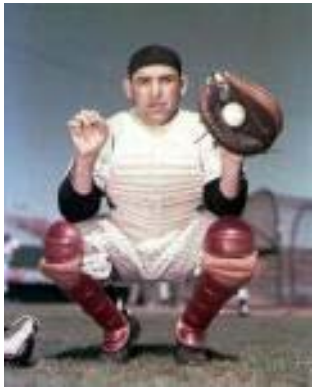
Tom Seaver
NY Mets #41

Lunar Surface Origins Exploration (LunaSOX)

Yogism: "It's like déjà vu all over again"
Heliophysics *of the* Moon and *from the* Moon



Yogi Berra
NY Yankees #8

John F. Cooper (PI) /NASA, Alexander Lipatov /UMBC,
Richard E. Hartle & Edward C. Sittler Jr. /NASA,
Kent Hills /QSS-NSSDC, Robert E. Johnson /UVA

2007 LunaSOX Proposal
Lunar Advanced Science and Exploration Research (LASER)
+ a few updates, e.g. Barrow 2008 & LunaSOX orbiter concept

Thanks to Joe Davila / NASA GSFC, Dave Williams / QSS-NSSDC, Joe Minow / NASA MSFC, Richard Elphic / NASA ARC

LunaSOX Objectives

- **Survey rich data sets available on solar wind interaction with the Moon from the Apollo ALSEP instrumentation on the surface and upstream geospace measurements.**
- **Apply hybrid kinetic multiscale simulations in conjunction with ALSEP measurements to globally model solar wind plasma and energetic ion fluxes into the surface.**
- **Assess effectiveness for future missions of secondary ion mass spectrometry (SIMS) for high-resolution and high-sensitivity composition measurements.**
- **Provide surface interaction modeling and space weathering map products for support of the upcoming and international missions to the Moon for orbital remote sensing.**

LunaSOX Relevance to NASA Strategic Goals

Strategic Sub-goal 3C: Advance scientific knowledge of the origin and history of the solar system, the potential for life elsewhere, and the hazards and resources present as humans explore space.

The solar wind plasma and energetic ion interaction with the Moon determines the global distribution of volatiles within the human-accessible regolith layer and ion sputtering can be utilized for resource mapping of the total volatile and refractory inventories. Full global 3-D hybrid code simulations will map global surface exposure to hazardous solar particle events.

Strategic Sub-Goal 3B: Understand the Sun and its effects on Earth and the solar system.

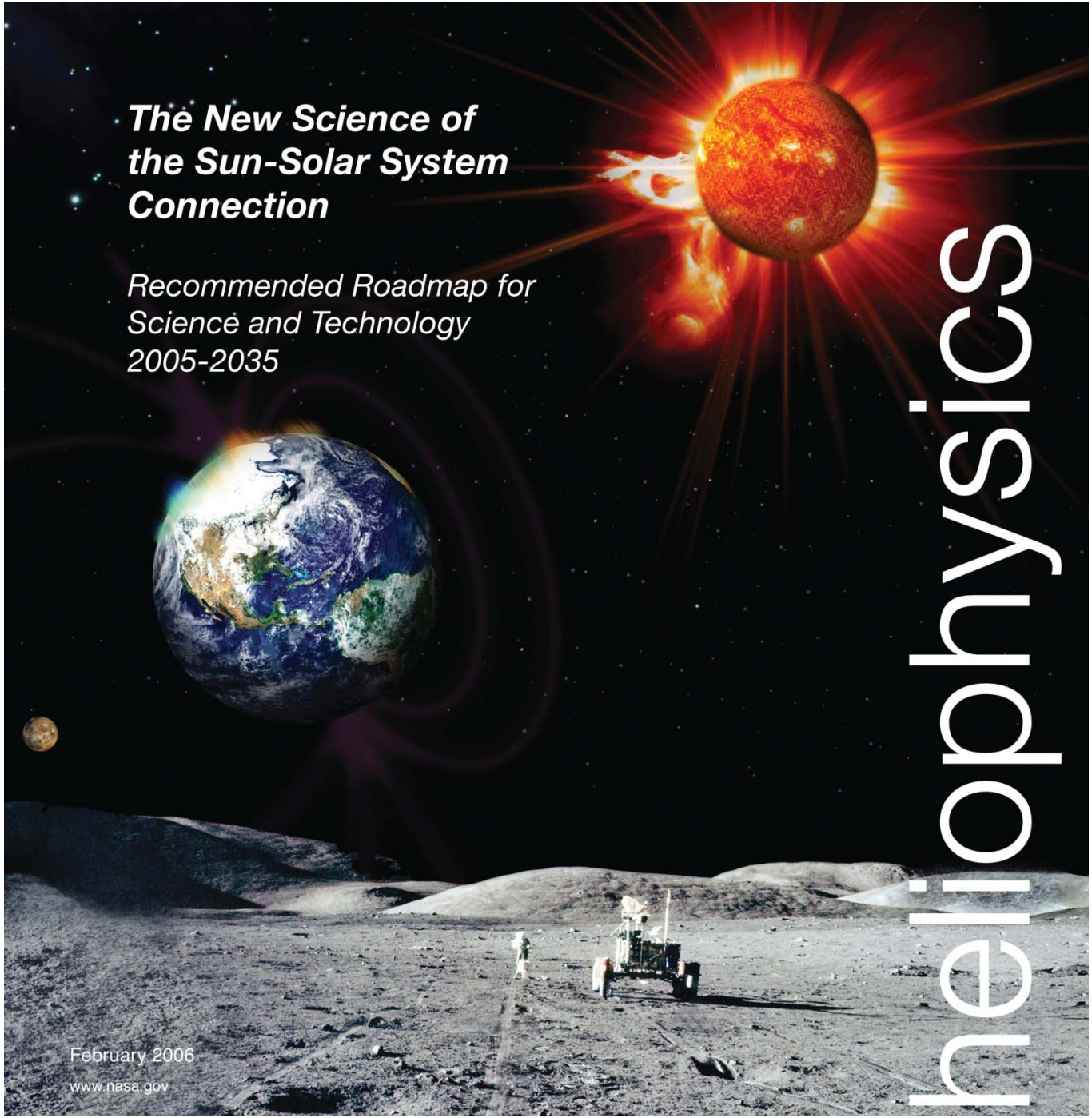
The Moon's remotely sensible surface and surface-accessible regolith records in its chemical composition the history of 4.5 billion years of solar wind and cosmic rays effects on the Earth-Moon system. This record is reduced or absent on Earth due to deflection of the solar wind and lower-energy cosmic rays by the geomagnetic field, and due to surface changes from active tectonism, associated volcanism, and surface weathering by atmospheric and hydrological processes.

Strategic Goal 6: Establish a lunar return program having the maximum possible utility for later missions to Mars and other destinations.

Mapping of chemical resources on the Moon from exogenic and internal sources prepares the way for human missions to the surface. Understanding effects of external space radiation on planetary surfaces and atmospheres paves the way for robotic and eventual human exploration of other planetary bodies.

The New Science of the Sun-Solar System Connection

Recommended Roadmap for Science and Technology 2005-2035



heliophysics

February 2006

www.nasa.gov

Heliophysics Science and the Moon, *Report to NASA Advisory Council – Heliophysics Subcommittee, NP-2007-07-80-MSFC, Pub 8-40716, NASA MSFC, Sept. 2007.*

Relevant Objectives for LunaSOX

- Characterize the Near-Lunar Electromagnetic and Plasma Environment
- Interaction of Plasma with the Moon
- Characterize and Understand the Interaction of Dust and Plasma on the Surface of the Moon and in the Lunar Exosphere
- Characterize Radiation Bombardment on the Lunar Surface and Subsurface
- History of the Sun and Cosmic Radiation
- History of the Inner Solar System According to the Lunar Cold Traps
- Analyze the Composition of the Solar Wind

And we also suggest:

Use the Moon as a heliophysics science platform to observe spatial and spectral structure of the solar corona and near-solar dust environment

LunaSOX Mission Implementation Description

***Location: LRO-type 50-km polar orbit after initial elliptical phase for lunar wake**

***Attitude control: 3-axis stabilized (ram, nadir, solar)**

Adjust to direction of solar wind, magnetosphere, & lunar neutral gas flows

Prograde and retrograde imaging of Sun at hourly lunar limb occultations

*** Instruments:**

Low-energy ion-neutral and energetic heavy ion mass spectrometers, magnetometer, electron reflectometer (20 kg/20 W)

UV-VIS-IR spectroscopic imagers - particular focus on near-IR for any lunar polar surface ice bands and for solar F-corona dust (30 kg/30 W)

Measurement Strategy:

- **Large scale lunar environment characterization in initial elliptical lunar orbit**
- **Primary near-lunar and remote surface measurements in circular polar orbit**
- **Hourly lunar limb occultations for solar F-corona, zodiacal light, and lunar atmospheric observations – doppler shift of solar Fraunhofer lines, dust absorption**

THAR'S GOLD IN THAM LUNAR HILLS

Jan 28 2006 By Stephen White

Helium 3 could hold key to the future of space exploration. It could be the 'cash crop' for the Moon

RUSSIA is planning to beat America back to the Moon to mine for an abundance of untapped riches.

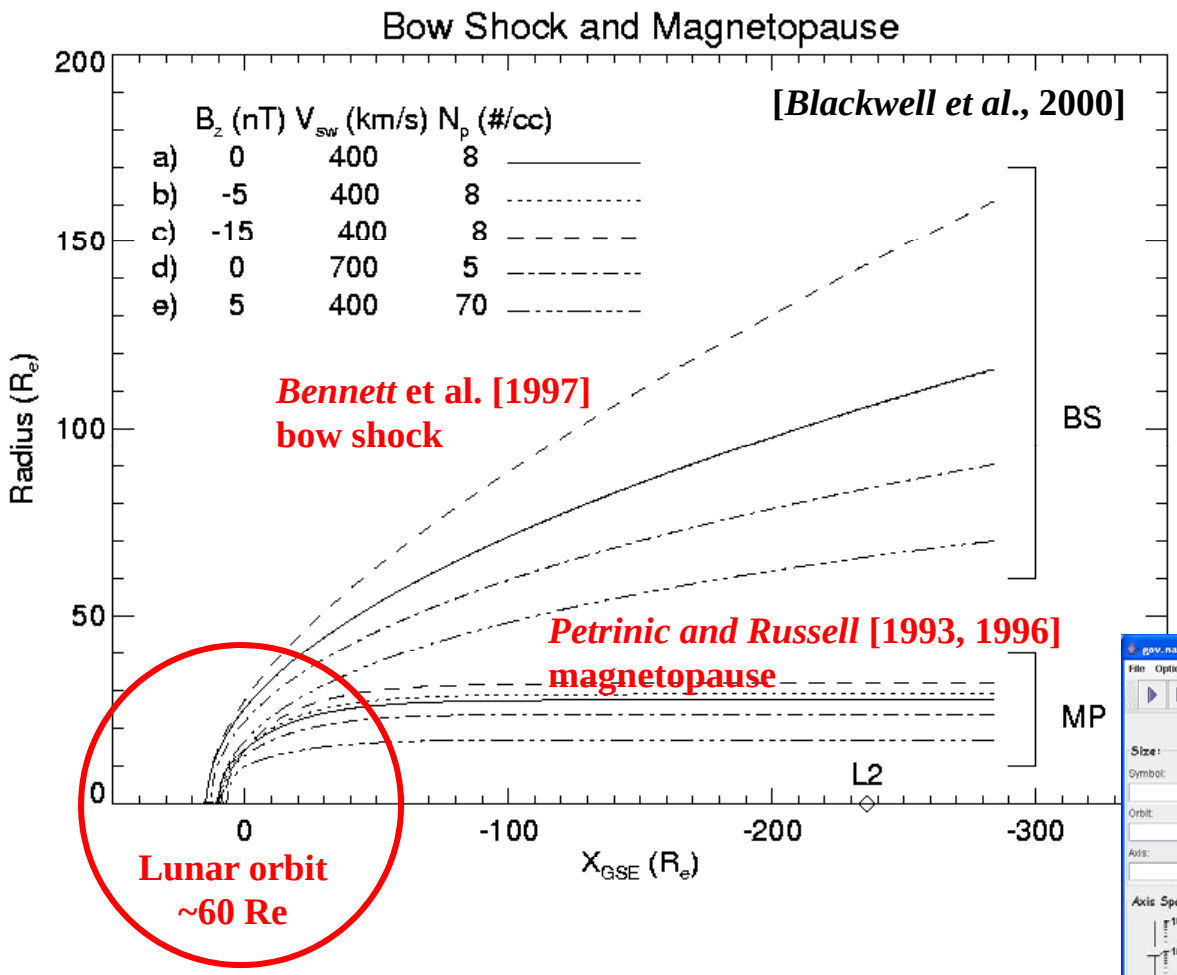
But it's not gold or diamonds they aim to bring back to Earth. … a total of 1,100,000 metric tons of He3 have been deposited by the solar wind on the Moon.

The total supply in the US strategic reserves is about 29 kg, and another 187 kg is mixed up with natural gas in storage.

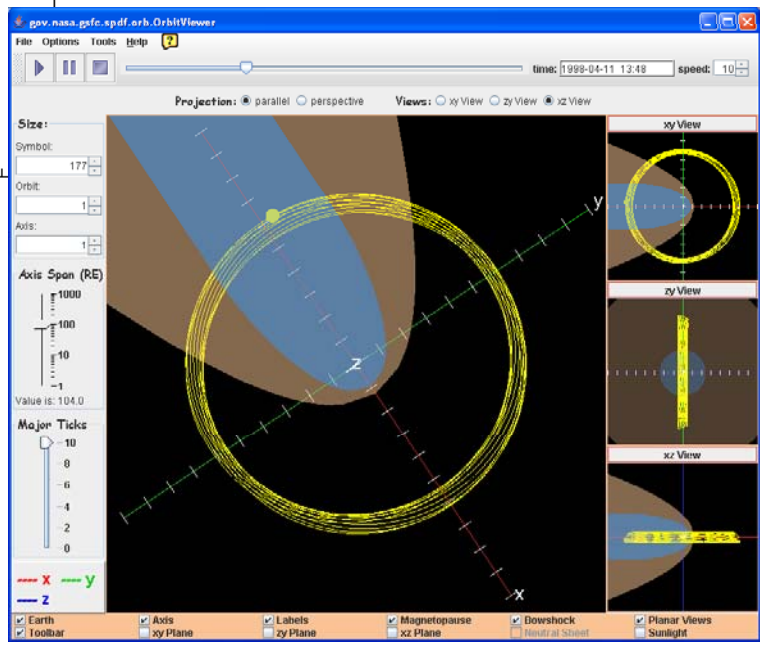
Nikolai Sevastyanov, head of Russia's giant Energia Space Corporation, said: "We are planning to build a permanent base on the Moon by 2015 and by 2020 we can begin the industrial-scale delivery of helium 3."

… solar wind-implanted particles are more abundant on the far side, because the Earth (its magnetosphere) shields the Moon's near side from the solar wind for part of each solar orbit … the greatest amounts of helium 3 will be found on the far side of the Moon. DailyRecord.co.uk

Bow Shock and Magnetopause Variability



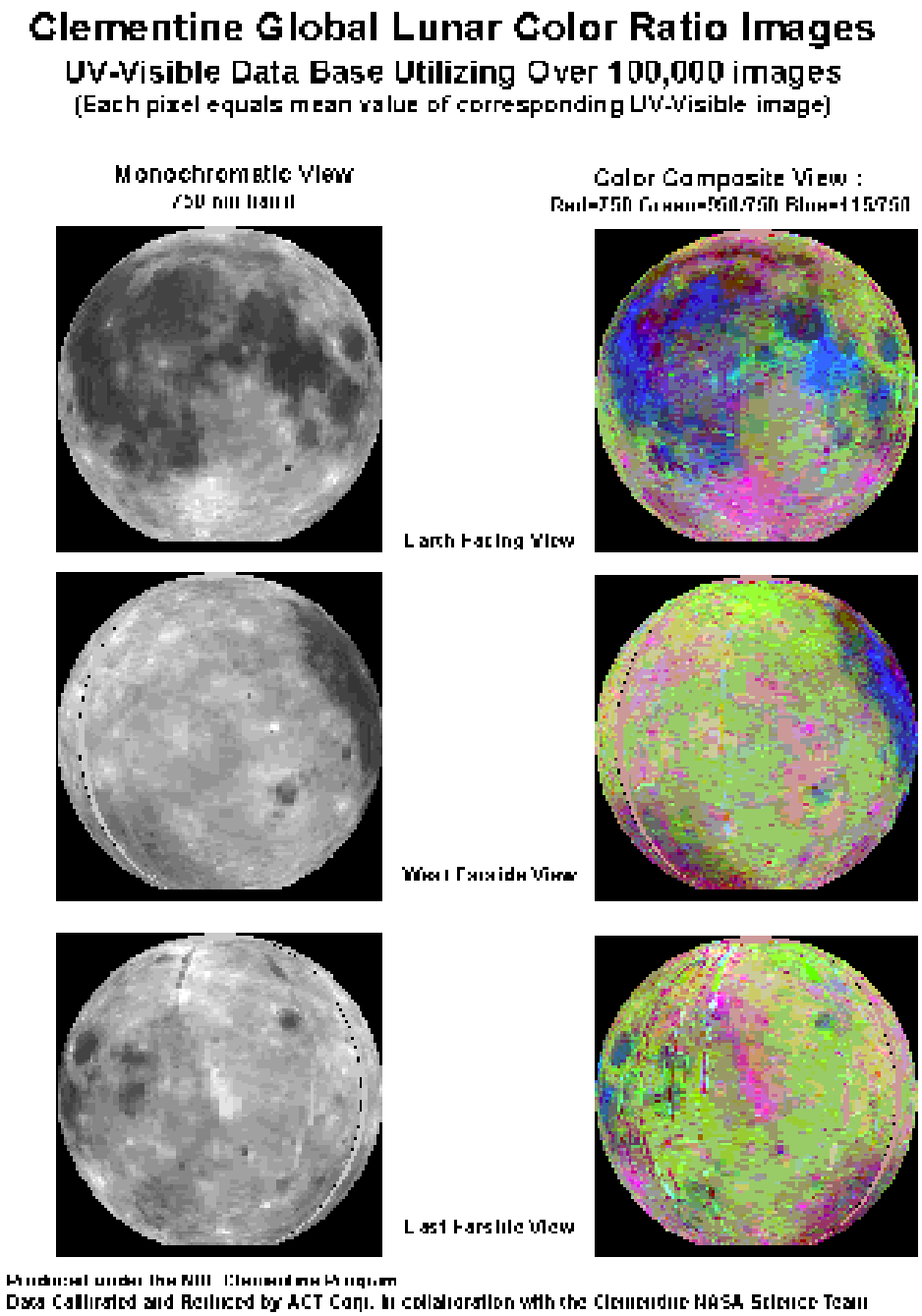
J. Minow, Barrow 2008



Fraction of Month in Plasma Environments

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

Near-far hemispheric asymmetry of intrinsic lunar composition impacts retention of solar wind volatiles

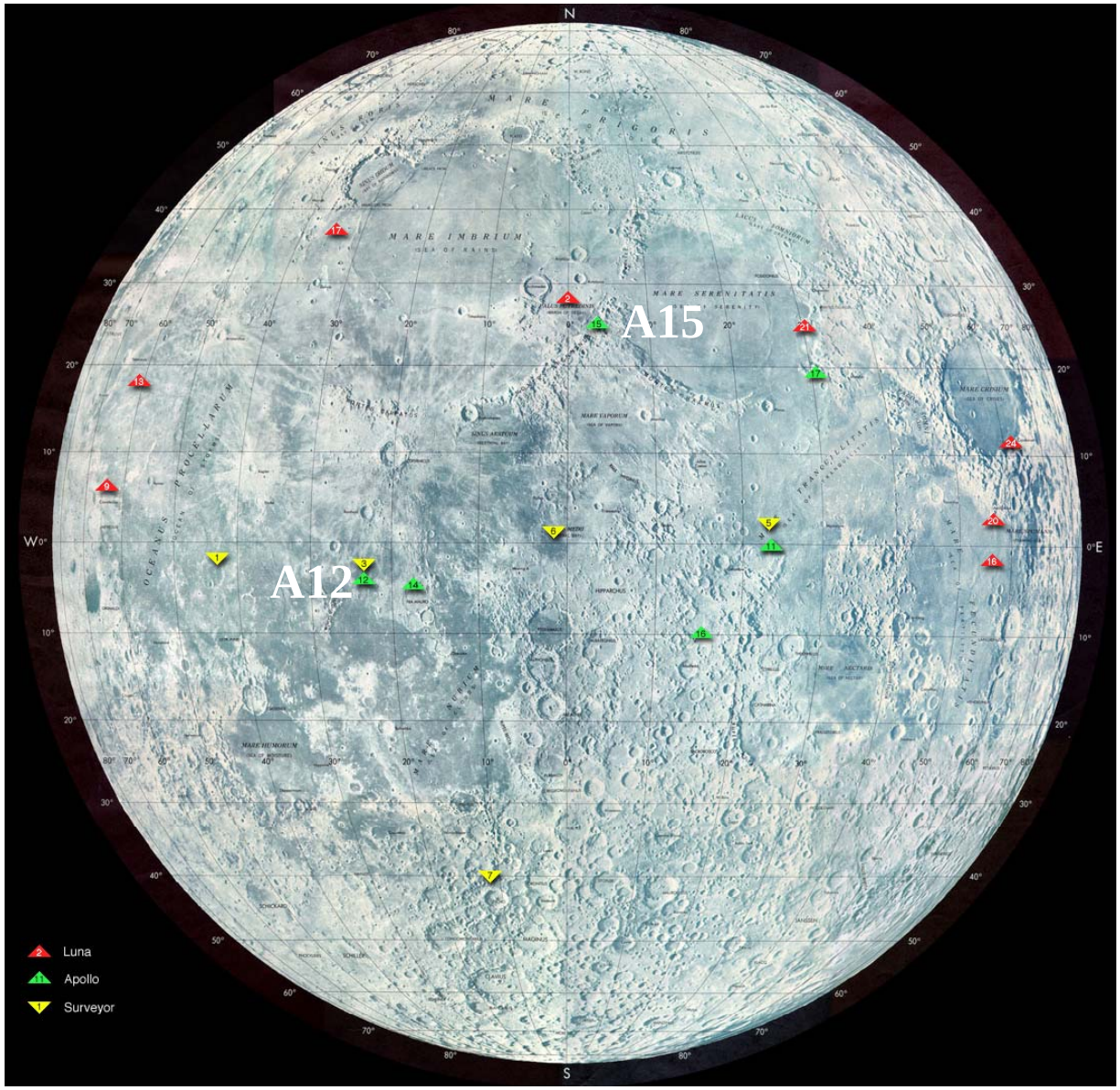


Near Side

Far Side

Far Side

Landed Robotic and Human Exploration – the Near Side



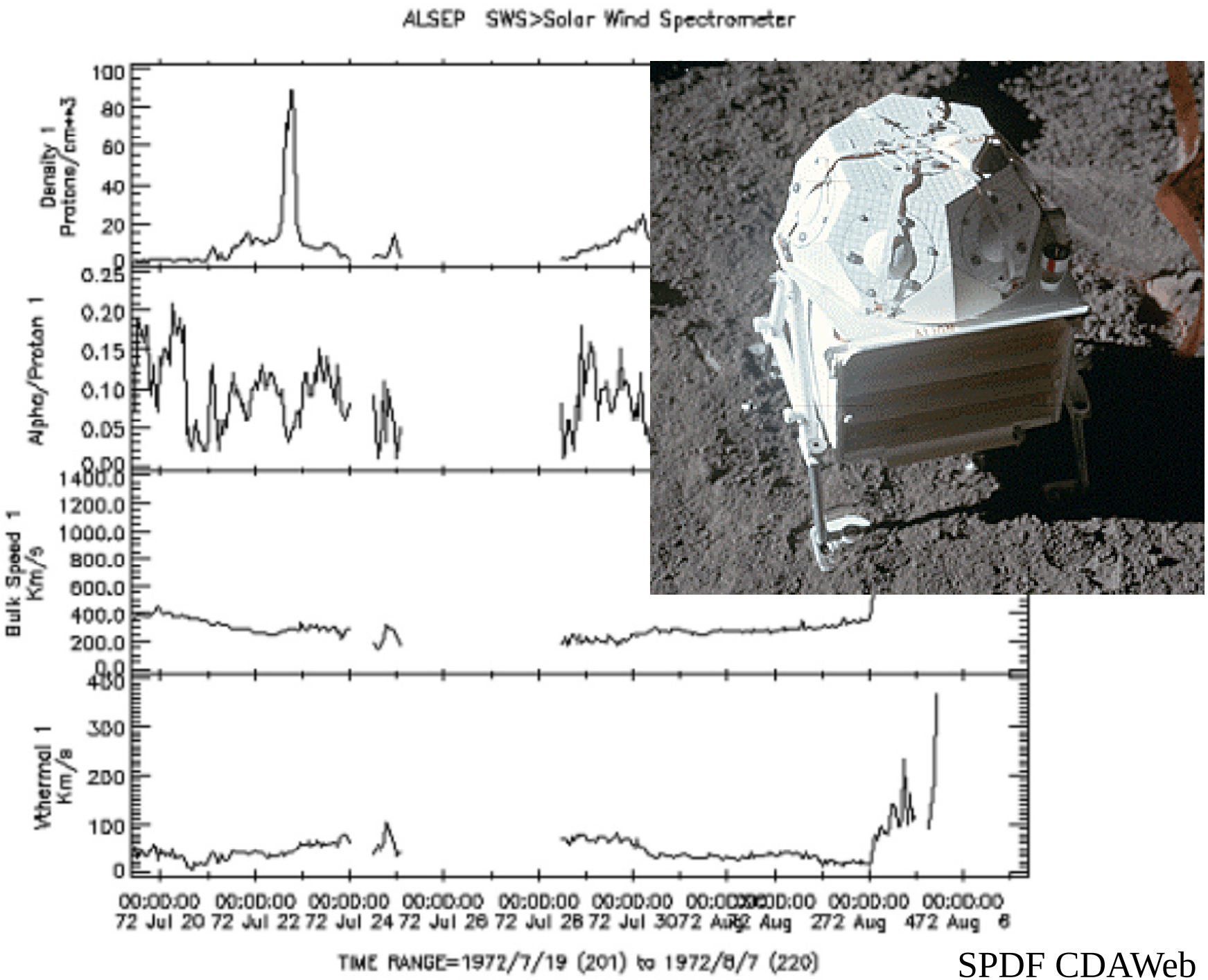
Dave Williams, NSSDC

Lunar Data Project
PDS Lunar Data Node

- Restore Older Lunar Data Archived in Inhospitable Formats
- Identify and Retrieve Unarchived Lunar Data
- Make Data Generally Digitally Accessible

- Avoid Repeating Experiments
- Use New Data Analysis Techniques and Hardware
- Explore Environmental Hazards
- Help Define Safe Landing Sites

Dave Williams, NSSDC


ALSEP SWS>Solar Wind Spectrometer
Density 1 Protons/cm**3
Alpha/Proton 1
Bulk Speed 1 Km/s
Vthermal 1 Km/s
72 Jul 20 72 Jul 22 72 Jul 24 72 Jul 26 72 Jul 28 72 Jul 30 72 Aug 2 72 Aug 4 72 Aug 6
TIME RANGE=1972/7/19 (201) to 1972/8/7 (220)

SPDF CDAWeb

Apollo 12/15 ALSEP Site Parameters and SWS Data Coverage (CDAWeb^)

	Latitude* (°North)	Longitude* (°East)	Radius (km)	Magnetic Field# (nT)	SWS Dates
Apollo 12	-3.00942	-23.42458	1736.014	38≺2	1969-11-19 1976-03-25
Apollo 15	26.13407	3.62981	1735.477	3≺3	1971-07-31 1972-06-30

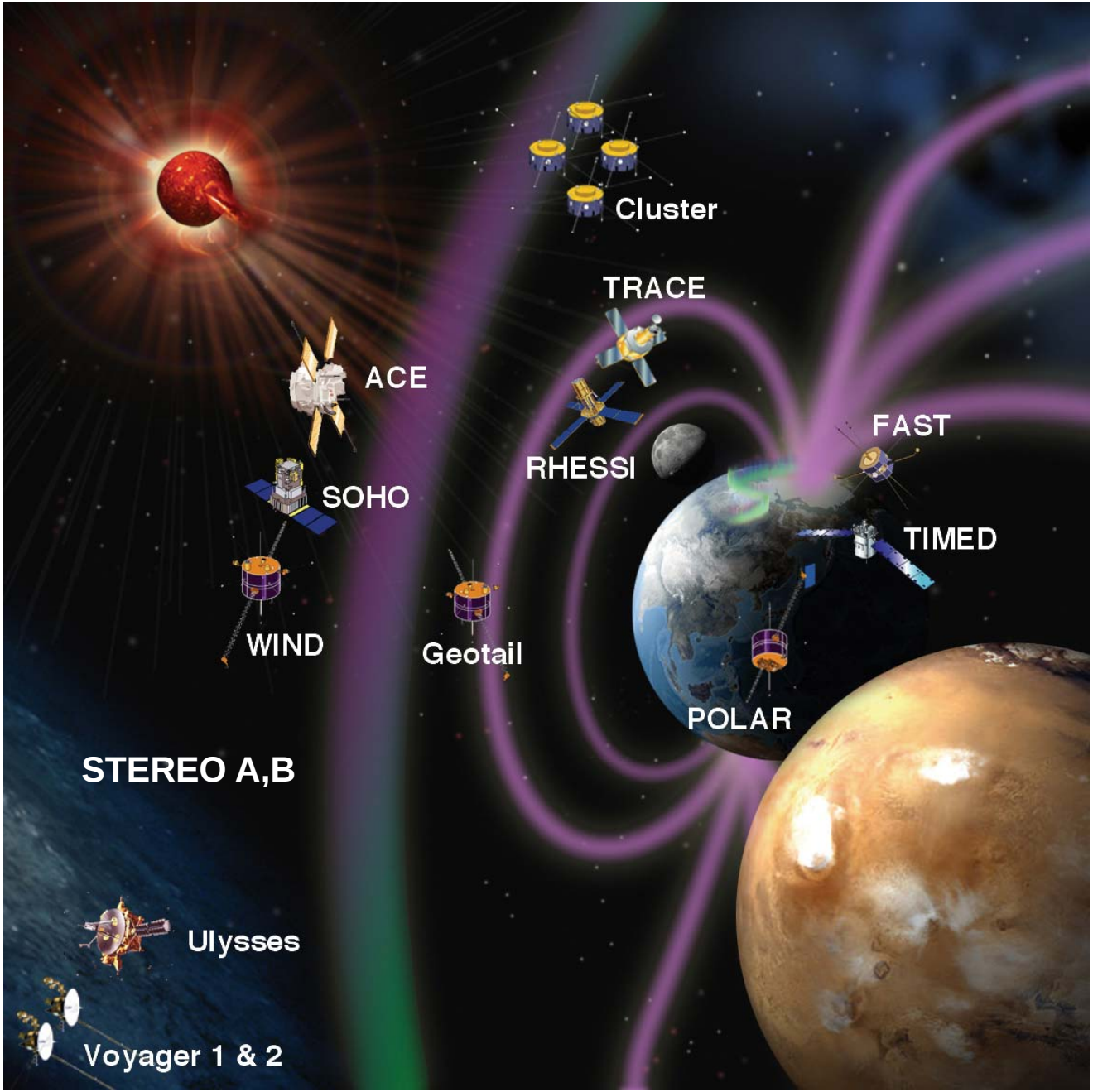
*Site coordinates based on the IAU Mean Earth Polar Axis coordinate system (Davies and Colvin, 2000).

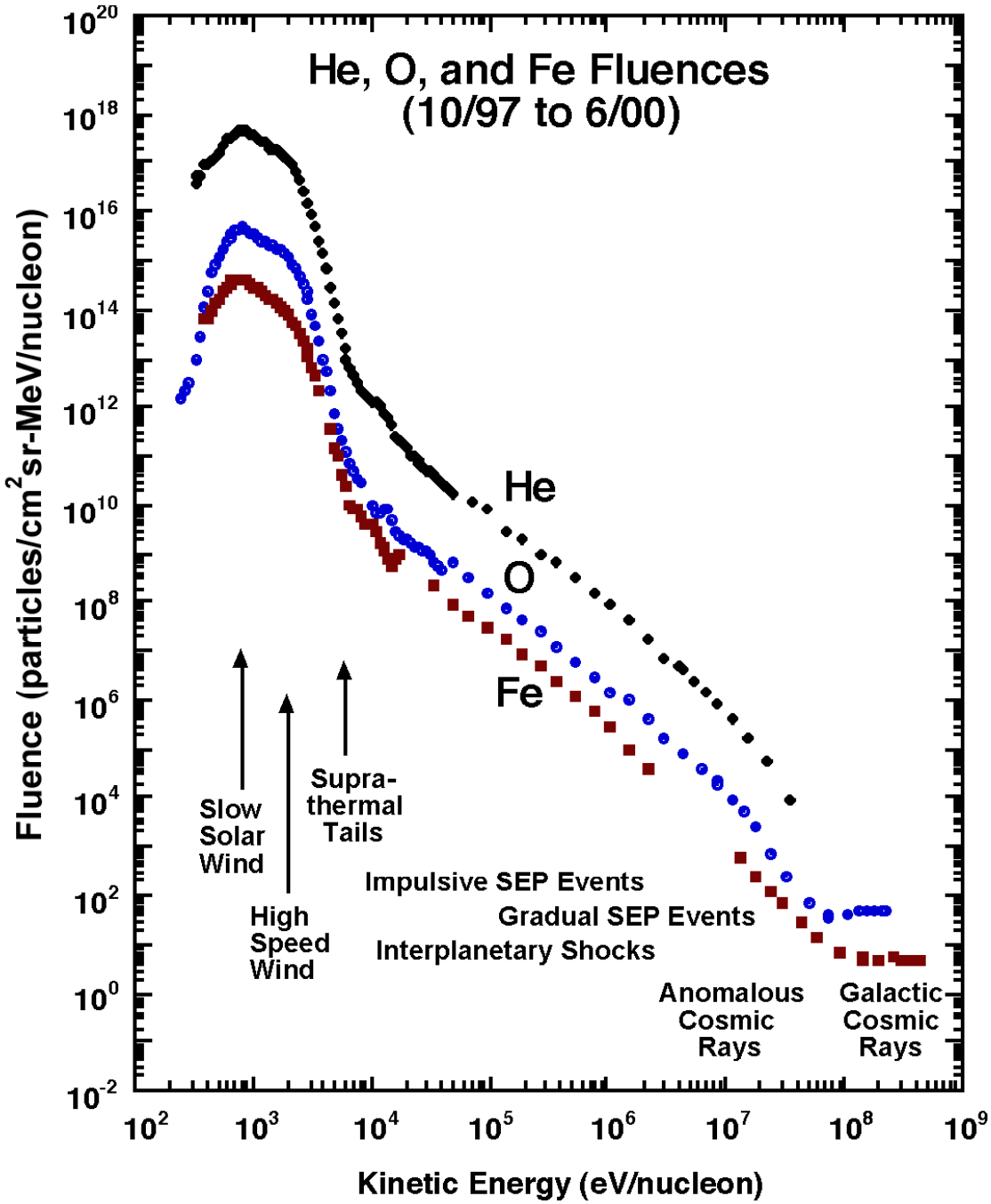
#ALSEP magnetometer measurements (Dyal et al., 1970, 1972, 1973)

^ Coordinated Data Analysis Web site for lunar-relevant data (http://cdaweb.gsfc.nasa.gov/lunar/)

LunaSOX project would provide first full hybrid kinetic simulation of ALSEP SWS data as correlated to upstream solar wind measurements.

Heliophysics Great Observatory - 2008





Advanced Composition Explorer (ACE)

Ion Composition Measurements 1997 – Present

Plasma to Cosmic Rays (eVs to GeVs)

<u>Data Sites</u>

ACE Science Center
Space Physics Data Facility
Virtual Heliospheric Observatory (VHO)

Lunar surface sputtering by solar wind & energetic ions generates a rich harvest of secondary ion species detectable from orbit

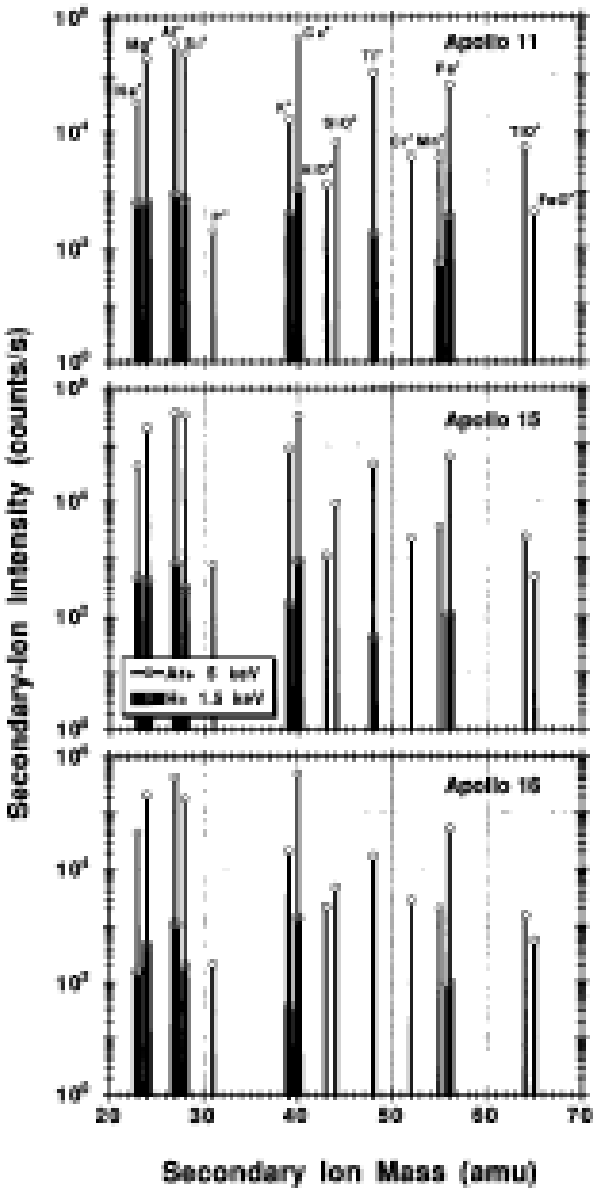


Fig. 1. Secondary-ion intensities of Na through FeO for incident ions of Ar at 5 keV, and solar wind-like ions of H at 1.5 keV, respectively. Secondary-ion intensities from the three lunar soil simulants are shown.

Elphic et al. [1991]

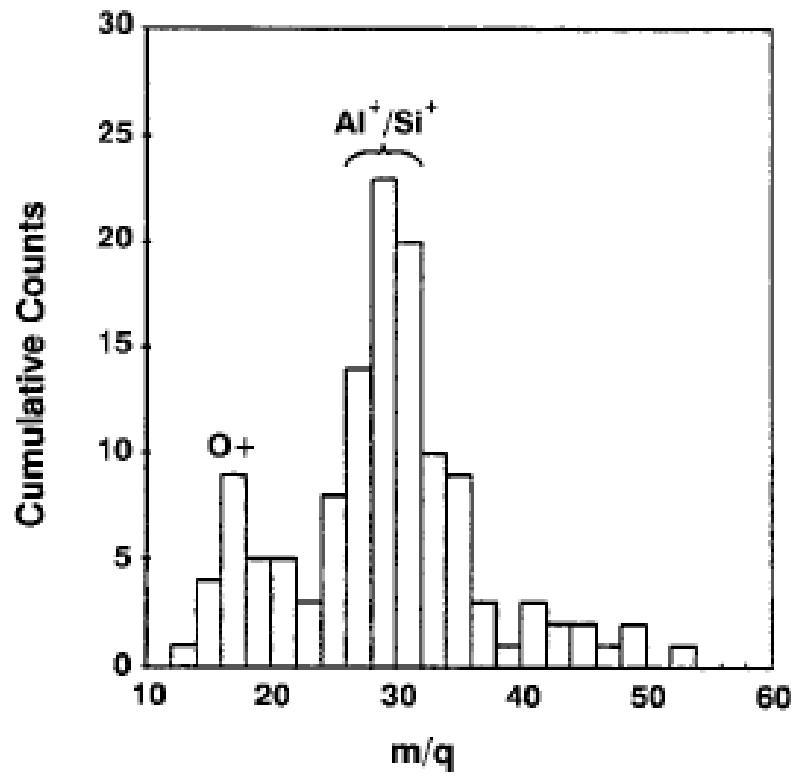
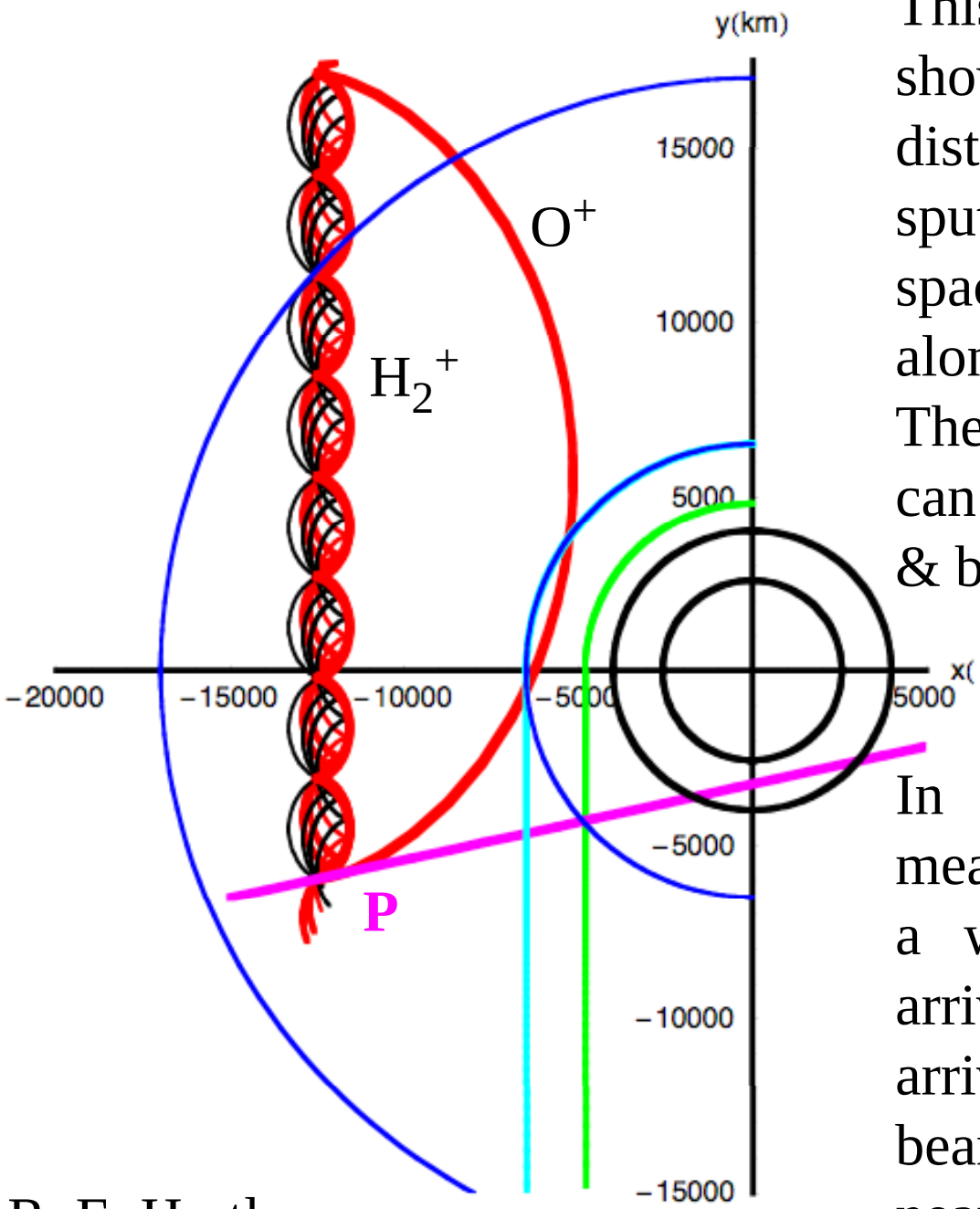


Figure 10. Mass-to-charge (m/q) spectra from the AMPTE/SULEICA instrument showing the detection of lunar ions when it was downstream of the Moon. Adapted from *Hilchenbach et al.* [1991].

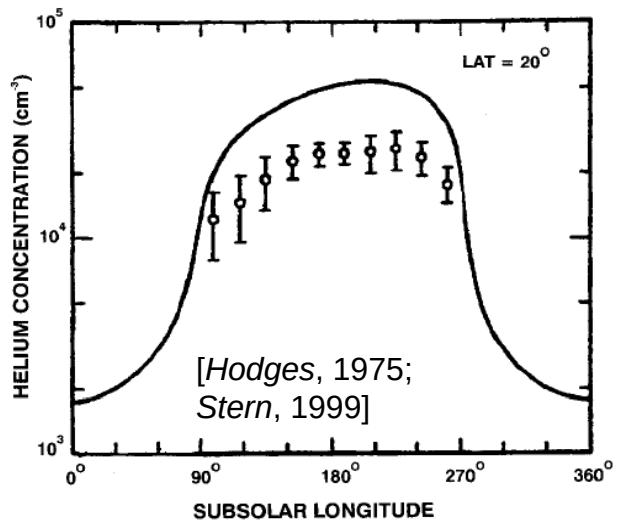
From Stern [1999]
and Hilchenbach et al. [1991]

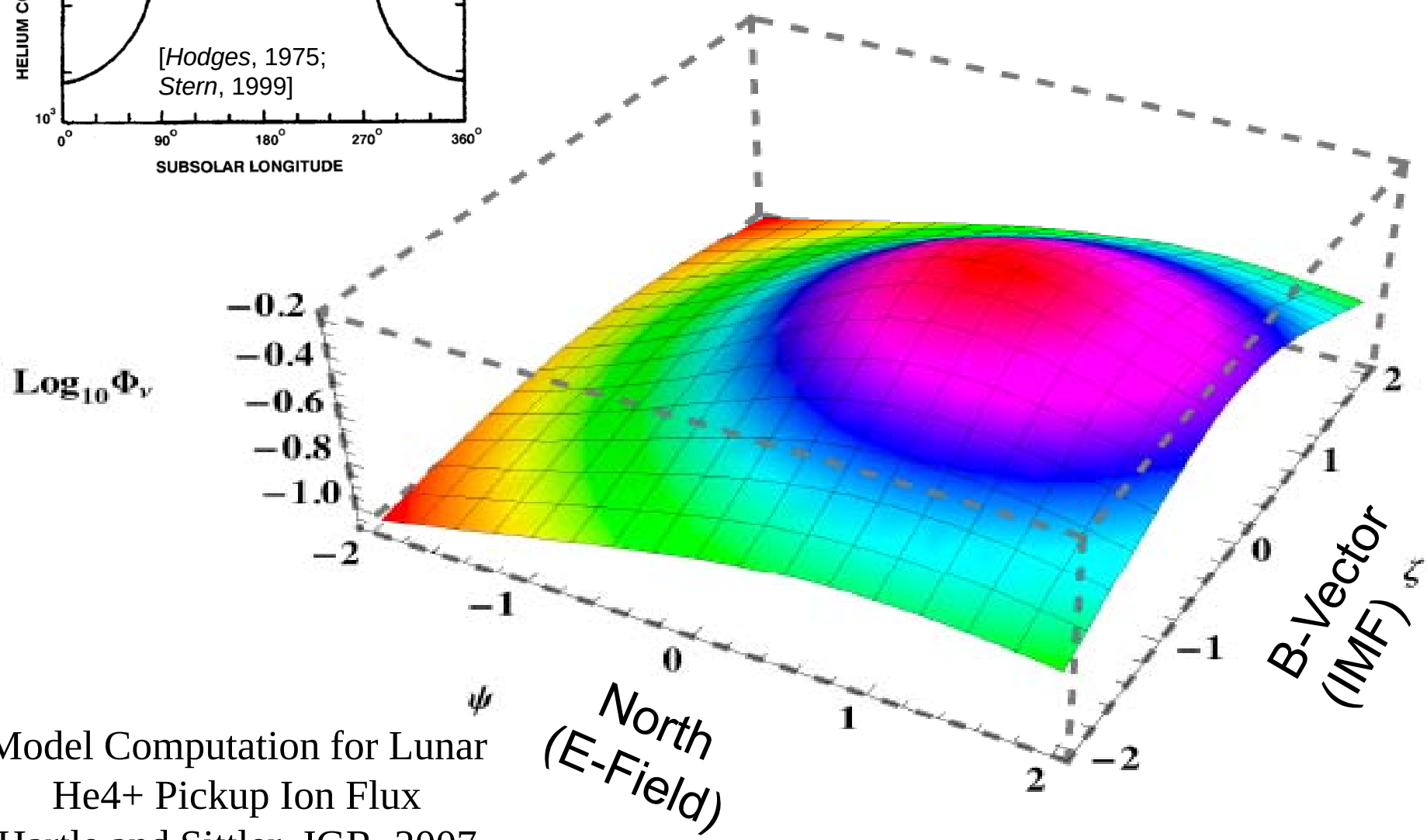


This moon-centric illustration shows the different directional distributions to be expected for sputtered ions measured by a spacecraft detector at point P along the pink trajectory line. The sample ions, H_2^+ and O^+, can originate from locii along red & black cycloidal origin curves.

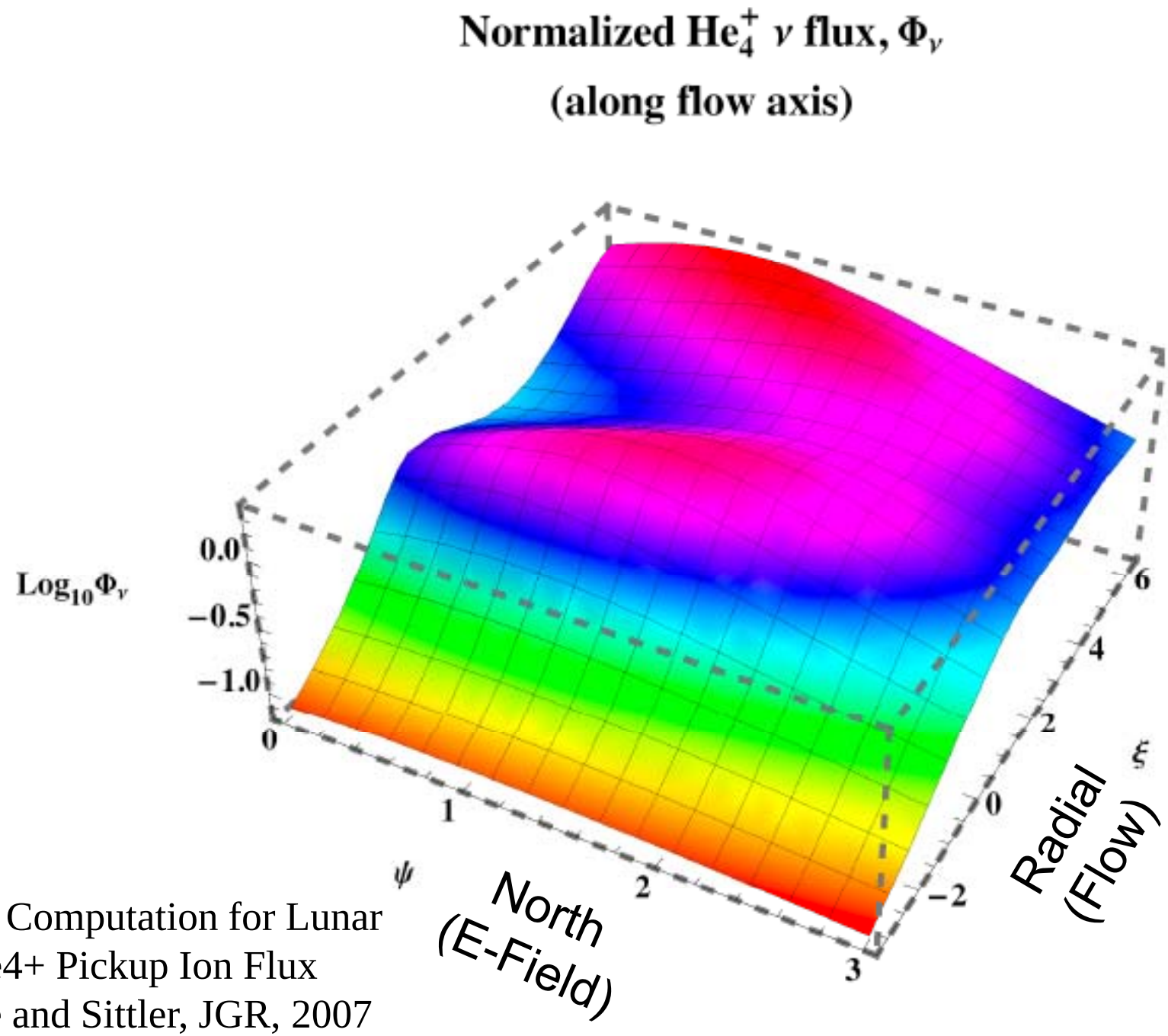
In a 3-D plasma ion measurement the lighter ion has a widely distributed range of arrival directions but the O^+ ion arrives in a relatively narrow beam if the source is localized near or at the lunar surface.

R. E. Hartle



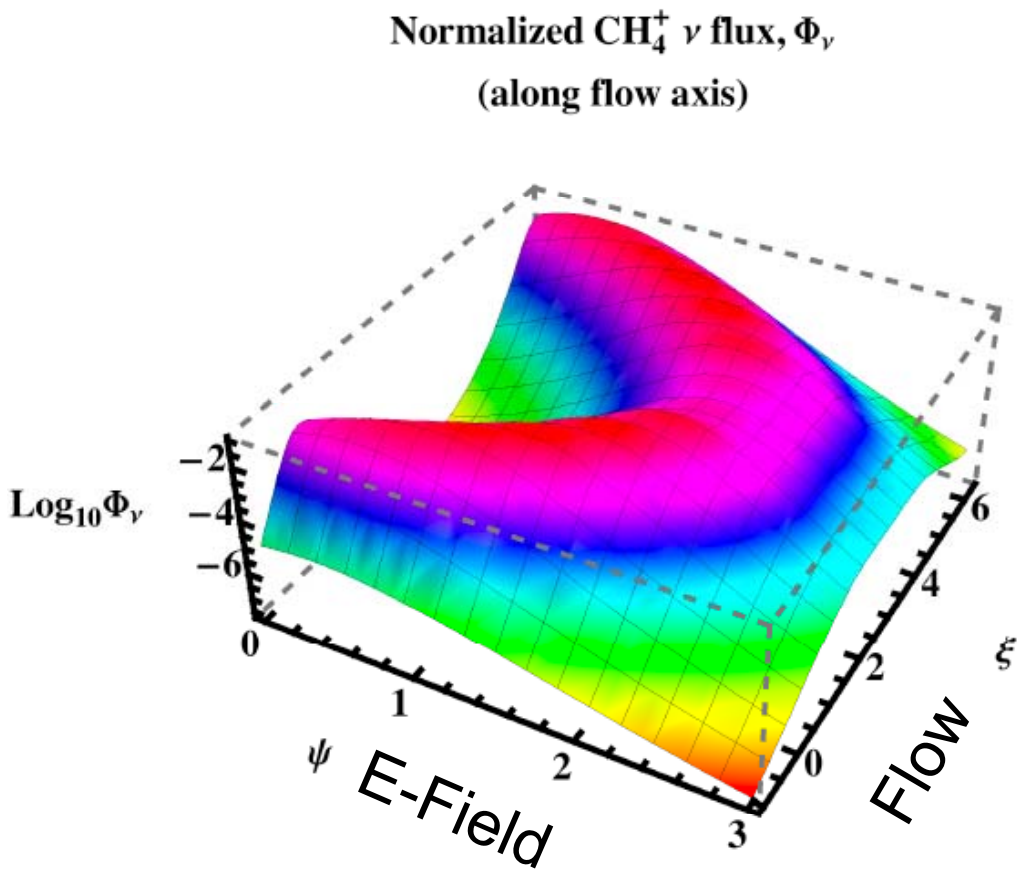


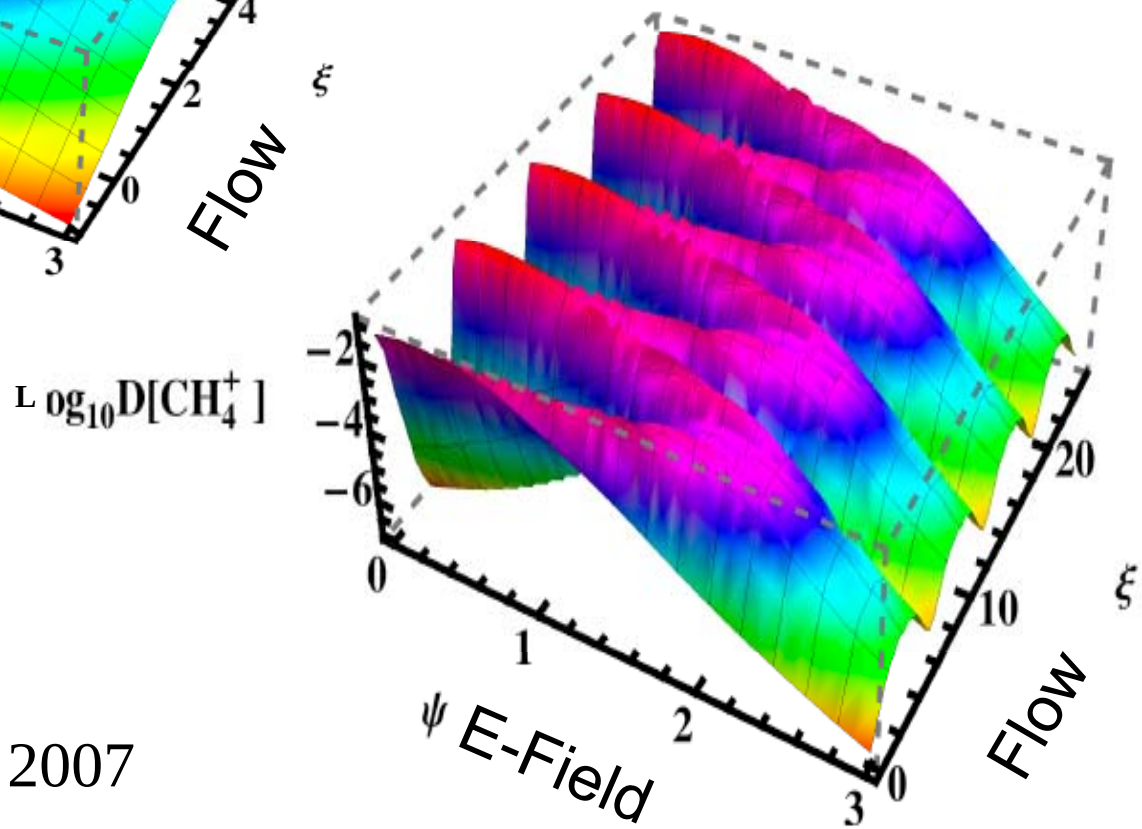
Model Computation for Lunar
He4+ Pickup Ion Flux
Hartle and Sittler, JGR, 2007



Model Computation for Lunar
He4+ Pickup Ion Flux
Hartle and Sittler, JGR, 2007

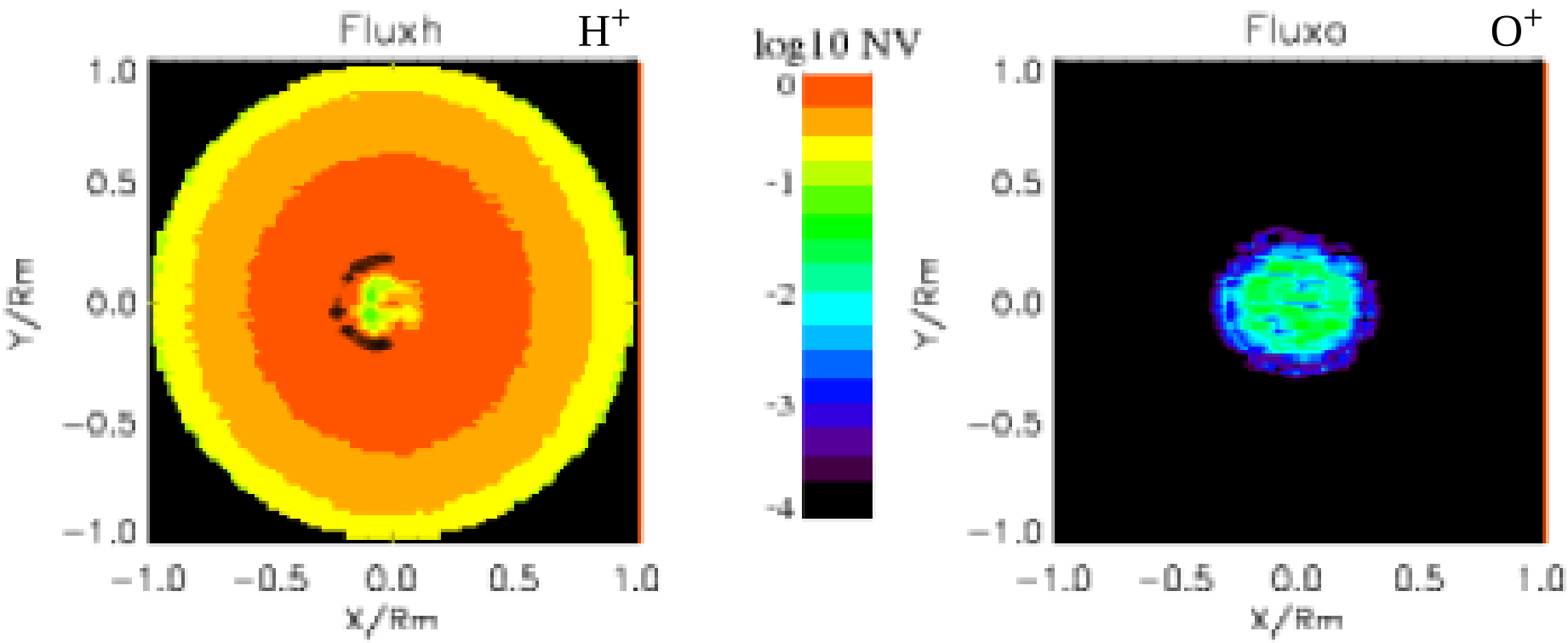
Titan Example for CH_4^+ Downstream PUI Cycloids - Similar for Moon





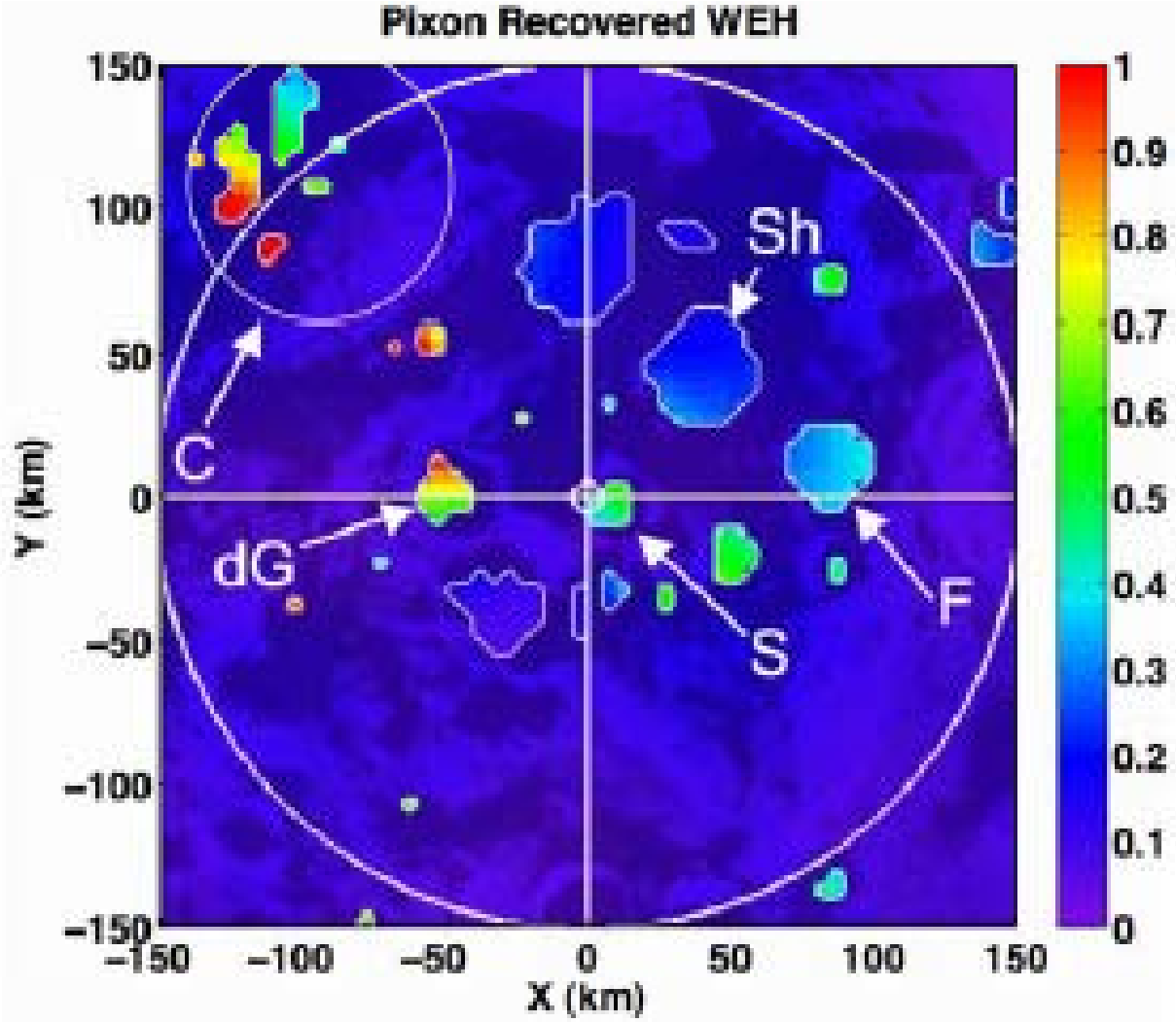
Hartle et al., Fall AGU, 2007

Simulation of Magnetic Anomaly Interaction for SW H^+ and PUI O^+



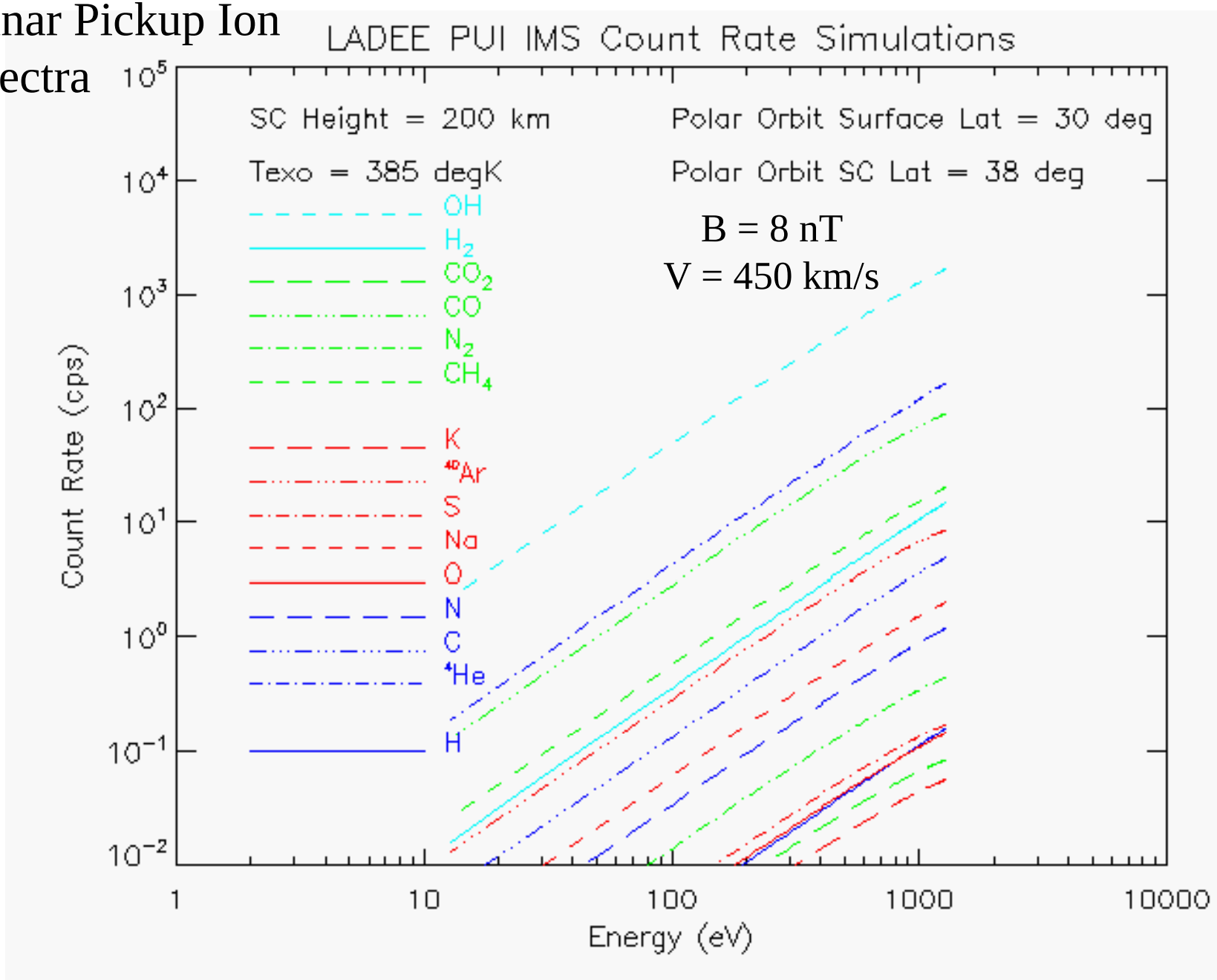
Dayside hemisphere distributions of surface fluxes for solar wind H^+ and atmospheric pickup O^+ ions incident on the Moon with simulated surface magnetic anomaly at the center. These X-Y views look in the +Z direction of bulk solar wind flow with the solar wind magnetic field in the +Y direction. The O^+ ions are swept by the solar wind into the moon in the central region around their points of origin, while H^+ ions impact the full sun-lit disk.

A. Lipatov (2007)



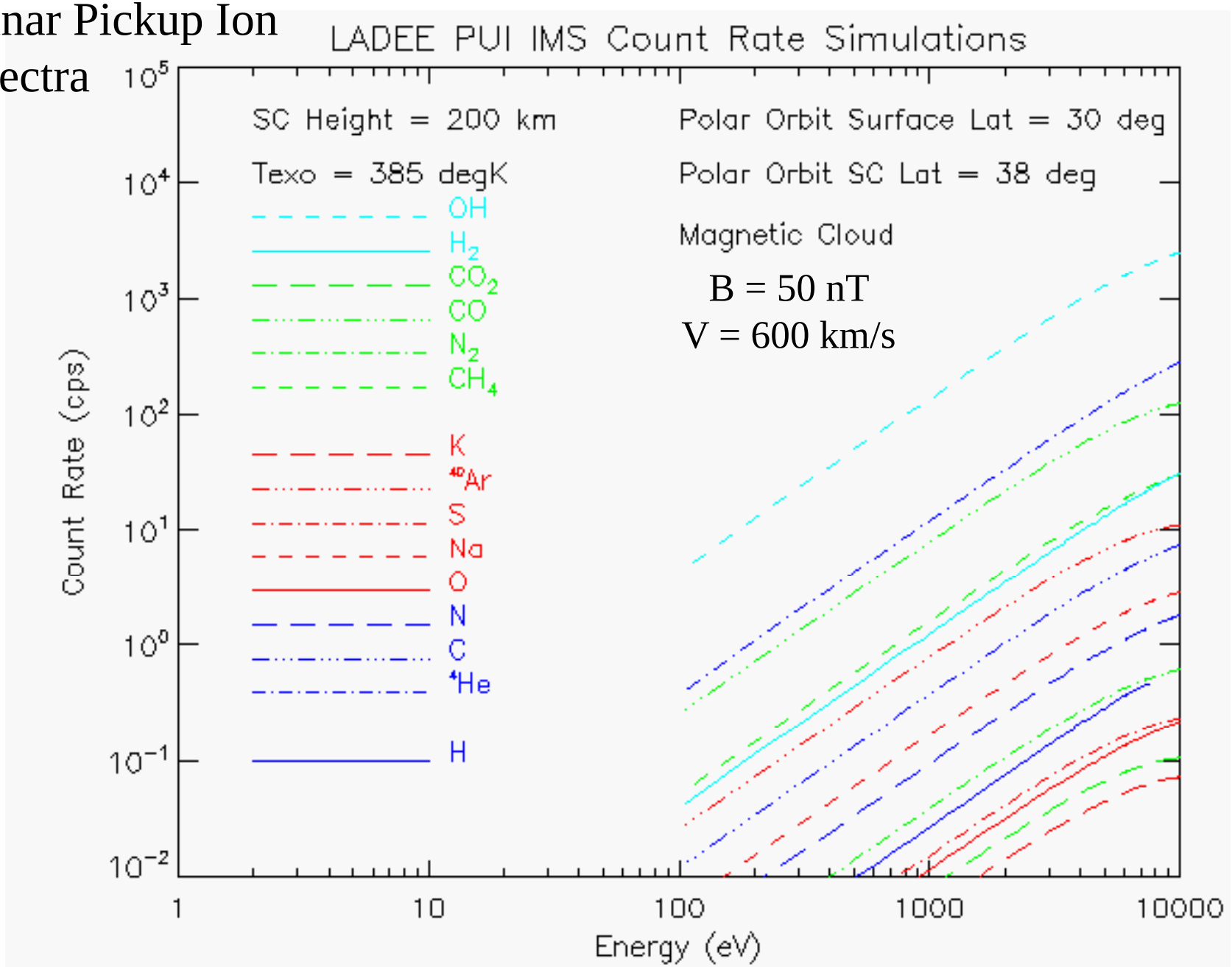
Water-equivalent hydrogen (WEH) in wt% corresponding to the Lunar Prospector epithermal neutron count rates (Elphic et al., 2007). Large circle denotes 85°S, and Shackleton crater (S), site of NASA's planned polar lunar base, is located nearly at the south pole.

Lunar Pickup Ion Spectra



Computed by E. C. Sittler Jr. based on abundances from R. Elphic

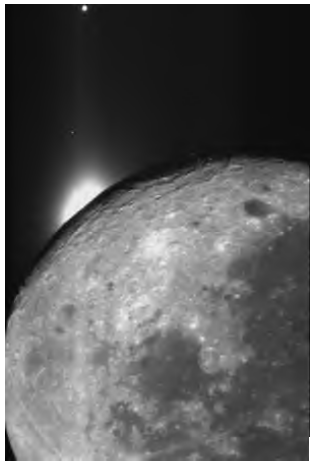
Lunar Pickup Ion Spectra



Computed by E. C. Sittler Jr. based on abundances from R. Elphic

Lunar Atmospheric Species	PUI Density /cc @ 1-Hz,1cm^2	Present Neutral Density Limits /cc [Stern 1999]
H	65	<17
He	336	2,000 (day)
C	164	<200
N	375	<600
O	321	<500
Na	17	70
S	167	<150
Ar	735	10^5 (day)
K	21	17
Xe	476	<3000
CH_4	11	10^4 (predawn)
N_2	140	800 (predawn)
CO	3.2	1,000 (predawn)
CO_2	115	1,000 (predawn)
H_2	7.6	<9,000
OH	6.3	$<10^6$

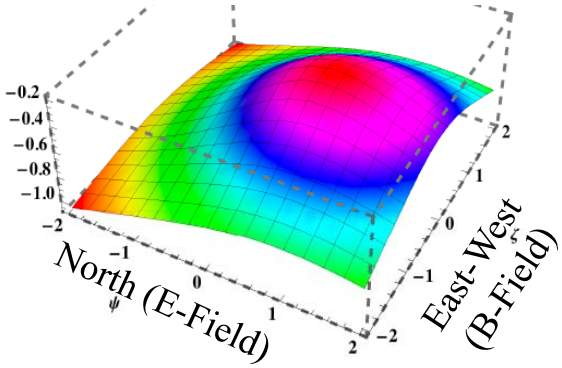
Lunar Surface Solar Origins Explorer (LunaSSOX)



Lunar Limb "Knife-Edge" for solar coronal occultation

Solar Wind Ion Implantation Injects Solar Coronal Composition Into the Lunar Surface and Solar Energetic Ions (SEP) Sputter Surface Atoms

Lunar He^+ Antisolar Pickup Ion Flux



Science Objectives:

- Upstream solar wind plasma ion contributions to lunar surface volatile composition via orbital measurements
- Global distribution of volatile and refractory surface composition via pickup ions from SEP ion sputtering
- Solar F-corona plasma composition & near-solar dust interaction via remote spectroscopic & doppler imaging

Associated Heliophysics RFAs:

F3. Understand role of plasma and neutral interactions in nonlinear coupling of solar system regions.

J4. Understand and characterize the space weather effects on and within planetary environments to minimize risk ..

Mission Implementation Description:

*Number of Spacecraft : 1 or more

*Location: lunar 50-km polar orbit, day-night orientation

*Attitude control: 3-axis stabilized (ram, nadir, solar)

* Instruments:

in situ low-energy ion-neutral and energetic heavy ion mass spectrometers , magnetometer (20 kg/20 W)

remote UV-VIS-IR spectroscopic imagers (30 kg/30 W)

Measurement Strategy:

- Lunar orbit for near-lunar plasma ion, gas, mag, SEP
- Lunar limb occultation from orbit for solar corona obs.

Enabling and Enhancing Technology Development:

- High resolution plasma and neutral gas composition spectrometers integrated to energetic ion detectors for complete characterization of plasma/SEP interactions
- Compact steerable high-resolution UV-VIS-IR spectroscopic imaging system for solar F-Corona, lunar surface & atmosphere, and other geospace observations – not diffraction limited by s/c occulter !
- Lightweight solar-powered spacecraft bus system for flexible lunar orbital and solar observation operations

John F. Cooper, Richard E. Hartle, Edward C. Sittler
NASA Goddard Space Flight Center, Greenbelt, Maryland
Contact: John.F.Cooper@nasa.gov (phone: 301-286-1193)

"Inner Source" Pickup Ions – Solar Dust Interaction at 10 – 50 R_{sun} ?

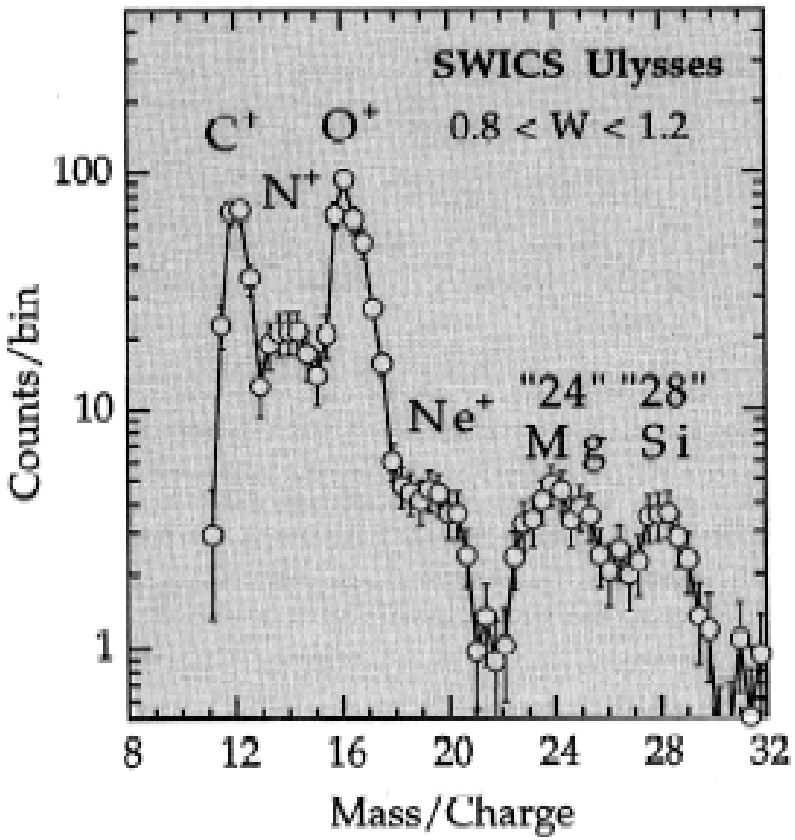


Figure 2. Mass per charge distributions of heavy pickup ions in the inner source. These data were taken over the same time period as in Figure 1. A five-point running average of counts in mass/charge bins > 17 was used to smooth the data. Peaks at mass/charge 24 and 28 are clearly visible, indicating the presence of singly charged Mg and Si (as well as C, N, O, and Ne) in the inner source.

Table 1. Element Abundance Ratios (Relative to Ne) of the Inner Source Pickup Ions, the Low Solar Wind, and Energetic Particles Accelerated in CIRs

Element	Inner Source[a]	Solar Wind[b]	CIR Particles[c]
H	7710±1560[d]	12000±5100	33100±10500
He	---------	900±260	1000±88
C	4.57±0.38	8.1±1.1	4.88±0.25
N	1.24±0.16	1.5±0.2	0.91±0.12
O	3.13±0.18	11.4±0.9	6.25±0.31
Ne	1.00±0.17	1.00±0.10	1.00±0.13
Mg	1.52±0.19	1.40±0.28	0.70±0.09
Si	0.99±0.18	1.36±0.17	0.70±0.19

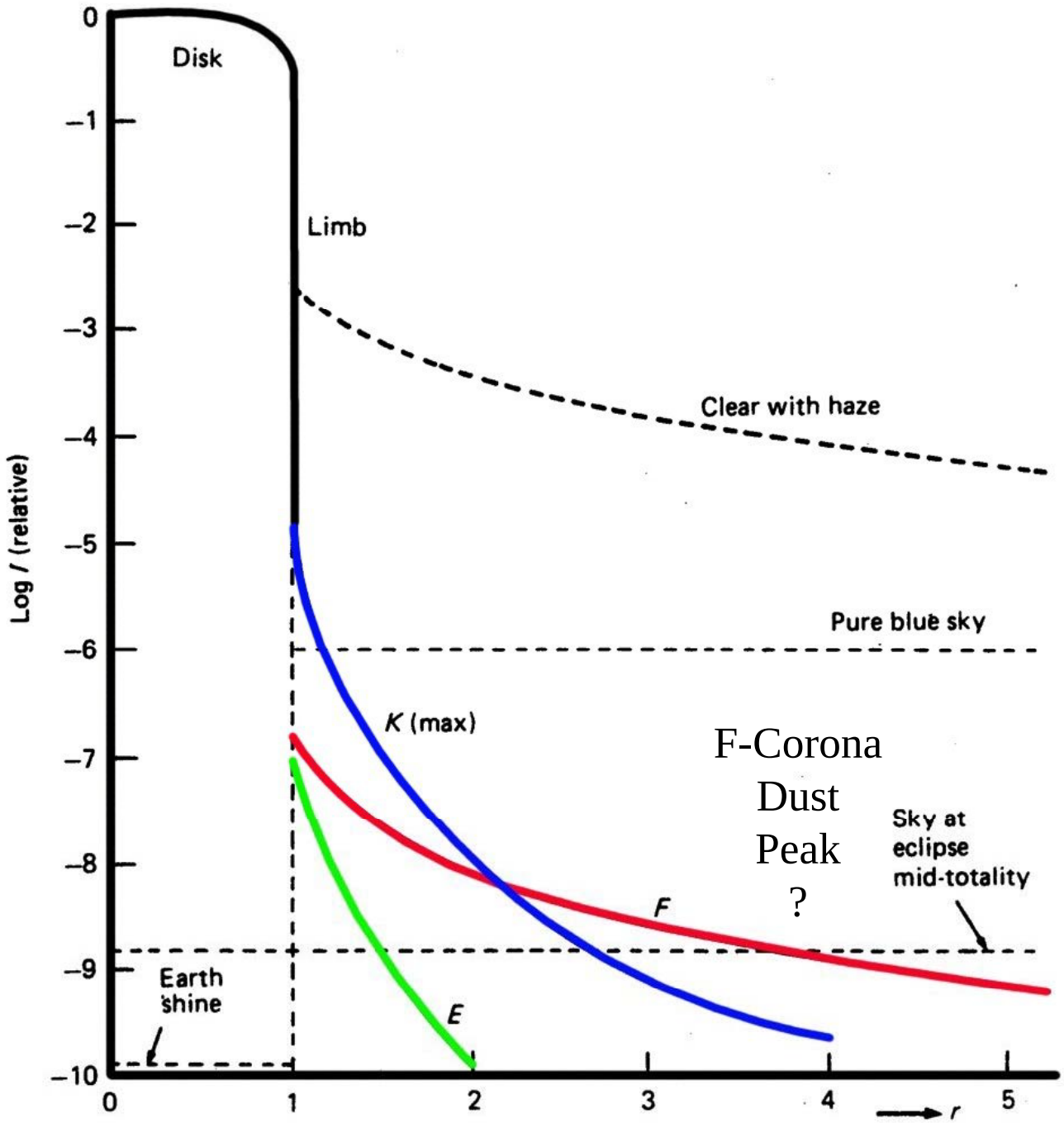
[a]Pickup ions from the low and middle latitude (< 60°) extended inner source (present work).

[b]Average of the fast and slow solar wind abundances compiled by *von Steiger et al.* [1997]. The solar wind Ne abundance we derived from SWICS data using a sophisticated composition analysis developed by N. A. Schwadron et al. (Techniques for analysis of data from time-of-flight instruments, submitted to *Journal of Geophysical Research*, 1999b).

[c]Compiled by *Keppler* [1998].

[d]Errors are due to statistical uncertainties only.

Near-solar plasma-dust PUI inner source contributes to lunar surface composition.


Disk
Limb
Clear with haze
Pure blue sky
K (max)
F
E
Earth shine
Sky at eclipse mid-totality
F-Corona
Dust
Peak
?
Log I (relative)
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
0
1
2
3
4
5
r

Apparent dust peaks at 4 R_{sun} were seen at some wavelengths (e.g., near IR) in 1966-67 to 1983 but not thereafter (Mann et al., 2004) – solar cycle effects?

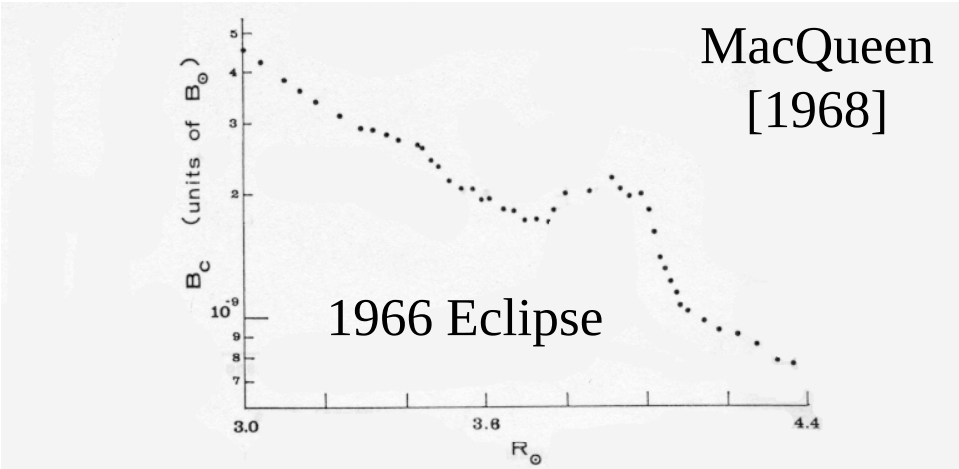


FIG. 5.—Radiance of the thermal-emission features observed during the period of totality, November 12, 1966. Plotted points are from two scans made in the ecliptic plane.

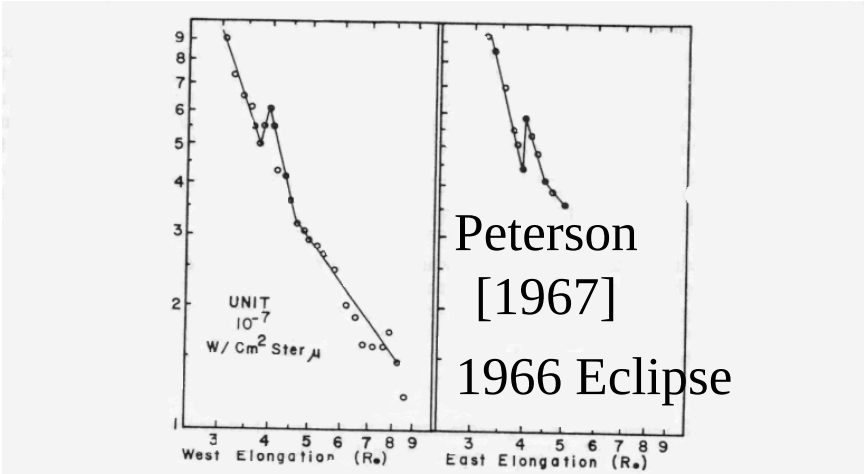


FIG. 1.—The absolute brightness of the outer corona at 2.2 μ showing the thermal radiation peaks at 4 $R_\odot$. Cloud interference is visible to the west of the Sun beyond 5 $R_\odot$. The recorder failed to ink to the east beyond 5 $R_\odot$.

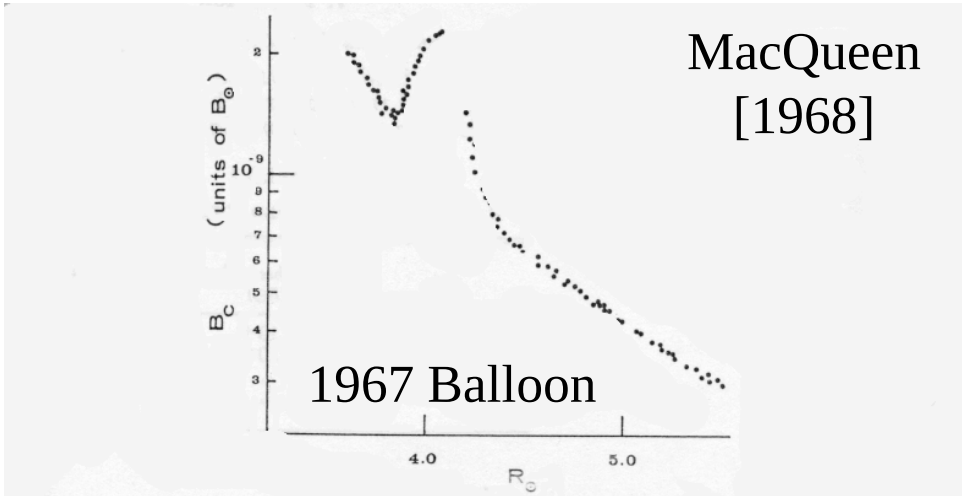


FIG. 6.—Radiance of the thermal-emission feature at 4 $R_\odot$ observed during the balloon flight of January 9, 1967. Plotted points are the results of eighteen scans and are normalized at 4.8 $R_\odot$. Units of the ordinate are those of the radiance of the mean solar disk at wavelength 2.2 μ.

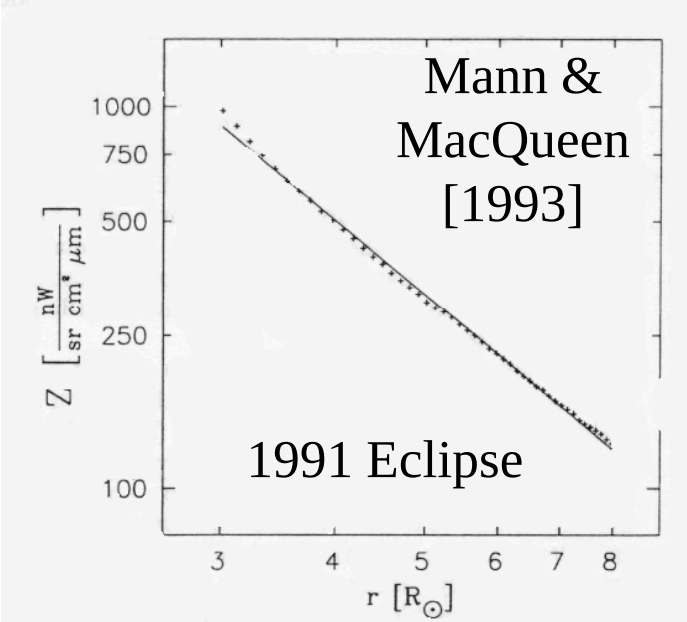
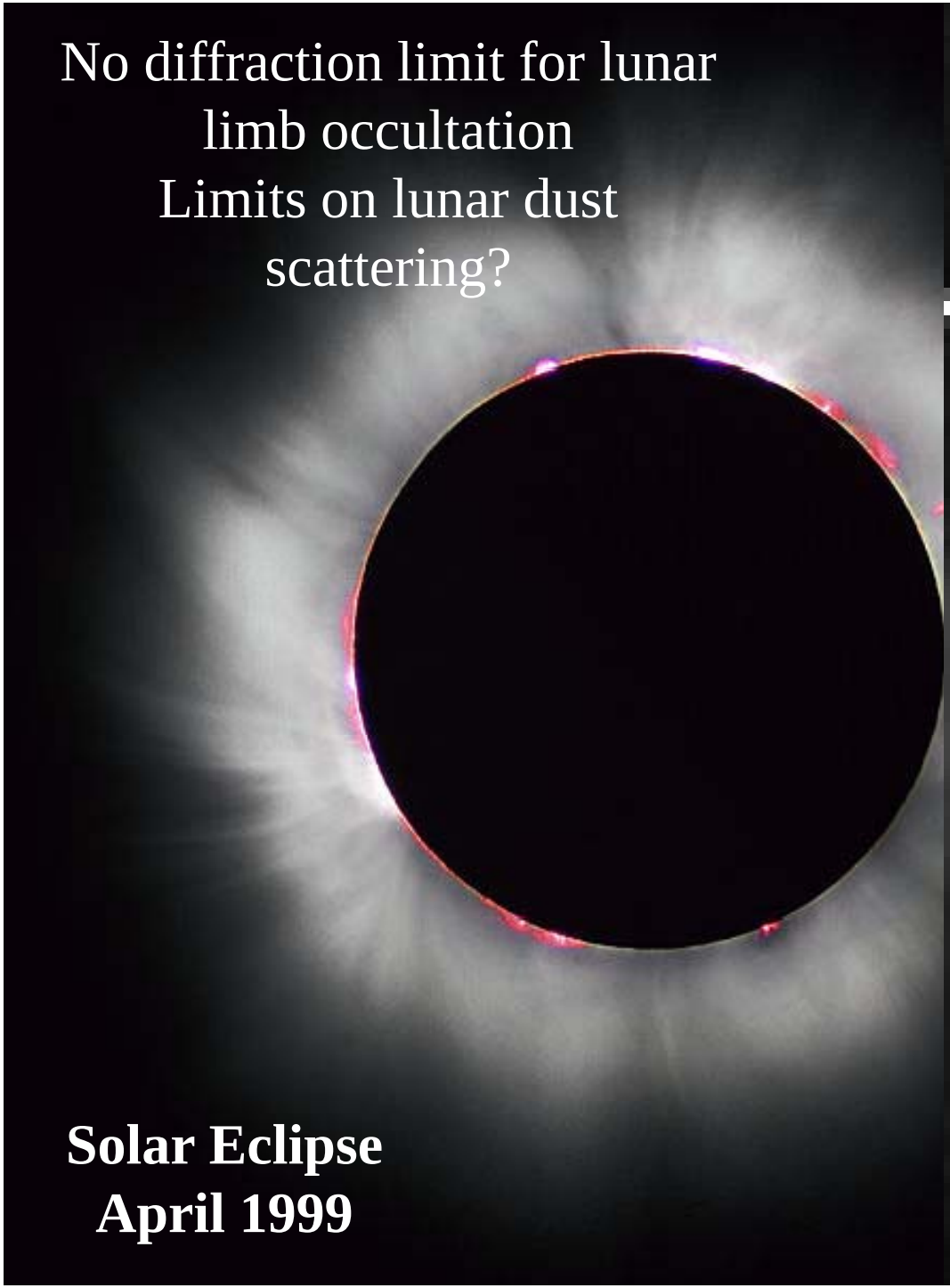
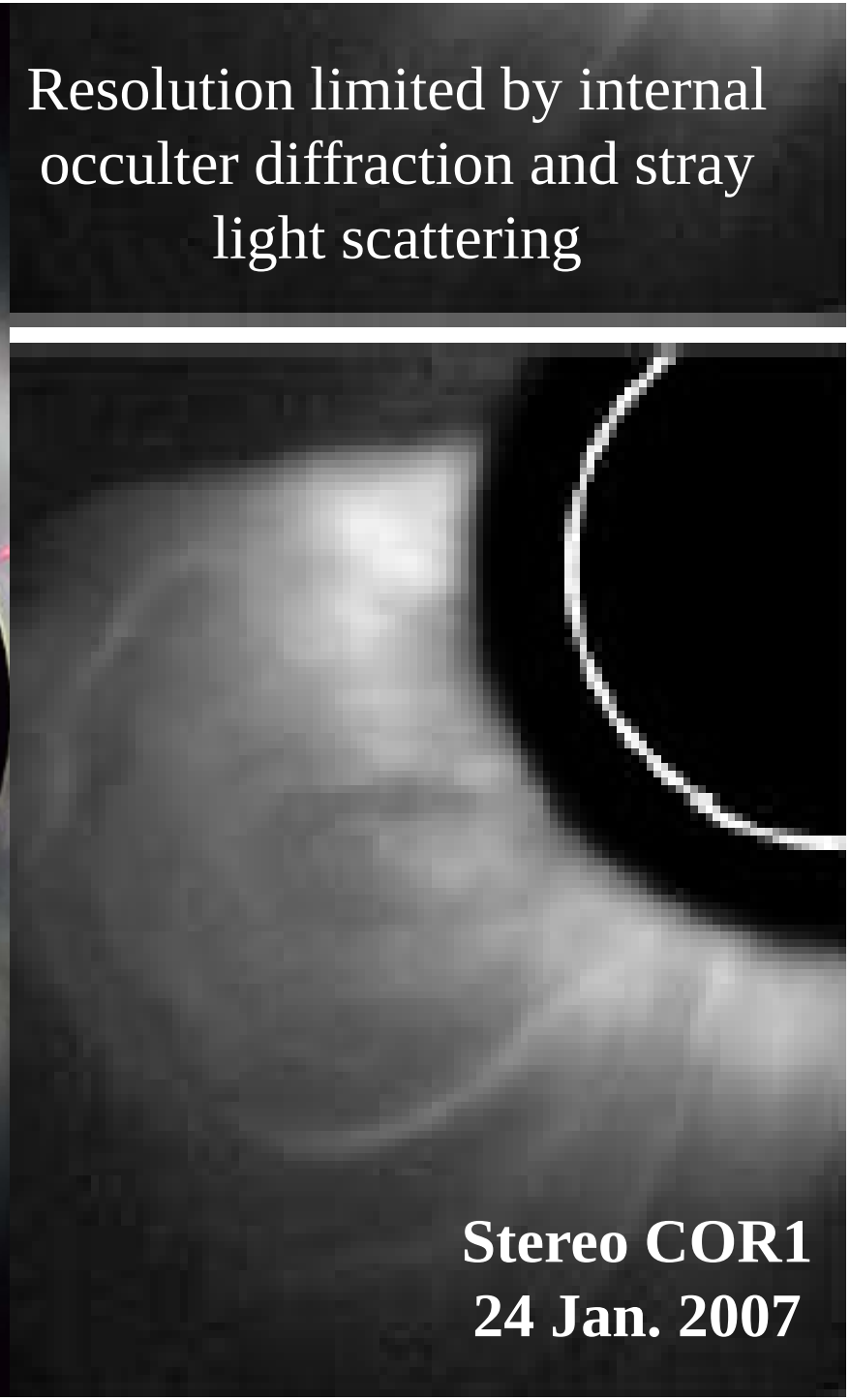
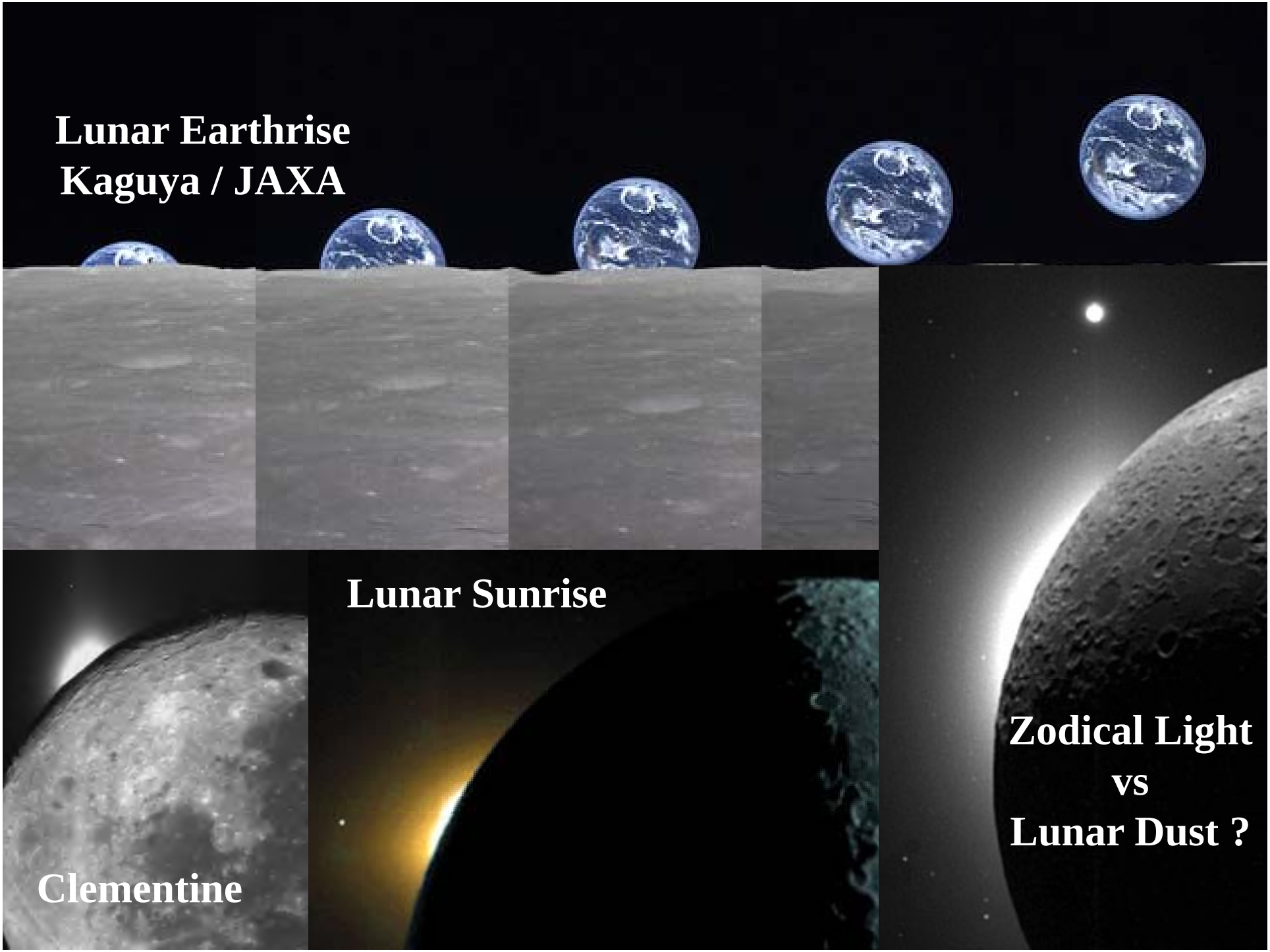


Fig. 1. Derived F-corona brightness at $\lambda = 2.12$ μm and fit with a radial power law


No diffraction limit for lunar limb occultation
Limits on lunar dust scattering?
Solar Eclipse
April 1999


Resolution limited by internal occulter diffraction and stray light scattering
Stereo COR1
24 Jan. 2007


Lunar Earthrise
Kaguya / JAXA
Lunar Sunrise
Clementine
Zodical Light
vs
Lunar Dust ?

Conclusions

- Solar wind interaction imparts exogenic source of volatile and some refractory mass flow from Sun to Moon surface
- Direct primary plasma & SEP ion measurements, coupled to those of sputtered pickup ions, support global mapping of exogenic and endogenic components of lunar surface composition
- Orbiter hourly lunar limb occultation of solar disk from LRO-type orbit would allow frequent periodic measurements of near-solar plasma-dust dynamics and composition in the “Inner Source” region contributing pickup ions to solar wind bombardment of the lunar surface. Lunar dust foreground effect needs more study.
- The Moon can be an integral part of the Heliophysics Global Observatory for solar and geospace observations