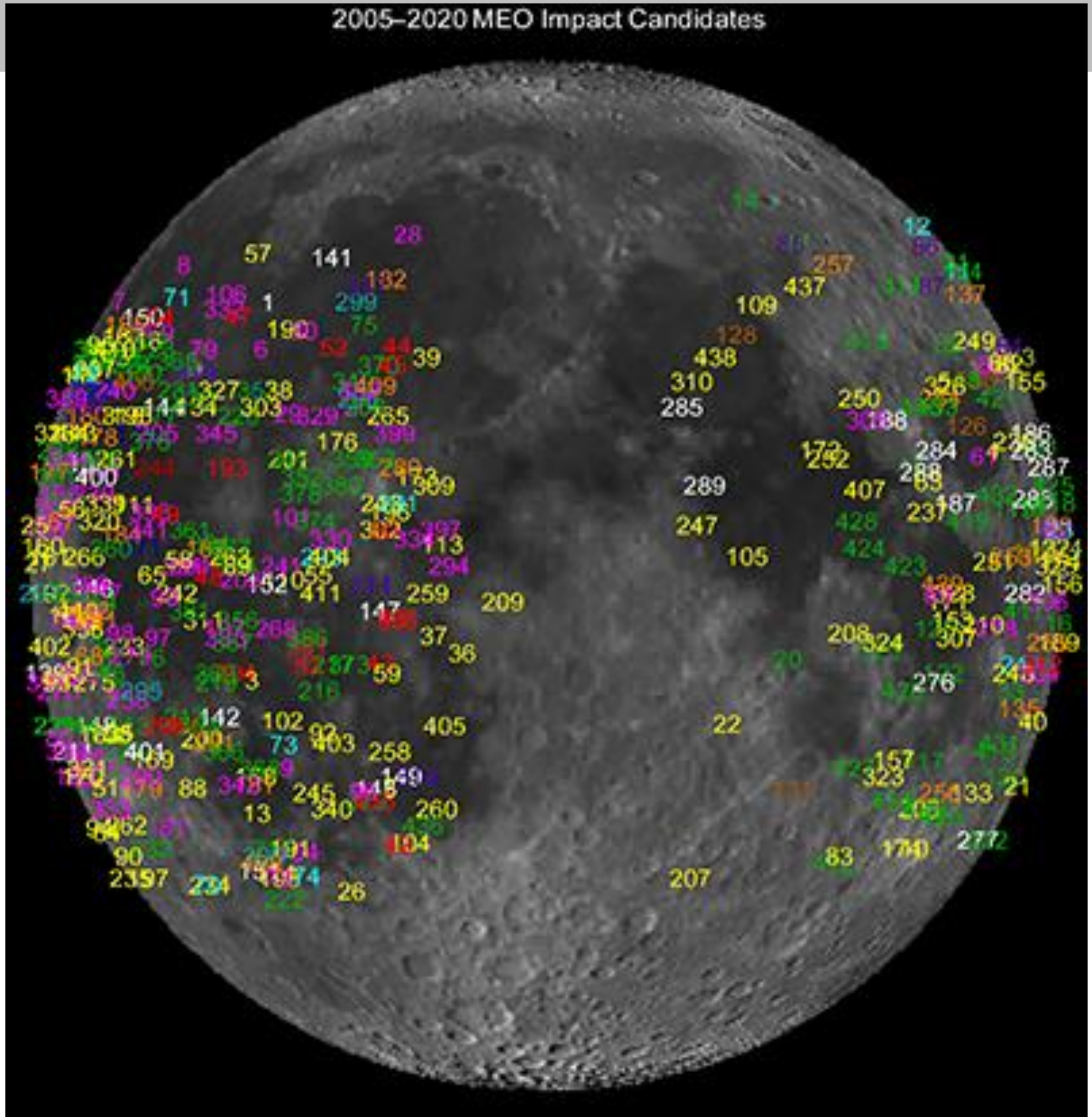


Sampling bias

2 May 2006

1/30 sec/frame



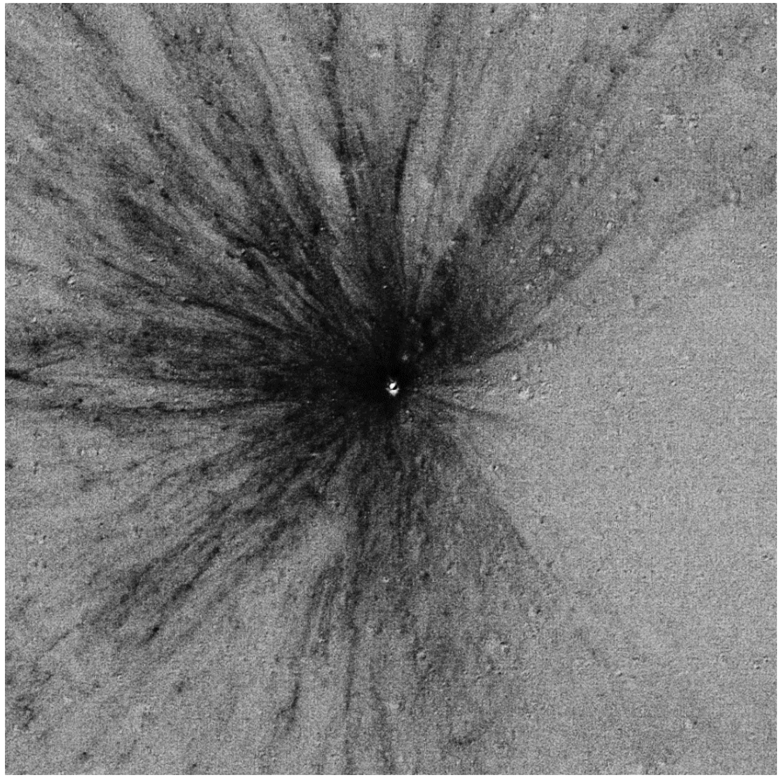


https://www.nasa.gov/centers/marshall/news/lunar/lunar_impacts.html

NASA/Meteor Environment Office

Lunar Ejecta (Secondary Meteoroids)

- Lunar meteoroid ejecta particles are potential threats to spacecraft and crew operating on or above the lunar surface.
- The secondary meteoroid ejecta environment is generated when primary meteoroids impact the lunar surface, generate a crater, and eject pieces of regolith.
- Impact risk is relatively low for direct primary meteor impact on vehicles, structures, or crew.
- Impact risk from secondary ejecta particles is greater due to the large number of ejecta particles generated during a single impact.
- Meteoroid impacts generating craters and ejecta is an ongoing process in the lunar environment.
- NASA is currently using Apollo-era estimates of lunar secondary ejecta while a revision is in development [DeStefano, 2021; Minow et al., 2022]



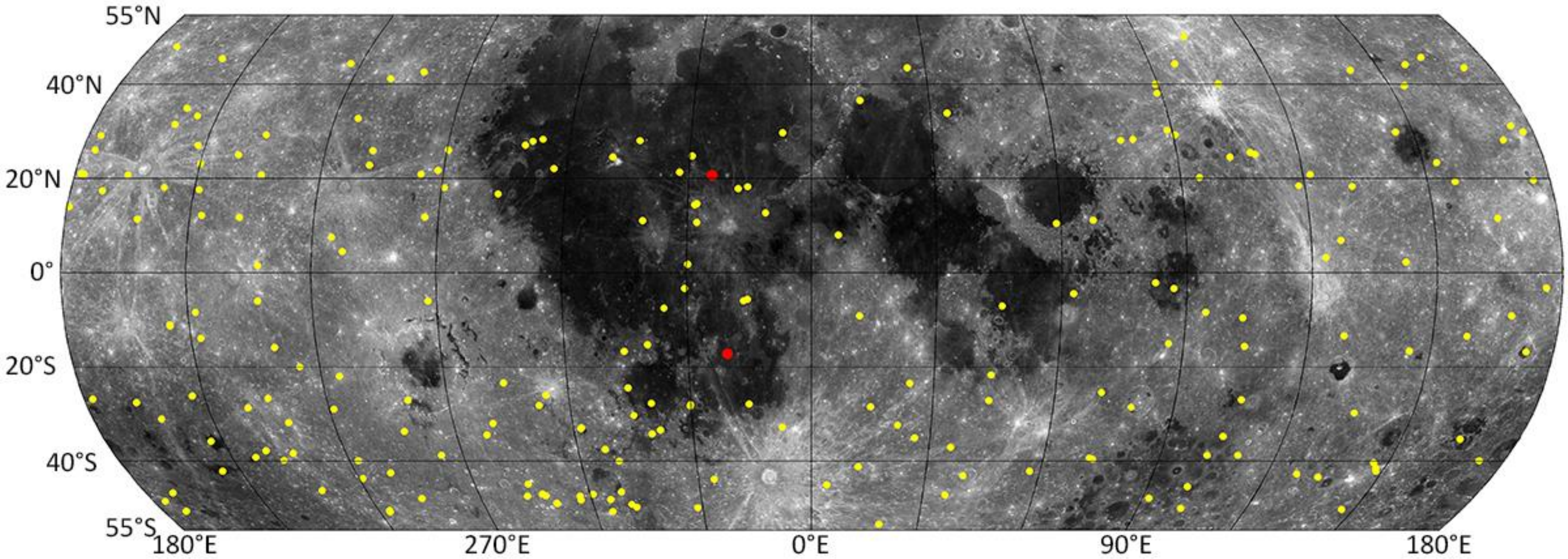
Crater
Area ~ 10^2 m^2

Ejecta
Area > 10^6 m^2

New 12-m-diameter crater with extended ejecta blanket formed between 25 October 2012 and 21 April 2013 discovered by comparing new and old images from the Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC). [NASA/GSFC/Arizona State University]

Lunar Ejecta (Secondary Meteoroids)

- Speyerer et al. 2016 report 222 new lunar craters obtained by comparing 14,092 Lunar Reconnaissance Orbiter Narrow Angle Camera before/after image pairs, images covers a period of ~6 years
- New crater diameters range from 10 m to 43 m, time gaps between before and after images range from 176 to 1,241 Earth days, and images represent 6.6% of the lunar surface
- Yellow dots mark new craters, red dots mark new craters where the impacts were also observed by Earth-based video monitoring
- New craters are appearing 33% more often than predicted by current models



[Speyerer et al., 2016, NASA/GSFC/Arizona State University]

NASA Lunar Design Environments

- NASA's *SLS-SPEC-159, Cross-Program Design Specification for Natural Environments (DSNE)* document contains environment specifications for NASA Exploration Systems Development (ESD) programs including the Artemis lunar programs

- Developed and maintained by the NASA Marshall Space Flight Center's EV44/Natural Environments Branch

- DSNE contains environment specifications for all relevant environments encountered during a lunar mission:
  - 3.1 Prelaunch – Ground Processing Phases
  - 3.2 Launch Countdown and Earth Ascent Phases
  - 3.3 In-Space Phases
  - 3.4 Lunar Surface Operational Phases
  - 3.5 Entry and Landing Phases
  - 3.6 Contingency and Off-Nominal Landing Phases
  - 3.7 Recovery and Post-Flight Processing Phases

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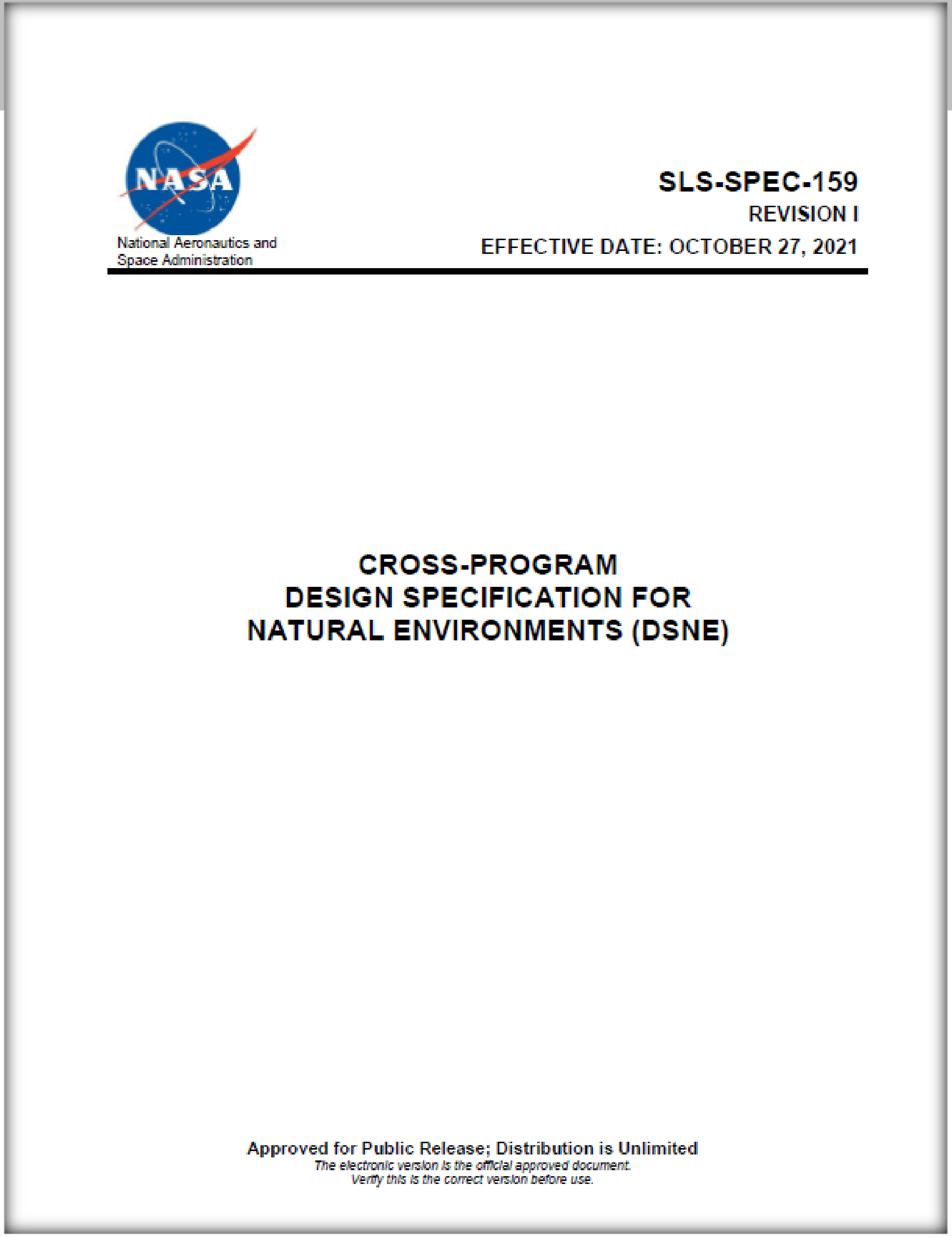

National Aeronautics and Space Administration

SLS-SPEC-159
REVISION I
EFFECTIVE DATE: OCTOBER 27, 2021

CROSS-PROGRAM DESIGN SPECIFICATION FOR NATURAL ENVIRONMENTS (DSNE)

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SLS-SPEC-159
REVISION I

3.3 In-Space Phases 84
3.3.1 Total Dose 85
3.3.2 Single Event Effects 152
3.3.3 Plasma Charging 180
3.3.4 Ionizing Radiation Environment for Crew Exposure 190
3.3.5 Reserved 196
3.3.6 Meteoroid and Orbital Debris Environment 196
3.3.7 Earth Gravitational Field 198
3.3.8 Lunar Gravitational Field 198
3.3.9 Thermal Environment for In-Space Hardware 200
3.3.10 Solar Illumination Environment for In-Space Hardware 209
3.3.11 In-Space Neutral Atmosphere (Thermosphere) Density 211
3.3.12 Geomagnetic Fields (Reserved) 212

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3.3 In-Space Phases 84
3.3.1 Total Dose 85
3.3.2 Single Event Effects 152
3.3.3 Plasma Charging 180
3.3.4 Ionizing Radiation Environment for Crew Exposure 190
3.3.5 Reserved 196
3.3.6 Meteoroid and Orbital Debris Environment 196
3.3.7 Earth Gravitational Field 198
3.3.8 Lunar Gravitational Field 198

3.4 Lunar Surface Operational Phases 212
3.4.1 Lunar Surface Geological and Geomorphological Environment 213
3.4.2 Lunar Regolith Properties 224
3.4.3 Lunar Surface Plasma Environment 260
3.4.4 Lunar Regolith Electrical Properties 265
3.4.5 Optical Properties 273
3.4.6 Lunar Thermal Environment 274
3.4.7 Lunar Ionizing Radiation Environment 286
3.4.8 Lunar Meteoroid and Ejecta Environment 289
3.4.9 Lunar Illumination 290
3.4.10 Lunar Neutral Atmosphere 292
3.4.11 Special Physical and Chemical Conditions of Regolith Inside Areas of Permanent Shadow(RESERVED) 292


Image: NASA

Questions?