The lunar surface: A dusty plasma laboratory

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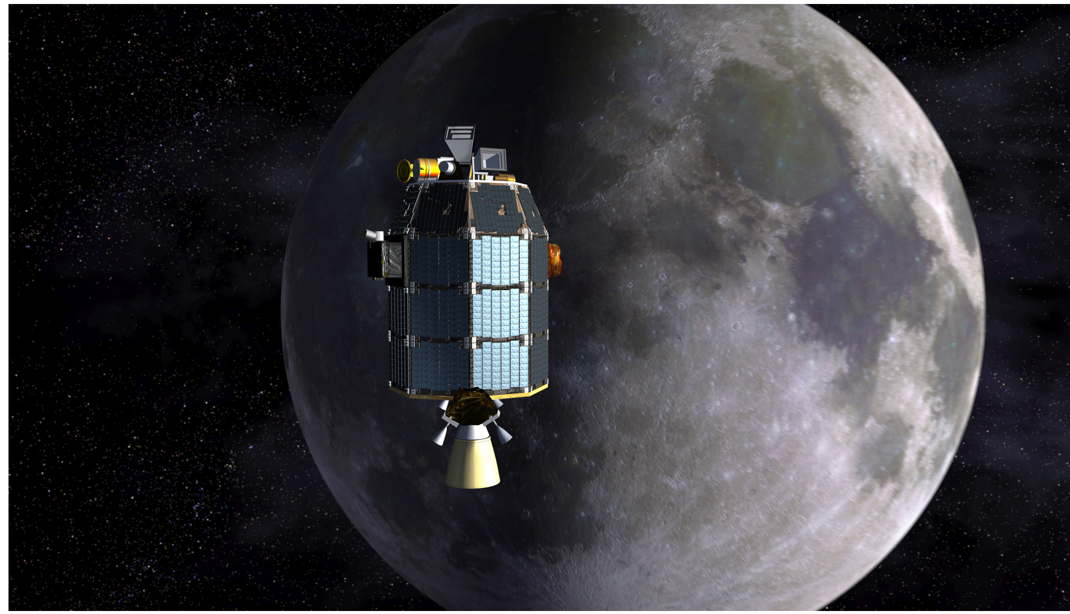


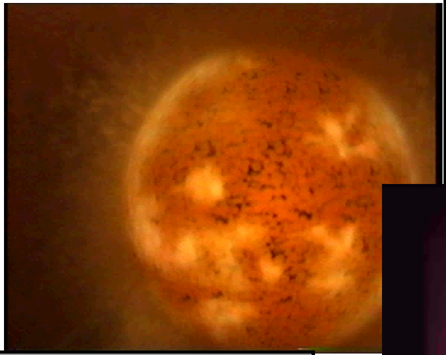
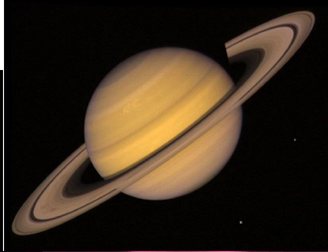
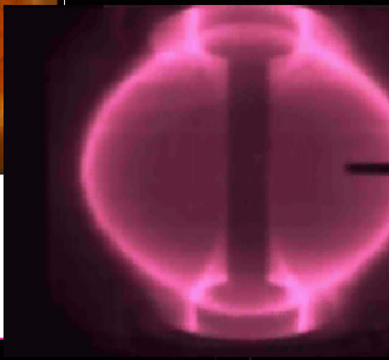
Outline:

1) Motivation
2) Dusty plasma primer
3) Dusty plasmas on the surfaces of airless bodies
4) Lunar Dust Experiment (LDEX) onboard the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission.

Where do we find plasmas?

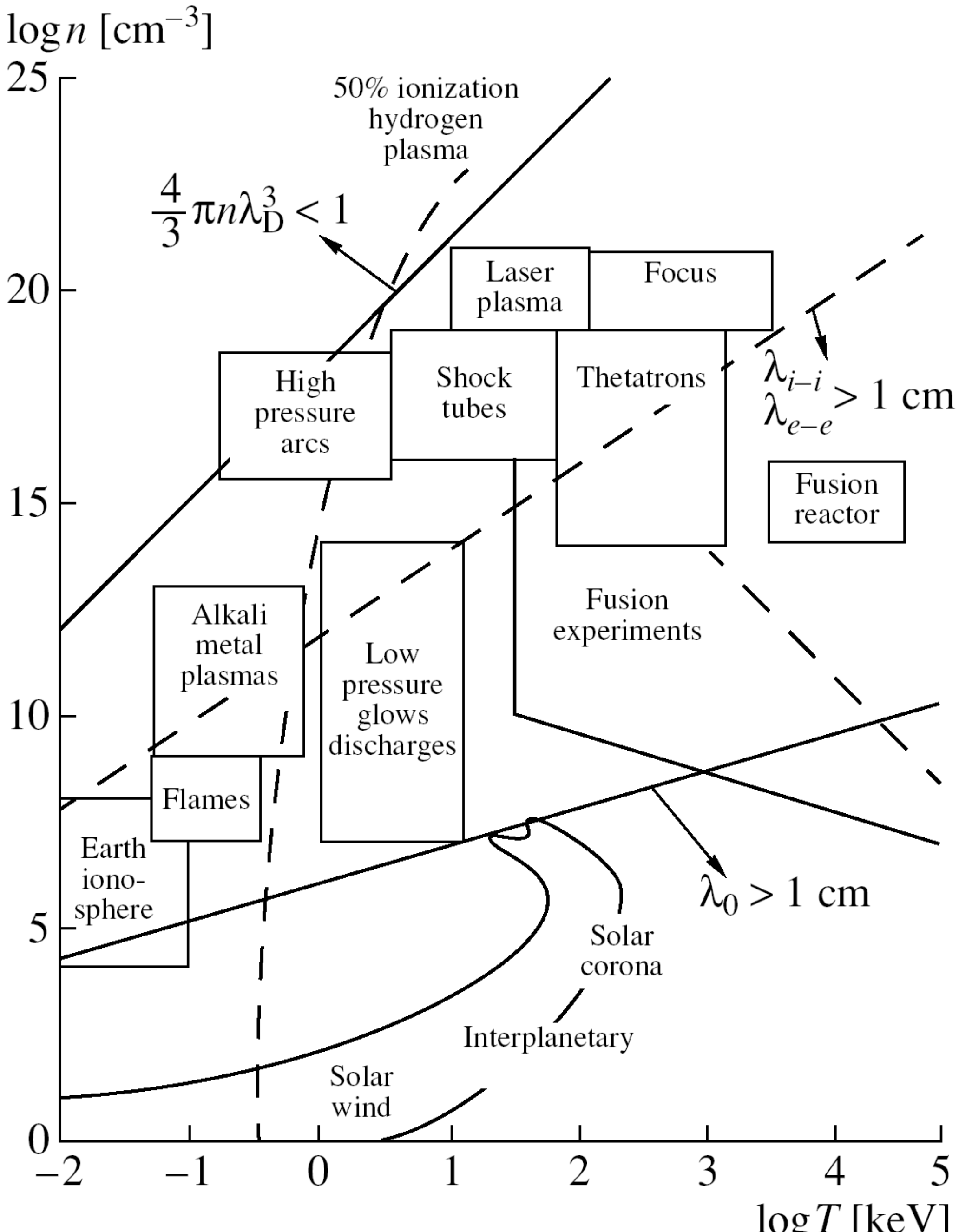
- 99% of the visible matter in the universe is ´plasma´.
- A large fraction of this plasma is ´dusty´:

Galaxies, interstellar clouds, star formation regions, planetary disks, comets, our atmosphere, planetary rings, all plasma processing devices, even plasma fusion reactors, etc.

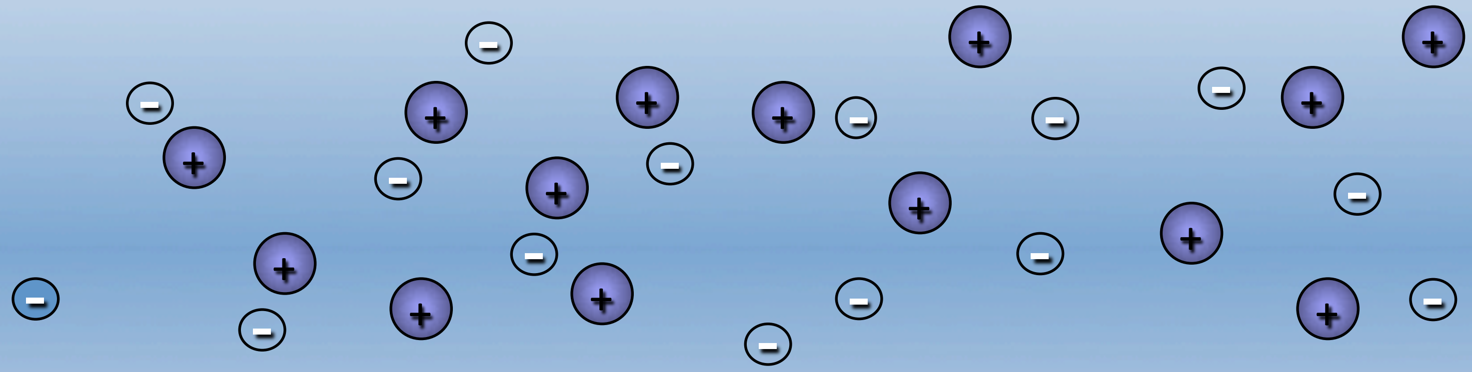






log n [cm^−3]
25
20
15
10
5
0
−2
−1
0
1
2
3
4
5
log T [keV]
50% ionization
hydrogen
plasma
$\frac{4}{3}\pi n\lambda_D^3 < 1$
Laser
plasma
Focus
High
pressure
arcs
Shock
tubes
Thetatrons
λ_{i-i}
$\lambda_{e-e} > 1$ cm
Fusion
reactor
Fusion
experiments
Alkali
metal
plasmas
Low
pressure
glows
discharges
Flames
Earth
iono-
sphere
$\lambda_0 > 1$ cm
Solar
corona
Interplanetary
Solar
wind

- Plasmas - Encyclopaedia Britannica:

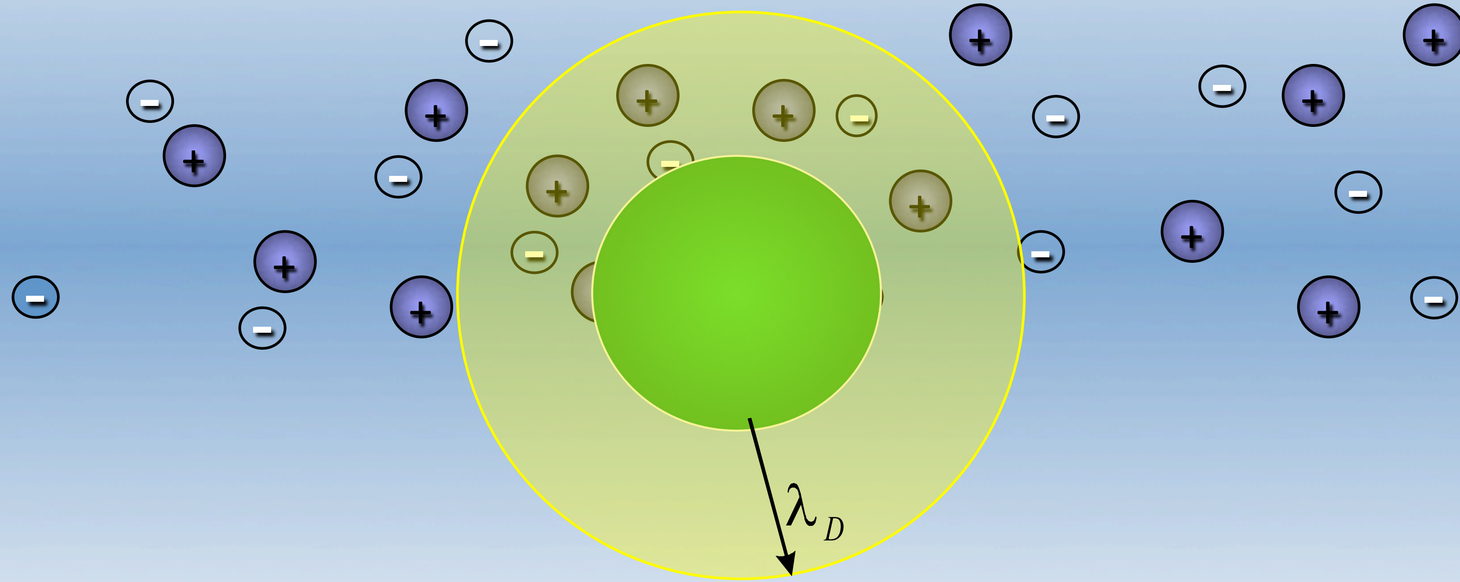
- A collection of positive and negative charges, about equal in number or density and forming a neutrally charged distribution of matter.



- Plasma state is called the fourth state of matter and is unique in the way in which it interacts with itself, with electric and magnetic fields, and with its environment.

- Dusty Plasmas

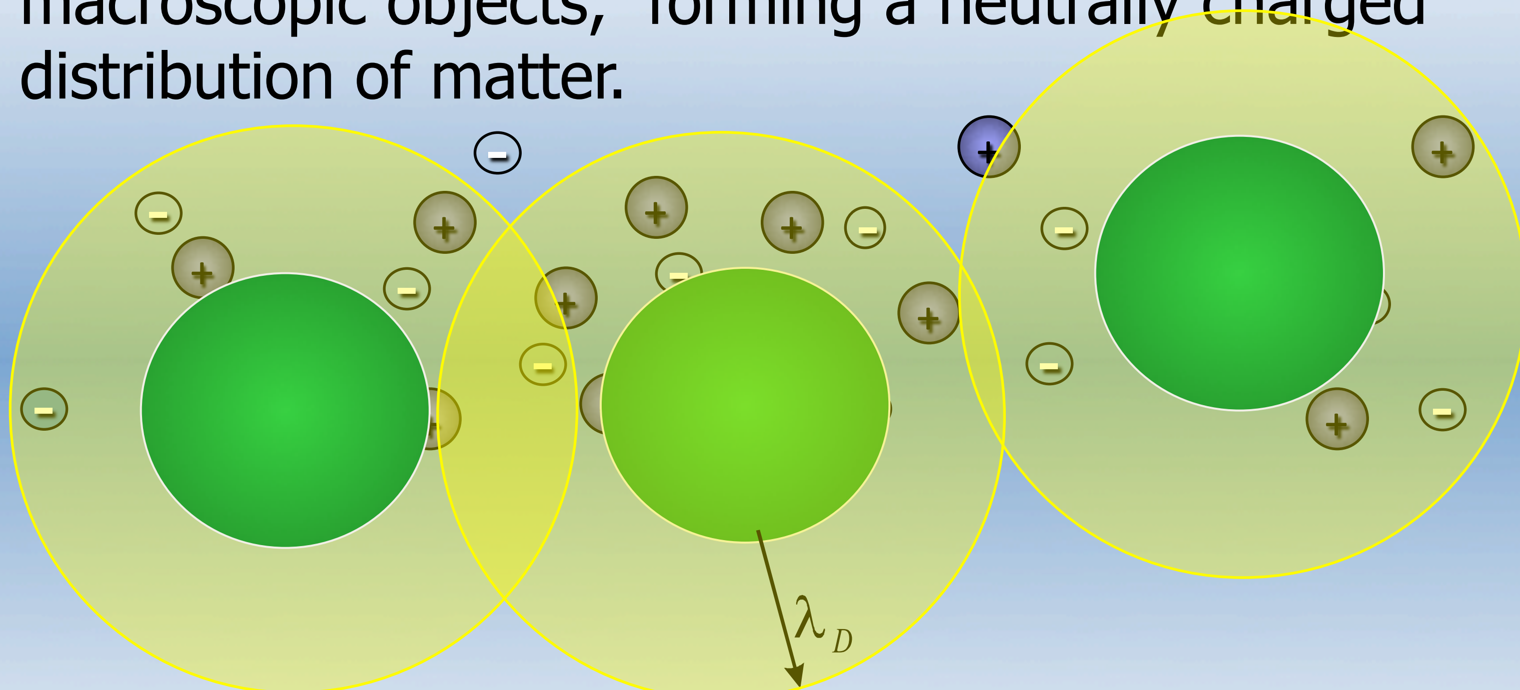
- A collection of positive and negative charges, and macroscopic objects, forming a neutrally charged distribution of matter.



Small particles absorb electron and ions and become charged

- Dusty Plasmas

- A collection of positive and negative charges, and macroscopic objects, forming a neutrally charged distribution of matter.



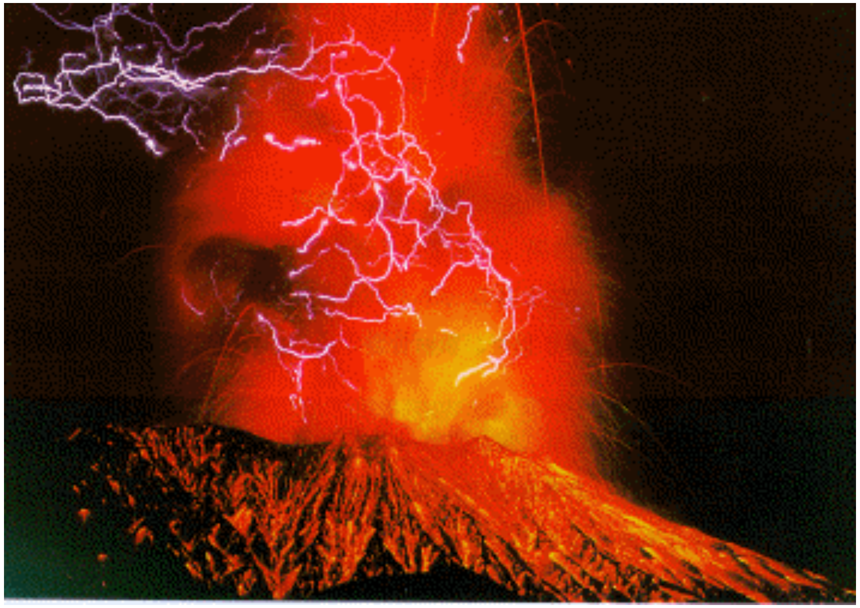
Small particles absorb electron and ions and become charged

Types of Dusty Plasmas:

$e, i_1, i_2, \ldots\ldots i_n$ and dust$^+$/dust$^-$ (comets, rings)

e and dust$^+$ (moon, asteroid surface)

dust$^+$ and dust$^-$ (sand storms)



New physics:

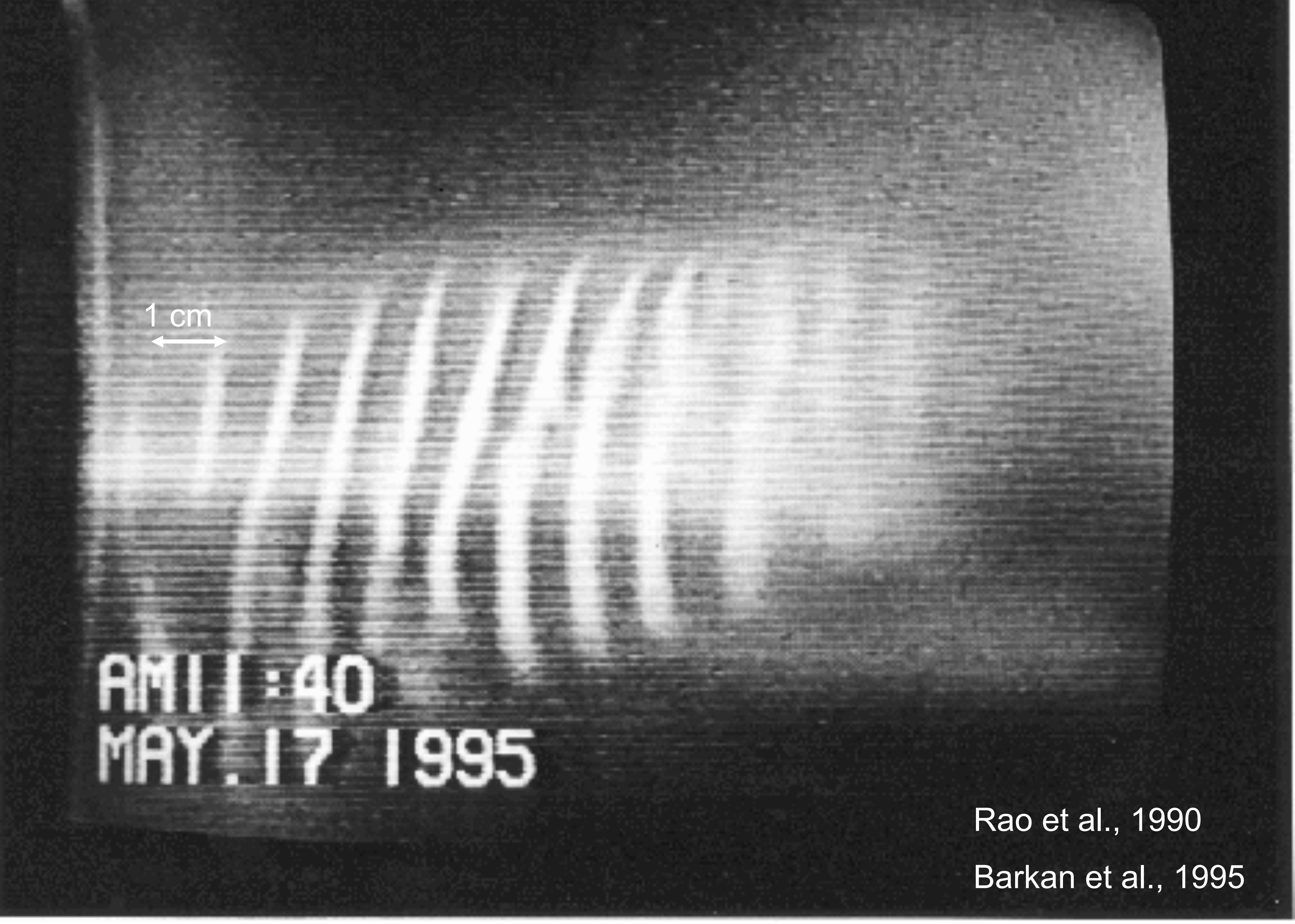
Dust is many orders of magnitude heavier than ions and can carry many orders of magnitude larger + or - time dependent charge.

- new spatial scales
- new time scales
- unusual dynamics
- new waves & instabilities

Dust charge:

- electron and ion fluxes
- secondary and photoelectrons
- dust – dust collisions

Dust - acoustic wave



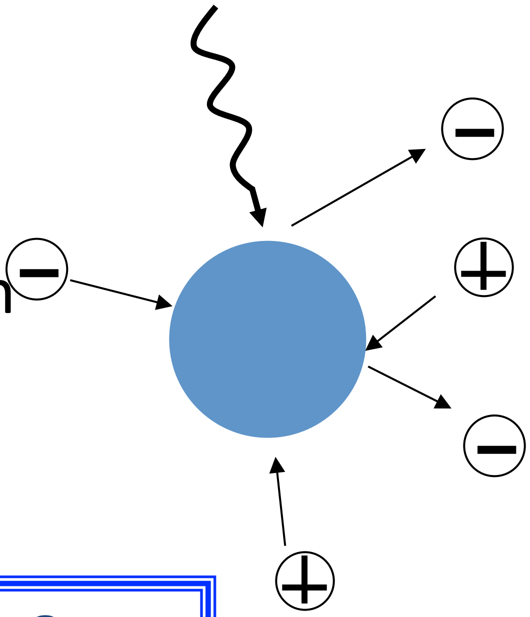
Rao et al., 1990

Barkan et al., 1995

2) Dusty plasma primer

Dust Charging Processes

- electron and ion collection
- secondary emission
- UV induced photoelectron emission
- ....



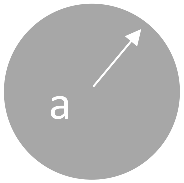
Total current to a grain = 0

$$\Sigma I = I_e + I_i + I_{sec} + I_{pe} = 0$$

The Charge on a Dust Grain

In typical lab plasmas $I_{sec} = I_{pe} = 0$

Electron thermal speed >> ion thermal speed so the grains charge to a negative potential V_S relative to the plasma, until the condition $I_e = I_i$ is achieved.



$$I_e = e n_e \sqrt{\frac{kT_e}{m_e}} \exp\left(\frac{eV_S}{kT_e}\right) \pi a^2$$

electron repulsion

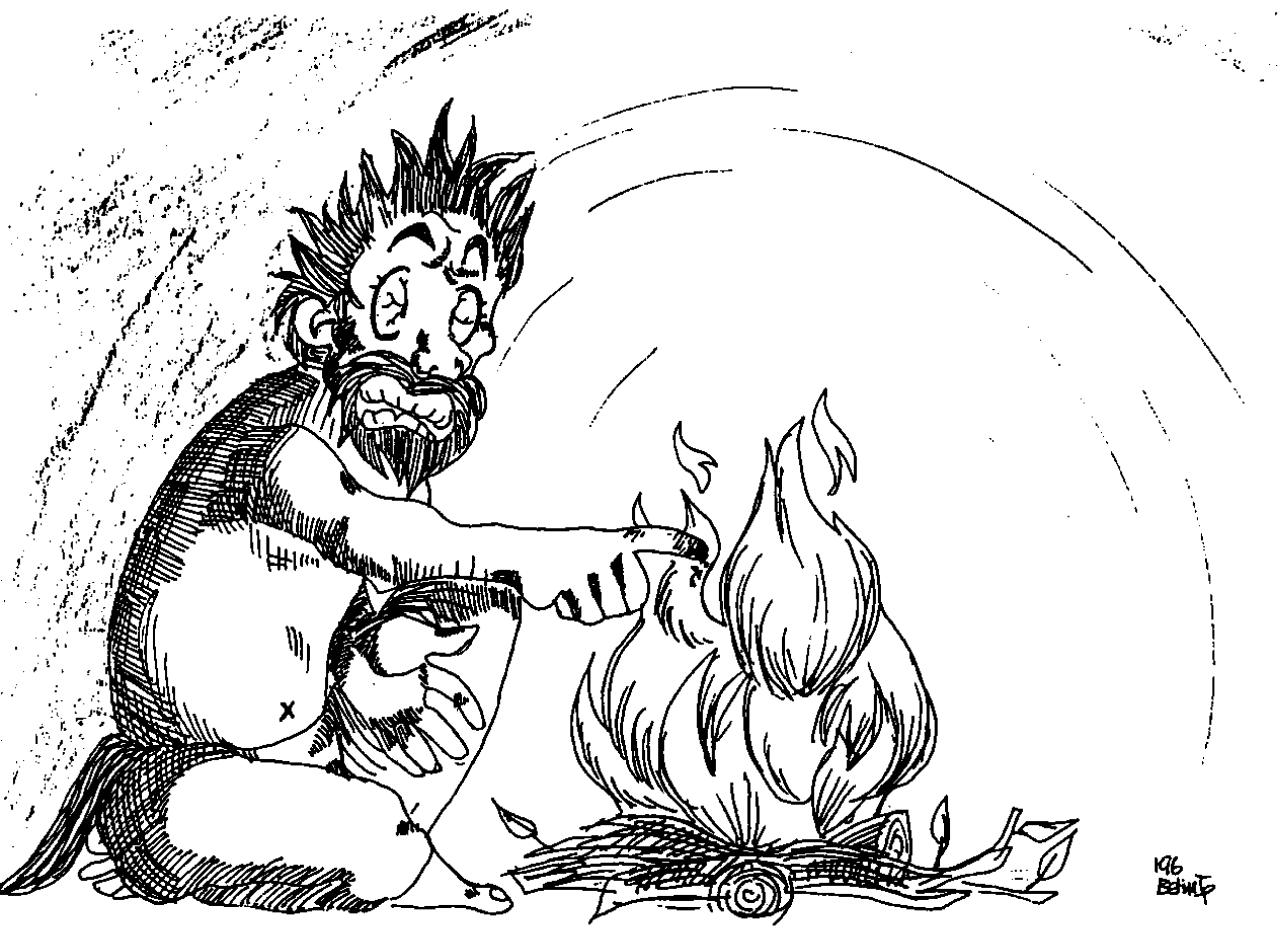
$$I_i = e n_i \sqrt{\frac{kT_i}{m_i}} \left(1 - \frac{eV_S}{kT_i}\right) \pi a^2$$

ion enhancement

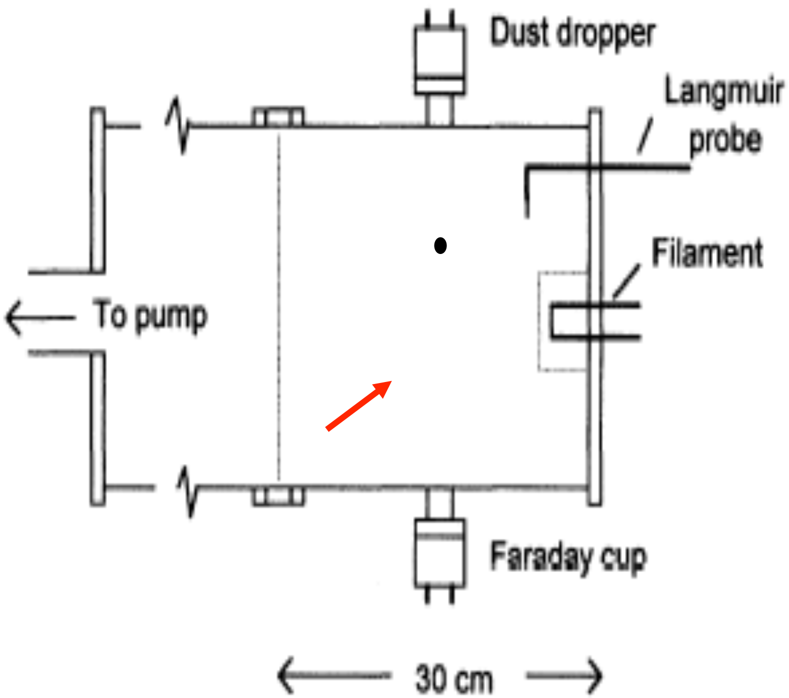
$Q = (4\pi\varepsilon_o a)\ V_S$

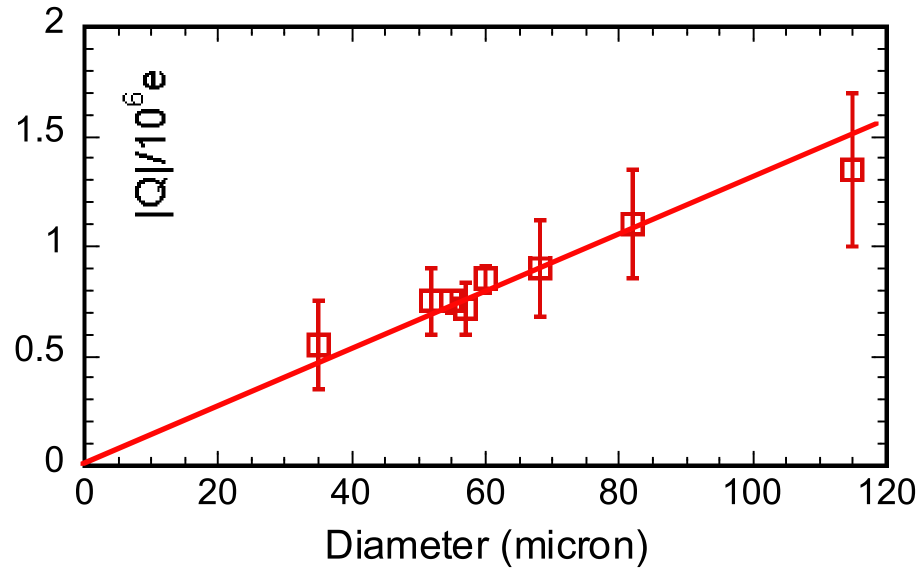
$Q_e = 700\ a_\mu V_S$

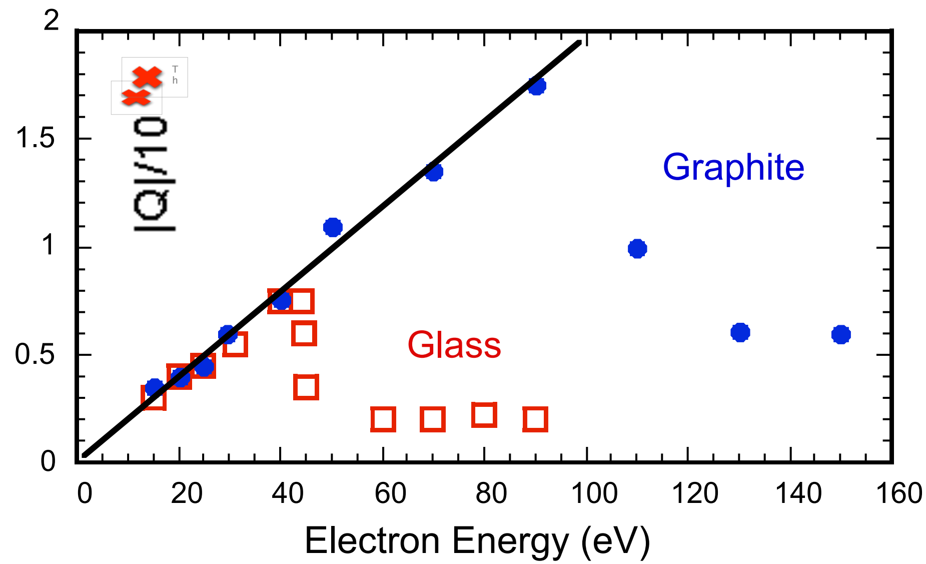
Typically V_S is independent of a



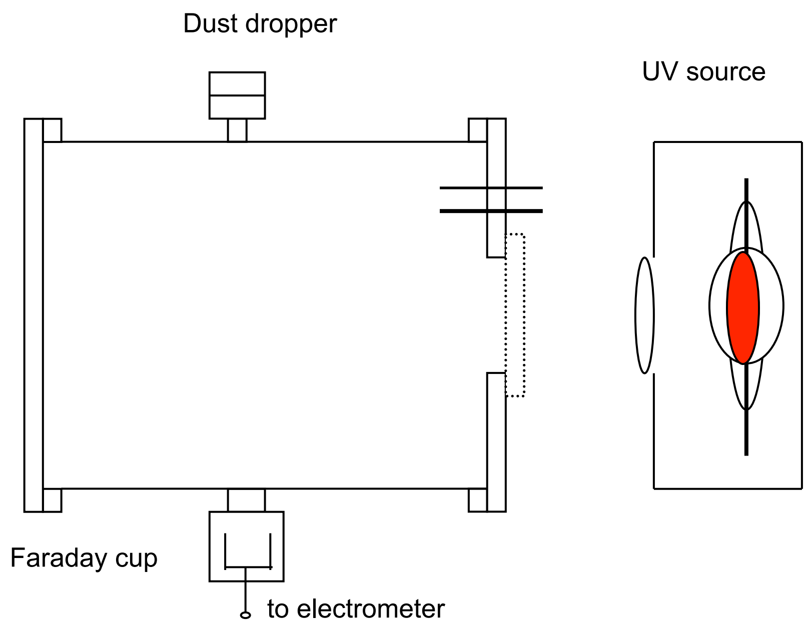
Dust Charge Measurements

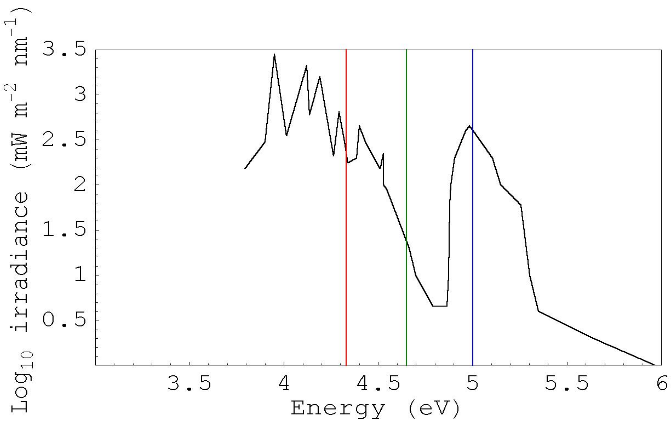




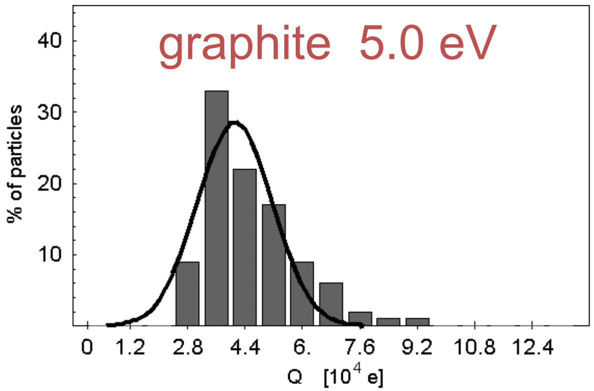


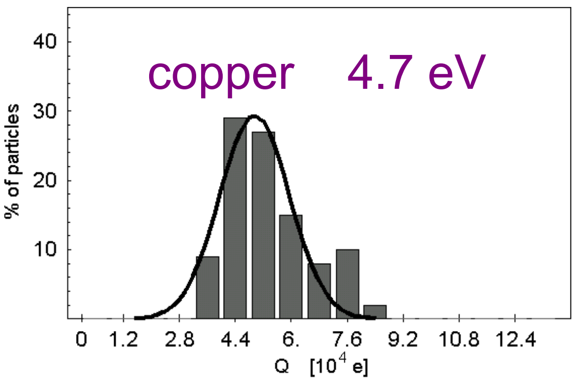
UV charging (I)

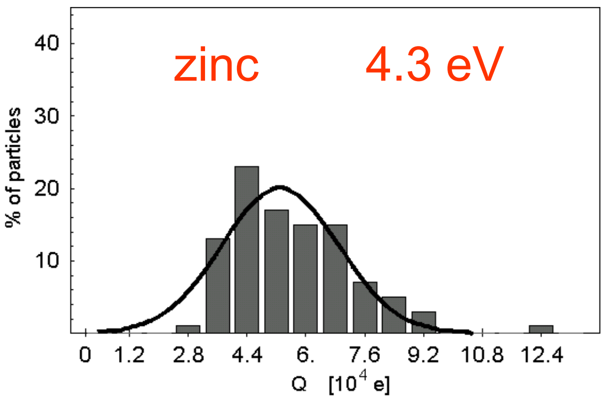




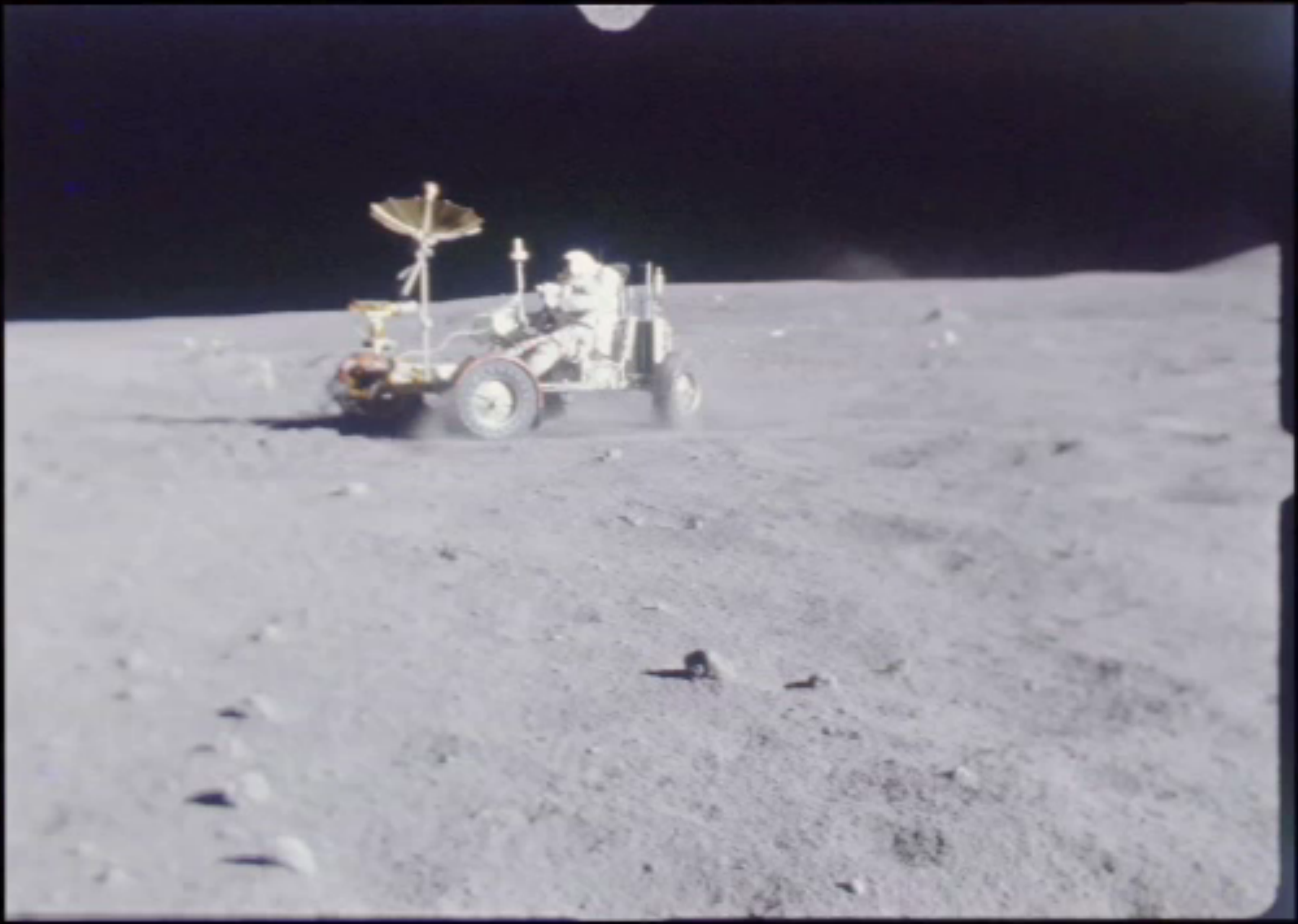
Spectral irradiance curve at 0.5 m for the 1kW Hg-Xe arc lamp.



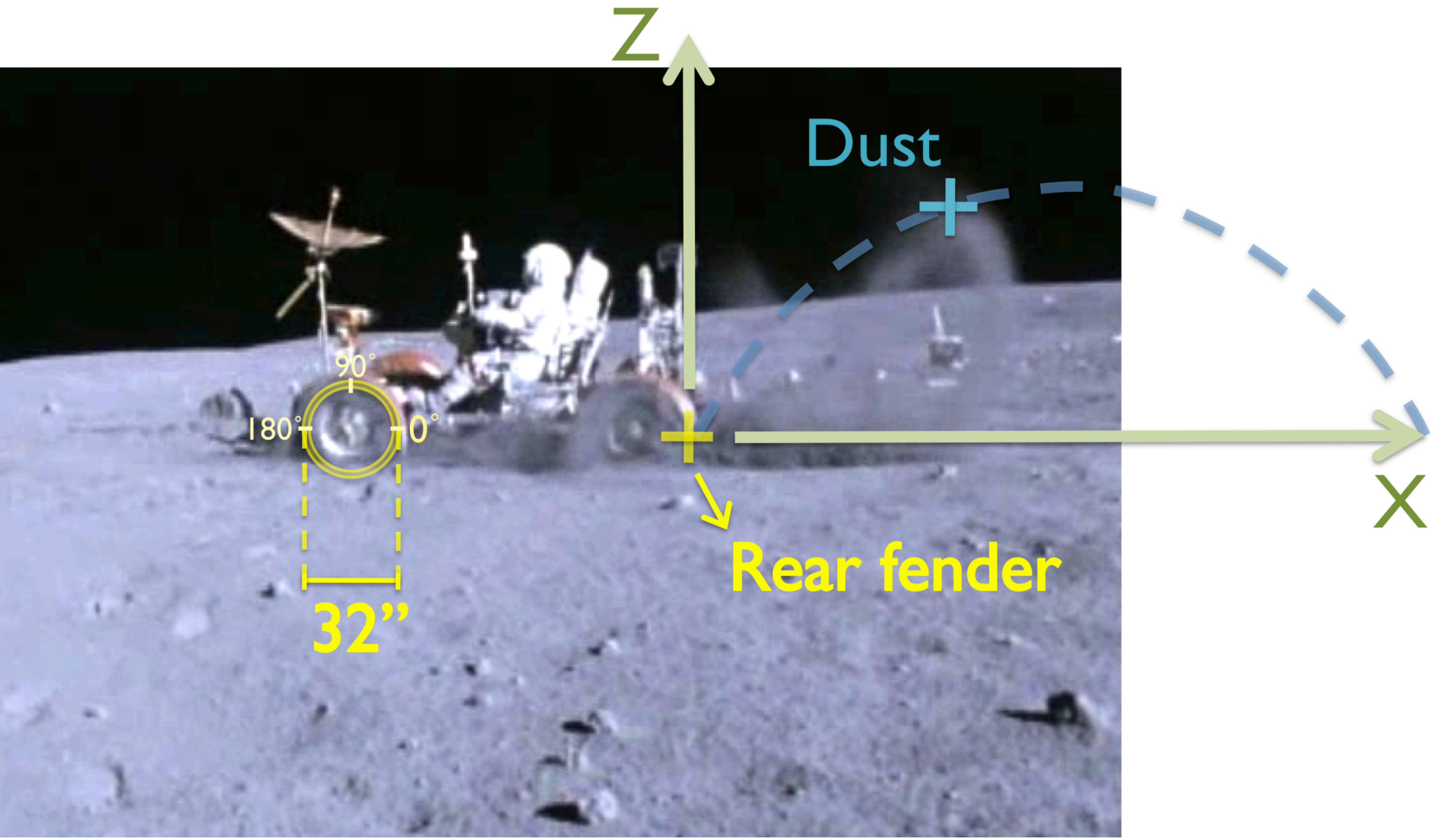




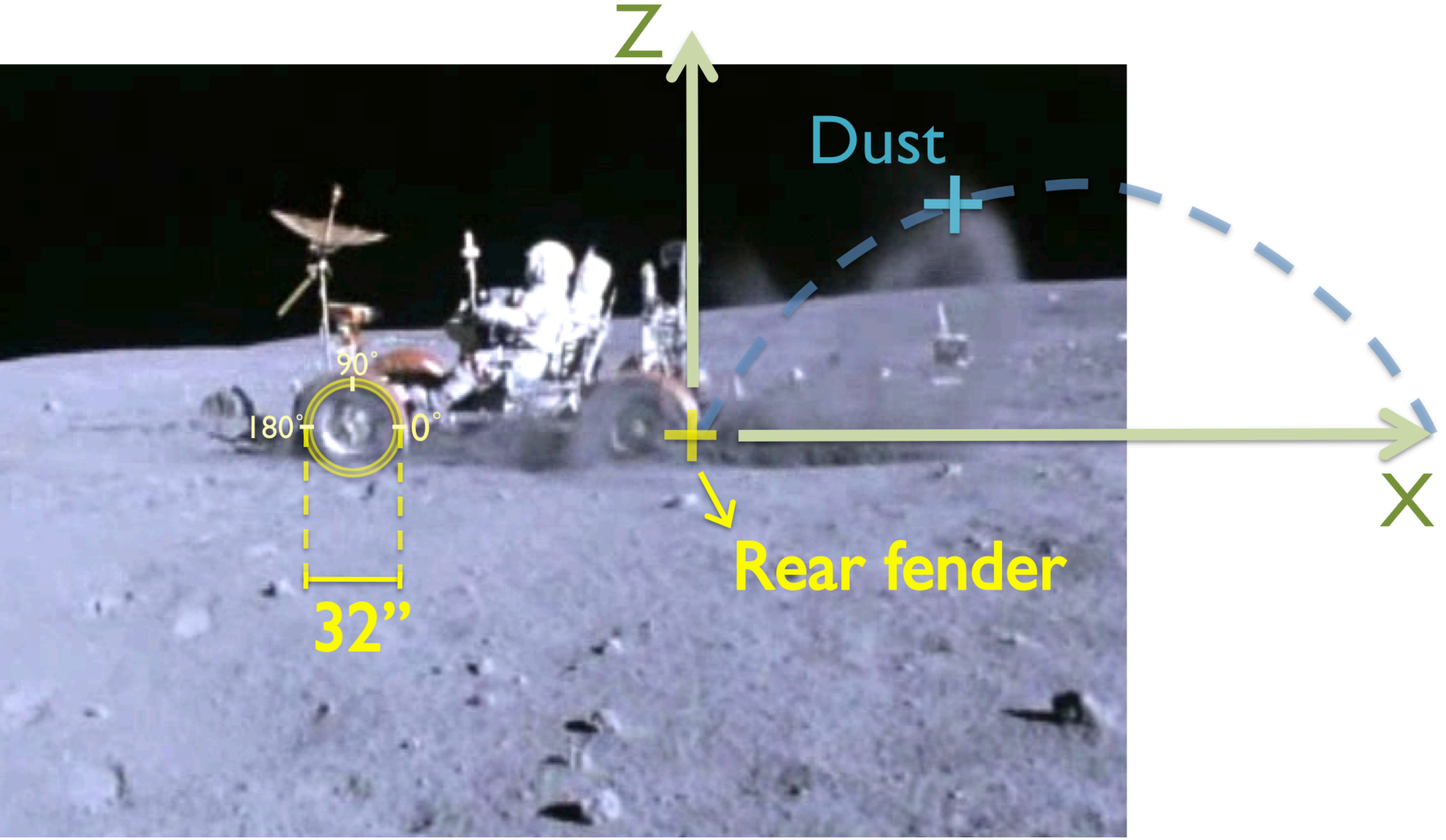
3) Dusty plasmas on the surfaces



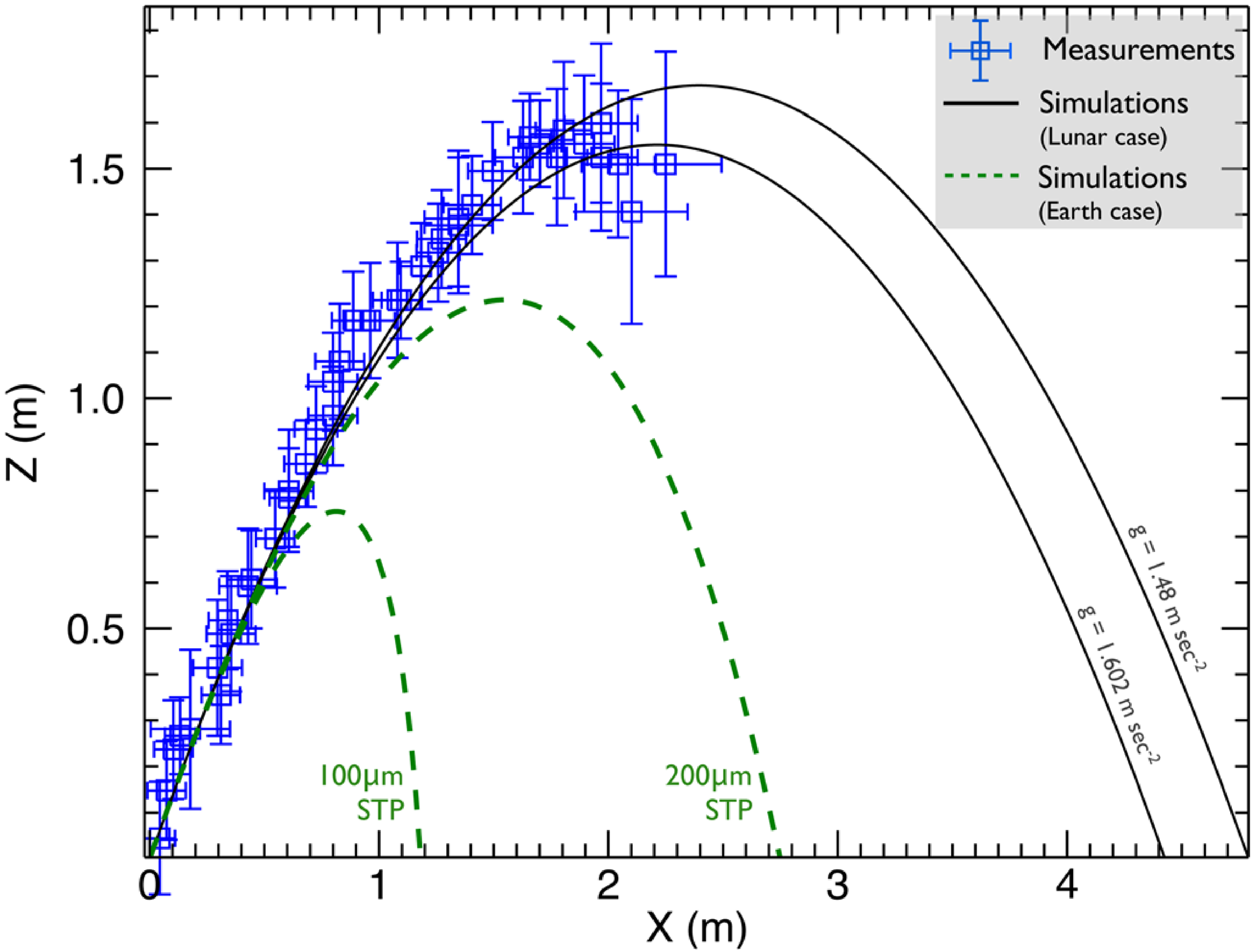
Rooster Tails

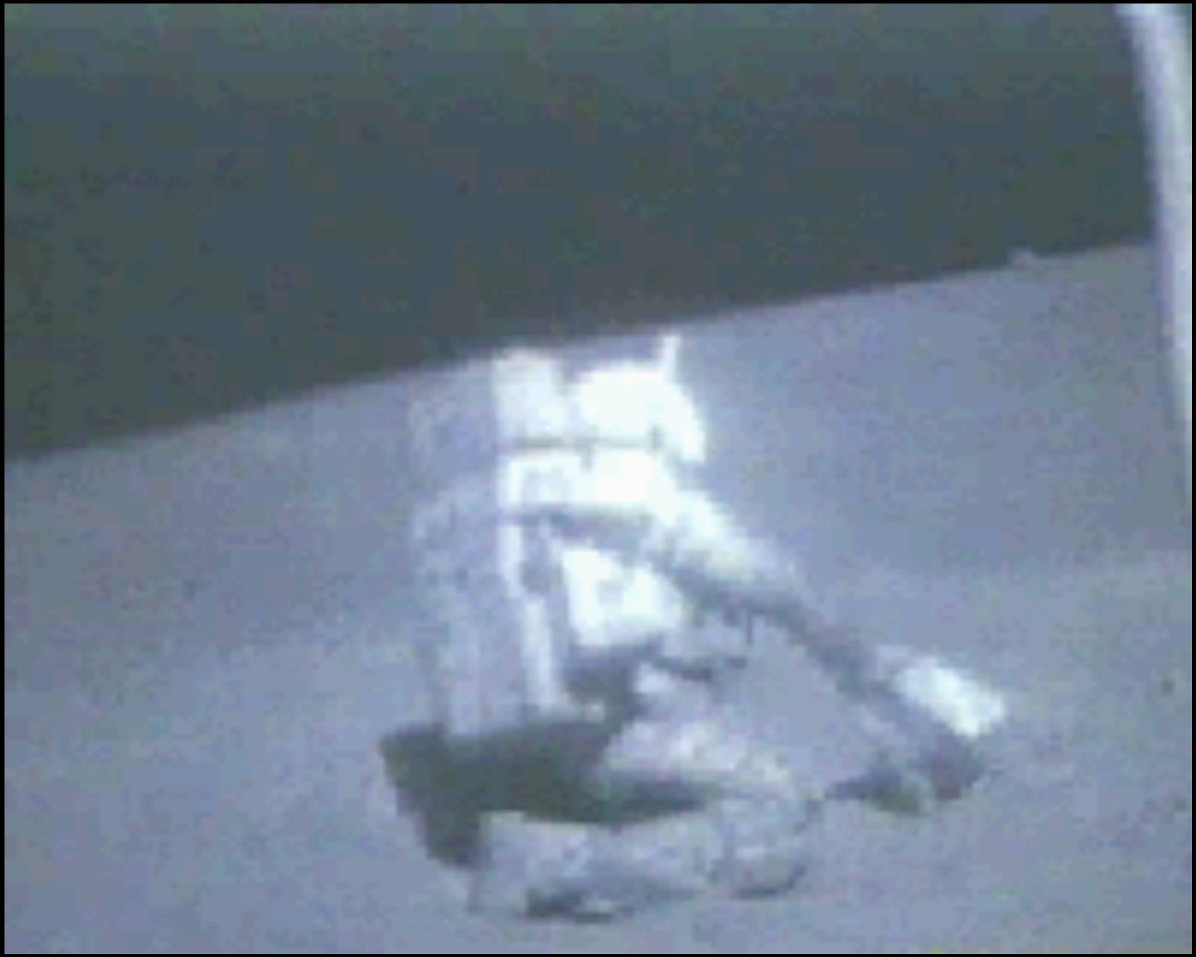


Rooster Tails

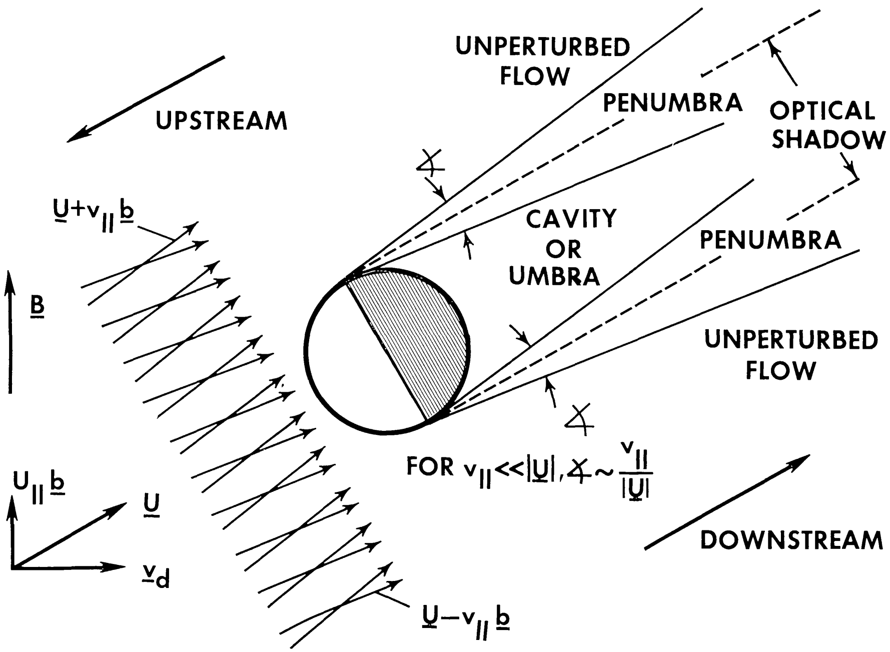


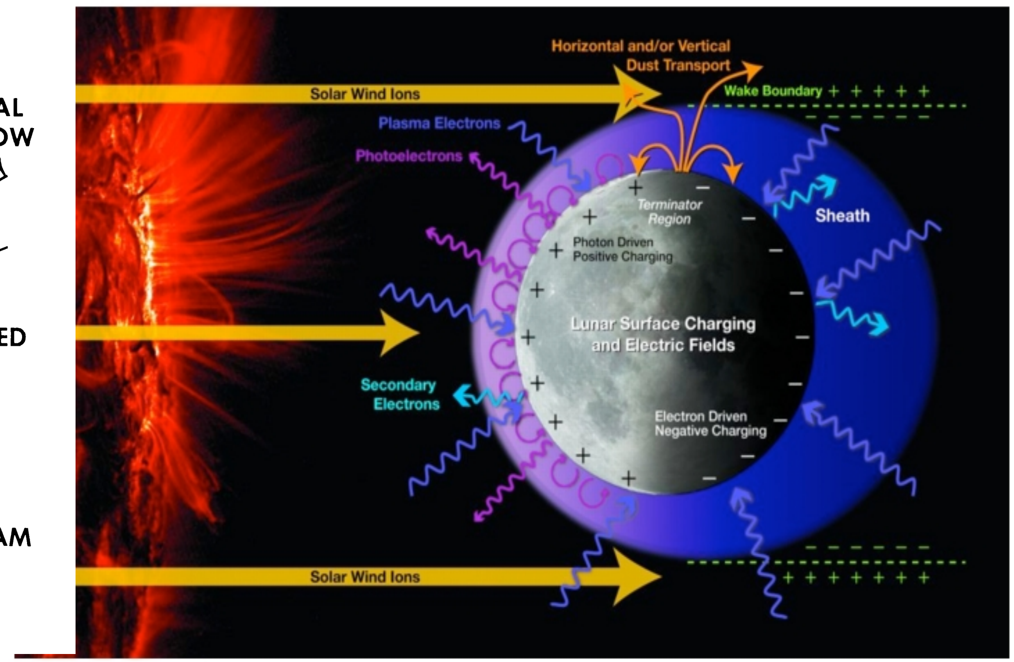
Measured Dust Trajectory - clip 1



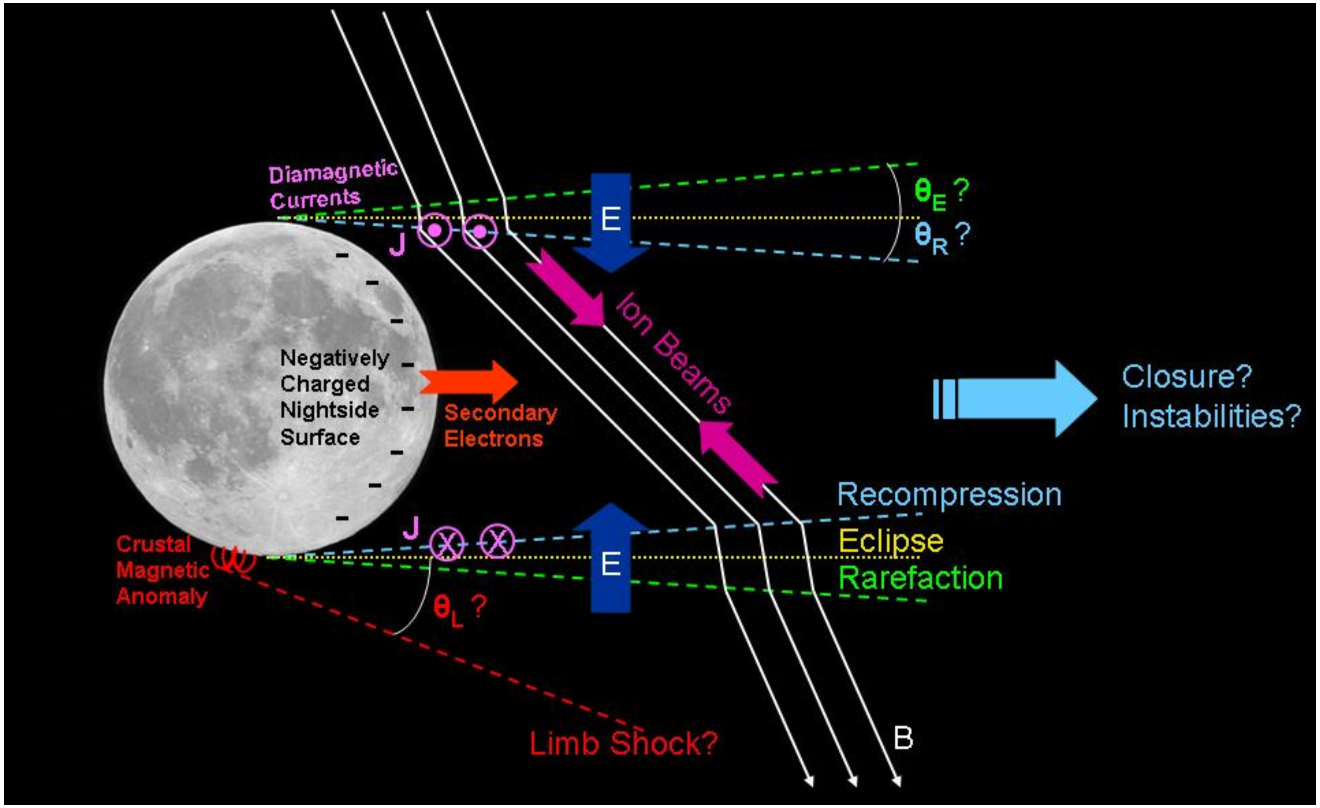


LUNAR DUST, PLASMA, AND UV ENVIRONMENT





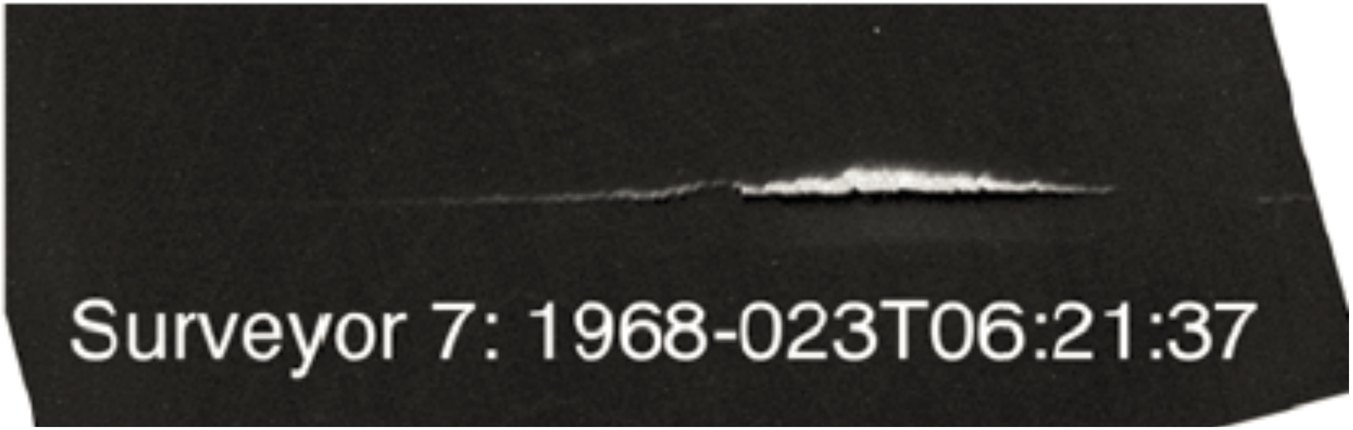
NIGHTSIDE CHARGING

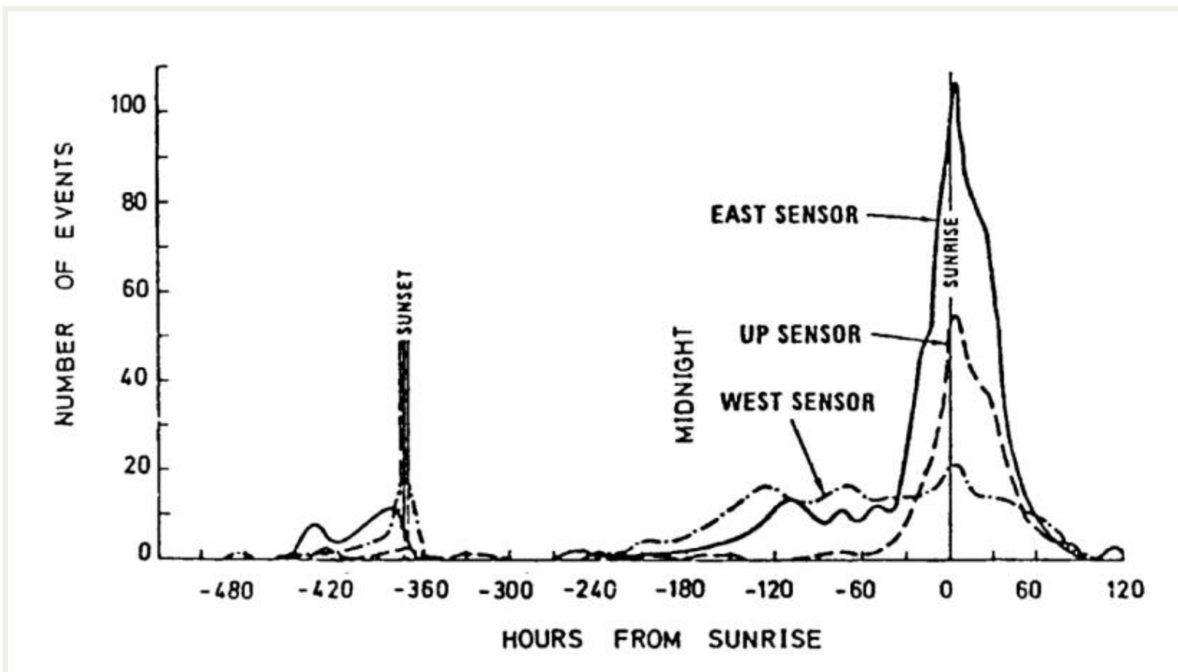


$$kT_e \approx m_p v_{sw}^2 / 2$$

Halekas, 2010

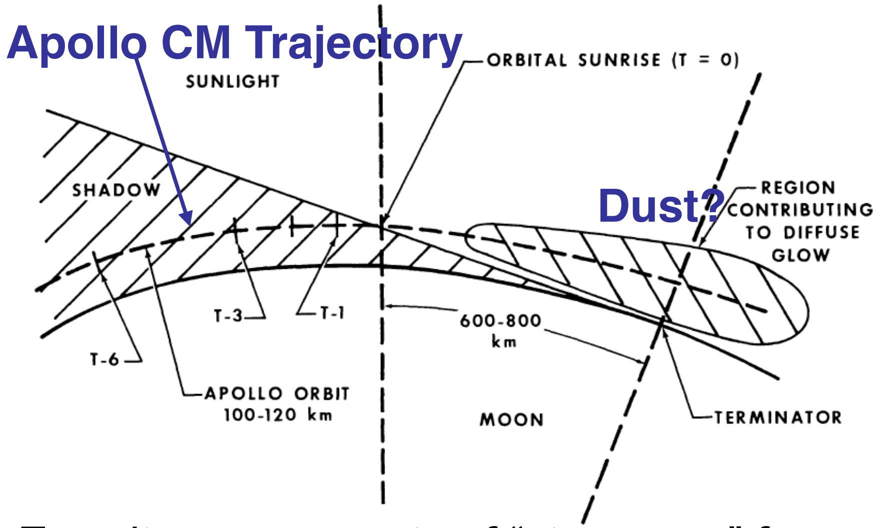
$$\phi \approx -m_p v_{sw}^2 / (2e)$$


Surveyor 7: 1968-023T06:21:37

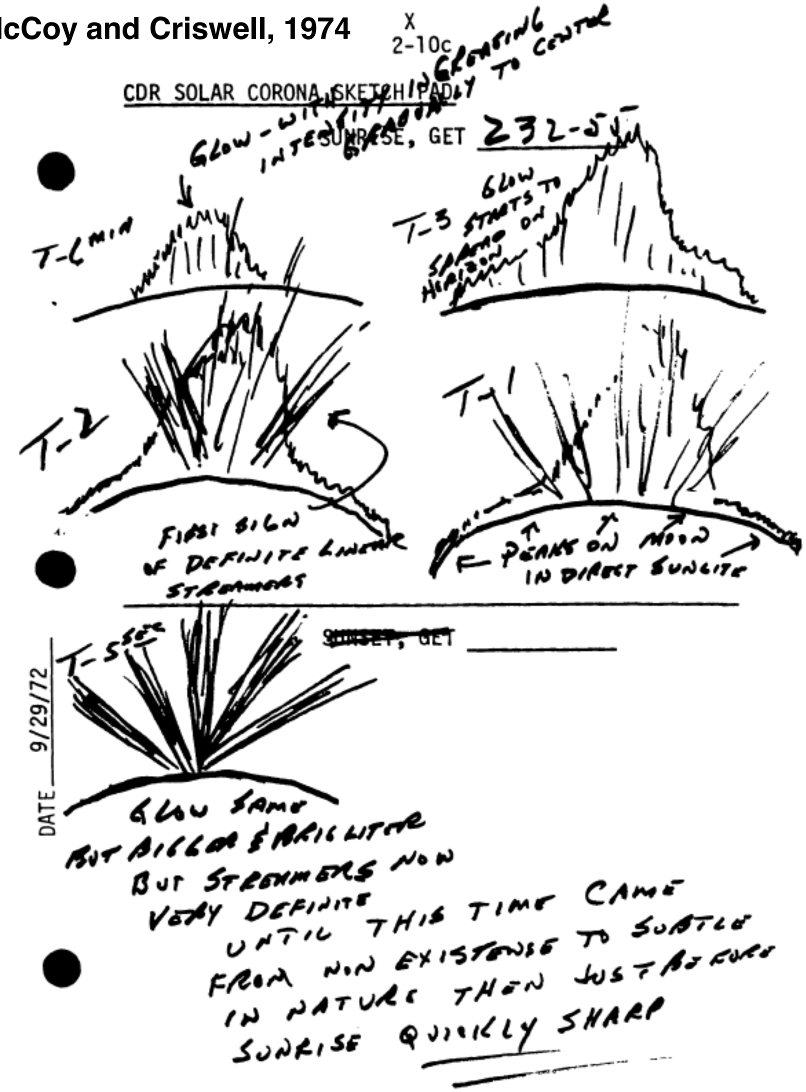

NUMBER OF EVENTS
100
80
60
40
20
0
SUNSET
MIDNIGHT
EAST SENSOR
SUNRISE
UP SENSOR
WEST SENSOR
-480
-420
-360
-300
-240
-180
-120
-60
0
60
120
HOURS FROM SUNRISE

APOLLO ERA UNRESOLVED OBSERVATIONS

Gene Cernan sketches from Apollo Command Module

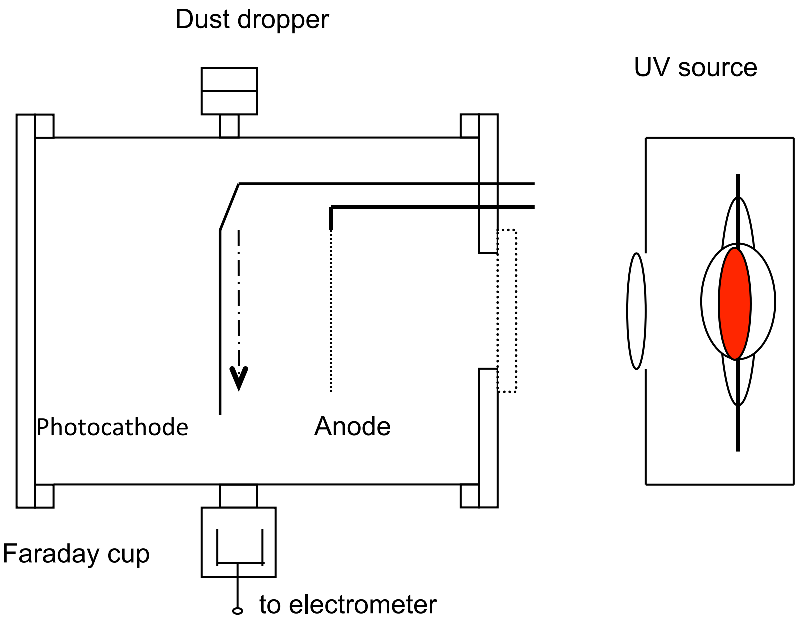


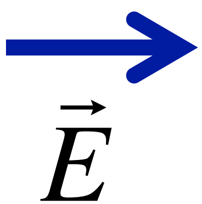
McCoy and Criswell, 1974

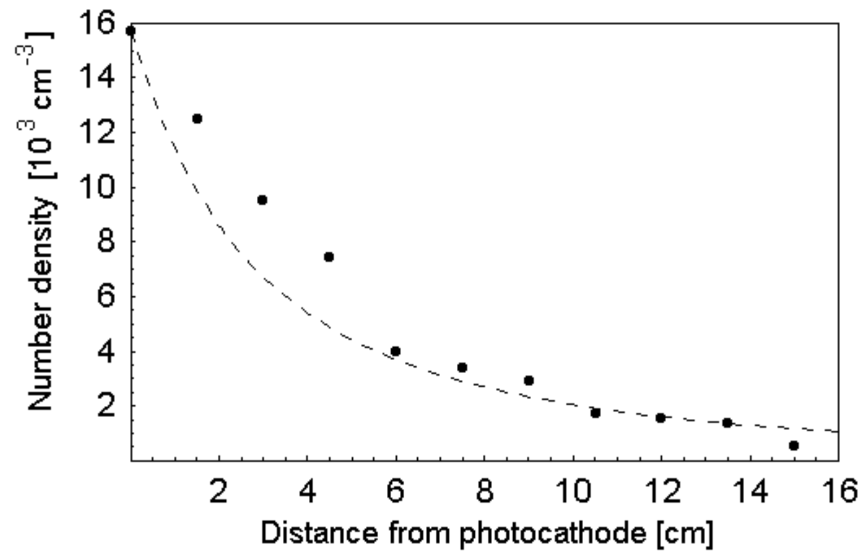


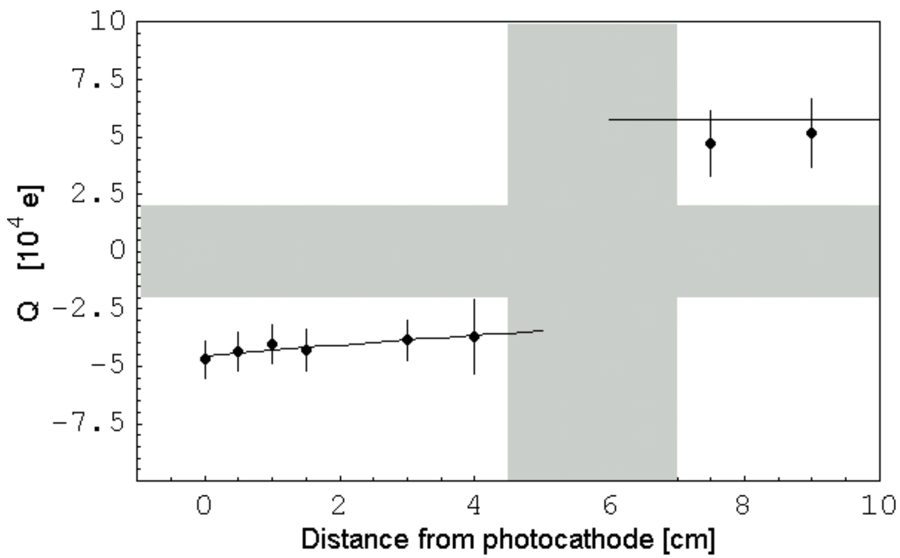
- Eyewitness accounts of “streamers” from Apollo command module
- Too bright to be meteoritic ejecta
- Exosphere and/or high altitude (50 km) dust is one possibility
- Key goal if LADEE is to help resolve this open question

UV CHARGING

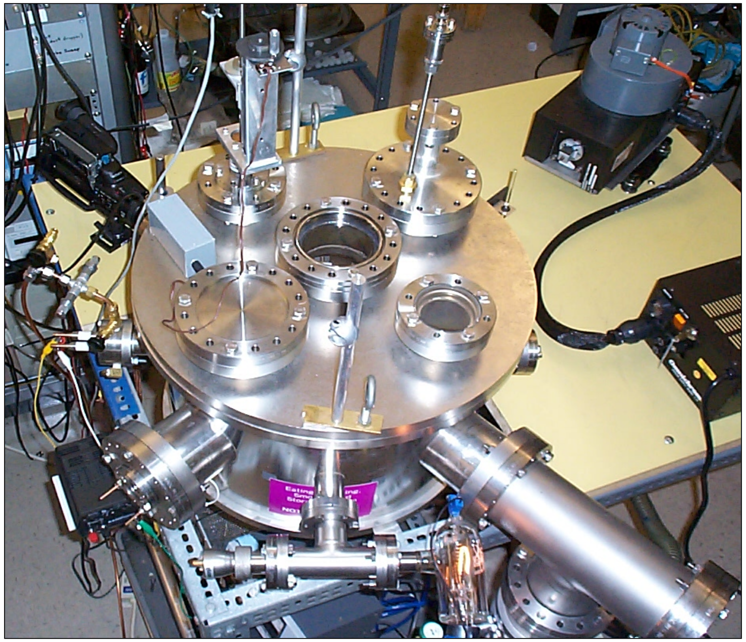

Dust dropper
UV source
Photocathode
Anode
Faraday cup
to electrometer

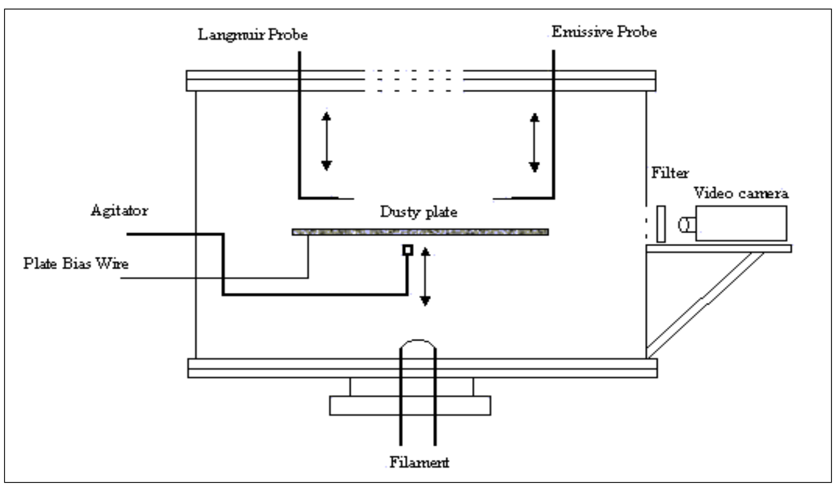

$\vec{E}$

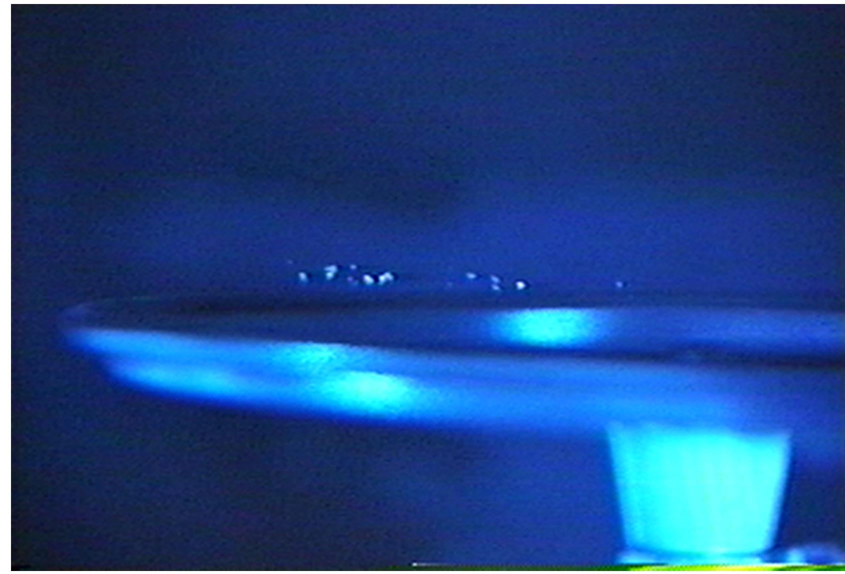

Number density [10^3 cm^-3]
16
14
12
10
8
6
4
2
2
4
6
8
10
12
14
16
Distance from photocathode [cm]


Q [10^4 e]
10
7.5
5
2.5
0
-2.5
-5
-7.5
0
2
4
6
8
10
Distance from photocathode [cm]

LEVITATING DUST

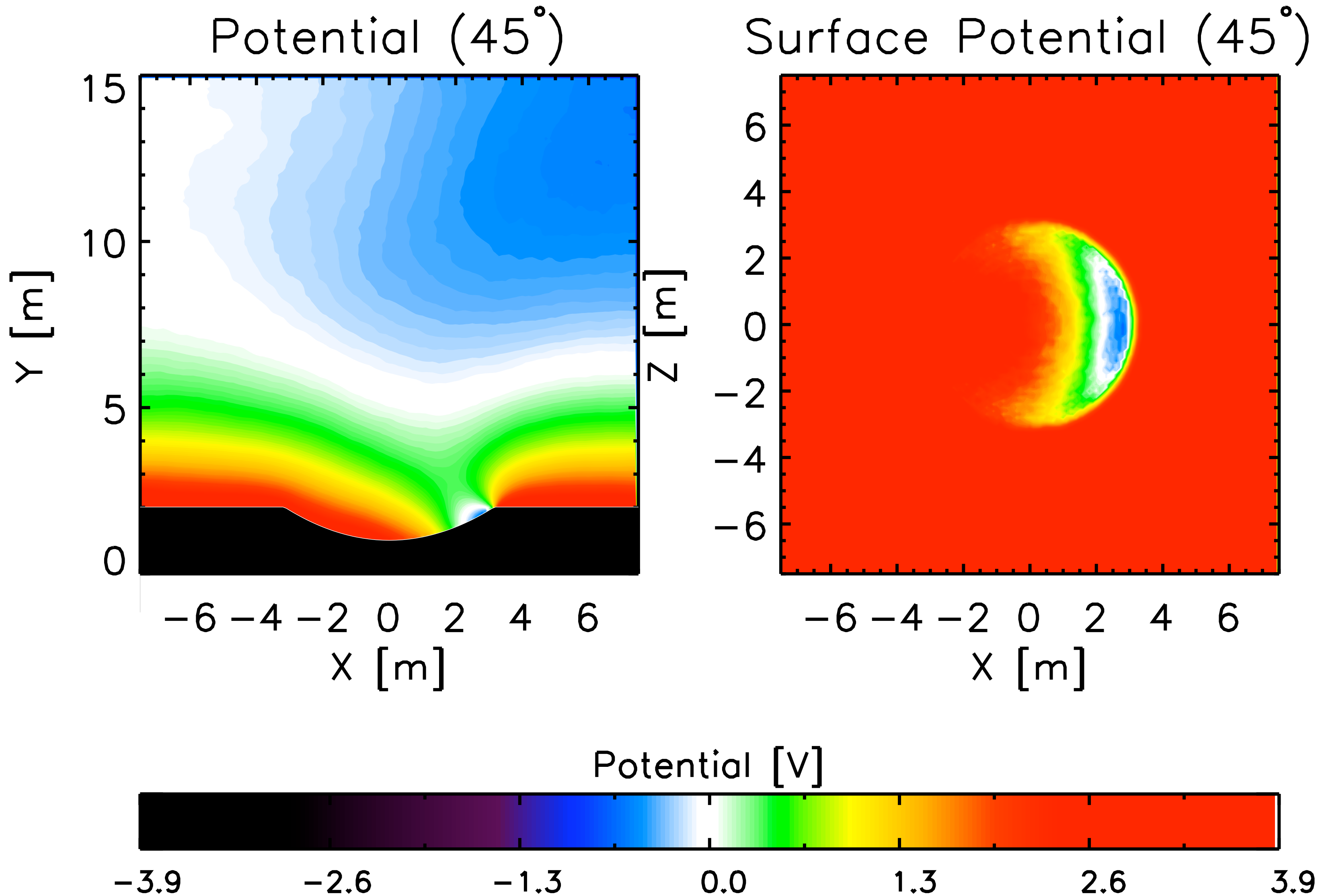




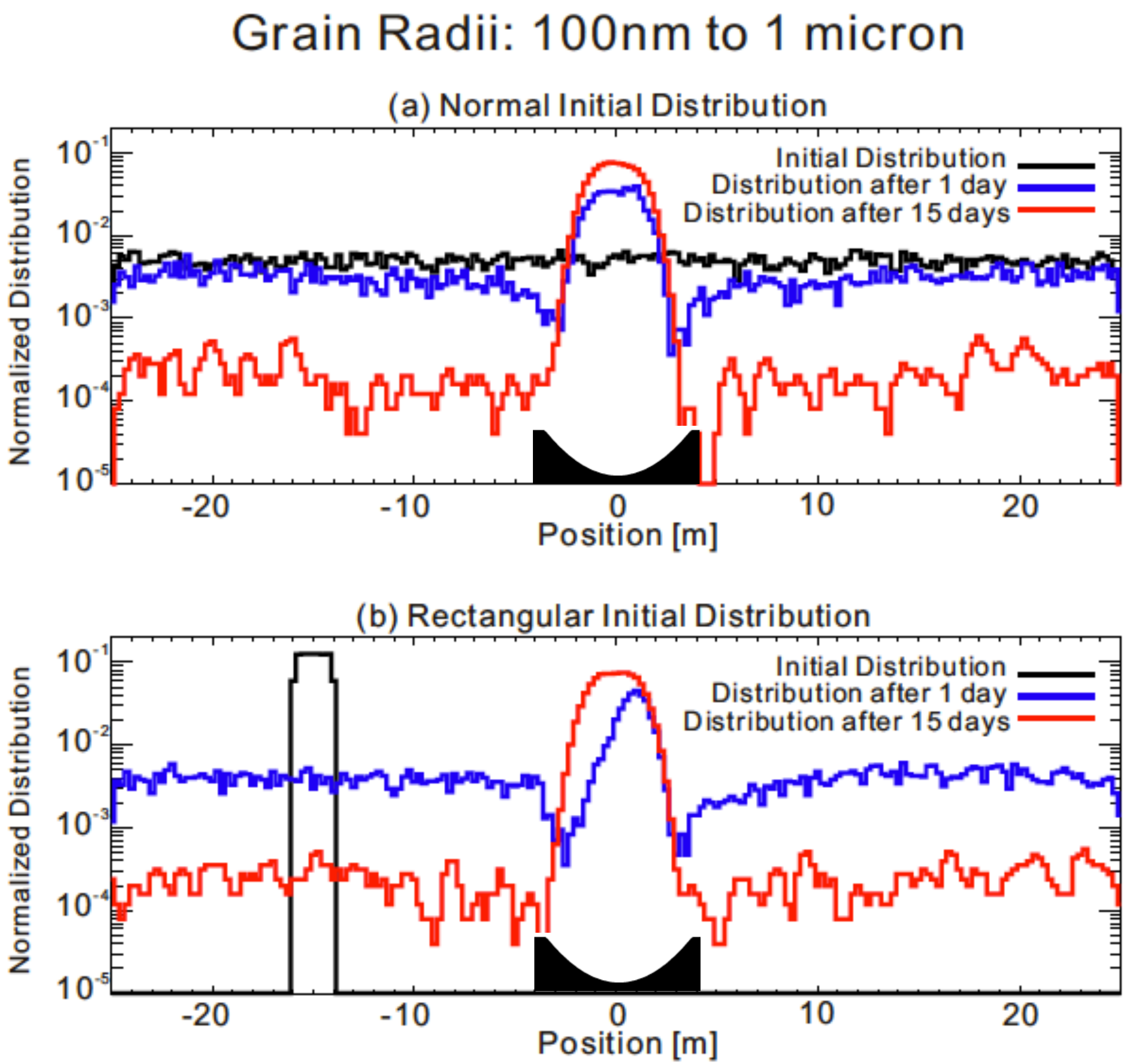


Sickafoose et al., 2002

Topography effects everything.



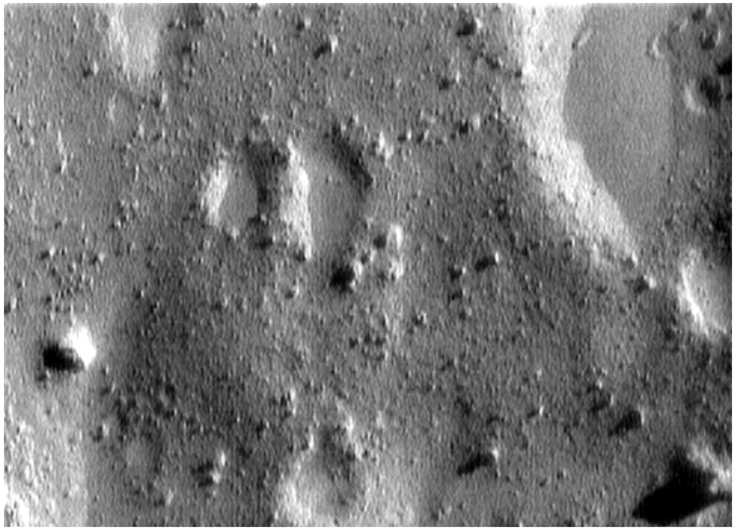
Dust accumulates in craters.



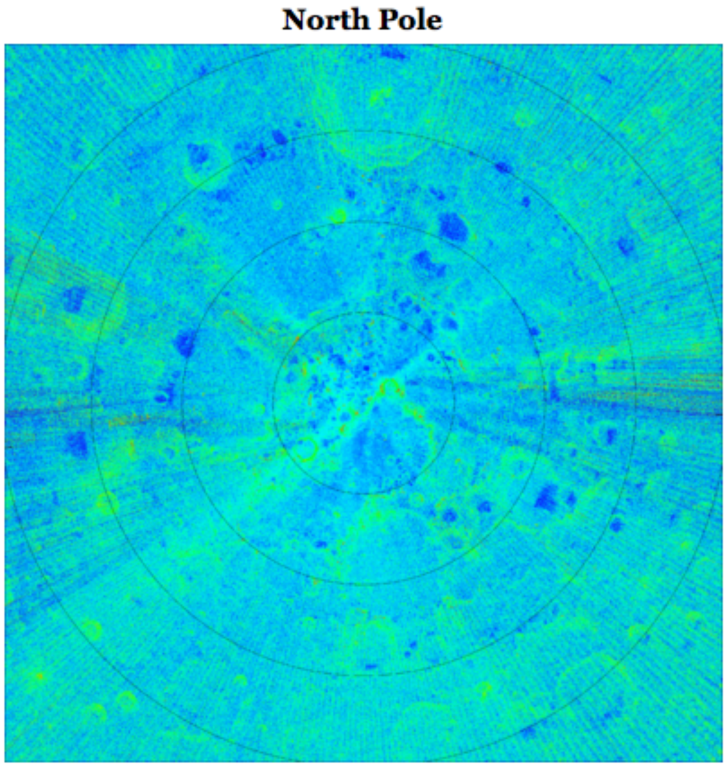
Poppe et al., 2012

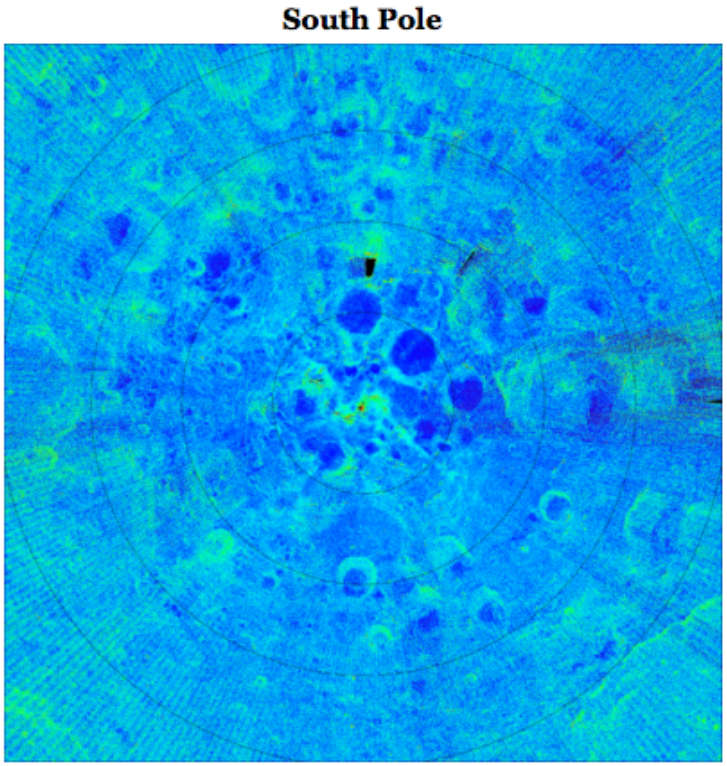
Dust ponds can form.

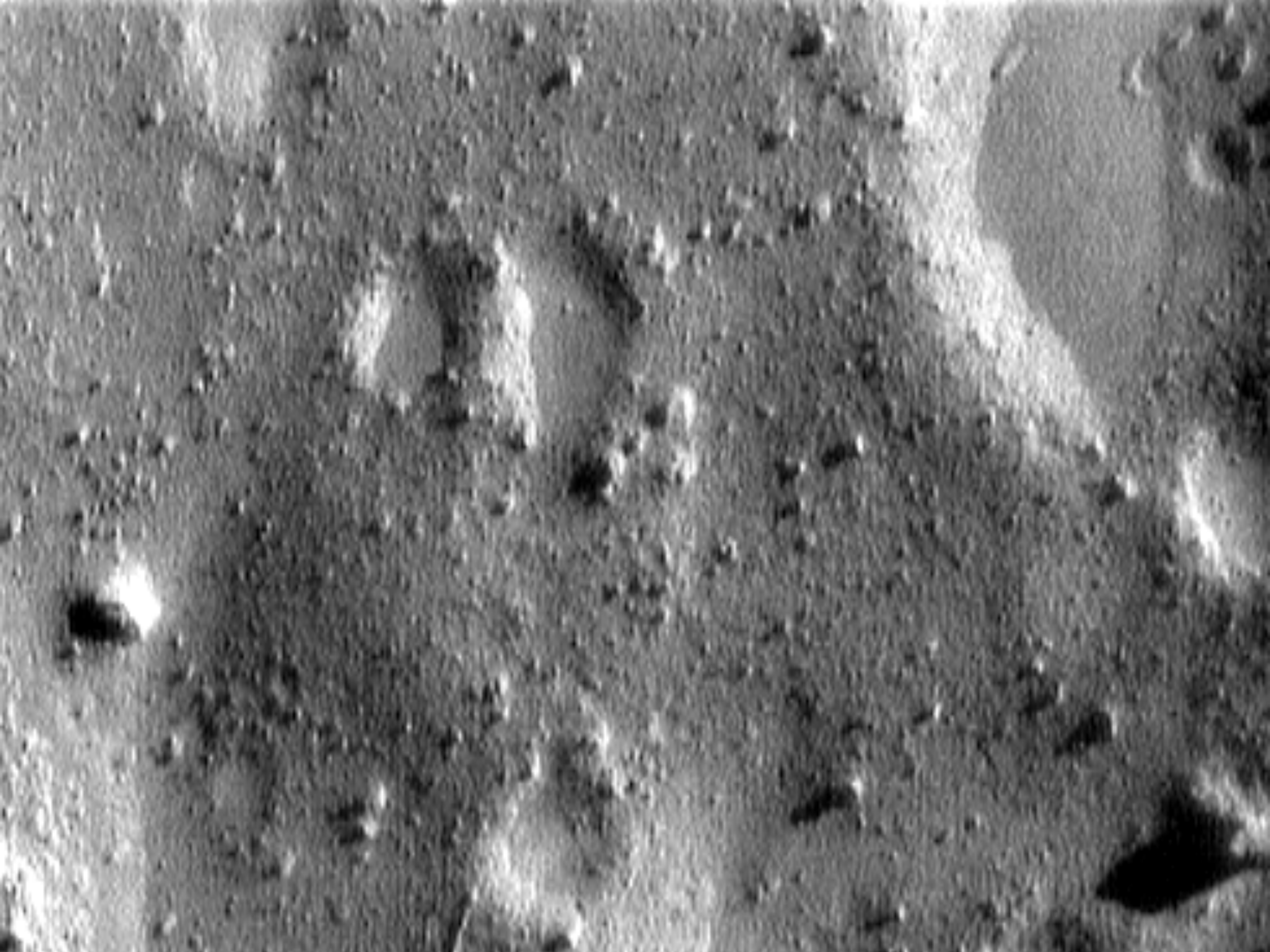
“Ponding” on Eros



LRO - LAMP

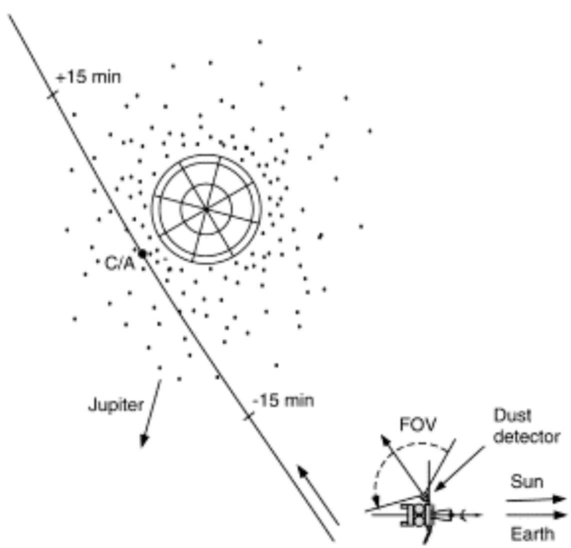


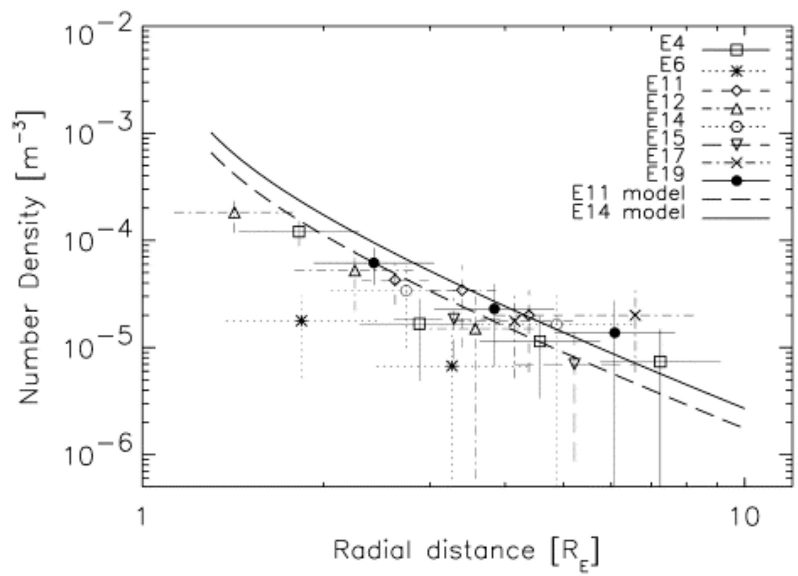




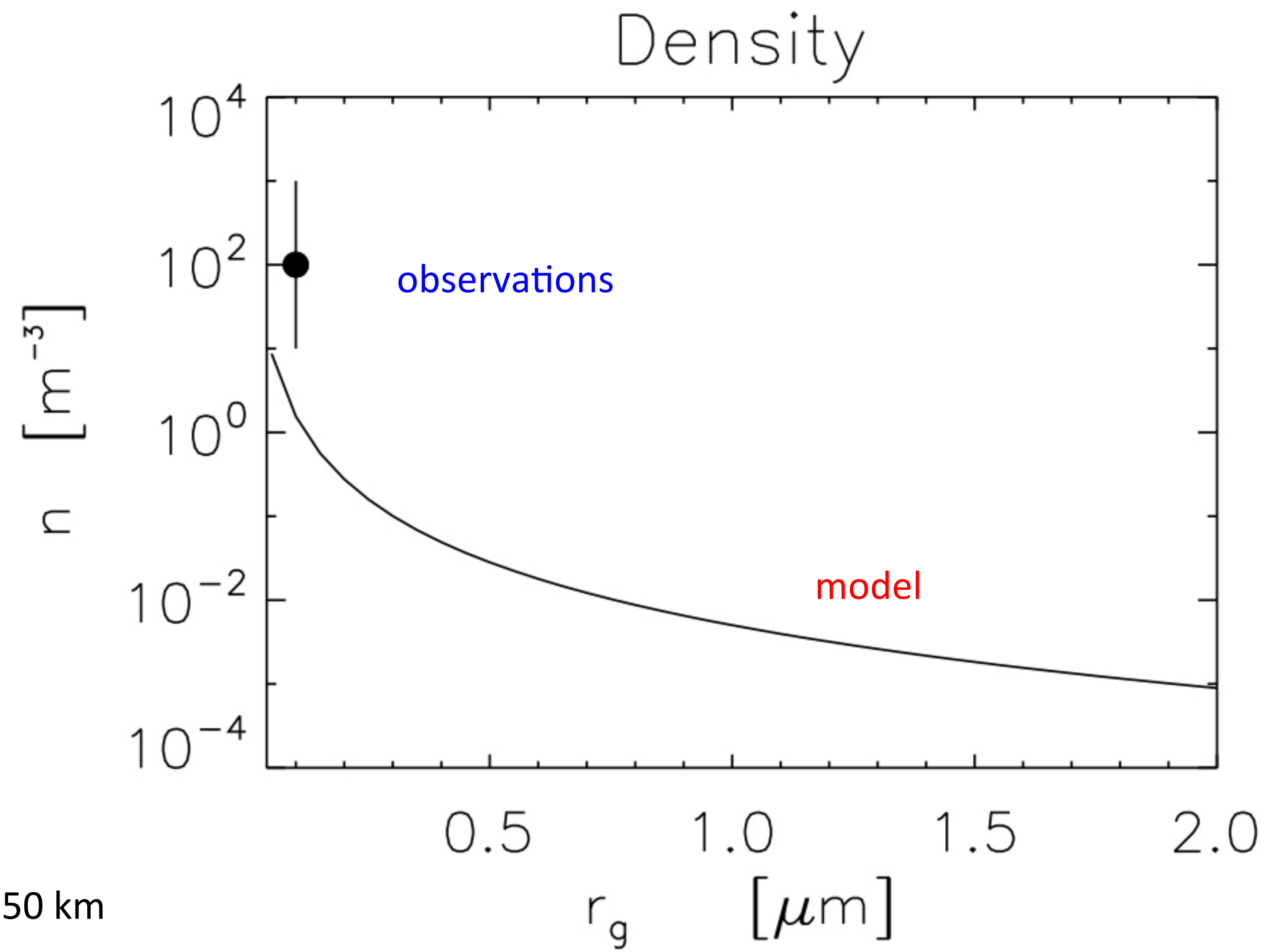
Lunar Dust Cloud

1) Spherically symmetric continually present ejecta cloud generated by interplanetary dust impacts
2) Temporal & spatial variability due to meteor showers on time scales of days
3) Density enhancements of small grains over the terminators due to plasma effects, expected to be correlated with solar wind conditions and UV variability on time scales of hours



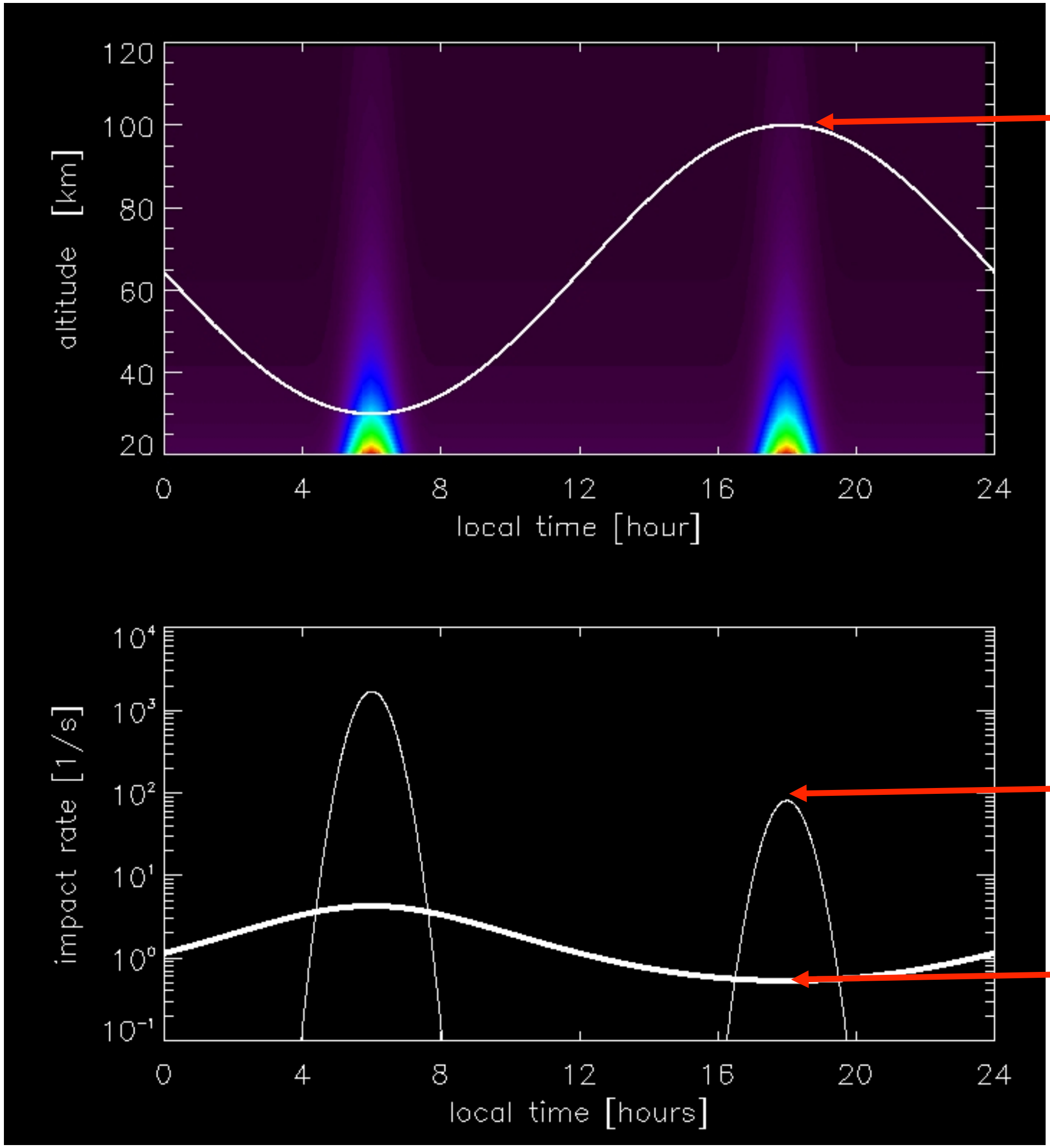


Lunar Dust Environment



h = 50 km

Expected Dust Impact Rates



30 x 100 km orbit

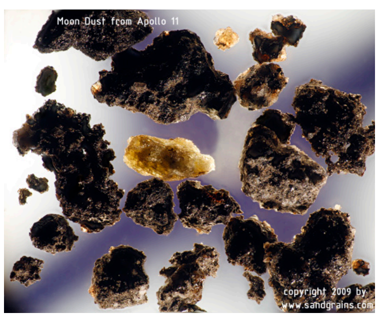
Periselene over the morning terminator

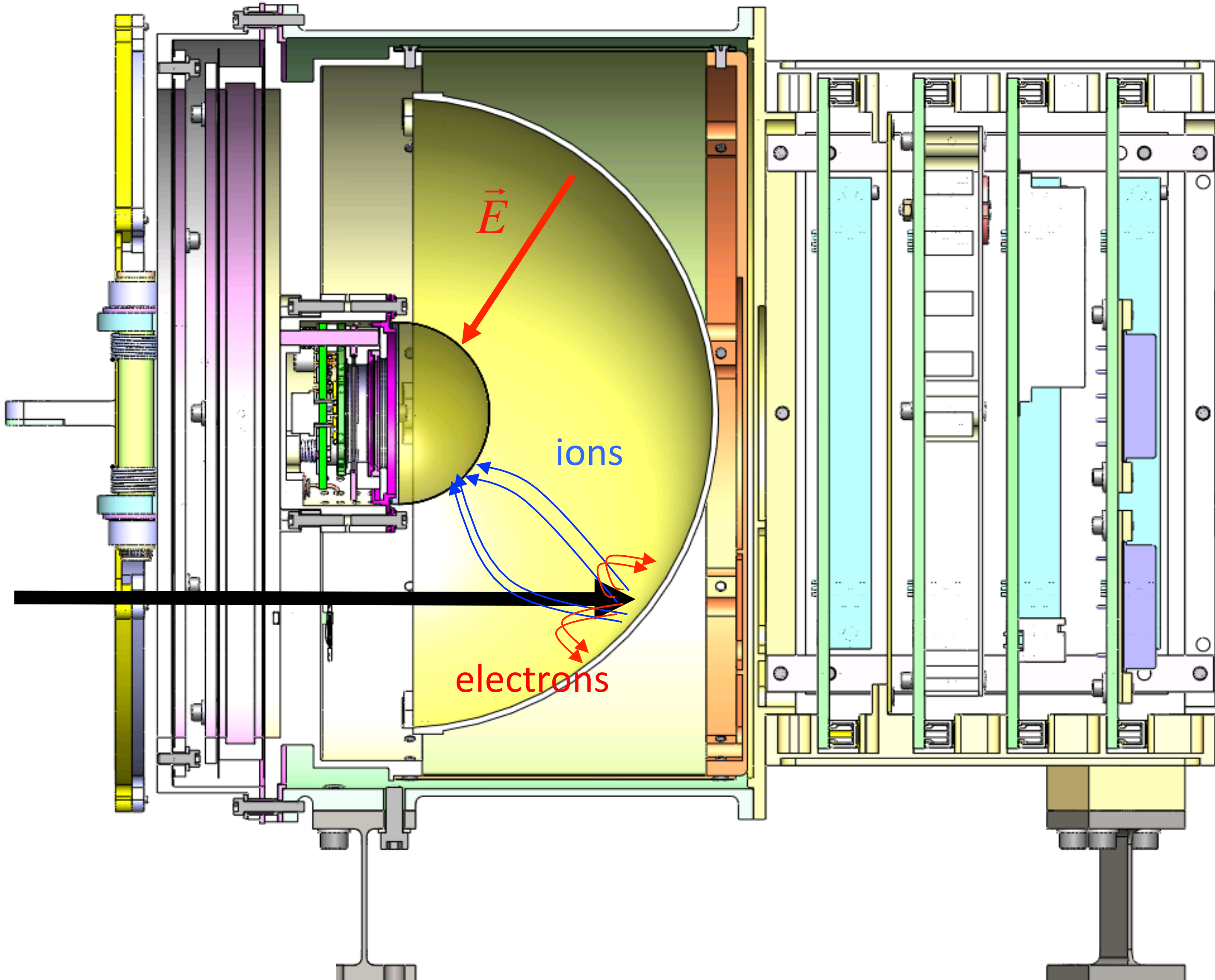
A = 100 cm^2

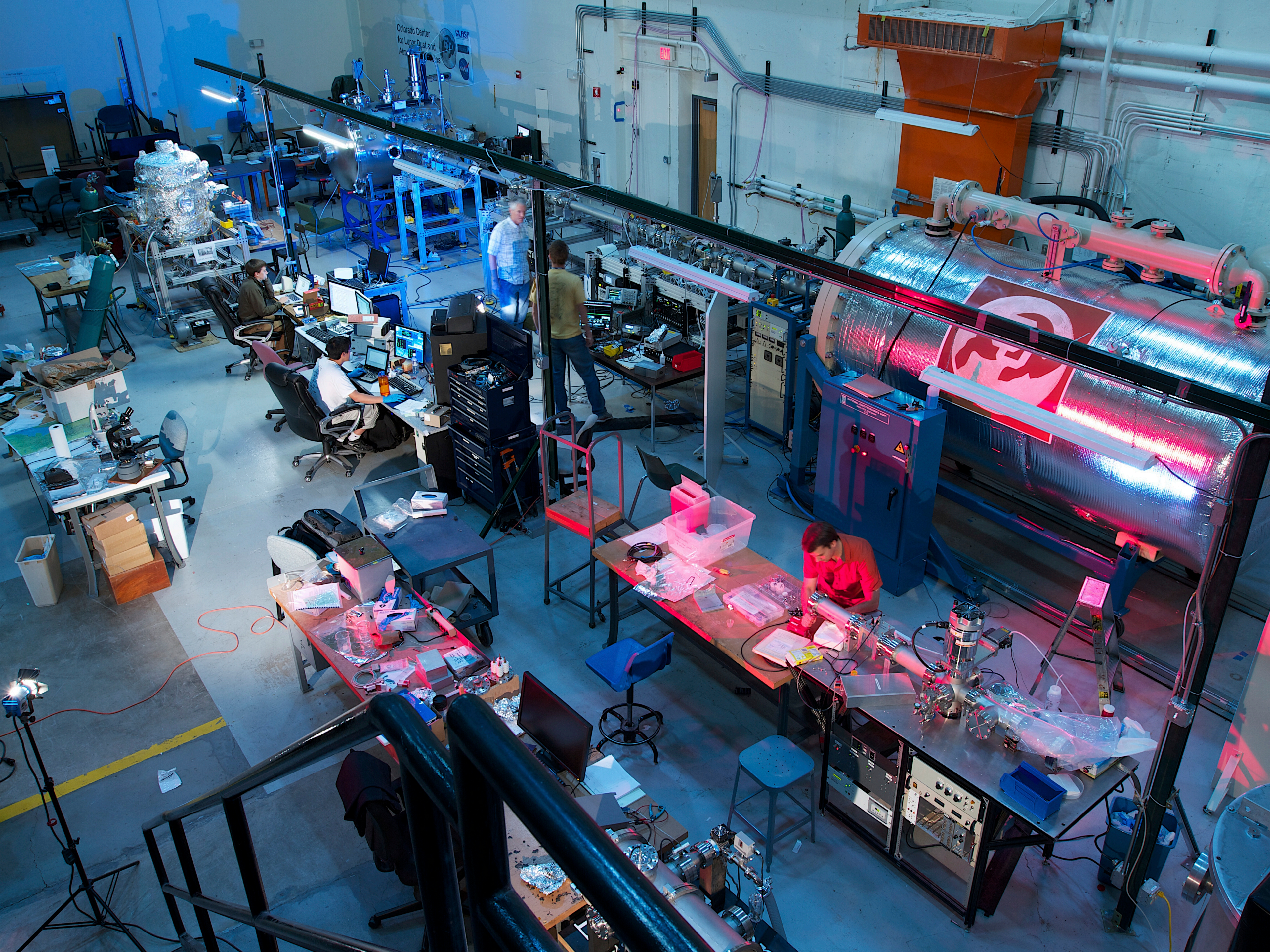
$< 0.3\ \mu m$

$> 0.3\ \mu m$

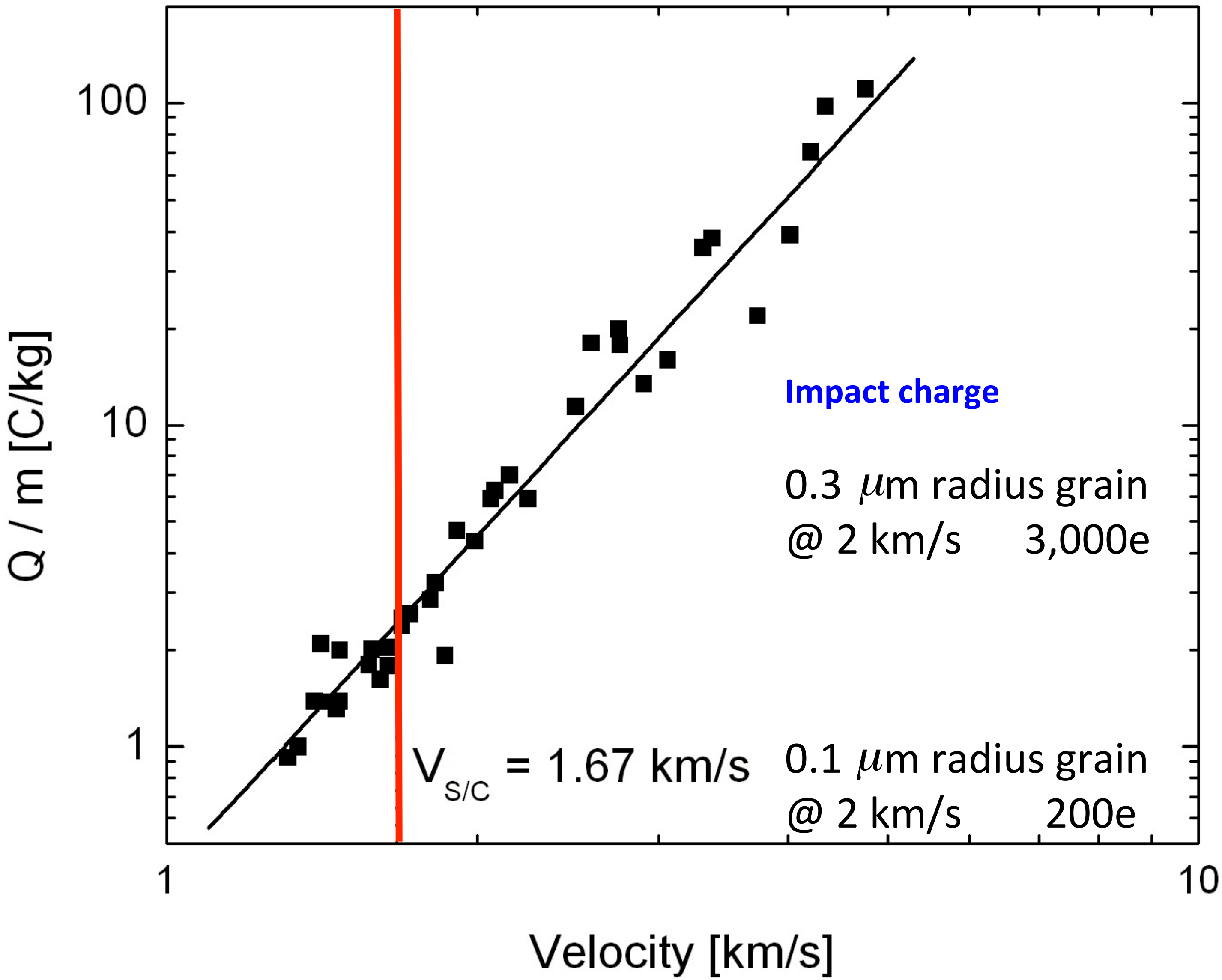
LDEX Instrument



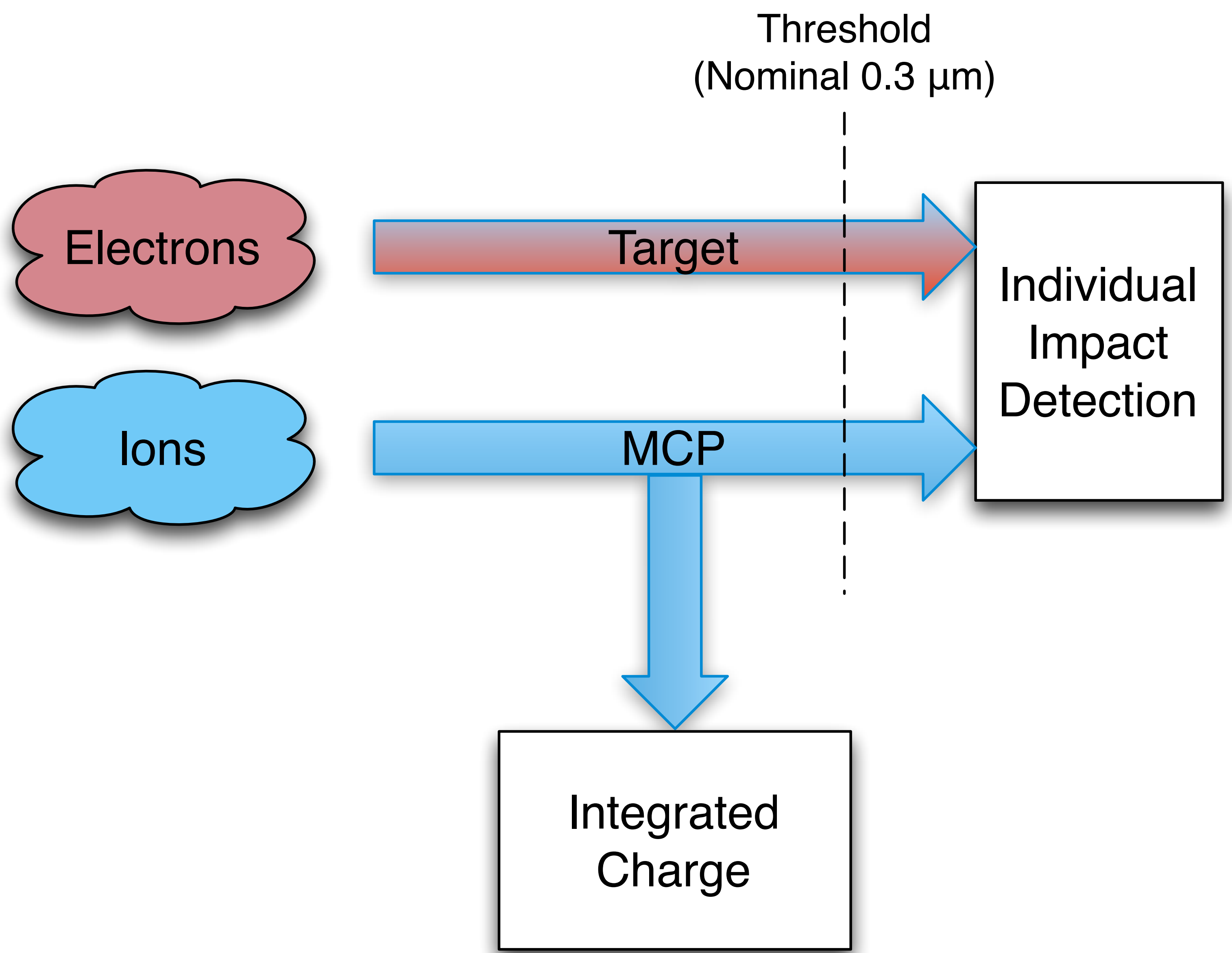



Colorado Center
LASP
NASA
EXIT

Impact Charge

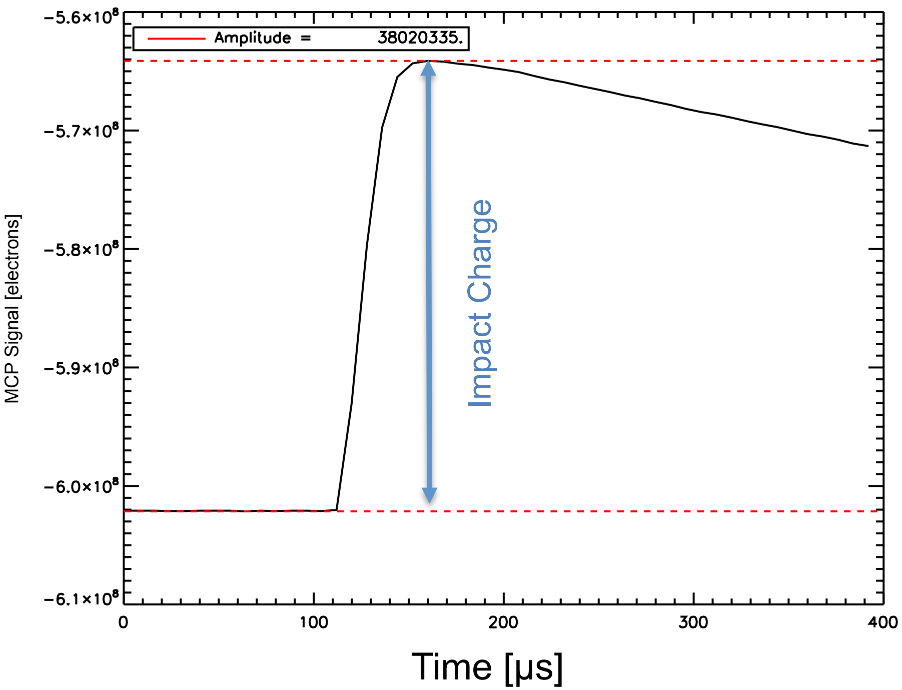


Science Channels

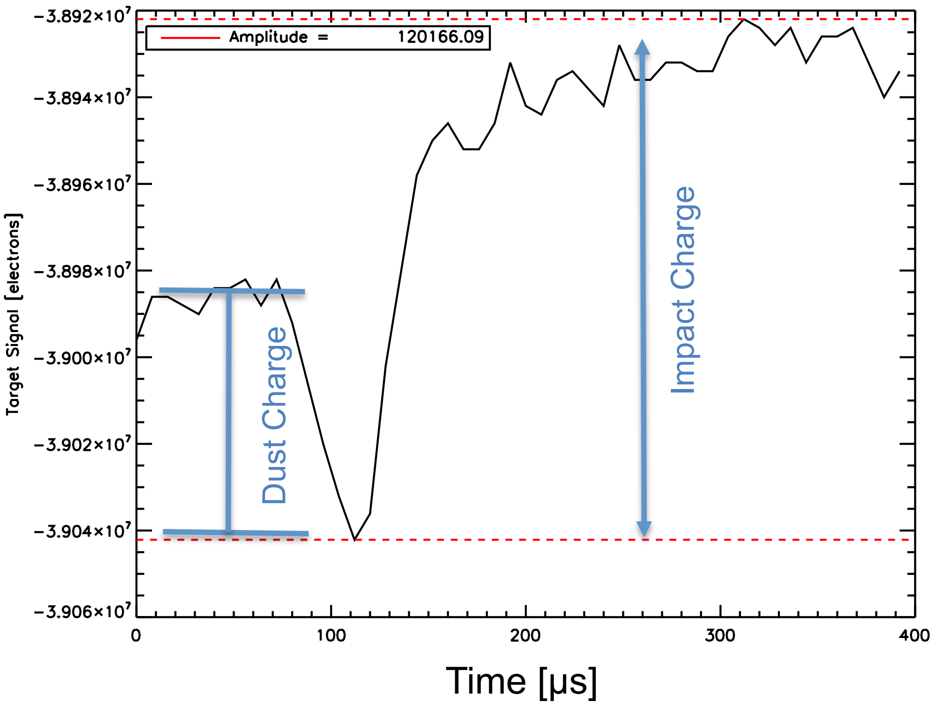


Individual Impacts

MCP Signal

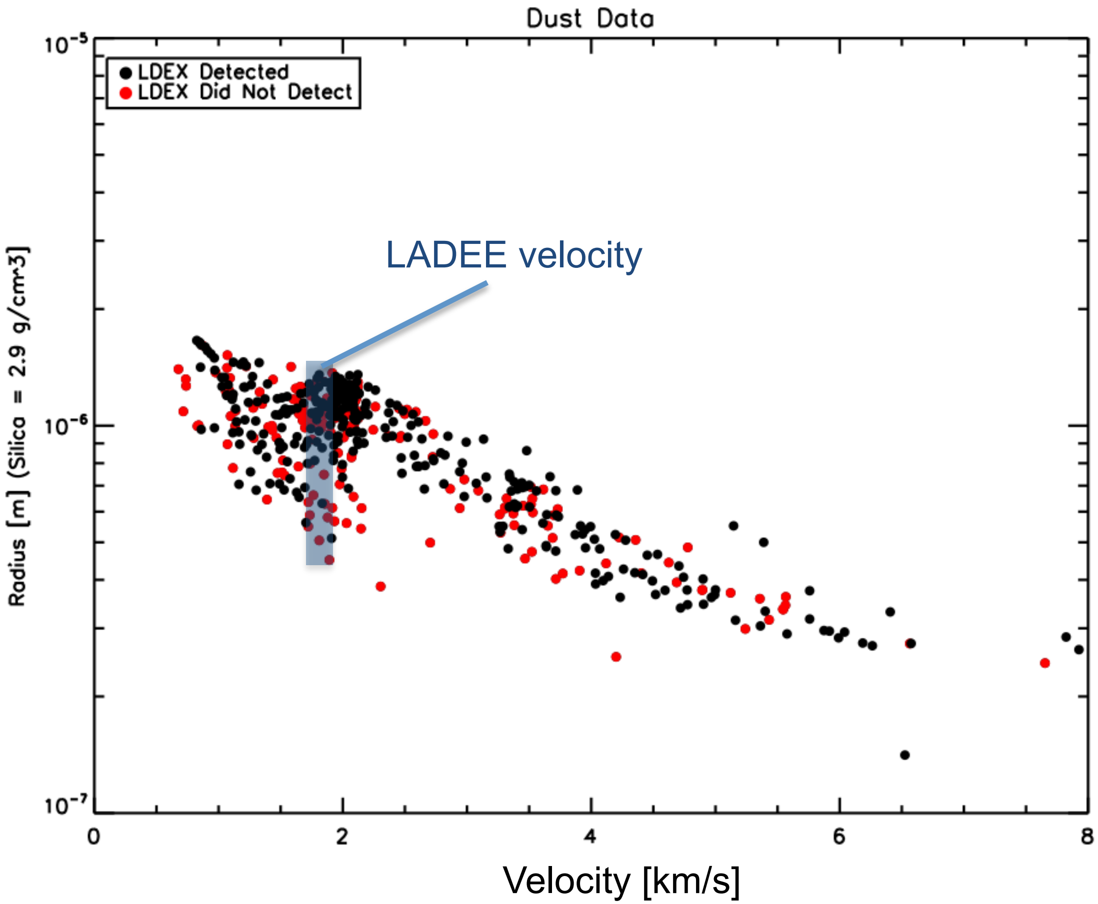


Target Signal



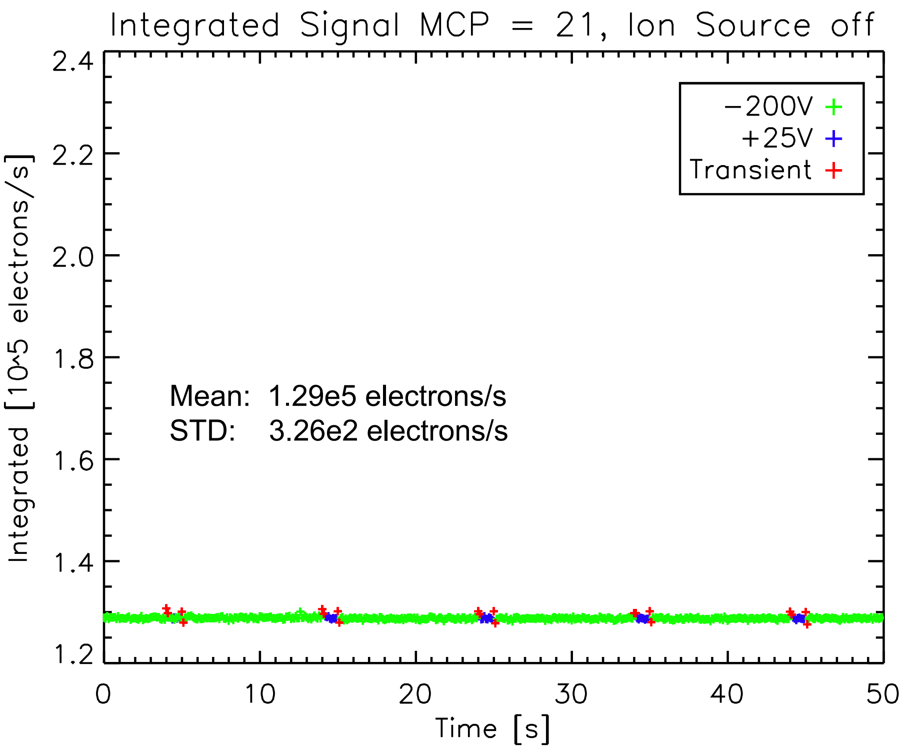
- CSA impact signal waveforms recorded (50 points, 8 μs spacing)
- Waveforms analyzed and impacts are validated
- The samples shown are for a 1.06 μm radius particle at 1.89 km/s velocity

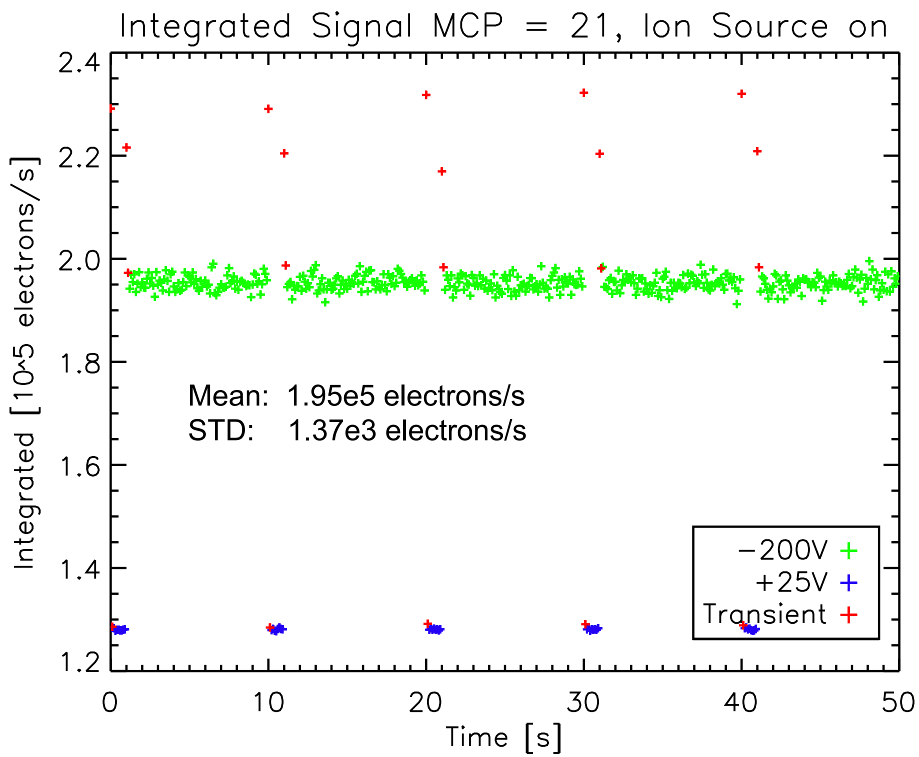
Testing and Calibration



- Performed at the CCLDAS facility
- Velocity range 1–8 km/s
- Size range 0.2 – 1.5 μm
- Total number of particles shown
- **Black**: particles detected by LDEX
- **Red**: not detected by LDEX
- **65%** is detected
- Dust flux is reduced by the 3 grids over the aperture (90% open area) and the 90% duty cycle of LDEX
- $(0.9)^4$ = **0.656**

Integrator Signal



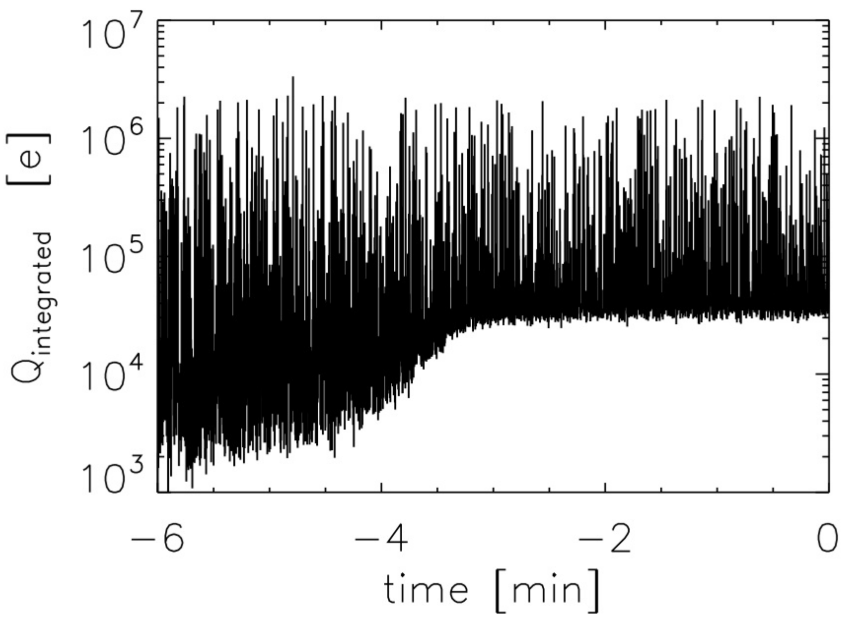


Integrator signal with nominal LDEX settings (100ms integration period) an ion source off/on. Blue and red periods are switching of the ion focusing grid.

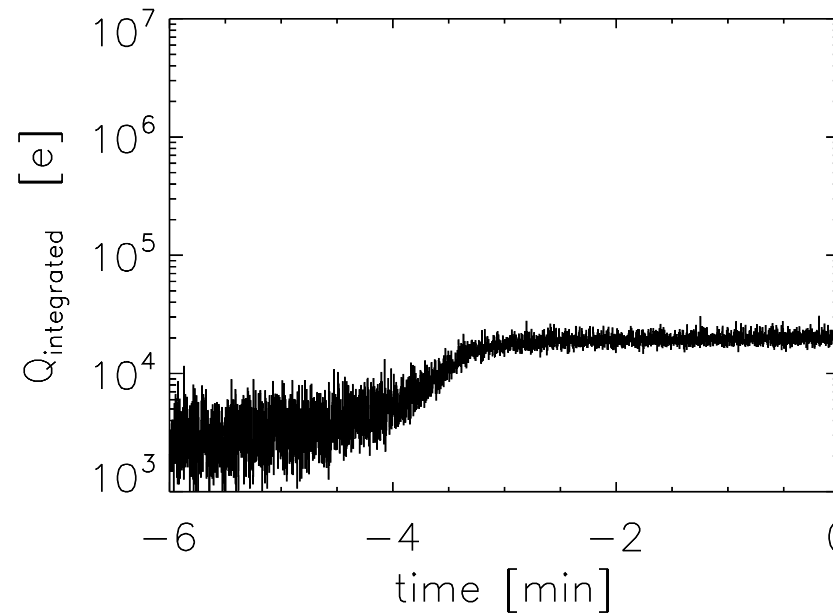
Note: The rejection of the ion signal is efficient.

Expected Integrated Signal

Total Signal



Integrated Below-Threshold Signal



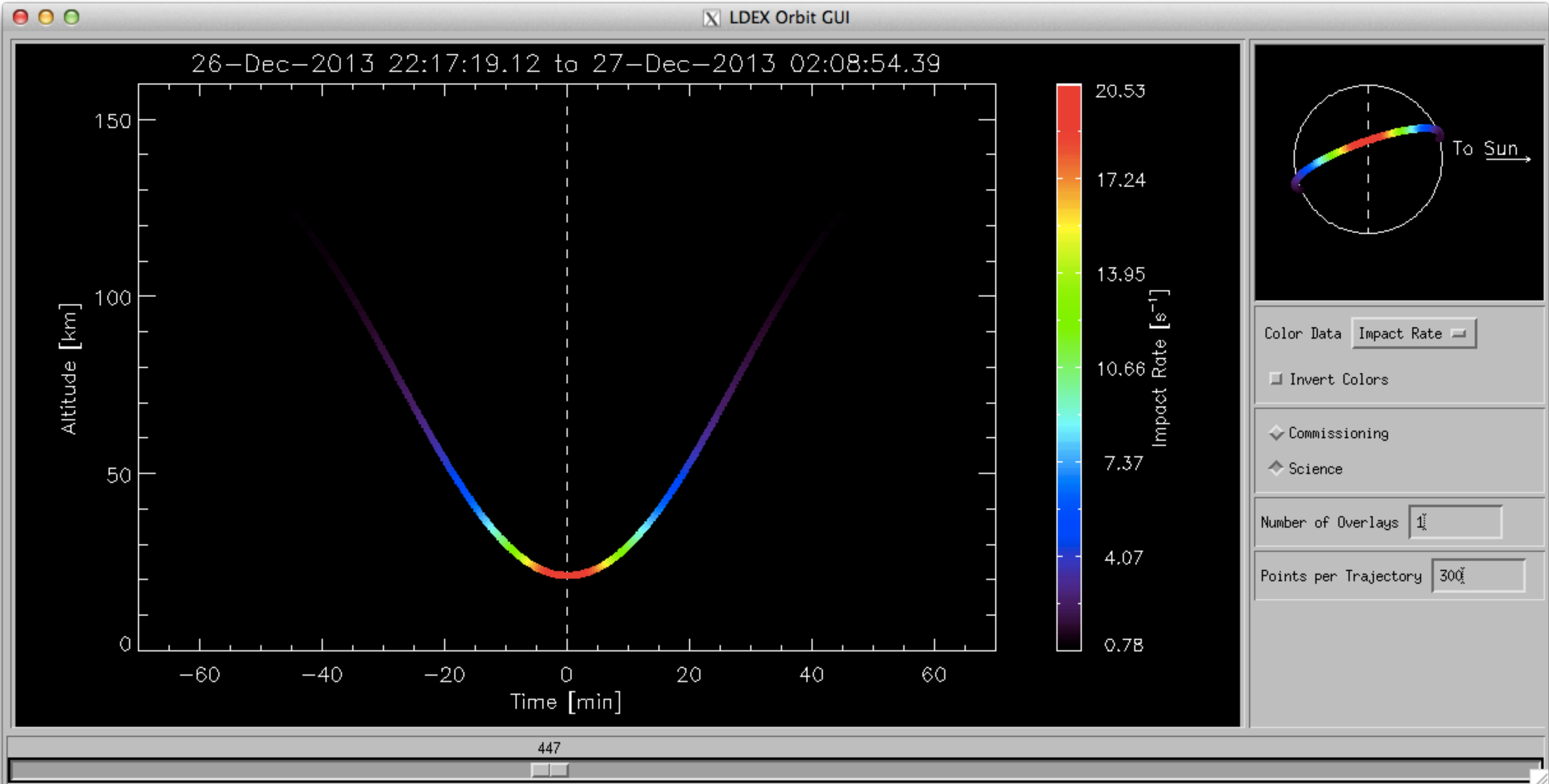
dt = 0.1 sec

Integrated signal allows for the detection of the existence of below-threshold population of dust grains ($r < 0.3$ µm)

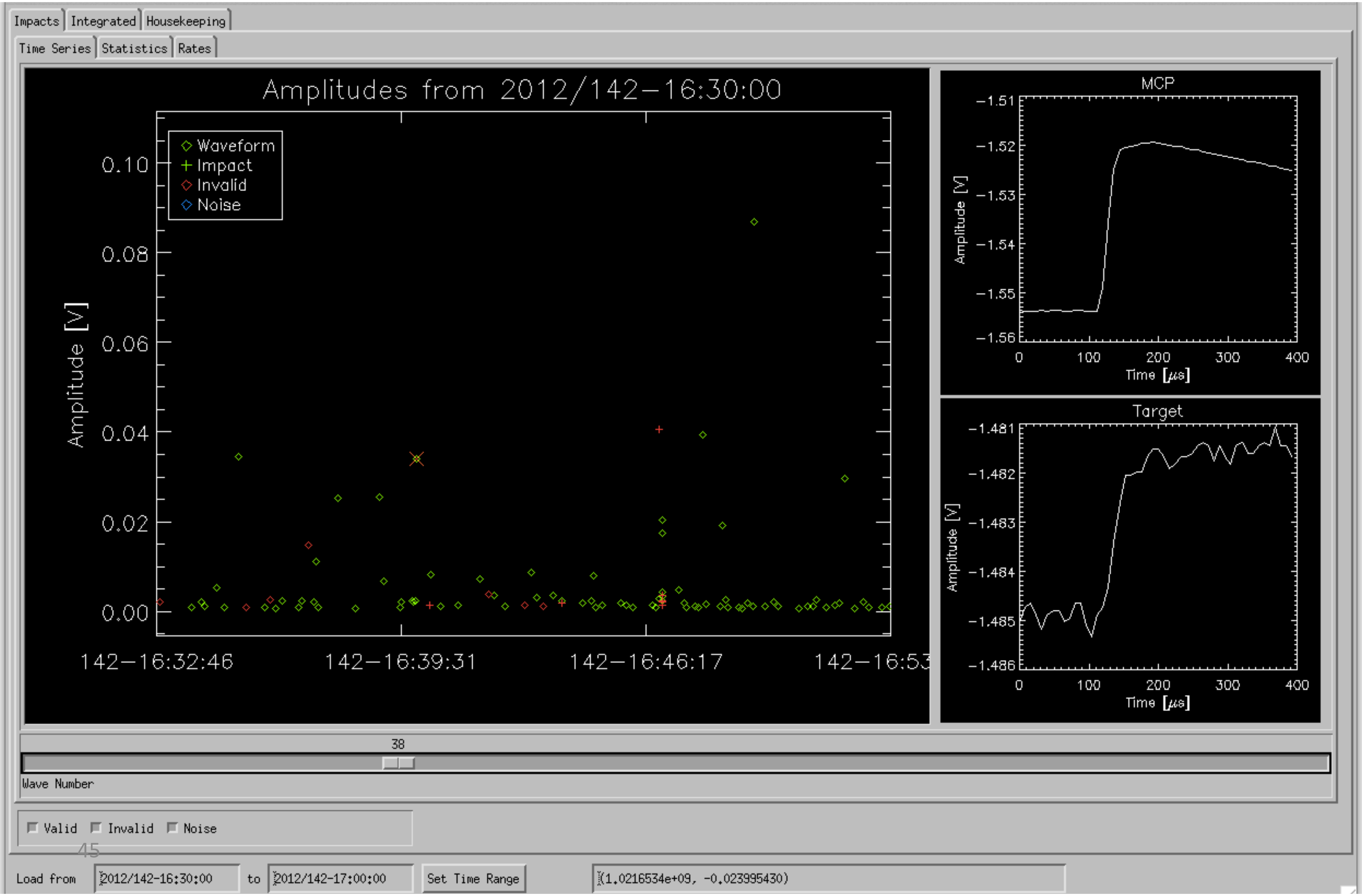
Quick Look Tools

- Predictive tools for threshold estimates
- Data analysis tools for quick turn-around

Orbit Impact Prediction / Visualization



Telemetry Quick-look



LDEX Measurement Requirements

Single grain detection:

✓ LDEX shall be capable of detecting individual dust particles that have a radius of less than 1 micron or greater.

✓ LDEX shall be capable of measuring the size distribution in at least 5 bins covering the dust particle radius range of 1 to 5 micron.

✓ LDEX shall be capable of detecting all particles with radii > 5 micron.

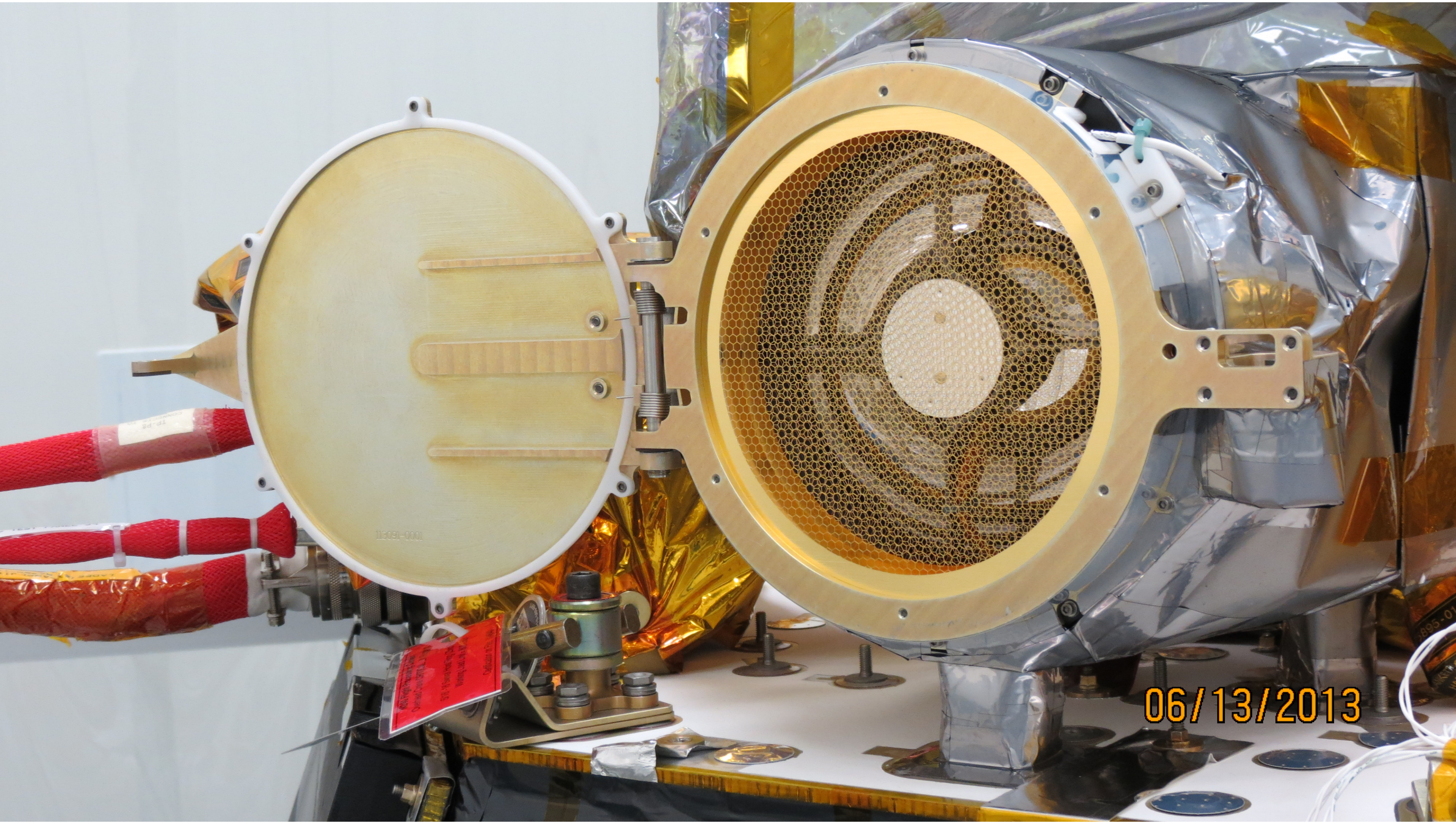
✓ LDEX shall be capable of detecting more than 1 dust particle impact per second.

Collective signal detection:

✓ LDEX shall be capable of detecting the collective signal of particles with the radius range of 0.1 micron to 1 micron.

✓ LDEX shall be capable of making more than 100 measurements of the collective signal within the six minutes immediately prior to sunrise terminator crossing in the lunar orbit (assuming a 50 km circular orbit).

LDEX

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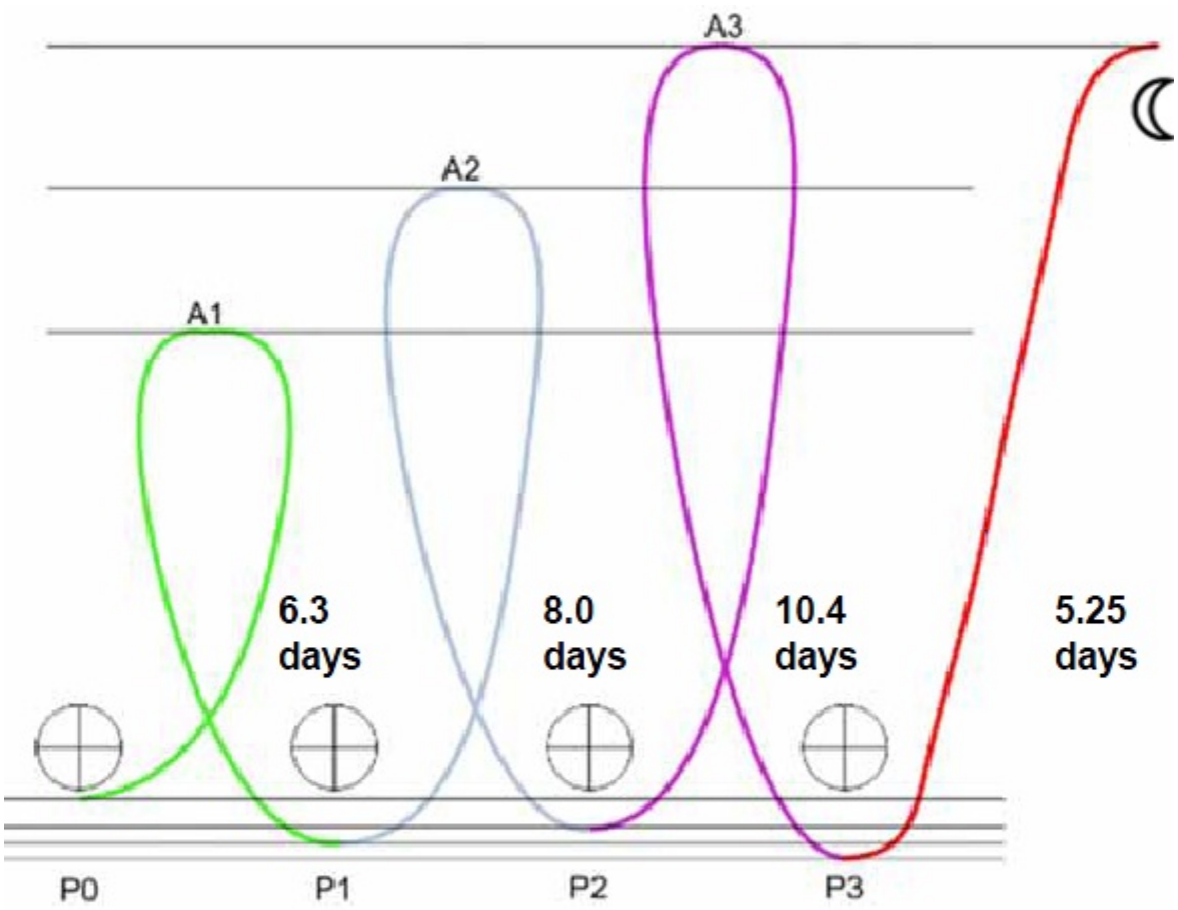
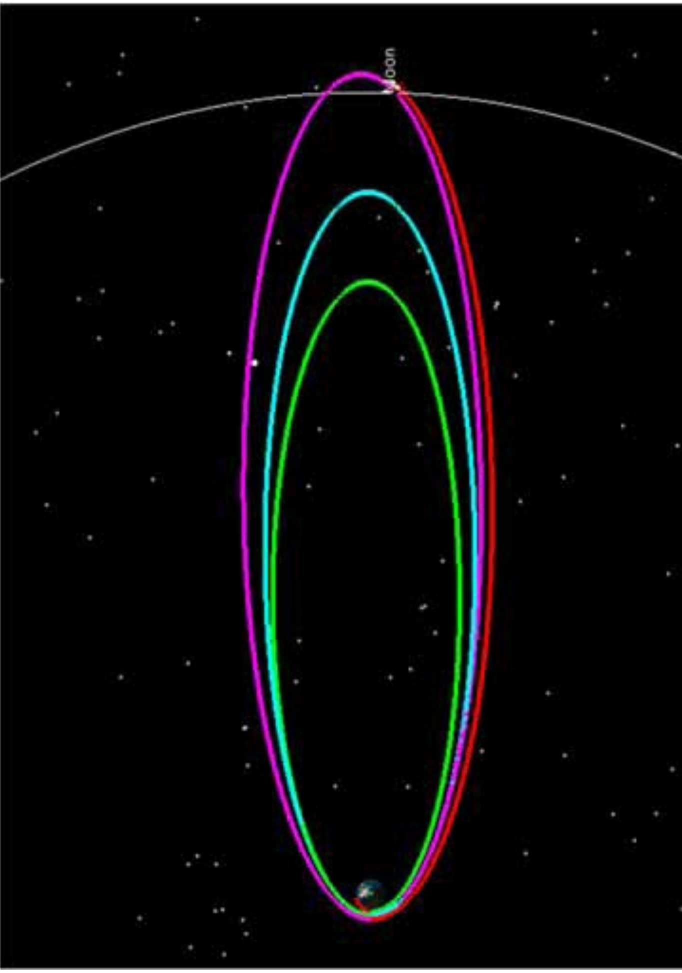
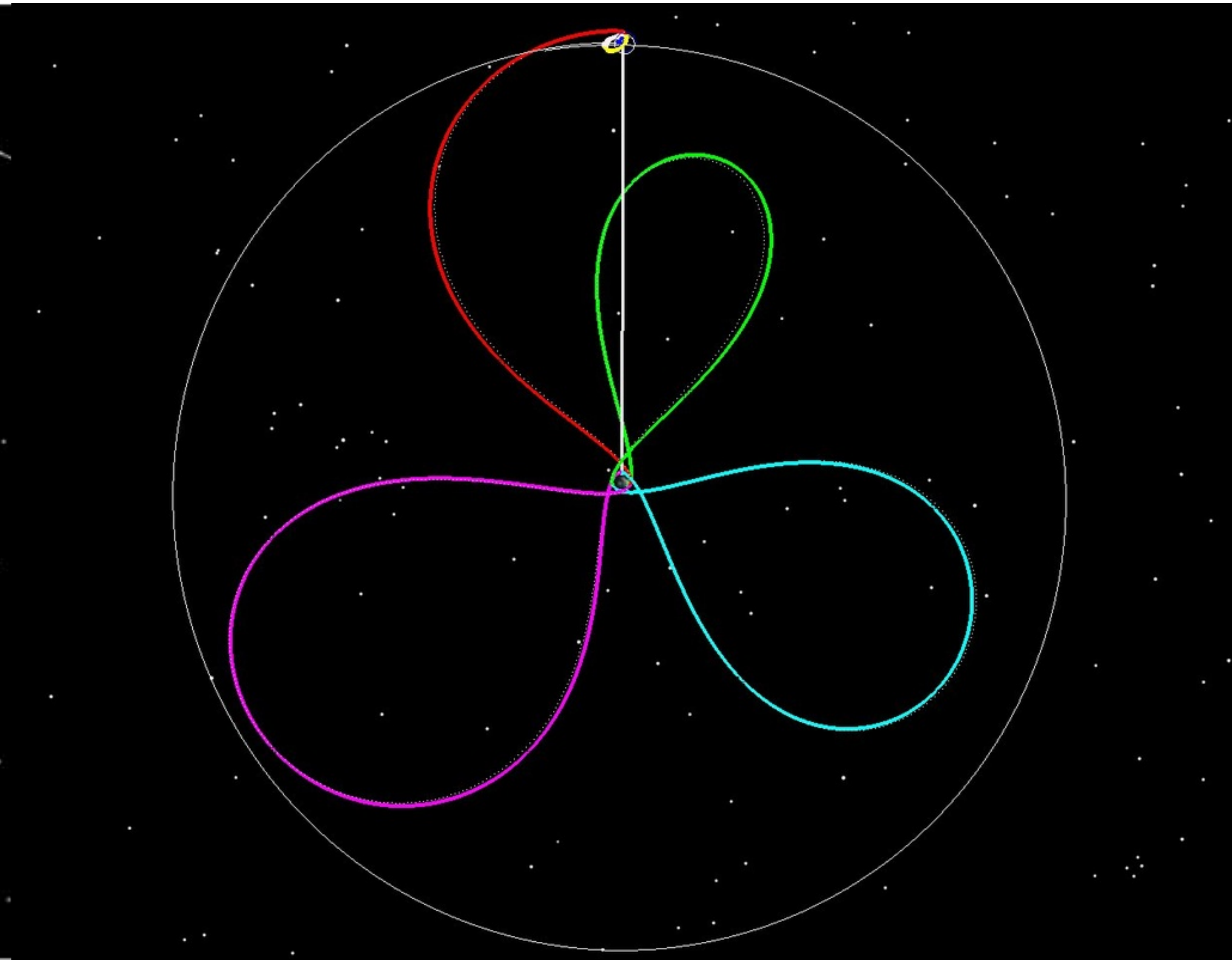
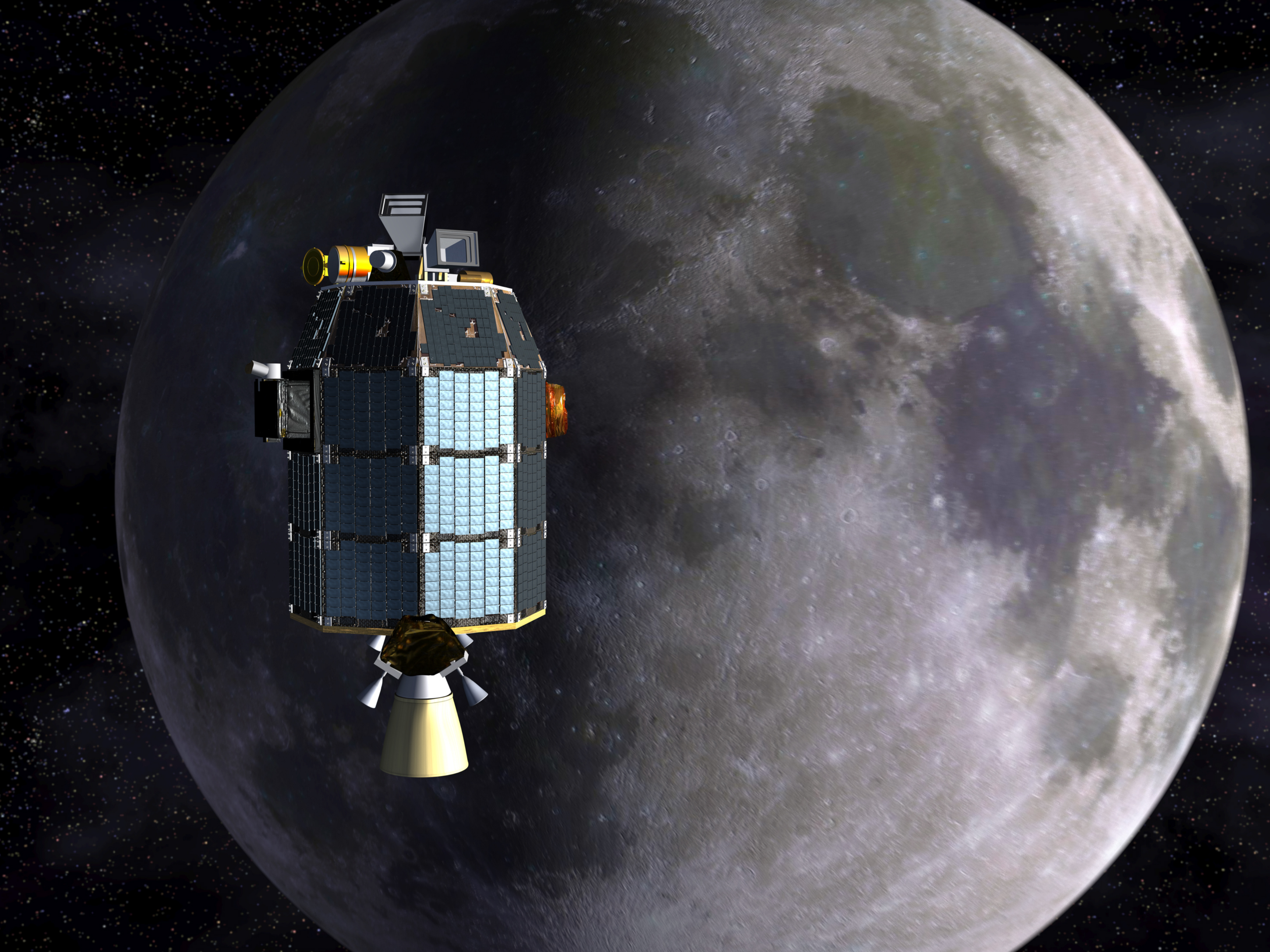
T004


OVERSIZE LOAD
DIGGING & RIGGING

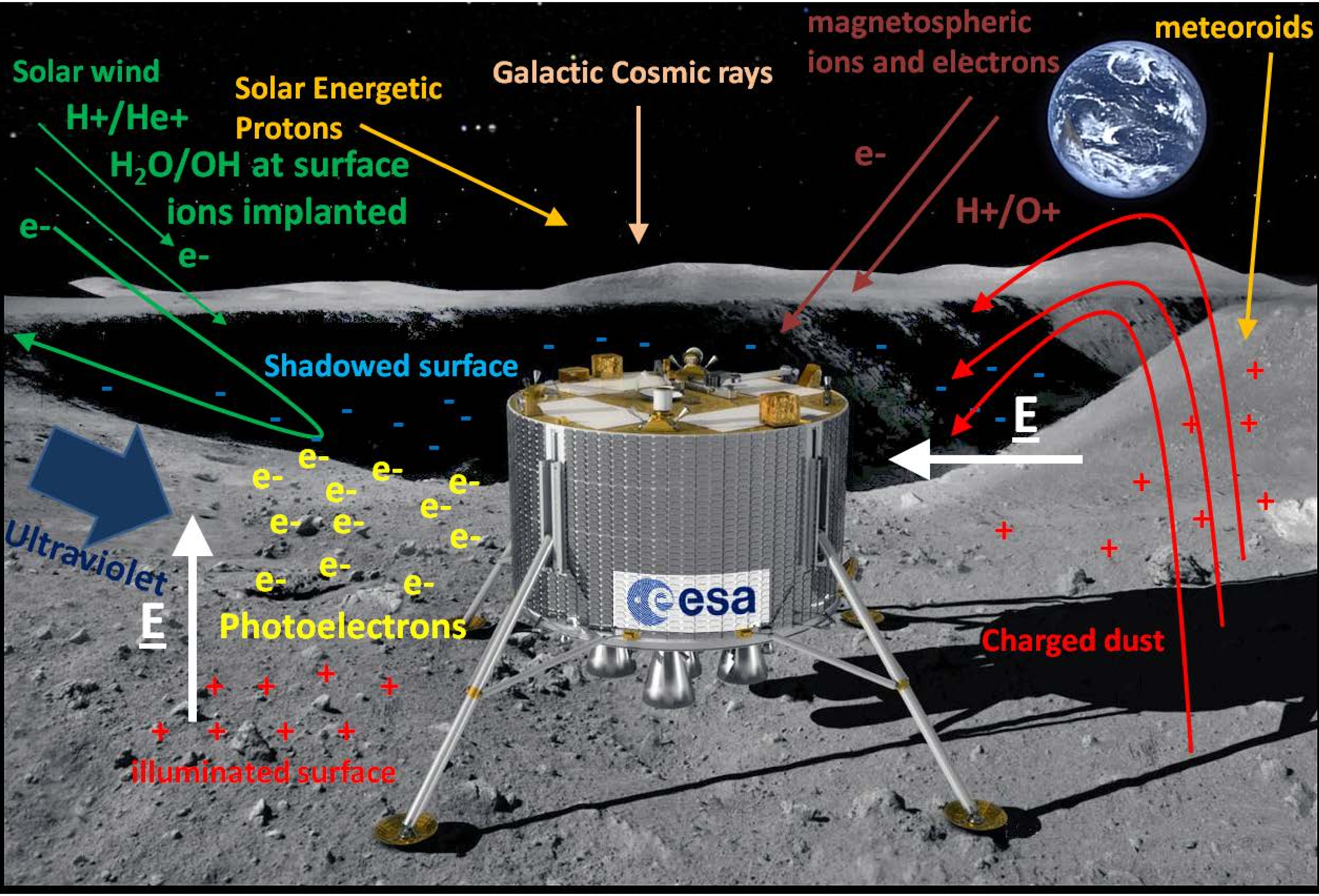

A3
A2
A1
6.3
days
8.0
days
10.4
days
5.25
days
P0
P1
P2
P3



SUMMARY

- Dusty plasma issues are relevant to a number of in situ and remote sensing observations.
- The analysis and interpretation of particles and fields, and dust measurements cannot be done one instrument at a time.
- LADEE will make observations around the Moon.



Solar wind
H+/He+
H_2O/OH at surface
ions implanted
e-
e-
Solar Energetic
Protons
Galactic Cosmic rays
magnetospheric
ions and electrons
e-
H+/O+
meteoroids
Shadowed surface
E
Ultraviolet
E
Photoelectrons
illuminated surface
Charged dust
esa