Inferring the scale height of the lunar nightside double layer

J. S. Halekas, R. P. Lin, and D. L. Mitchell

Space Sciences Laboratory, University of California, Berkeley, California, USA

Received 14 August 2003; revised 23 September 2003; accepted 15 October 2003; published 12 November 2003.

[1] Earlier analyses of Lunar Prospector (LP) data found that the shadowed lunar surface charges negative. The potential difference between the surface and LP has unexplained dependences on solar zenith angle and tip angle. The dependence on tip angle may arise because electrons with pitch angles close to the loss cone angle on field lines with higher tip angles encounter a smaller average potential before reflecting (the technique used to infer potentials relies upon loss cone angle measurements). The correlation may therefore be due to a systematic measurement error. However, since this "measurement error" depends upon the ratio of gyroradius to double layer scale height, it allows us to estimate the scale height. By comparing data with the results of particle tracing simulations, we estimate an average nightside scale height of a few km. This is somewhat larger than the electron Debye length, but much smaller than recent theoretical estimates. *INDEX TERMS:* 6250 Planetology: Solar System Objects: Moon (1221); 5421 Planetology: Solid Surface Planets: Interactions with particles and fields; 7815 Space Plasma Physics: Electrostatic structures; 7855 Space Plasma Physics: Spacecraft sheaths, wakes, charging. **Citation:** Halekas, J. S., R. P. Lin, and D. L. Mitchell, Inferring the scale height of the lunar nightside double layer, *Geophys. Res. Lett.*, *30*(21), 2117, doi:10.1029/2003GL018421, 2003.

1. Introduction

[2] Any body in a plasma with comparable electron and ion densities and temperatures charges negative due to the higher current from the more mobile electrons, forming a double layer (where a layer of negative charge on the surface is surrounded by a region depleted in negative charge), unless another current source (e.g., photoemission) exists to prevent charging. The night side of the Moon, where photoemission cannot occur, should therefore charge negative (see, e.g., *Knott* [1973] and *Manka* [1973]). Suprathermal ion data from the SIDE experiment on Apollo 14 indicated lunar potentials of $\sim$100 V negative near the terminator [*Lindeman et al.*, 1973], and a more recent analysis of data from the Magnetometer/Electron Reflectometer (MAG/ER) instrument on LP showed that the lunar night side charges to an average potential of $\sim$35 V negative with respect to the LP spacecraft (and is likely even more negative with respect to the ambient plasma, since LP should also charge negative) [*Halekas et al.*, 2002]. In the solar wind, it is even more negative compared to the solar wind plasma, due to the ambipolar potential drop across the wake boundary identified by *Ogilvie et al.* [1996]. This paper deals mainly with the potential drop near the surface, rather than that across the wake boundary.

[3] The MAG/ER instrument uses vector magnetic field data and measurements of the electron distribution from 10 eV to 20 keV to measure adiabatic electron reflection and thereby infer the strength of crustal magnetic fields [*Lin et al.*, 1998]. In the absence of lunar magnetic and electric fields, ambient electrons travelling along field lines that intersect the surface are almost all absorbed. However, in the presence of lunar magnetic and/or electric fields, some electrons reflect adiabatically. The reflection process depends upon the pitch angle α (the angle between velocity and magnetic field). Reflected electrons are seen up to a cutoff pitch angle α_c, beyond which there is a "loss cone" devoid of particles (where electrons have been absorbed by the surface). If the reflection is purely magnetic, the loss cone is independent of energy; however, if electric fields are also present, the loss cone angle depends on energy. Assuming adiabatic behavior, one can derive that $\sin^2 \alpha_c = B/B_m\ (1 + eU_m/E)$ [*Halekas et al.*, 2002], with B the magnetic field at LP, B_m the field at the surface, E the kinetic energy, and U_m the potential at the surface (assuming zero potential at LP). One can then use measurements of α_c at different energies to determine both the crustal magnetic field magnitude and the potential difference between LP and the surface. Using measurements of 220, 340, and 520 eV electrons, this analysis was performed for the entire LP data set [*Halekas et al.*, 2002].

[4] The initial analysis of data in the solar wind wake found intriguing anti-correlations between the magnitude of the inferred potential difference and both the angle from the sub-solar point (solar zenith angle or SZA) and the angle between the magnetic field and the normal to the surface (tip angle). No convincing explanation for these observations was found, though it was suggested that the dependence on SZA might result from the variation of electron density and temperature on SZA in the wake (density decreases and temperature increases with increasing SZA on the night side), and that the dependence on tip angle might result from differences between electron and ion motion [*Halekas et al.*, 2002].

2. Possible Explanations for Variations in Inferred Potential Difference

[5] Recent theoretical results show that even the low electrical conductivity of the nightside lunar surface may be sufficient to ensure a nearly constant surface potential (due to very low plasma density) [*Borisov and Mall*, 2002]. This suggests a different interpretation of the dependence on SZA. Though the surface potential is nearly constant, the

0094-8276/03/2003GL018421$05.00

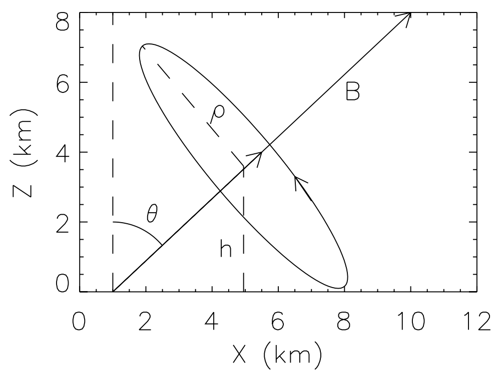

Figure 1. Schematic illustration showing the orbit of an electron with gyroradius ρ on a field line with tip angle θ, at the point of reflection.

spacecraft potential may still change with SZA, with a changing spacecraft potential likely indicating a changing plasma potential. Intriguingly, the ambipolar potential drop across the wake boundary ensures that the center of the wake is at a more negative potential than the wake boundary. If the surface potential is indeed approximately constant, this variation in plasma potential could lead to an anti-correlation between potential difference and SZA like that observed. It remains unclear whether this can explain the observations, especially since the relevant measurements of the wake-associated potential drop were made ~10,000 km down the wake [*Ogilvie et al.*, 1996]. Though the range of parameter space covered by geotail (magnetosphere) data is much smaller, we do not find a similar dependence on SZA, lending support to the hypothesis that the dependence on SZA is related to the solar wind wake interaction.

[6] This hypothesis, of course, does not explain the dependence on tip angle. However, the apparent variation with tip angle may be a result of the technique we use to infer potential differences, which relies critically upon measurements of the loss cone angle. We therefore need to understand what happens to an electron that reflects just before its trajectory intersects the lunar surface. On a field line normal to the surface, an electron's gyrocenter can nearly reach the surface without its orbit intersecting the surface. However, for a field line tilted away from the normal, the gyrocenter cannot reach as close to the surface without some part of its orbit intersecting the surface. This is illustrated schematically in Figure 1. For an electron with gyroradius ρ travelling on a field line with tip angle θ, the gyrocenter will only reach a height of $h = \rho \sin \theta$ above the surface before part of its orbit intersects the surface. For the energies in question and typical magnetic fields, electron gyroradii are on the order of ~2–10 km. If the scale height of the double layer is comparable to or smaller than this, the average potential felt by electrons with pitch angles near the loss cone angle will be significantly smaller on field lines with higher tip angles. Our technique will therefore result in smaller inferred potential differences for higher tip angles, as observed.

3. Simple Quasi-Adiabatic Theory

[7] If the scale height of the nightside double layer is comparable to or smaller than the electron gyroradius, the adiabatic approximation is not valid. However, an adiabatic or quasi-adiabatic approach is often still a good first approximation. We calculate the gyro-averaged potential for an electron that reflects just above the surface. To first approximation, electrons should behave as though they reflect adiabatically in this average potential. We assume an exponential dependence for the potential $U = U_m \exp(-z/\lambda)$, where λ is the scale height, and average this potential over the orbit a ssuming constant velocity. This results in $\langle U \rangle = U_m I_0((\rho/\lambda) \sin \theta) \exp(-(\rho/\lambda) \sin \theta)$, where I_0 is the I Bessel function of order zero. In actuality, the velocity is slightly smaller near the surface where the potential is larger (this can also lead to an electric field drift), and therefore the true gyro-averaged potential is somewhat greater. However, for the electron energies and potentials in question, this is only a small correction, and our approximation should be good enough to get a feeling for the expected dependence on tip angle. We note that the effect should also depend upon the ratio of the gyroradius to the scale height. Any further refinement would be excessive, since electrons will not actually behave adiabatically. Furthermore, we have not taken into account potentially significant gyrophase effects.

4. Simulations

[8] To further investigate the apparent dependence of potential difference on tip angle, we used simulations which do not assume adiabatic behavior. In each simulation we started populations of a few thousand electrons at a nominal spacecraft altitude of 40 km with randomly distributed initial velocities (assuming isotropic initial distributions) and energies of 220, 340, and 520 eV and followed them using a particle tracing code that employed a Runge-Kutta method. We assumed a simple magnetic field geometry with straight converging magnetic field lines and an exponential dependence for the potential as above. We varied the magnetic field ratio, surface potential and scale height for different runs, but held the magnetic field at the surface at 20 nT for all simulations. This value is somewhat higher than the average ambient field of ~10 nT, so is appropriate for a region with some crustal fields. However, the results do not depend strongly on magnetic field ratio, and therefore we can scale the results for different surface magnetic fields (and thus different electron gyroradii).

[9] We followed all downward-going electrons until they either intersected the lunar surface or reflected and returned to the spacecraft altitude, then calculated the loss cone angle of the distribution. For most cases, non-adiabatic scattering was minimal and the loss cone angle distinct and easily determined. However, for the smallest scale heights, especially at tip angles of 15–30°, non-adiabatic scattering made determination of the loss cone angle difficult. For these cases, we used a computer algorithm to fit a step function to the electron distribution, as in the original data analysis. For a few particularly troublesome cases, averages of several runs were necessary to determine a cutoff angle. Once we determined the loss cone angles for all three energies, we fit them to a function (derived above assuming adiabatic behavior) to calculate the potential difference, as in the original data analysis [*Halekas et al.*, 2002]. There is a fair amount of scatter in the inferred potentials, as one might

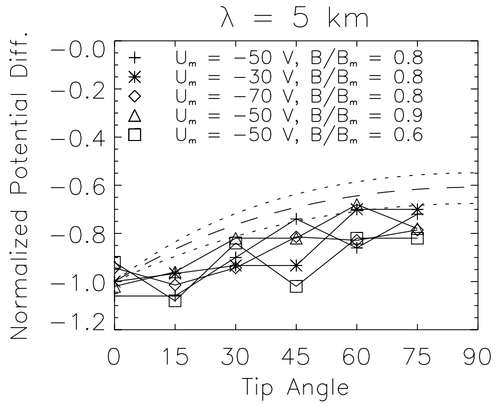

Figure 2. Results of simulations with various lunar surface potentials and magnetic field ratios. Also shown are quasi-adiabatic predictions for the average electron gyroradius (dashed) and the gyroradius corresponding to the minimum and maximum energies (dotted).

expect from the degree of non-adiabaticity and the relatively small number of electrons (not to mention the fact that we fit to a function that assumes adiabaticity, despite clearly non-adiabatic behavior). However, these same sources of error and scatter also affect the original data analysis, so we consider these simulations realistic.

[10] We show simulation results for a scale height of 5 km and a variety of surface potentials and magnetic field ratios in Figure 2. A quasi-adiabatic approximation predicts that the results should be roughly invariant, since each run has the same ratio of gyroradius to scale height. Indeed, within the scatter of the simulation results, we find similar results for all runs. In all cases, as expected, there is a clear trend toward lower inferred potential differences for higher tip angles, though not to the degree predicted by a quasi-adiabatic approximation. The discrepancy may be partly due to the slightly smaller electron velocity near the surface (leading to a slightly higher gyro-averaged potential); however, it seems unlikely that this small correction could explain the offset seen here. Instead, the discrepancy is likely due to truly non-adiabatic effects.

[11] Even for the scale height of 5 km assumed in Figure 2 (comparable to the average electron gyroradius of ~3 km), the effect of tip angle is only moderate, with the ratio of

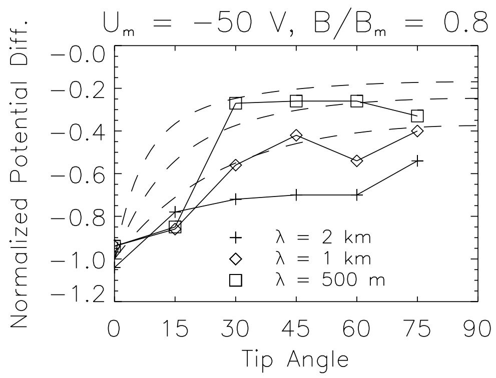

Figure 3. Results of simulations with various double layer scale heights. Also shown are quasi-adiabatic predictions for the same scale heights, for the average electron gyroradius.

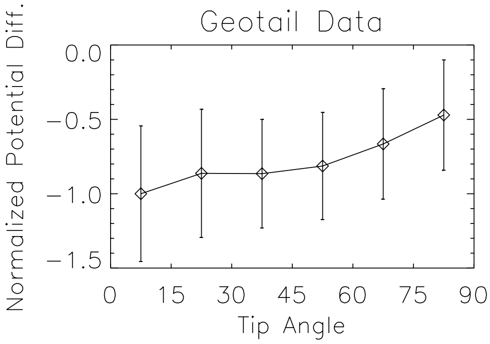

Figure 4. Average tip angle dependence of inferred potential difference for nightside data taken when the Moon was in the Earth's geotail. Error bars correspond to the standard deviation of the data points in each tip angle bin.

inferred potential to actual potential on the order of 0.7–0.9 even for high tip angles. We show simulations for smaller scale heights in Figure 3. As expected, smaller scale heights result in larger discrepancies between inferred and actual potentials, with the ratio between the two as small as 0.25–0.35 for high tip angles and a scale height of 500 m. Again, the effect is not as great as predicted by a quasi-adiabatic approximation, presumably due to non-adiabatic behavior.

5. Comparison With Data

[12] We use our simulation results, along with previously analyzed data, to constrain the average double layer scale height. Measurements were made in regions with different magnetic topologies and the results may depend subtly on these differences. However, as a quasi-adiabatic approximation and simple particle tracing simulations show, to first order our results should not depend strongly on magnetic field topology. Therefore, comparing simulation results with data allows us to obtain an order of magnitude estimate of the scale height.

[13] In the nightside geotail, the ambient magnetic field tends to lie along the Earth-Sun axis, so tip angle and SZA are strongly anti-correlated. Therefore, it is not possible to separate their effects. However, if any dependence on SZA is due solely to solar wind wake effects, as our data and other results suggest, this should not be an issue for the geotail data. We therefore show geotail data for all SZA greater than 110° (ensuring that both the surface and LP are in shadow) in Figure 4, binned into six tip angle bins, with error bars for each bin (all normalized by the average inferred potential for the lowest tip angle bin). The scatter in inferred potential difference for each tip angle bin is substantial. We should not find this surprising, since we average over many parameters, including electron density, temperature, etc. Even with the large error bars we can discern a clear trend with tip angle, with inferred potential differences at the highest tip angles about half those for tip angles near zero.

[14] We show nightside solar wind wake data in Figure 5, separated into different ranges of SZA, and similarly normalized. We do not show error bars; however, the scatter is very similar to that in Figure 4. As for geotail data, we find a clear trend with tip angle, with inferred potential differences at the highest tip angles a factor of 0.3–0.5 those for tip

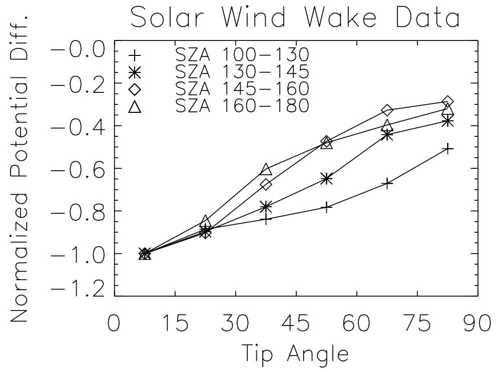

Figure 5. Average tip angle dependence of inferred potential difference for nightside data taken when the Moon was in the solar wind, separated into four SZA bins. Error bars for each bin are not shown, but are very similar to those in Figure 4.

angles near zero. We also find some indication of a trend in SZA, but given the scatter involved we find it difficult to determine the significance of this trend. If this trend is real, it might indicate a variation in double layer scale height with SZA. However, this would suggest a thicker double layer at smaller SZA, while theoretical calculations predict the opposite [*Borisov and Mall*, 2002].

[15] For both nightside geotail and solar wind wake data we find an average ratio between inferred potential differences at the highest tip angles to those near zero tip angle of 0.3–0.5. This ratio is closest to that found in our simulation for a scale height of 1 km. Our simulations assumed a surface magnetic field of 20 nT (appropriate for regions with moderate crustal magnetic fields), implying an average electron gyroradius of ~3 km, and therefore an average ratio of gyroradius to scale height of ~3. For regions of the Moon with weak or nonexistent magnetic crustal fields, this ratio would imply an average scale height of more like ~2 km (in actuality, the scale height likely remains relatively constant, with the ratio of gyroradius to scale height changing with crustal field strength). For the Moon as a whole, therefore, an average ratio of ~3 implies an average double layer scale height of ~1–2 km.

6. Conclusions

[16] The results of quasi-adiabatic calculations and particle tracing simulations show that the variation in potential difference with tip angle reported by *Halekas et al.* [2002] is very likely a result of the method used to infer these potential differences. However, this "measurement error" can be exploited to provide a constraint on the double layer scale height in the nightside geotail and solar wind wake regions. By comparing our data with simulation results, we infer average scale heights in both these regions of ~1–2 km.

[17] For typical nightside geotail and solar wind wake electron temperatures of 50–100 eV and densities of 0.01–0.1 cm^{-3}, the electron Debye length should be ~150–750 m. Since the surface potential is comparable to the electron temperature, though, it is not surprising to find a scale height somewhat larger than the Debye length (the derivation of Debye shielding assumes $eU/kT \ll 1$). Interestingly, previous measurements near the terminator on the lunar day side in the solar wind also implied scale heights of ~1 km, two orders of magnitude larger than the local solar wind Debye length of ~10 m [*Benson*, 1977]. On the other hand, our scale height estimates are substantially smaller than recent theoretical estimates of nightside double layer thicknesses on the order of ~200 km in the solar wind wake [*Borisov and Mall*, 2002].

[18] **Acknowledgments.** This work was partially supported by a NASA GSRP fellowship received by JSH. Some support was also provided by NASA through grant NAG5-9305.

References

Benson, J., Direct measurement of the plasma screening length and surface potential near the lunar terminator, *J. Geophys. Res.*, *82*, 1917–1920, 1977.

Borisov, N., and U. Mall, The structure of the double layer behind the Moon, *J. Plasma Phys.*, *67*, 277–299, 2002.

Halekas, J. S., D. L. Mitchell, R. P. Lin, L. L. Hood, M. H. Acuña, and A. B. Binder, Evidence for negative charging of the lunar surface in shadow, *Geophys. Res. Lett.*, *29*(10), doi:10.1029/2001GL014428, 2002.

Knott, K., Electrostatic charging of the lunar surface and possible consequences, *J. Geophys. Res.*, *78*, 3172–3175, 1973.

Lin, R. P., D. L. Mitchell, D. W. Curtis, K. A. Anderson, C. W. Carlson, J. McFadden, M. H. Acuña, L. L. Hood, and A. B. Binder, Lunar surface magnetic fields and their interaction with the solar wind: Results from Lunar Prospector, *Science*, *281*, 1480–1484, 1998.

Lindeman, R., J. W. Freeman, and R. R. Vondrak, Ions from the lunar atmosphere, *Proc. Lunar Science Conf.*, *4*, 2889–2896, 1973.

Manka, R. H., Plasma and potential at the lunar surface, in *Photon and Particle Interactions with Surfaces in Space*, edited by R. J. L. Grard and D. Reidel, 347–361, Dordrecht, Netherlands, 1973.

Ogilvie, K. W., J. T. Steinberg, R. J. Fitzenreiter, C. J. Owen, A. J. Lazarus, W. M. Farrell, and R. B. Torbert, Observations of the lunar plasma wake from the WIND spacecraft on December 27, 1994, *Geophys. Res. Lett.*, *23*(10), 1255–1258, 1996.

J. S. Halekas, R. P. Lin, and D. L. Mitchell, Space Sciences Laboratory, University of California, Berkeley, CA 94720, USA. (jazzman@ssl.berkeley.edu)