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# BOUNDING EXTREME SPACECRAFT CHARGING IN THE LUNAR ENVIRONMENT

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## Abstract

Robotic and manned spacecraft from the Apollo era demonstrated that the lunar surface in daylight will charge to positive potentials of a few tens of volts because the photoelectron current dominates the charging process. In contrast, potentials of the lunar surface in darkness which were predicted to be on the order of a hundred volts negative in the Apollo era have been shown more recently to reach values of a few hundred volts negative with extremes on the order of a few kilovolts. The recent measurements of night time lunar surface potentials are based on electron beams in the Lunar Prospector Electron Reflectometer data sets interpreted as evidence for secondary electrons generated on the lunar surface accelerated through a plasma sheath from a negatively charged lunar surface. The spacecraft potential was not evaluated in these analyses and therefore represents a lower limit to the magnitude of the lunar negative surface potential.

This paper explores the implications of spacecraft charging on the value of lunar surface potentials obtained from the energy of electron beams measured in low lunar orbit. We first model the Lunar Prospector spacecraft potentials using a Nascap-2k surface charging analysis to evaluate spacecraft potential differences between the spacecraft structure and the ambient plasma environment in lunar orbit. The potential difference between the spacecraft and plasma environment is then added to the potential difference between the lunar surface and the ambient space environment to obtain the total potential difference between the lunar surface and the spacecraft. An estimate of the true lunar surface potential is then obtained by equating the electron beam energy measured in lunar orbit to the energy gained by an electron as it moves from the lunar surface potential to the potential of the spacecraft. This method provides a bound for the magnitude of the true lunar surface potential.

## Introduction

Charging of surfaces in the lunar environment due to unequal collection of electron and ion currents from the plasma environment has been of interest since the early days of lunar exploration. Theoretical studies initially predicted that lunar potentials would range from values of a few tens of volts positive in daylight to hundreds or even thousands of volts negative in darkness [Opik and Singer, 1960; Grobman and Blank, 1969; Freeman et al., 1973; Knott, 1973; Manka, 1973; Freeman and Ibrahim, 1975]. The predictions validated by in-situ measurements of charged particles on the lunar surface which showed potentials of about +10 volts in daytime [Freeman et al., 1973], -50 volts to -100 volts at the terminator [Lindeman et al., 1973; Bensen, 1977].

Potentials of the lunar surface at night have more recently been inferred from Lunar Prospector Electron Reflectometer data to be on the order of tens to hundreds of volts negative on the average [Halekas et al., 2002, 2005a,b] with extremes of a few kilovolts negative [Halekas et al., 2007]. The technique used to infer the potential of the lunar surface at night is a remote sensing technique based on the Electron Reflectometer electrostatic analyzer measurements of electron

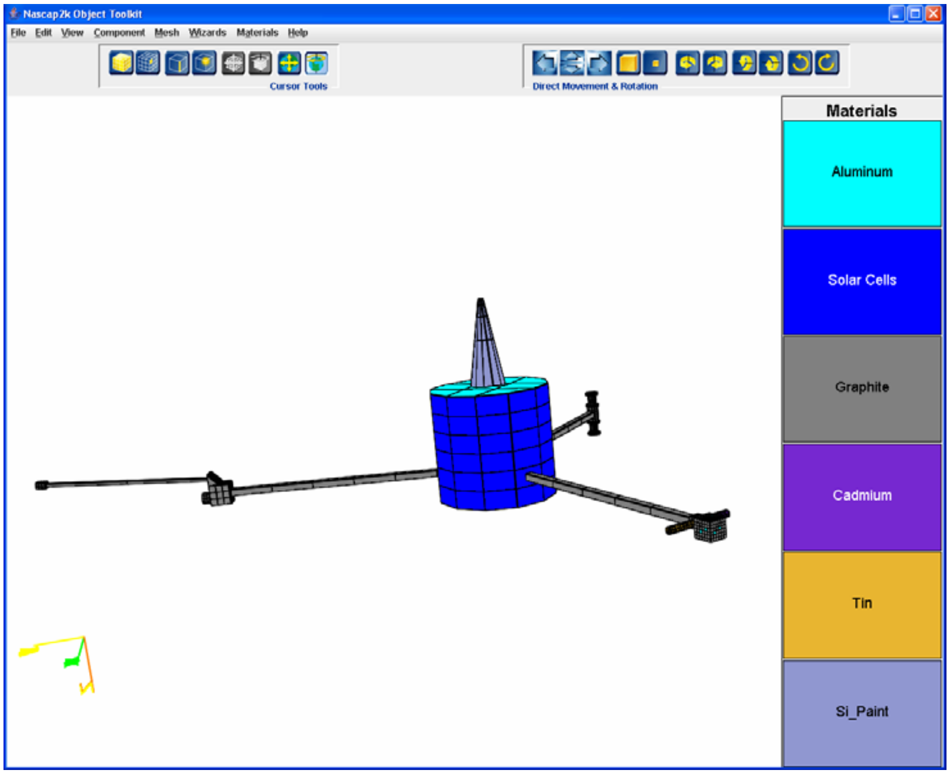


**Figure 1.** Candidate Lunar Prospector model using the Object Tool Kit module of Nascap-2k. Material used on the spacecraft surface are identified by the color coding on the right of the figure.

distribution functions in low lunar orbit [Halekas et al., 2002]. Electron beams which appear to arrive from the direction of the Moon are interpreted as arising from low energy (approximately a few eV) secondary electrons accelerated upward through the potential difference between the lunar surface and the spacecraft. Spacecraft potentials are not available from the Lunar Prospector data set so the lunar potentials provided by the electron beam energy represent at best a lower limit on the magnitude of the true lunar surface potential [Halekas et al., 2002, 2005a].

The goal of the paper is to explore the implications of non-zero spacecraft potential on remote sensing techniques used to estimate lunar surface potentials from electron flux measurements in low lunar orbit. Our study discusses the NASA and Air Force Charging Analyzer Program (Nascap)-2k surface charging results for a candidate Lunar Prospector spacecraft and their implications to final lunar surface potentials when results are added to potential measurements of the moon reported in Halekas et al, 2005b and Stubbs et al., 2006a.

Charging analyses were performed using the Nascap-2k surface charging code. Cases were performed using environments from these papers and extrapolating free field, 150° wake, and 180° wake plasma environment parameters. All six environments were run with the Nascap-2k code in eclipse, while the free field environments from Environments 1 and 2 (see Table 1 for specific number densities and temperatures) were additionally run in sunlight.

## Spacecraft Model

The Lunar Prospector model used for this study was built using the Object Toolkit (OTK) Module for the Nascap-2k surface charging code. Materials and dimensions used are not guaranteed to be exact. They are the best estimate of the authors at the time of the paper. The body of the spacecraft has solar cells on the sides and aluminum on the top and bottom. The antenna is covered with a silicon paint, which uses the Kapton (insulating) default material properties. The booms leading to the instrument

**Table 1. Lunar Charging Environments**

| | $N_e$ ($cm^{-3}$) | $N_i$ ($cm^{-3}$) | $T_e$ (eV) | $T_i$ (eV) | $\phi_{moon}$ (volts) | $\phi_{SC}$ calculated using Nascap-2k (volts) | |
|---|---|---|---|---|---|---|---|
| Environment 1* | | | | | | | |
| Free Field 0° | 7.88 | 7.88 | 14.5 | 8.09 | +40 | -28 to -2 (sunlight) | -32 to -17 (eclipse) |
| Wake 150° | 0.094 | 0.094 | 110 | 110 | -294 | 0.6 to 2.5 (eclipse) | |
| Wake 180° | 0.0234 | 0.0234 | 65.3 | 65.3 | -296 | 0.2 to 2.0 (eclipse) | |
| Environment 2[ξ] | | | | | | | |
| Free Field 0° | 3 | 3 | 14 | 14 | +0 | -24 to 4 (sunlight) | -32 to -17 (eclipse) |
| Wake 150° | 0.010 | 0.010 | 45 | 45 | -175 | -12.2 to -9.8 (eclipse) | |
| Wake 180° | 0.005 | 0.005 | 50 | 50 | -200 | -0.15 to 0.6 (eclipse) | |

*Halekas et al. [2005]
[ξ] Stubbs et al. [2006a]

packages, the bottom of the spacecraft, and most of the surface area of the instruments are covered with the Nascap-2k default material, graphite. This yields conductive material properties, consistent with good spacecraft design. The neutron spectrometer consists of two cylinders, one covered in cadmium and the other covered in tin. These are user defined materials in Nascap-2k and are basically the same material properties as the default material, aluminum. The alpha particle spectrometer is a box co-located with the neutron spectrometer. The box is covered with graphite with aluminum plates on five of the six sides. All materials, including the instrument packages, are grounded to the spacecraft structure. Figure 1 shows the OTK model of Lunar Prospector that will be used for the Nascap-2k analyses in this report.

## Environment

Environment input parameters for the surface charging studies described in this report are given in Table 1. We have adopted these values because they include lunar surface potentials inferred from Lunar Prospector Electron Reflectometer observations of electron beams from low lunar orbit [Halekas et al., 2002, 2005b] and the corresponding solar wind plasma density and temperature environments required for input to the Nascap-2k charging code.

Environment 1 free field environments are obtained from Table 1 of Halekas et al., 2005b where solar wind measurements from the Wind spacecraft are used to establish upstream plasma conditions external to the lunar wake (0 degrees from the wake axis). Wake plasma parameters are obtained from the electron density and temperature ratios as a function of angle from the wake axis given in Figures 11 and 12 of Halekas et al., 2005b. Parameters used to extract appropriate electron density and temperature values within the lunar wake are:

- $N/N_o$ for 0°, 150°, and 180°, respectively, are approximately 1.000, 0.005 and 0.003,
- $T/T_o$ for 0°, 150°, and 180°, respectively, are approximately 1.0, 7.6 and 4.5, and
- Potential for 0°, 150°, and 180°, respectively, are approximately +40, -294, and -296 volts for Halekas et al., 2005b and +0, -175, and -200 volts for Stubbs et al., 2006a..

Kappa temperatures are converted to Maxwell-Boltzmann temperatures using the relation

$$T_{MB} = \left[ \frac{\left( \kappa - \frac{3}{2} \right)}{\kappa} \right] T_{\kappa} \qquad (1)$$

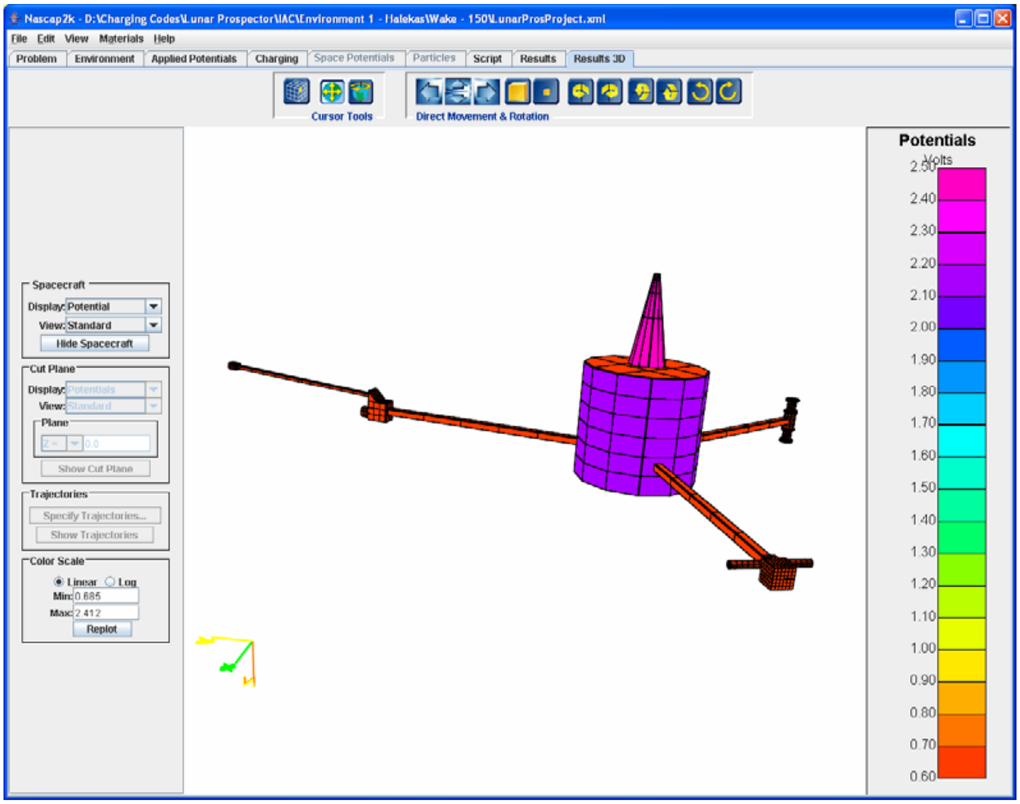

**Figure 2**. Nascap-2k Lunar Prospector Surface Potentials plot using the wake-150° environment of Halekas et al., 2005 using the candidate Lunar Prospector model in Nascap-2k in darkness.

where the Maxwell-Boltzmann temperature $T_{MB}$ and the kappa temperature $T_\kappa$ are related by the kappa parameter, $\kappa$. $T_\kappa$ values derived from fits to the Lunar Prospector electron records are converted to Maxwell-Boltzmann temperatures for use here because Nascap-2k currently only considers Maxwell - Boltzmann velocity distributions when computing current densities in the charging models that are being considered here. Quasi-neutrality is assumed, consistent with assumptions used by previous authors in analysis of lunar wake charging processes [Halekas et al., 2002; Stubbs et al. 2006a,b] and Ti ~ Te is similarly assumed within the wake [Stubbs et al. 2006a,b] although Halekas et al. 2002 assume that $T_i$ ~ 0.2 $T_e$ within the wake regime.

Environment 2 are derived from Lunar Prospector results given in Figure 3 of Stubbs et al. [2006a] with the assumption of quasi-neutrality and $T_i \sim T_e$ within the wake.

## Charging Results

For this study, eight different charging runs were preformed with six different environments. Environments used were taken from Halekas et al., 2005b and Stubbs et al., 2006a and modified for a free field, 150° wake, and 180° wake environments. All six environments were run in darkness/eclipse, while both free field environments were additionally run in full sunlight for comparison. The sunlight runs had sun at full intensity in the negative x direction with the photoemission spectrum on. All runs went to equilibrium.

### Environment 1

Charging results given in this section were performed using the environment modified from Halekas et al, 2005b. The first four cases outlined below are: free field 0° in sunlight, wake 150°, wake 180°, and free field 0° with the last three in eclipse.

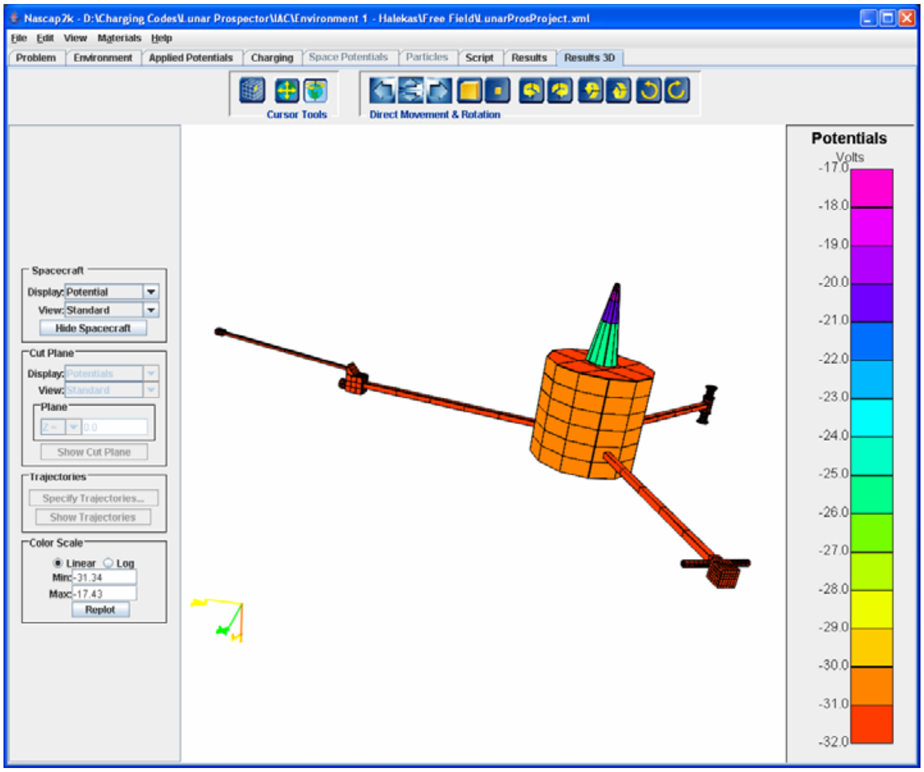


**Figure 3**. Nascap-2k Lunar Prospector Surface Potential in Darkness. The free field environment of Halekas et al., 2005 defines the charging environment.

Free Field 0° - sunlight

Differential charging for the free field case in sunlight using Environment 1 ranged from -28 to -2 volts. Ground and exposed conductors were -5.4 volts. This is considerably more positive than the later run in darkness using this same free field environment. This highlights the results of the photoelectric effect of materials in sunlight. The differential charging of the solar arrays on the light side were -12.8 to -4.5 volts. The solar arrays that were in darkness charged to -27.4 volts. The silicon paint on the antenna charged between -11.6 and -5.9 volts. The larger negative potentials are results from shadowed regions on the model.

Wake 150° - darkness

The differential charging of the 150° wake environment ranged from 0.6 to 2.5 volts. Outside materials with graphite and aluminum coverings as well as spacecraft ground charged to 0.9 volts. The solar cells charged to 2.1 volts and the antenna (silicon paint) charged to 2.4 volts, both with no or very little variability. Refer to Figure 2 for surface potential results of this run.

Wake 180° - darkness

Differential charging levels for this case were minor, ranging from 0.2 to 2.0 volts. Coverings with graphite and aluminum and spacecraft ground charged to 0.3 volts. The solar cells charged to 0.9 volts and the antenna charged to 1.9 volts.

Free Field 0° - darkness

This case was run to compare surface charging results of sunlit and eclipsed spacecraft in the same environment. The differential charging of the free field environment ranged from a minimum of -32.0 to a maximum -17.0 volts. Surfaces covered in graphite and aluminum (i.e., conductors) and ground charged to -31.3 volts while the solar cells charged to -30.3 volts. The silicon paint covering the antenna had the most variability with a range of -26 volts closest to the spacecraft body to -18 at the top of the antenna.

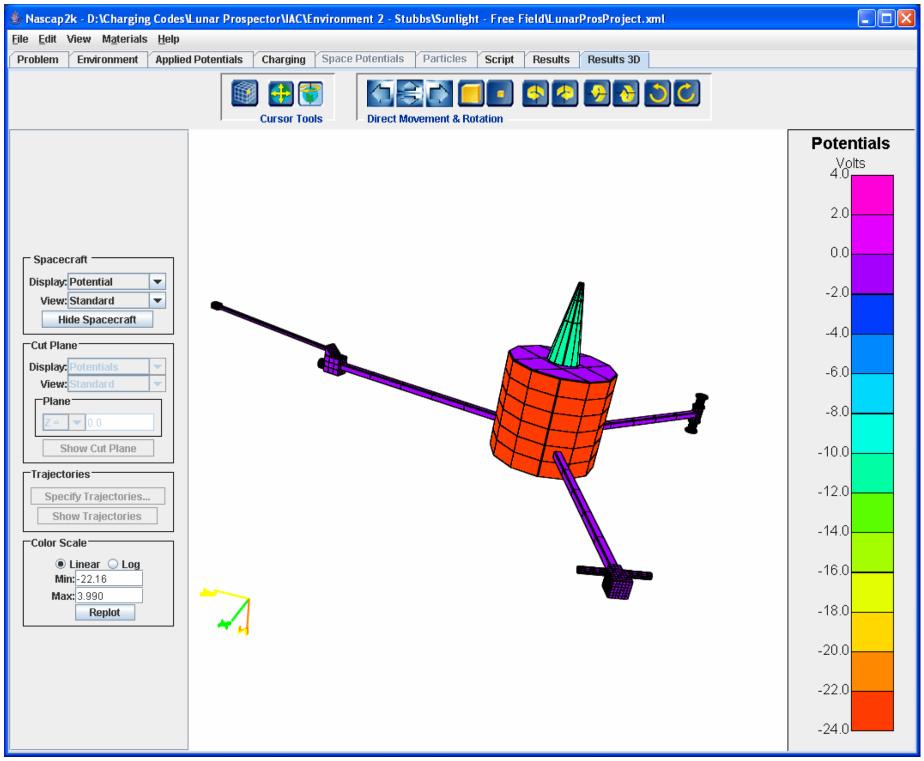


**Figure 4**. Nascap-2k Lunar Prospector Surface Potentials in Sunlight. The free field environment of Stubbs et al., 2006a defines the charging environment used in the charging analysis.

Recall this particular case is in darkness and one would expect minimal to no differential charging on the solar array materials as well as minimal charging for the various dielectric materials due to no photoelectric effect. Refer to Figure 3 for a surface potential plot of results in Nascap-2k.

Environment 2

In this section we show results using environments from Stubbs et al., 2006a. The free field environment was run in sunlight and darkness, while the 150° wake and 180° wake runs were in darkness.

Free Field 0° - sunlight

Differential charging levels ranged from -24 to 4 volts positive for the free field environments using Environment 2 with sunlight on at full intensity. Ground and exposed conductors charged to -0.7 volts. The solar arrays ranged in potential from -0.9 to 2.0 volts on the sunlit side, while the arrays charged to -22.2 volts in darkness. Silicon paint on the antenna charged between -5.3 to -1.5 volts in sunlight to -10.3 volts in darkness. Refer to Figure 4 for results of the surface potentials for this run.

Wake 150° - darkness

Differential charging for the 150° wake case in darkness ranged from -12.2 to -9.8 volts. Spacecraft ground and exposed conductors charged to -12.1 volts. Solar cells charged to -11.9 volts. And the antenna had minimal differential charging of -10.4 at the area closest to the spacecraft to -9.9 volts at the top.

Wake 180° - darkness

Very minimal differential charging occurred for this case as well, with a range of -0.15 to 0.6 volts over the entire spacecraft structure. Ground and other exposed conductors charged to -0.14 volts. Solar cells charged mostly to -0.02 volts with areas connecting to the booms charging to -0.01 volts. The antenna had differential charging of 0.5 to 0.4 volts.

Free Field 0° - darkness

Differential charging levels for this case ranged from -32 to -17 volts. Graphite, aluminum, and ground all charged to -31.7 volts. The solar cells charged to -31.1 volts. The antenna (silicon paint) had the most variability in differential charging with results from -26.3 volts at points closest to the spacecraft to -17.8 volts at the top.

## Discussion

Electron beams observed in Lunar Prospector Electron Reflectometer records are interpreted as low energy secondary electrons generated by impact of primary energetic electrons and ions on the lunar surface and accelerated through the potential difference between the lunar surface and the spacecraft [Halekas et al., 2002, 2005a]. Beams observed at the spacecraft location will therefore exhibit a kinetic energy given by

$$K_{beam} = q(\phi_{sc} - \phi_{ls}) \quad (2)$$

when the lunar surface is charged negative, where $K_{beam}$ is the kinetic energy of the beam, q it the electron charge, $\phi_{sc}$ is the potential of the spacecraft and $\phi_{ls}$ is the potential of the lunar surface. This result assumes the spacecraft is located outside of the night time plasma sheath so the electron is accelerated through the complete potential difference across the sheath, a reasonable assumption because the minimum altitude for Lunar Prospector operations was approximately 20 km compared to nighttime Debye lengths of 150 – 750 m and the 1 to 2 km scale height of the double layer at night [Halekas et al., 2003].

Electron beam measurements at the location of the Lunar Prospector spacecraft are at best only an estimate of the lower limit of the lunar surface potential because the spacecraft potential must also be included in the analysis. Equation (2) shows that when the spacecraft is charged positive relative to the local plasma environment the energy of the electron beam observed at the spacecraft location is greater than the energy obtained by traversing the plasma sheath. The more typical case of a negative spacecraft potential in darkness will result in a reduction in the beam energy observed at the spacecraft location. Lunar potentials inferred from the electron beam energy in the case of negative spacecraft potentials will be larger than when the spacecraft potential is neglected.

For example, Halekas et al., 2005b infer lunar surface potentials of -294 volts and -296 volts for 150° and 180° wakes, respectively, in the conditions represented by the Environment 1 case described above. The Nascap-2k charging analyses using Environment 1 in darkness give spacecraft ground potentials of +0.9 and +0.3 volts in the 150° and 180° wakes, respectively. The Electron Reflectometer is grounded to the spacecraft frame so the spacecraft ground potential is the same as the Electron Reflectometer potential [Andolz, 1998]. The lunar surface potentials corrected for spacecraft charging are within a volt of the values reported by Halekas et al., 2005b in this case.

In contrast, the Nascap-2k results for the spacecraft ground potential is -12.1 volts and -0.14 volts for the case of the 150° and 180° wakes, respectively, using Environment 2 in darkness. Stubbs et al., 2006a infer a lunar surface potential uncorrected for spacecraft charging of -175 volts and -200 volts for these cases. Correcting for spacecraft potential, the lunar surface potentials are approximately -163 volts and -200 volts, respectively, for the 150° and 180° wakes.

## Acknowledgements

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# Bounding Extreme Spacecraft Charging in the Lunar Environment

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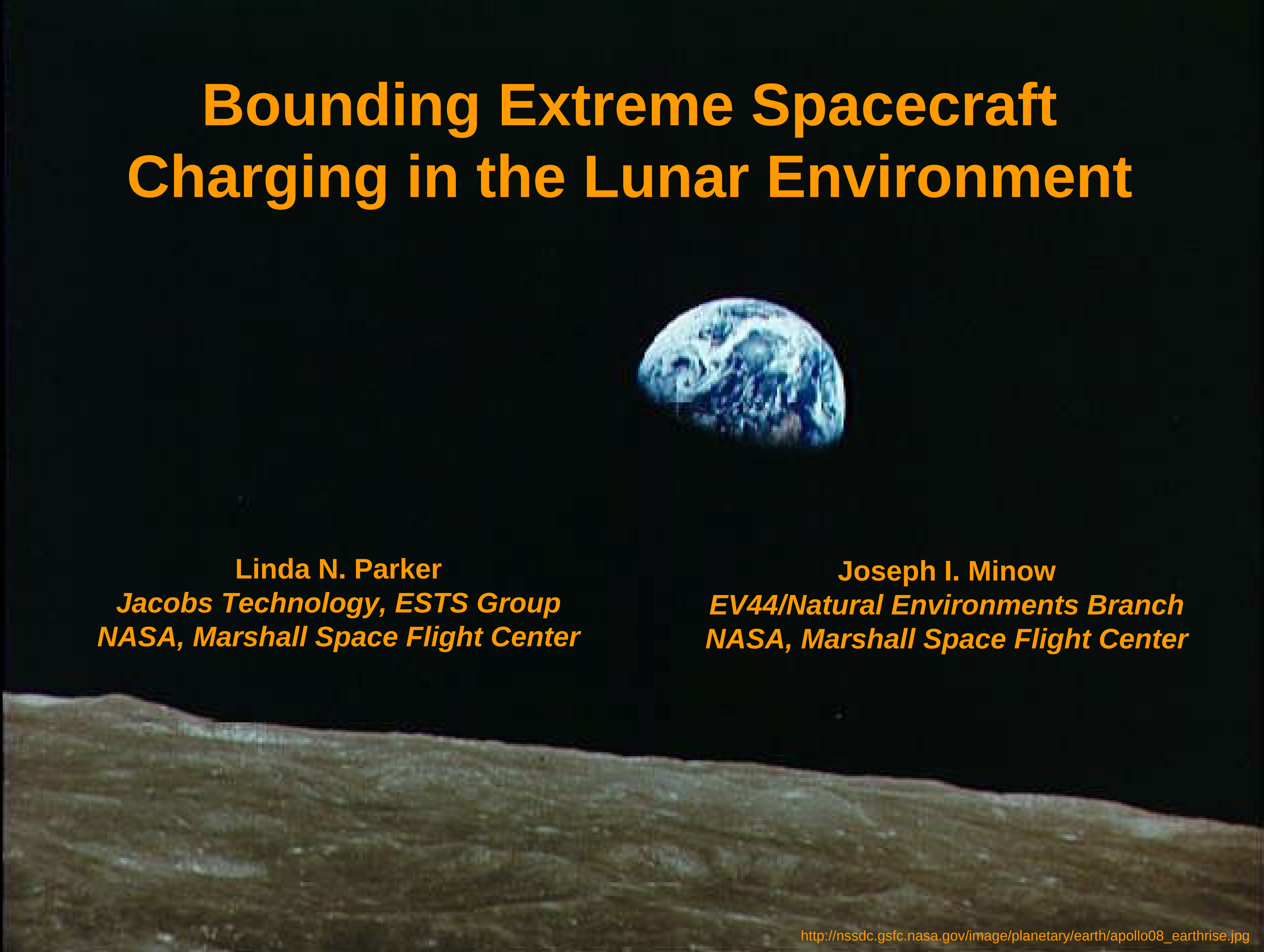

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# Introduction

This presentation describes a method for including effects of spacecraft potential on estimates of lunar surface potentials from spacecraft electron flux measurements in low lunar orbit

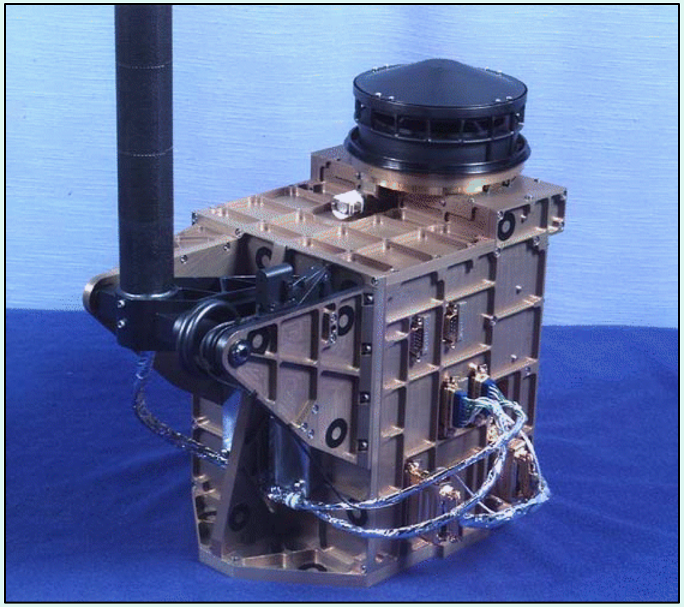
Outline

- Background
- Electron Reflectometer
- Lunar environments
- Nascap-2k Model
- Charging Results

# Background

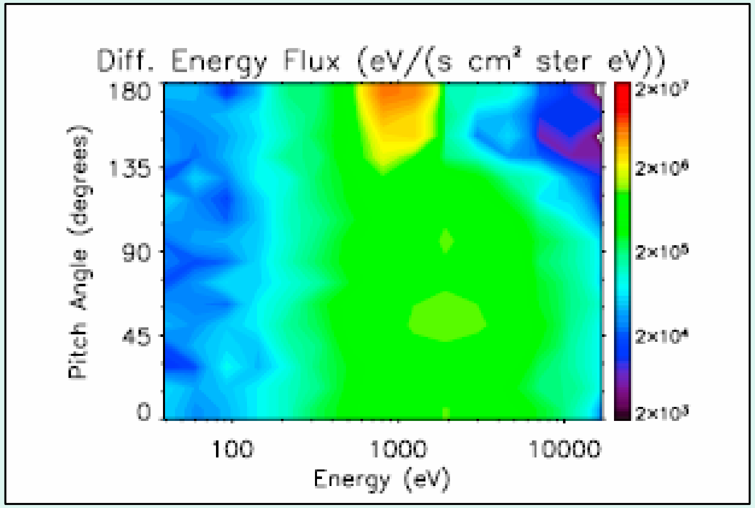
- Theoretical studies initially predicted that lunar potentials would range from values of a few tens of volts positive in daylight to hundreds or even thousands of volts negative in darkness.
- Apollo
  - Daytime few volts positive (+10 volts)
  - Night, hundred volts negative (-50 to -100 volts)
- Lunar Prospector
  - Night, few hundred volts to kilovolts negative

# Electron Reflectometer



http://www.lpi.usra.edu/expmoon/prospector/prospector.html

Electron Reflectometer



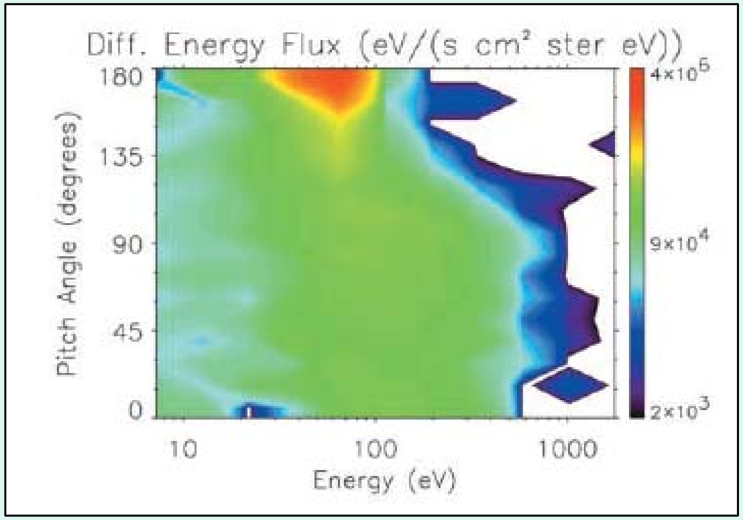

**11 March 1998/15:31 UT:**
**Moon in plasmasheet, LP and conjugate point on lunar surface in shadow [Halekas et al., 2005]**

- **Remote sensing technique used to infer the potential of the lunar surface at night [Halekas et al., 2002].**
- **Electron beams arriving from the direction of the Moon are interpreted as arising from low energy (approximately a few eV) secondary electrons accelerated upward through the potential difference between the lunar surface and the spacecraft.**

# Electron Reflectometer

- Electron beams in ER records are interpreted as electron acceleration signature. (Halekas et al., 2002)

- Low energy secondary electrons generated by primary electron impact on lunar surface accelerated upwards through plasma sheath.

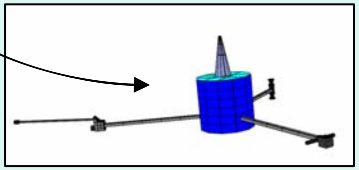



31 March 1999/13:39 UT: Moon in magnetotail, LP in shadow [Halekas et al., 2002]

$\phi_{\text{space}}$

$\phi_{\text{moon}}$

$$K_{beam} \approx q\phi_{moon} = q(\phi_{sc} - \phi_{moon})$$



$\phi_{\text{SC}}$

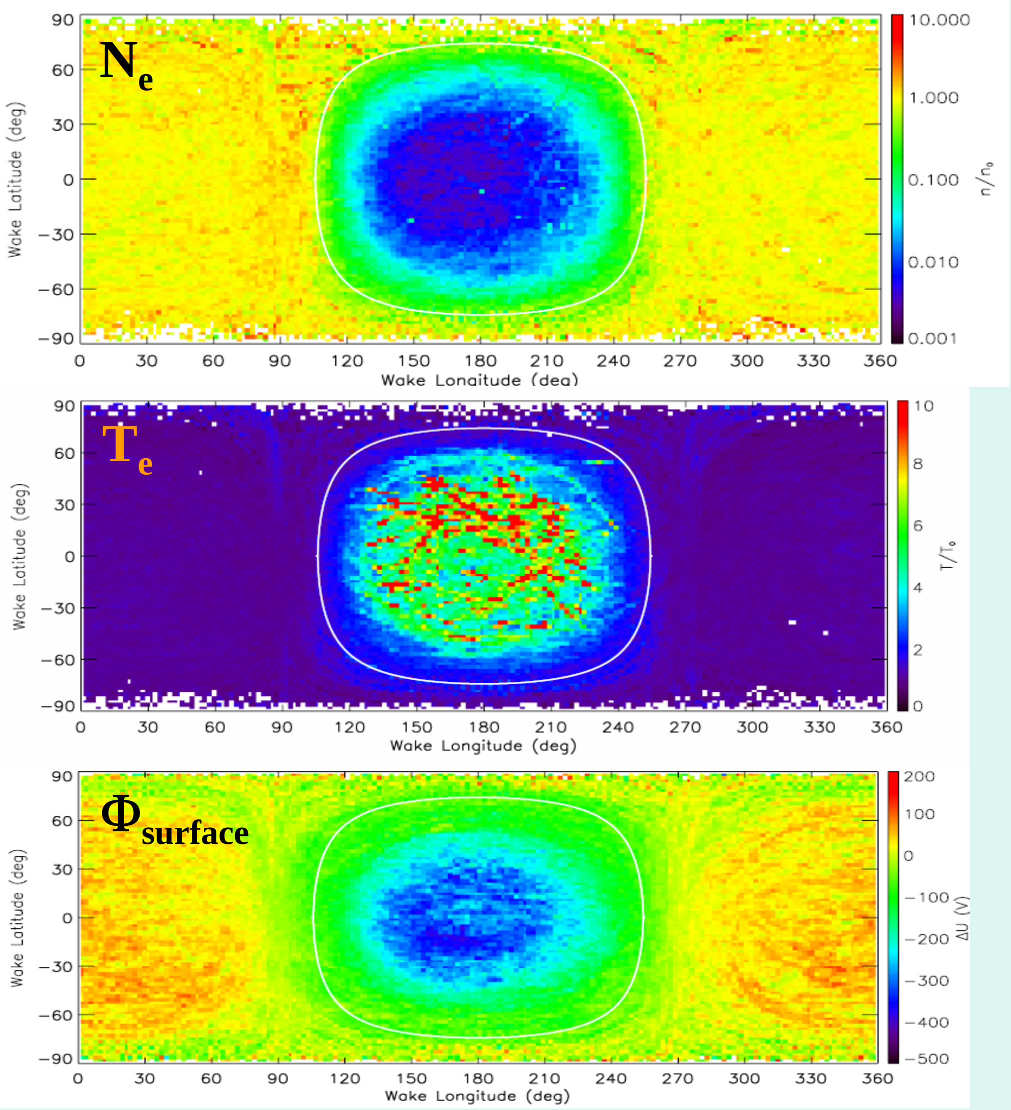
# Charging in Lunar Wake

**Survey of lunar wake electron environments, surface potential**

**--Lunar Prospector ER**

**--20-115 km**

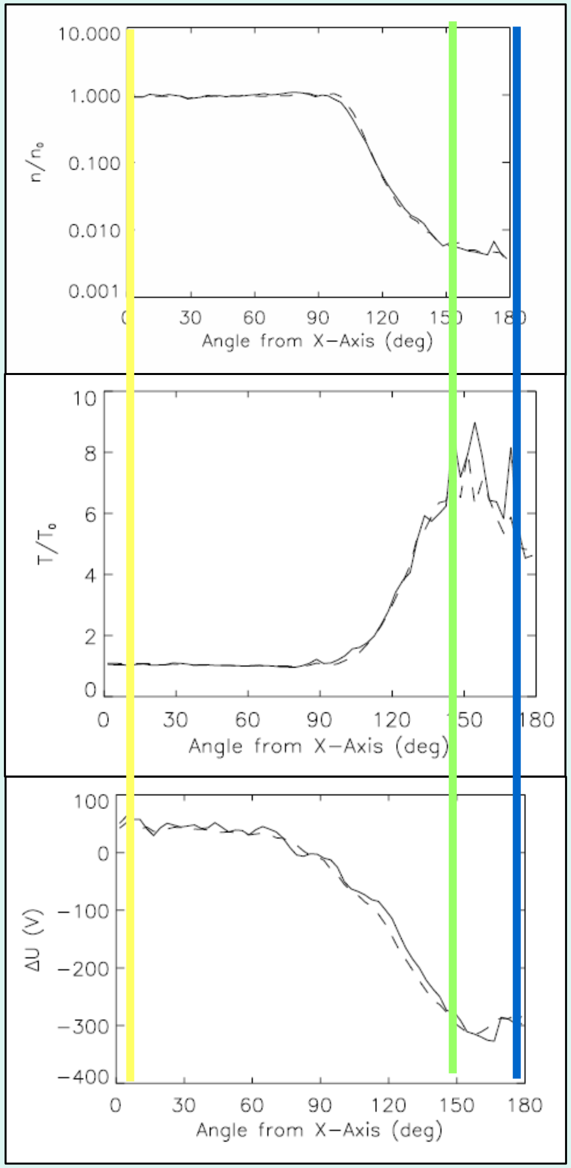
**--Wake properties relative to ambient solar wind**




[*Halekas et al*. 2005]

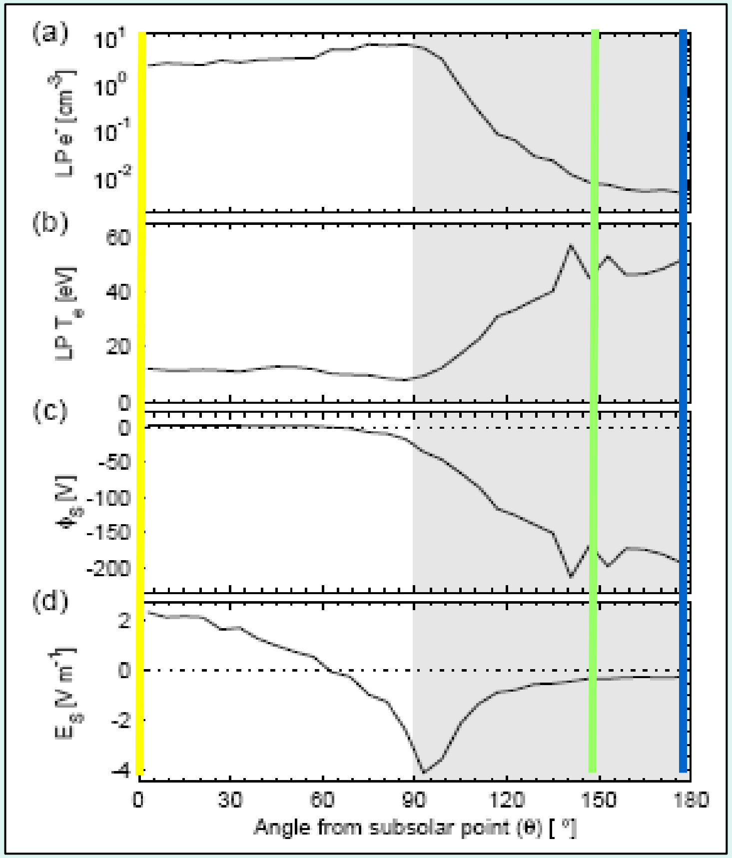
# Halekas Environment Parameters

| | $N/N_o$ | $T/T_o$ | $\phi_{moon}$ (volts) |
|---|---|---|---|
| 0° | 1.0 | 1.0 | +40 |
| 150° | 0.005 | 7.5 | -294 |
| 180° | 0.003 | 4.5 | -296 |




from Halekas et al. 2005

# Stubbs Environment Parameters




[Stubbs et al., 2006]

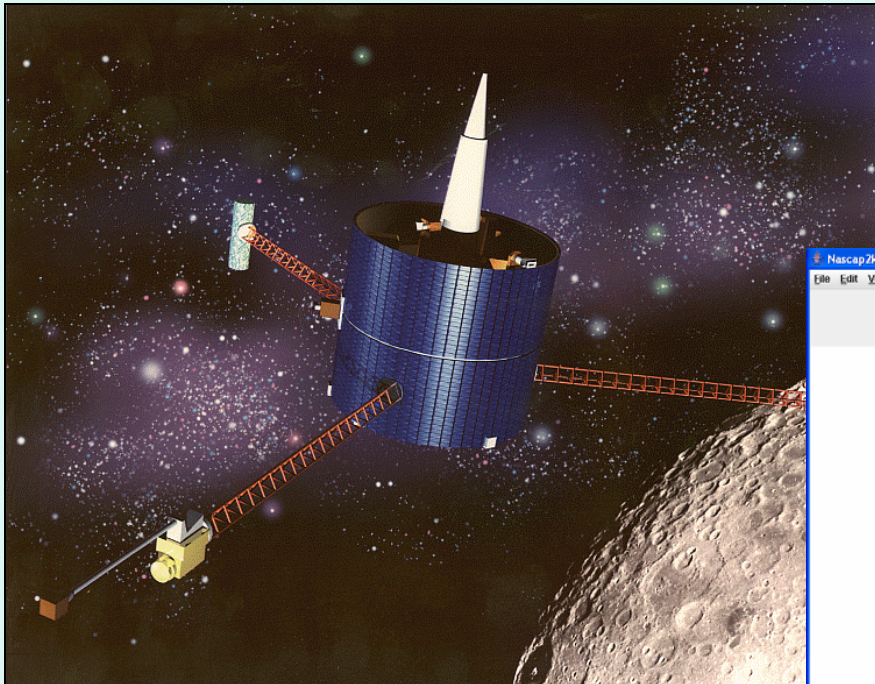
| | N | T | $\phi_{moon}$ (volts) |
|---|---|---|---|
| 0° | 3.0 | 14.0 | +0 |
| 150° | 0.01 | 45 | -175 |
| 180° | 0.005 | 50 | -200 |

# Lunar Charging Environments

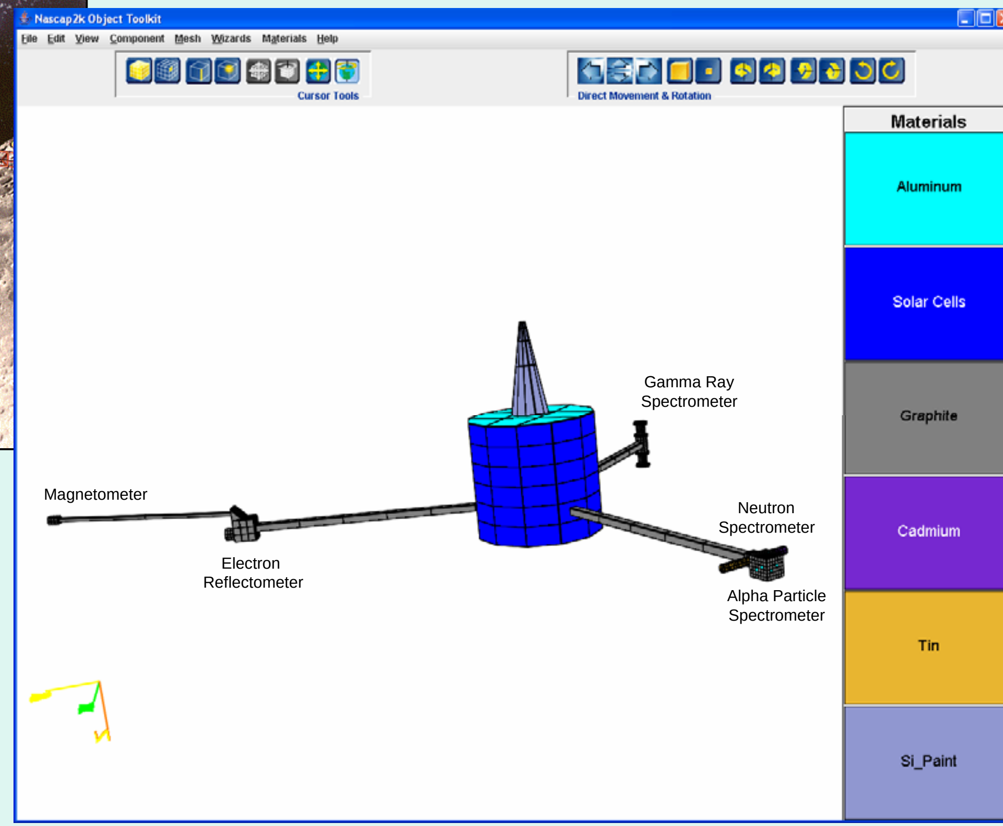
| | $N_e$ ($cm^{-3}$) | $N_i$ ($cm^{-3}$) | $T_e$ (eV) | $T_i$ (eV) | $\phi_{moon}$ (volts) |
|---|---|---|---|---|---|
| **Environment 1 Halekas et al. [2005]** | | | | | |
| **Free Field 0°** | **7.88** | **7.88** | **14.5** | **8.09** | **+40** |
| **Wake 150°** | **0.094** | **0.094** | **110** | **110** | **-294** |
| **Wake 180°** | **0.0234** | **0.0234** | **65.3** | **65.3** | **-296** |
| **Environment 2 Stubbs et al. [2006a]** | | | | | |
| **Free Field 0°** | **3** | **3** | **14** | **14** | **+0** |
| **Wake 150°** | **0.010** | **0.010** | **45** | **45** | **-175** |
| **Wake 180°** | **0.005** | **0.005** | **50** | **50** | **-200** |

$$T_{MB} = \left[ \frac{\left(\kappa - 3/2\right)}{\kappa} \right] T_{\kappa}$$

# Nascap-2k Charging Model



http://www.lpi.usra.edu/expmoon/prospector/prospector.html




Candidate Lunar Prospector model using the Object Tool Kit module of Nascap-2k.

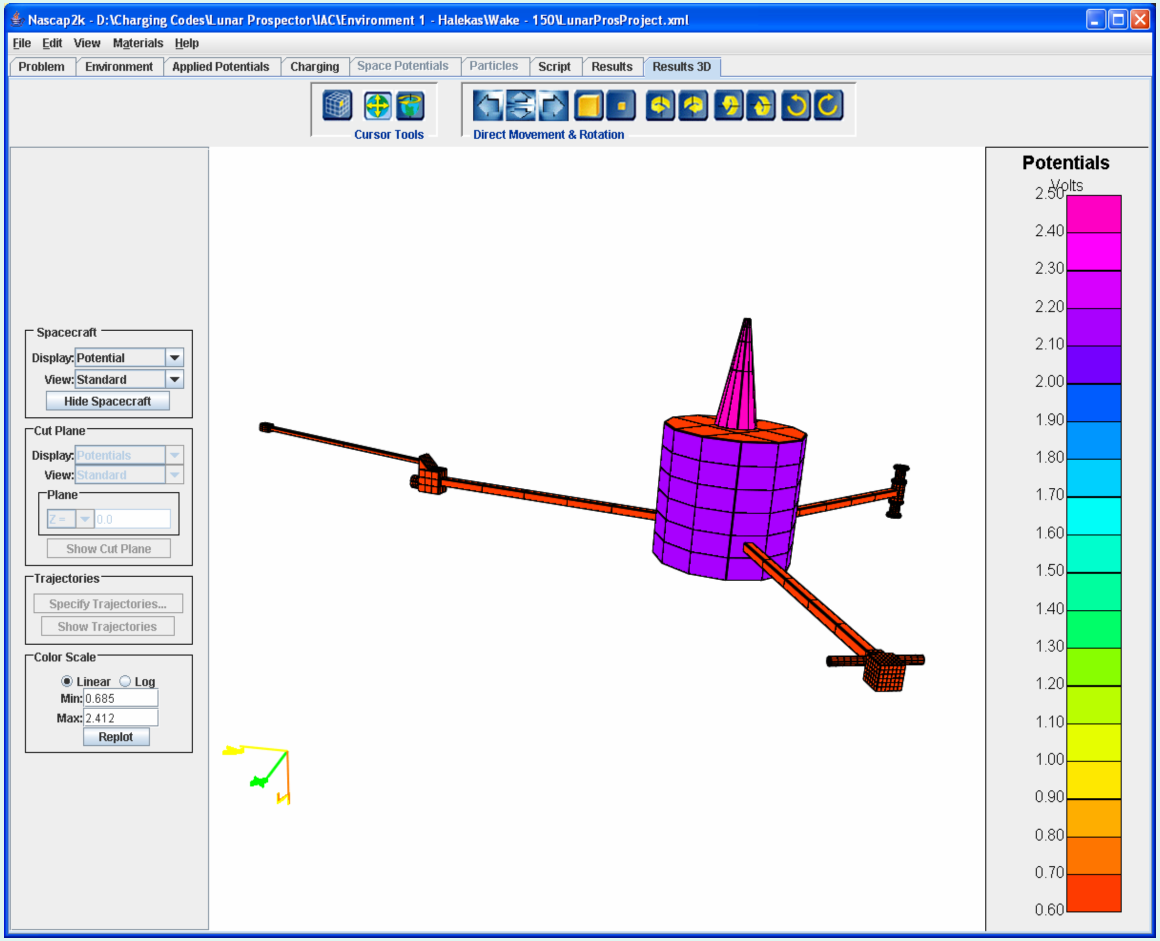
# Nascap-2k Results

Halekas Environment Wake 150°
darkness

$N_e = N_i = 0.094\ cm^{-3}$

$T_e = T_i = 110\ eV$

$\phi_{moon} = -294\ V$
$\phi_{LP} = 0.6 – 2.5\ V$



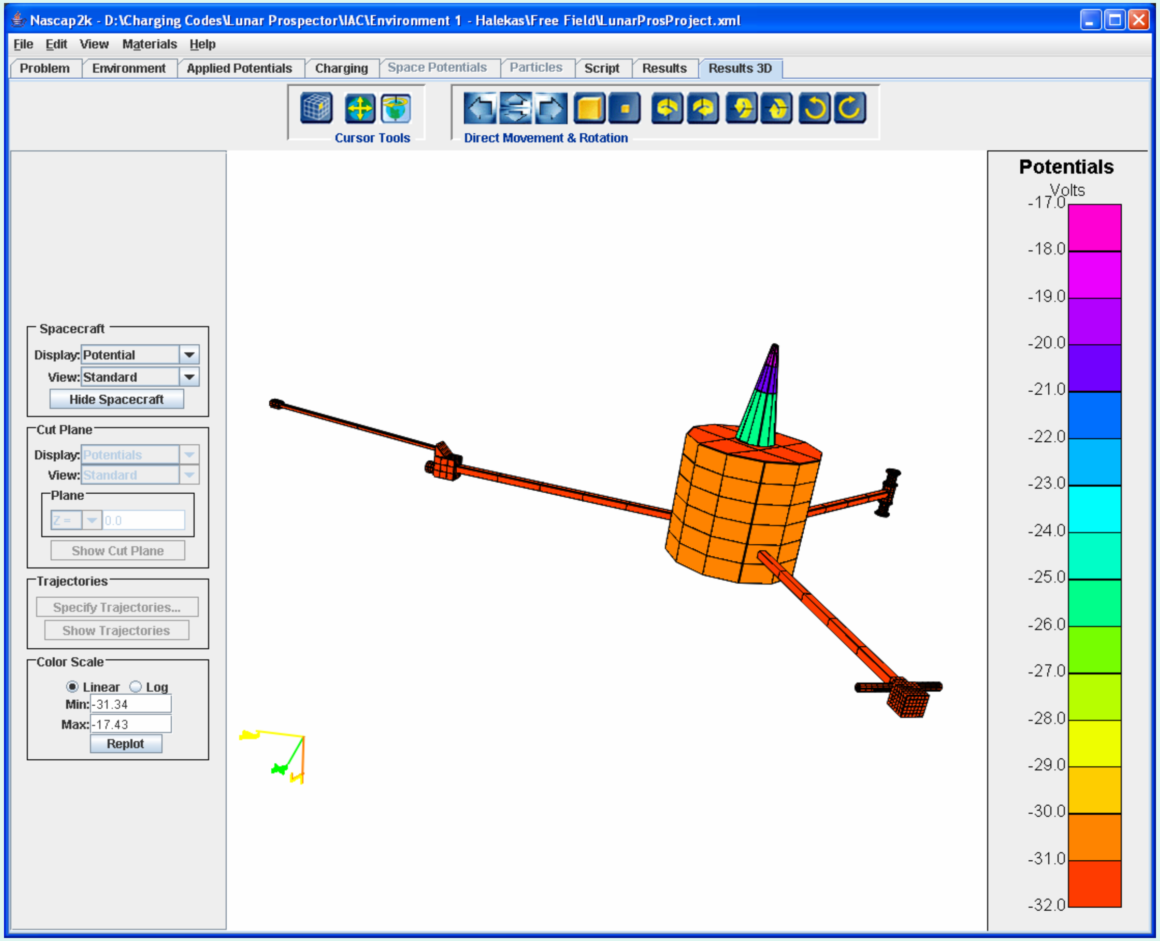
# Nascap-2k Results



Halekas Environment
Free Field
darkness

$N_e = N_i = 7.88\ cm^{-3}$
$T_e = 14.5\ eV$
$T_i = 8.09\ eV$

$\phi_{moon} = 40\ V$
$\phi_{LP} = -32\ to\ -17\ V$



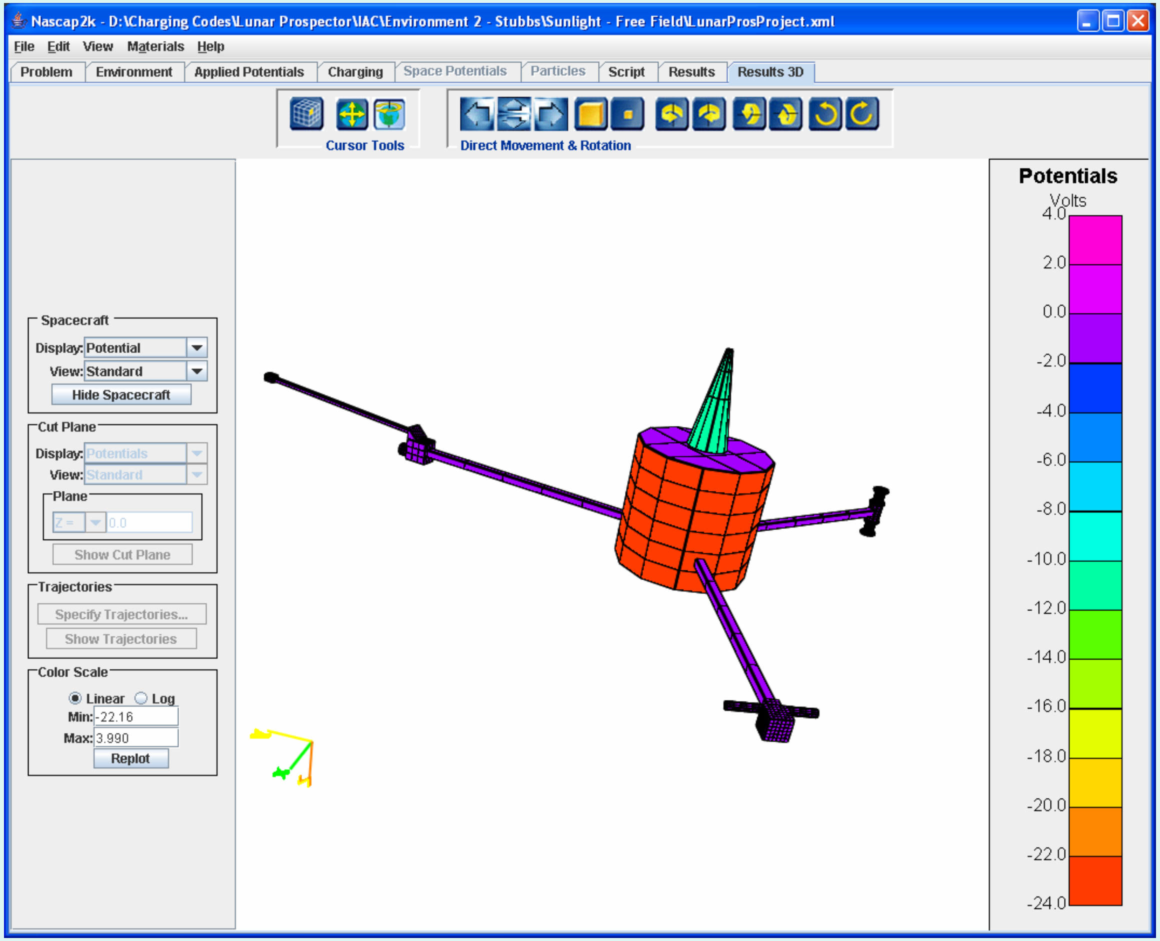
# Nascap-2k Results

Stubbs Environment
Free Field
Sun

$N_e = N_i = 3\ cm^{-3}$

$T_e = T_i = 14\ eV$

$\phi_{moon} = 0\ V$
$\phi_{LP} = -24\ to\ 4\ V$



# Results

| | $\phi_{moon}$ (volts) | $\phi_{SC\ ground}$ Nascap-2k (volts) | Adjusted $\phi_{moon}$ (volts) |
|---|---|---|---|
| **Environment 1 Halekas et al. [2005]** | | | |
| **Free Field 0°** | **+40** | **-5.4 in sunlight and -31.3** | **45.4 And 71.3** |
| **Wake 150°** | **-294** | **~1** | **-293** |
| **Wake 180°** | **-296** | **~0.5** | **-295.5** |
| **Environment 2 Stubbs et al. [2006a]** | | | |
| **Free Field 0°** | **+0** | **-0.7 in sunlight and -31.7** | **0.7 And 31.7** |
| **Wake 150°** | **-175** | **-12.1** | **-162.9** |
| **Wake 180°** | **-200** | **-0.14** | **~ -200** |

$$K_{beam} = q(\phi_{sc} - \phi_{ls})$$