INFORMATION TO USERS

This material was produced from a microfilm copy of the original document. While the most advanced technological means to photograph and reproduce this document have been used, the quality is heavily dependent upon the quality of the original submitted.

The following explanation of techniques is provided to help you understand markings or patterns which may appear on this reproduction.

1. The sign or “target” for pages apparently lacking from the document photographed is “Missing Page(s)”. If it was possible to obtain the missing page(s) or section, they are spliced into the film along with adjacent pages. This may have necessitated cutting thru an image and duplicating adjacent pages to insure you complete continuity.

2. When an image on the film is obliterated with a large round black mark, it is an indication that the photographer suspected that the copy may have moved during exposure and thus cause a blurred image. You will find a good image of the page in the adjacent frame.

3. When a map, drawing or chart, etc., was part of the material being photographed the photographer followed a definite method in “sectioning” the material. It is customary to begin photoging at the upper left hand corner of a large sheet and to continue photoging from left to right in equal sections with a small overlap. If necessary, sectioning is continued again — beginning below the first row and continuing on until complete.

4. The majority of users indicate that the textual content is of greatest value, however, a somewhat higher quality reproduction could be made from “photographs” if essential to the understanding of the dissertation. Silver prints of “photographs” may be ordered at additional charge by writing the Order Department, giving the catalog number, title, author and specific pages you wish reproduced.

5. PLEASE NOTE: Some pages may have indistinct print. Filmed as received.

Xerox University Microfilms
300 North Zeeb Road
Ann Arbor, Michigan 48106
75-22,055

REIFF, Patricia Hofer, 1950-
MODIFICATION OF PARTICLE FLUXES AT THE
LUNAR SURFACE BY ELECTRIC AND MAGNETIC FIELDS.

Rice University, Ph.D., 1975
Physics, astronomy & astrophysics

Xerox University Microfilms, Ann Arbor, Michigan 48106

THIS DISSERTATION HAS BEEN MICROFILMED EXACTLY AS RECEIVED.
Modification of Particle Fluxes at the Lunar Surface
By Electric and Magnetic Fields
by
Patricia H. Reiff

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

Thesis Director's Signature:

Houston, Texas
April, 1975
ACKNOWLEDGMENTS

It is with pleasure I acknowledge the guidance and support of my thesis advisor, Dr. David L. Reasoner. Although on leave of absence from Rice during the bulk of this study, he still made many helpful suggestions (much to the delight of the Phone Company).

I am indebted to my two in loco advisors: Dr. William J. Burke and Dr. Thomas W. Hill. They provided a "sounding board" for many of the ideas and constructs in this thesis. In addition, Dr. Burke was instrumental in the development of the charge separation model. Dr. Hill carefully reviewed the manuscript, making suggestions on both content and presentation.

For magnetic field data I acknowledge Dr. David S. Colburn of the NASA/Ames Research Center. For SIDE resonance information I thank Dr. John W. Freeman, Jr. and Mr. Mohamed Ibrahim. For an excellent job of typing this thesis, I thank Dr. Libby Potter.

This research was in part funded by NASA Contract NAS-9-5884 and NASA Grant NSG-07025.

Finally, I wish to praise my parents, Dr. William H. Reiff and Dr. Maxine Hoffer Reiff, for their moral and financial support. They inspired in me faith in God and faith in my abilities, without which this study would not have been possible.
# TABLE OF CONTENTS

| CHAPTER 1 | INTRODUCTION | 1-1 |
| CHAPTER 2 | DESCRIPTION OF THE INSTRUMENTS | 2-1 |
| Charged Particle Lunar Environment Experiment | 2-1 |
| Explorer 35 ARC Magnetometer | 2-4 |
| Suprathermal Ion Detector Experiment | 2-4 |
| Magnetospheric Regions | 2-5 |
| CHAPTER 3 | DEVELOPMENT OF THE MODEL | 3-1 |
| Lunar Surface Effects | 3-1 |
| Magnetic Field Shadowing | 3-5 |
| Local Magnetic Effects | 3-16 |
| Combined Effects of the Local and External Magnetic Fields | 3-21 |
| The Photoelectric Field | 3-24 |
| Charge Separation Region | 3-27 |
| The Composite Electric Field | 3-32 |
| Summary of the Model | 3-35 |
| CHAPTER 4 | EVALUATION OF THE MODEL | 4-1 |
| Shadowing Observations | 4-1 |
| Plasma Sheet Spectra | 4-4 |
| SIDE Resonance Phenomena | 4-7 |
| The Neutral Sheet | 4-10 |
| Summary | 4-12 |
| CHAPTER 5 | SUMMARY AND DISCUSSION | 5-1 |
| Summary | 5-1 |
| Implications | 5-2 |

REFERENCES
CHAPTER 1
INTRODUCTION

The Charged Particle Lunar Environment Experiment (CPLEE) is an ion-electron spectrometer located on the lunar surface at the Apollo 14 site. The objective of the experiment is to measure particle fluxes, both from local lunar sources, and from interplanetary and magnetospheric plasmas. Examples of particle fluxes from lunar sources include the lunar photo-electron layer [Reasoner and Burke, 1972] and ionized constituents of dust clouds from impact events [Reasoner and O'Brien, 1972]. Measurements from interplanetary and magnetospheric sources include the magnetosheath [Reiff and Reasoner, 1975], the plasma sheet [Rich et al., 1973], the plasma mantle [Moore et al., 1974], and solar-flare particles [Moore et al., 1973]. For most of the interplanetary and magnetospheric measurements, the interaction of the plasmas with the lunar surface was assumed to be negligible with the exception of the effects of the local surface photoelectric potential.

The lunar surface is bathed in sunlight during the lunar day, causing photoelectrons to be emitted from the surface. As the kinetic energy imparted the photoelectrons generally far exceeds their gravitational escape energy, they would escape in the absence of an electric field. This escape, however, leaves the surface charged positively, and the resulting electric field, in a steady-state equilibrium, is sufficient to return the photoelectrons so that no net
current exists. If the surface is immersed in a plasma, the current balance includes the incoming fluxes due to the ambient plasma. Since the incoming flux of electrons is generally larger than the incoming flux of protons, the effect of the ambient plasma is generally to lower the equilibrium surface potential.

This effect has been observed by CPLEE. As photoelectrons with kinetic energies less than the surface potential energy will return to the lunar surface, Reasoner and Burke [1972] have used the maximum downwelling photoelectron energy seen as an estimate of the lunar surface potential. The potential so estimated is about 200 volts for the high latitude tail and about 70 volts for the plasma sheet [Rich et al., 1973]. The 70 V figure, however, encounters serious difficulties when current balance using the measured fluxes is used to calculate the surface potential [Burke et al., 1975]. The potential so calculated is nearer to 20 V [Rich, 1973]. An undershoot potential of the type of Guernsey and Fu [1970] would not explain the data; in fact, the equilibrium surface potential would be lowered by that mechanism [see, for example Burke et al., 1975]. Another observational estimate of the lunar surface potential in the plasma sheet has been made by Freeman and Ibrahim [1974], using Suprathermal Ion Detector Experiment (SIDE) data. By stepping the potential of their detector aperture with respect to the local surface potential, they detect "resonances" - enhanced photoion fluxes - when their instrument entrance aperture is stepped negative with respect
to the surface. The combination of the relative potential of the instrument and the observed energy of the ions implies a potential difference of 10 - 15 V between the region of ionization and the surface. Thus a mechanism for the return of electrons up to 60 eV above the photoelectron potential must be found to explain the CPLEE data.

The "crossover" energy, i.e. the largest energy at which downwelling photoelectrons are seen, is not constant in the plasma sheet. Intense, hot plasma sheet fluxes have been observed after substorms, in which no downwelling photoelectrons with energies greater than 40 eV were observed [Burke et al., 1973; Moore et al., 1974]. However, in at least one other case (presented later in this thesis), the incoming plasma-sheet electron fluxes were similar or larger; yet downwelling photoelectrons were seen with energies of up to 100 eV. Clearly the simple model of returning electrons by the photoelectric surface potential is insufficient.

CPLEE data contains other heretofore unexplained results. The first includes shadowing of plasma sheet electrons and, to a lesser extent, protons, during periods when the Explorer 35 ARC magnetometer indicated, by the diamagnetic effect, the presence of the plasma sheet. A possible explanation was put forth by Rich [1973], who used Anderson's [1970] model of emptying flux tubes of plasma as they intersect the lunar surface. After one bounce period the particles within a flux tube will have been absorbed by the lunar surface, and no fluxes would be observed. This explanation would necessitate
a given flux tube remaining in contact with the moon for a fairly long period of time (minutes or more); yet the variation in the magnetic fields and the random flapping motion of the tail [Bowling and Wolf, 1974] would seem to preclude that interpretation.

The second set of data as yet unexplained occurs just at neutral sheet crossings. Differential flux spectra show extremely narrow, intense fluxes peaked either below the instrument's lower-energy cutoff (40 eV), or else in the 50 - 70 eV range. The cutoff energy is generally lower in the B analyzer than in the A (see instrument description below), indicating an electric field pointed dusk-to-dawn. Acceleration by the cross-tail electric field, which is generally directed dawn-to-dusk, is in the wrong direction to explain this acceleration.

This thesis presents a model that explains, at least qualitatively, all of the difficulties outlined above. The model includes shadowing by the lunar surface, including the effects of both ambient and local magnetic fields. For certain conditions, a charge separation region occurs above the lunar surface. In a manner similar to that proposed by Willis [1970] at the magnetopause, an electric field is set up to draw the electrons in (or keep the protons out, whichever is easier). It is the total electrostatic potential that is measured by the CPLEE instrument: the charge separation potential $\phi_{cs}$ plus the potential due to photoelectrons $\phi_{pe}$. Flux balance calculations (and the SIDE measurements) determine only $\phi_{pe}$.
The next chapter describes the instruments used in this thesis: the CPLEE instrument, the Explorer 35 ARC magnetometer, and the SIDE instrument. The third chapter develops the shadowing/charge-separation model; the fourth chapter discusses and evaluates the model with plasma sheet and other data, and the final chapter discusses the implications of the model on data previously reported.
CHAPTER 2
DESCRIPTION OF THE INSTRUMENTS

Charged Particle Lunar Environment Experiment

The Charged Particle Lunar Environment Experiment (CPLEE) is a lunar-based ion-electron spectrometer, measuring particle fluxes in the energy range 40 eV to 20 keV. A description of the CPLEE instrument and deployment is given by O'Brien and Reasoner [1971]; therefore, only a summary will be given here.

A photograph of the deployed instrument is shown in Moore [1974]; a sketch of the instrument is shown in Figure 2-1. The instrument, measuring 20 x 20 x 11.5 cm, with mass of 2.7 kg, is oriented east-west at the Apollo 14 ALSEP site (lunar latitude 3° 40' S and lunar longitude 17° 27' W). The instrument contains two charged-particle analyzers, one whose look direction is lunar vertical (analyzer "A"), and one whose look direction is 60° to the west of vertical (analyzer "B"). The look directions sweep through space throughout the lunar month, as shown in Figure 2-2.

Each analyzer is of the Switched Proton-Electron Channeltron Spectrometer (SPECS) type [cf. O'Brien et al., 1967]. A schematic of an analyzer is shown in Figure 2-3. Particle entry is through a series of collimating slits, thence through a pair of deflecting plates. Particles of one sign are selected on the basis of energy-per unit-charge into five C-shaped channel electron multipliers (channels 1 - 5); particles of
Figure 2-1. A diagram of the CPLEE instrument. The A analyzer views vertically, the B, to the west.
Figure 2-2. Ecliptic plane projection of the orbit of the moon, showing the look directions of the two analyzers. The axis of symmetry of the figure is the "solar-wind" x-axis, rotated 4° from the earth-sun line.
Figure 2-3. Schematic of a physical analyzer.
the other sign are similarly deflected into a large-aperture, helical electron multiplier (channel 6). A particle entering the aperture strikes the curved wall, emittingsecondary electrons which are accelerated down the multiplier, causing a cascade of secondaries down the tube, with a final multiplication factor of about $10^7$. The total potential drop is nominally 2800 or 3200 V (selected by ground command); in practice, the potential is low, by 40 to several hundred volts. However, performance is unaffected if a potential of 2300 V can be maintained. Aperture biases and auxiliary electrodes were included to prevent secondary electrons from increasing the background level.

The normal mode of operation is the "Automatic" mode, where the deflection plate voltage is cycled through $+3500$, $+350$, $+35$, $+0$, $-3500$, $-350$, $-35$, and $-0$ volts, in order. Figure 2-4 is a schematic of the deflection cycle. The $-0$ V setting is a test oscillator, the $+0$ V setting is a background measure, and the sign of the other 6 steps indicates the sign of the particles entering channels 1 - 5. This automatic sequence can be stopped by ground command, and measurements can be made at any one deflection voltage ("Manual" mode). The accumulation time is 1.2 seconds, and the readout, encoding, transmission, and reset time is 1.2 seconds. The A analyzer accumulates while B resets and vice versa. A manual cycle therefore takes 2.4 seconds to complete, and an automatic cycle 19.32 seconds.

The analyzers were extensively calibrated for electrons.
**CLEEE TIMING SEQUENCE**

<table>
<thead>
<tr>
<th>FRAME NO</th>
<th>ALSEP</th>
<th>CPLEE PHYS/AN</th>
<th>READOUT OF A DURING B MEAS, ETC.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>A</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>B</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>A</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>B</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>A</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>B</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>A</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>B</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>A</td>
<td>B</td>
<td></td>
</tr>
</tbody>
</table>

**DEFLECTION VOLTAGE**

- +3500
- +350
- +35
- BKG
- -350
- -35
- -3500
- CAL

**19.3 SEC (NORMAL)**

*Figure 2-4. Schematic of the CPLEE timing sequence.*
Energy passbands for each analyzer/channel/deflection voltage combination are shown in Figures 2-5 and 2-6 [from Rich, 1973]. Multiplication factors for converting count rate (counts/1.2 sec) to differential flux (particles/(cm$^2$-sec-ster-eV)) are shown in Table 2-1. The proton channels were not ground calibrated. The figures in parentheses are design calculations; those not in parentheses are in-flight calibrations, using simultaneous solar-wind data from the Solar Wind Spectrometer Experiment.

The detector is also responsive to solar ultraviolet light, but only when the sun is within 2° of the analyzer's field of view. This effect is easily predictable and detectable. Fortunately for this study, Analyzer A's contamination is over several hours before mean dawn-side sheath entry, and Analyzer B's contamination begins near dawn-side sheath exit.

The instrument was deployed at approximately 1744 GMT on February 5, 1971 (Julian day 36). A brief function test using a $^{63}$Ni beta source in the dust cover was performed when the instrument was first commanded on at 1900 GMT February 5. CPLEE was then put in standby mode until after LM ascent, when it was commanded on at 1910 and the dust cover jettisoned at 1930 GMT February 6. Essentially continuous data from both analyzers were returned starting then until the failure of analyzer B on April 8, 1971 at 2155 GMT. The high fluxes of the geomagnetic storm of April 9, 1971 were mistakenly identified as evidence of internal problems, and the instrument was put in standby mode until April 16, 1971. Useful data from
Figure 2-5. Energy passbands for the electron channels of Analyzer A. [From Rich, 1973].
Figure 2-6. Energy passbands for the electron channels of Analyzer B. [From Rich, 1973].
TABLE 2-1

CPLEE Count Rate to Differential Flux

[Counts/1.2 sec] to [#/(cm²-sec-ster-eV)]

<table>
<thead>
<tr>
<th>Step, Detector</th>
<th>Center Energy (eV)</th>
<th>Flux units/count</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Analyzer A</td>
<td>Analyzer B</td>
</tr>
<tr>
<td>-35,1</td>
<td>40</td>
<td>45</td>
</tr>
<tr>
<td>-35,2</td>
<td>50</td>
<td>54</td>
</tr>
<tr>
<td>-35,3</td>
<td>65</td>
<td>70</td>
</tr>
<tr>
<td>-35,4</td>
<td>94</td>
<td>100</td>
</tr>
<tr>
<td>-35,5</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>-35,6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-350,1</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>-350,2</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>-350,3</td>
<td>750</td>
<td>750</td>
</tr>
<tr>
<td>-350,4</td>
<td>1100</td>
<td>1100</td>
</tr>
<tr>
<td>-350,5</td>
<td>2000</td>
<td>2300</td>
</tr>
<tr>
<td>-350,6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-3500,1</td>
<td>4800</td>
<td>5000</td>
</tr>
<tr>
<td>-3500,2</td>
<td>5800</td>
<td>6000</td>
</tr>
<tr>
<td>-3500,3</td>
<td>7200</td>
<td>7500</td>
</tr>
<tr>
<td>-3500,4</td>
<td>10000</td>
<td>10000</td>
</tr>
<tr>
<td>-3500,5</td>
<td>20000</td>
<td>23000</td>
</tr>
<tr>
<td>-3500,6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+35,1</td>
<td>(60)</td>
<td>(55)</td>
</tr>
<tr>
<td>+35,2</td>
<td>(70)</td>
<td>(65)</td>
</tr>
<tr>
<td>+35,3</td>
<td>(84)</td>
<td>(85)</td>
</tr>
<tr>
<td>+35,4</td>
<td>170</td>
<td>(100)</td>
</tr>
<tr>
<td>+35,5</td>
<td>300</td>
<td>220</td>
</tr>
<tr>
<td>+35,6</td>
<td>75</td>
<td>85</td>
</tr>
<tr>
<td>+350,1</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>+350,2</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>+350,3</td>
<td>750</td>
<td>750</td>
</tr>
<tr>
<td>+350,4</td>
<td>1100</td>
<td>1100</td>
</tr>
<tr>
<td>+350,5</td>
<td>2000</td>
<td>2200</td>
</tr>
<tr>
<td>+350,6</td>
<td>750</td>
<td>800</td>
</tr>
<tr>
<td>+3500,1</td>
<td>4800</td>
<td>5000</td>
</tr>
<tr>
<td>+3500,2</td>
<td>5800</td>
<td>6000</td>
</tr>
<tr>
<td>+3500,3</td>
<td>7200</td>
<td>7500</td>
</tr>
<tr>
<td>+3500,4</td>
<td>10000</td>
<td>10000</td>
</tr>
<tr>
<td>+3500,5</td>
<td>20000</td>
<td>22000</td>
</tr>
<tr>
<td>+3500,6</td>
<td>9000</td>
<td>8000</td>
</tr>
</tbody>
</table>
analyzer A were collected from then until June 6, 1971, when its power supply also failed. Although Analyzer A has operated during portions of 1972 through 1975, this was the end of useful data from 1971.

**Explorer 35 ARC Magnetometer**

David S. Colburn of the Ames Research Center, Moffett Field, California, has generously provided magnetic field data for this study. The satellite, which is in lunar orbit, has an aposelene of 5.4 \( R_m \) and periselene of 1.4 \( R_m \). Of the 11.5 hour period, only for times in which the satellite is in neither solar shadow nor radio shadow from the earth is data sent. The instrument is described in Mihalov et al. [1968].

Due to a partial failure of the sun sensor, the longitude angle of the magnetic fields is subject to offset. There is one component that changes slowly from month to month, and a component that varies with orbit period. One may normalize this longitude angle with high latitude tail field measurements, which generally point along the earth-sun line. An error of about 10° is unavoidable.

**Suprathermal Ion Detector Experiment**

The Suprathermal Ion Detector Experiment (SIDE) is an ion spectrometer similar to CPLEE in that it uses channel electron multipliers, coupled with a stepped deflection voltage, to measure fluxes for ions with a given energy per unit charge. The experiment has also a mass analyzer and a voltage stepper...
supply to change the electrostatic potential of its aperture relative to the surface. The experiment, which uses funnel-shaped analyzers, has a greater sensitivity but longer cycle time than CPLEE. It cannot measure electron fluxes. For a description of the instrument, see Freeman et al., [1972].

Magnetospheric Regions

Figure 2-7 is a cutaway view of the magnetosphere [from Hardy, 1975], showing the different plasma regions mentioned in this study. These include the solar wind (external), the bow shock, the magnetosheath, the high latitude tail, the plasma sheet, and plasma mantle or boundary layer. For a review of these, see Roederer [1974].
Figure 2-7. A cutaway view of the magnetosphere [from Hardy, 1975]. The bow shock separates the solar wind from the magnetosheath; the magnetopause separates the magnetosheath from the magnetosphere. The magneto-spheric tail extends antisunward from the earth. The plasma sheet lies in the midregion of the tail. The boundary layer (or plasma mantle) has been observed around the edges of the tail at 18 \( R_E \) by HEOS (labeled PLASMA MANTLE) and VELA (labeled BOUNDARY LAYER). This type of plasma has also been observed at lunar distance, exterior to the plasma sheet, even to the center of the tail (SIDE/CPL). It is assumed that the mantle covers the top and bottom edges of the tail at lunar distance, also; however, no satellite has explored that region.
CHAPTER 3
DEVELOPMENT OF THE MODEL

Lunar Surface Effects

The lunar surface is an absorber of incident plasmas. This will affect both the particle population in space and the particle population observed by a lunar-based detector. We shall classify these interactions into two broad categories: global (the interaction of the moon as a whole affecting the particle population in space) and local (the surface and fields near the surface affecting fluxes in a small region of the moon). We shall describe two types each of global and local interactions, and their consequences to particle detection.

The first type of global interaction occurs in a flowing plasma. A plasma void occurs on the downstream side of the moon [Michel, 1964]. If the flow is supersonic, a recompression shock cone trails the moon [Michel, 1965, 1968], diverting the converging flow around the void into parallel flow behind the void. The flow into the front side should be unperturbed, however - the moon "surprises" the flow. Thus, in this case one expects essentially unperturbed flow on the upstream hemisphere, and no fluxes on the downstream hemisphere.

The second kind of global interaction occurs in a region of trapped or quasitrapped plasma. The quasitrapped case in the magnetospheric tail was discussed by Anderson [1970] for a downtail source of energetic protons and electrons. A void
region again occurs downstream (in this case, on the sunward side). Frontside (i.e., sunward side) fluxes would cease one bounce period after the flux tube intersected the moon, while backside fluxes would continue as usual. Fresh flux tubes would intersect the moon at about the $E \times B$ convection velocity. For a quasitrapped population with a near-earth source, the situation would be reversed (backside fluxes cease, frontside fluxes continue). For a stably trapped population with only a small source, fluxes should be observed into both the near and far hemispheres for the first bounce period, and then effectively cease on both sides. Each of these cases may be important in the plasma sheet under certain conditions and for certain energy ranges, provided that the flux tube intersects the moon for time scales longer than a particle bounce period. For the particles reported by Anderson, the bounce period was short (seconds) and the interaction was observed. For the lower-energy particles in the plasma sheet at lunar distance, the bounce period is much longer — about a minute for a 200 eV electron and about 20 minutes for a 1.5 keV proton [Rich, 1973].

As the flapping velocity of the tail has been deduced to be typically 90 km/sec at a distance of 30 $R_E$ [Bowling and Wolf, 1974], it seems unlikely that this kind of interaction is important for the plasma sheet at lunar distance, as it is unlikely that a given flux tube would remain in contact with the moon for times scales long enough to empty the tube.

The next two effects are essentially local in lunar extent and will be discussed here in detail. Both effects have
much less stringent time restrictions: *i.e.* the magnetic field geometry must be stable on time scales on the order of cyclotron periods, instead of bounce periods.

The first local effect we will call "magnetic field shadowing" to distinguish it from the bulk shadowing effects described above. It is a geometrical effect of the cyclotron motion of particles around field lines. A given external magnetic field (with no electric fields in the moon's rest frame) will not, in general, allow isotropic fluxes to the surface. Particles will preferentially strike areas where the magnetic field is normal to the surface. This effect, which is due to the radius of the moon $R_m$ being larger than the cyclotron radius $r_c$, is only weakly energy dependent so long as $r_c \ll R_m$. What is important to note is that this type of shadowing will gate fluxes to the surface (affecting the photoelectric potential) even without local electric or magnetic fields.

The second type of local shadowing is due to local magnetic fields. Local fields can severely deflect or reflect incident particles. For magnetic fields of sufficient strength and extent, one may stand off the solar wind (creating a small bow shock near the surface) [Siscoe and Goldstein, 1973]. For strengths and/or scale lengths less than that, the situation is more complicated. The magnetic shadow zones discussed above will be altered in an energy-dependent way. Electrons will penetrate the field a much smaller depth than protons, leading to a charge separation electric field.

This chapter will discuss the latter two types of local
shadowing. The next section calculates the geometrical open and shadow zones analytically and discusses their importance on particle measurements at the surface. The following section uses lunar portable magnetometer measurements [Dyal et al., 1972], to estimate the remanent magnetic field at the ALSEP site. The observations are fit well by a buried dipole oriented vertically, yielding a magnetic field near CPLEE of about 75 $\gamma$. The effects of this dipole, deflecting incident fluxes, are next shown, given external fields of 0, 5, and 10 $\gamma$. Störmer type trajectories are numerically computed using the vector sum of the lunar dipolar field and an external field of 5 $\gamma$ in various orientations. In this way the complete "open zones" are computed for 200 eV and 70 eV electrons. The open zones are shown to be energy dependent.

The last section discusses the charge separation region. The features of the charge separation region are discussed qualitatively. We then use the model to make predictions about the height and strength of the charge separation region, given various incident plasmas.
Magnetic Field Shadowing

The cyclotron motion of particles in a magnetic field implies that, for given magnetic field configurations, a particle detector is effectively viewing particles emanating from the surface. For example, if the external field is parallel to the local lunar surface, a detector looking vertically will be observing particles with 90° pitch angles. At some time during the previous cyclotron period, the particle was on the surface, with its velocity pointed vertically upwards. Thus the detector, although looking vertically upwards, is viewing the surface. This we call "shadowing" as the detector is in the shadow of the surface. Note that in this case, particles of all energies are shadowed [Fig. 3-1].

For the other extreme, the magnetic field perpendicular to the local surface, a vertically-looking detector is observing particles of 0° pitch angle, and no shadowing occurs for particles of any energy or sign. For intermediate magnetic field orientations, or analyzers at an angle to the vertical, the situation is more complicated. In general, for any detector, there will exist magnetic field directions for which the detector views space, and field directions for which the detector views the surface. The magnetic field directions for which a given detector views space are in roughly a cone around the detector's look direction. There are two such "open zones" for each detector - one in each hemisphere.

A simple geometrical argument implies that a magnetic
Figure 3-1. For a vertically-looking detector, and the external magnetic field parallel to the surface, particles of all energies are shadowed.
field direction that makes equal angles with the detector and the surface is inside an open zone. Consider a field line B in the plane of the analyzer's look direction and the normal to the surface [Figures 3-2], such that the angle between the field line and the detector (i.e. the pitch angle observed, \( \alpha \)) equals the angle between the field line and the surface [Figures 3-2 a, c, and e]. Simple geometry shows the vertical velocity is always less than or equal to zero (equals zero one-half cyclotron period before entering the detector). Thus the particle is arriving from space, and the field is within an open zone for that detector.

We can also estimate the minimum angle \( \delta \) between the field line and the surface, for which the particle just barely misses the surface [Figures 3-2 b, d, and f]. The cyclotron motion defines a helical path whose projection on that plane is a sine wave about that field line, as shown in Figures 3-2. At \( t = 0 \), the particle enters the detector and the projection of the sine wave is zero. At \( t = -(2n+1)\pi/2\omega, \ n = 0, 1, 2... \), this projection is at its maximum excursion from the field line: the cyclotron radius \( a = (v/\omega) \sin \alpha \). Here \( \omega = \) angular cyclotron frequency = eB/m. The particle is nearest the surface at \( t = -3\pi/2\omega \). At that time the particle's distance along the field line is \( v \ t \cos \alpha = (3v \pi/2\omega) \cos \alpha \). Thus the angle \( \delta \) between the field line and the surface is given by \( \tan \delta = a/vt \cos \alpha = v \sin \alpha/(3v\pi/2) \cos \alpha = (2/3\pi) \tan \alpha \). Knowing the angle \( \beta \) between the detector and the vertical, one solves for \( \delta \) by \( \delta + \alpha = 90^\circ - \beta \).
Figure 3-2a.

β = 0

Figure 3-2b. Critical magnetic field directions such that the particle just clears the local surface.
Figure 3-2e.

$\beta = 25^\circ$

Figure 3-2f.
A similar critical angle \( \delta \leq \alpha \) applies to magnetic fields not in the plane of the detector and the normal to the surface (see below). Thus the vertically oriented magnetic field is special in that not only are all energies allowable for a vertical detector, but all energies are allowable for all detectors: i.e. only for this field orientation are isotropic fluxes allowed to the surface.

The open and shadow zones may be calculated in two ways. The first involves tracing the trajectory of the appropriate antiparticle out from the detector and seeing whether the particle strikes the surface. One may then use a suitable grid search method to find the boundaries of the zones. This is a tedious process, at best. Given certain approximations, however, the problem may be handled analytically. Both methods have been done, with good agreement between the methods.

The geometry for the shadowing solution is shown in Figure 3-3. The \( x \) direction is toward local lunar vertical (the direction of analyzer A). The \( z \) direction is toward local north (approximately ecliptic north), and the \( y \) direction is toward local east. We define a spherical polar coordinate system \((r, \phi, \theta)\), except that \( \theta \) is defined as the latitude instead of the colatitude, for ease of comparison with external fields. Here \( \theta = 0 \) in the \( xy \) plane, measured clockwise around the \( y \)-axis; \( \phi = 0 \) in the \( xz \) plane, measured counterclockwise around the \( z \) axis. As the \( z \) direction defined here is within a few degrees of ecliptic plane north, we need only rotate in the ecliptic plane to go from the above-defined
Figure 3-3. Geometry for the analytic shadowing solution.
lunar coordinates to solar ecliptic coordinates. The magnitude of this rotation is the solar ecliptic longitude of the A analyzer, which we call SELODA. The sense of the transformation is that $\phi_A = \phi_{SE} - \text{SELODA}$. SELODA goes through 360° in a lunar month, increasing about half a degree an hour and can therefore be treated as a constant for a given particle trajectory. We shall call this lunar local longitude $\phi_A$ (or just $\phi$) to distinguish it from the solar ecliptic longitude $\phi_{SE}$. Let $\beta$ be the local lunar longitude of an analyzer, assuming that the analyzer is in the xy plane. For CPLEE analyzer A, $\beta = 0$; for analyzer B, $\beta = -60°$.

The assumptions for the analytic solution are as follows:

a) no large-scale electric field exists in the rest frame of the moon (e.g., the plasma flow velocity is much smaller than the thermal velocity); b) the height of the instrument is negligible compared to the cyclotron radius of the particles; c) the cyclotron radius is much smaller than the lunar radius - thus we approximate the lunar surface by a plane; d) the magnetic field is uniform in space and steady in time for several cyclotron periods. These assumptions combine to make the solution independent of particle energy and magnetic field strength, as we shall see later.

The analytic solution (here done for electrons) follows a positron out of the instrument and finds, for each lunar phi angle of the external magnetic field, the largest theta angle for which the particle just clears the surface. That is, when $x = 0$, $dx/dt = 0$. The coordinates of the magnetic
field in the surface system are these:

\[
\mathbf{B} = \mathbf{B} \hat{\mathbf{B}} = B (\cos \theta \cos \phi \hat{x} + \cos \theta \sin \phi \hat{y} \\
+ \sin \theta \hat{z})
\]

(3-2)

The initial velocity out of the detector is

\[
\mathbf{v} = v \hat{v} = v (\cos \beta \hat{x} + \sin \beta \hat{y} + 0 \hat{z})
\]

(3-3)

Here the carats indicate unit vectors in the direction of the corresponding vector. Thus the pitch angle of the particle is given by

\[
\cos \alpha = \mathbf{B} \cdot \mathbf{v} / Bv = \cos \theta \cos \phi \cos \beta + \cos \theta \sin \phi \sin \beta \\
= \cos \theta \cos (\phi - \beta)
\]

(3-4)

A particle in a uniform magnetic field will describe a helical path around the field line. The guiding center will move along the field line with velocity \( \mathbf{v}_\parallel = v \cos \alpha \hat{B} \). In a system of coordinates moving with the guiding center, a positron describes a circle with gyroradius

\[
a_c = v_\perp / \omega = v \sin \alpha / \omega = m(v \sin \alpha) / eB
\]

(3-5)

If we consider a new primed coordinate system with its origin at the guiding center, oriented such that

\[
\hat{z}' = \hat{B}; \ \hat{x}' = \hat{v}_\perp; \ \hat{y}' = \hat{B} \times \hat{v}_\perp
\]

(3-6)

the velocity of the particle would be, in primed coordinates describing a left-hand trajectory:

\[
\mathbf{v}' = v_\perp \cos \omega t \hat{x}' - v_\perp \sin \omega t \hat{y}'
\]

(3-7)

and the position in the primed coordinates would be
\[ r' = a_c \sin \omega t \hat{x}' + a_c \cos \omega t \hat{y}' \quad (3-8) \]

All that remains is to find the initial position of the guiding center, from
\[ r(t = 0) = r'(0) + r_{gc}(0) = 0 \quad (3-9) \]

whence \[ r_{gc}(0) = -a_c \hat{y}' \]

So the complete solution of the particle trajectory is (translating the origin of the primed coordinates back to the detector)
\[ r''(t) = r'(t) + r_{gc}(t) \]
\[ = a_c \sin \omega t \hat{x}' + a_c (\cos \omega t - 1) \hat{y}' + vt \hat{z}' \quad (3-10) \]

To return to the unprimed coordinates, we use a matrix transformation, recalling the definitions (3-2), (3-3), and (3-6) and the fact that
\[ \hat{x}' = \hat{v}_o = (v_\perp o - v_\parallel o) / v_\perp o \quad (3-11) \]

The transformation becomes \[ r = M \cdot r'' \] or
\[ \begin{pmatrix} x \\ y \\ z \end{pmatrix} = M \begin{pmatrix} x'' \\ y'' \\ z'' \end{pmatrix} \quad (3-12) \]

with \( M \) given by
\[ \sin \alpha \begin{bmatrix} 
\cos \beta - \cos \alpha \cos \theta \cos \phi & -\sin \theta \sin \beta & \cos \theta \cos \phi \\
\sin \beta - \cos \alpha \cos \theta \sin \phi & \sin \theta \cos \beta & \cos \theta \sin \phi \\
-\cos \alpha \sin \theta & \cos \theta \sin (\beta - \phi) & \sin \theta \sin \alpha 
\end{bmatrix} \quad (3-13) \]
We are interested in the x component of this:

\[ x(t) = a_c \left( \frac{\sin \omega t}{\sin \phi} (\cos \beta - \cos \alpha \cos \theta \cos \phi) \right) + a_c (1 - \cos \omega t) (\sin \theta \sin \beta / \sin \alpha) + vt \cos \alpha \cos \theta \cos \phi \]

(3-14)

\[ = \frac{v}{\omega} \left[ (1 - \cos T)(\sin \theta \sin \beta) + \sin T \cos \beta + (T - \sin T) \cos \alpha \cos \theta \cos \phi \right] \]

where we have introduced \( T = \omega t \). The x-velocity becomes

\[ v_x(T) = v \left[ \sin T (\sin \theta \sin \beta) + \cos T \cos \beta + (1 - \cos T) \cos \alpha \cos \theta \cos \phi \right] \]

(3-15)

Setting \( x(t) = 0 \), \( v_x(t) = 0 \), and using expression (3-4) for \( \cos \alpha \), we get two equations, three unknowns (\( T, \theta, \) and \( \phi \)). Note that the solution is not dependent on particle energy or magnetic field strength:

\[ \cos^2 \theta \cos(\phi - \beta) \cos \phi (T - \sin T) = (\cos T - 1) \sin \theta \sin \beta - \sin T \cos \beta \]

\[ \cos^2 \theta \cos(\phi - \beta) \cos \phi (1 - \cos T) = -\sin T \sin \theta \sin \beta - \cos T \cos \beta \]

(3-16)

This reduces to

\[ \sin \theta = \frac{[\cot \beta (\sin T - T \cos T)]/[T \sin T + 2 \cos T - 2]}{\cos (\phi - \beta) \cos \phi = \frac{(\cos T - 1) \sin \theta \sin \beta - \sin T \cos \beta}{(T - \sin T) \cos^2 \theta}} \]

\[ \cong f(\phi) \]

(3-17)

Note that for \( \theta = 0 \), we find \( T = \tan T \), or \( T = 0.95(\pi/2) \),
justifying the assumption used in finding $\delta$ above. One can now parameterize the solution (via $T$), find $\theta$, and solve for $\phi$ iteratively, via

$$\phi_{\text{next}} = \cos^{-1}\left[\frac{f(\phi)}{\cos (\phi - \phi)}\right] \quad (3-18)$$

Solutions for the open-closed boundary are shown in Mercator projection in Figure 3-4. The figures are symmetric in the sense that if $(\phi, \theta)$ is on the boundary, so is $(\phi + 180^\circ, \theta)$. Although the A analyzer solution is symmetric about the equator $(\phi, \theta) \to (\phi, -\theta)$, the B analyzer solution is not, as the B analyzer can view much higher southern latitudes than northern ones.

For comparison, electron shadow zones using a $15^\circ$ grid are shown in Figure 3-5a, for a 100 eV particle in a 5 $\gamma$ field. A similar grid for 100 eV protons is shown in Figure 3-5b. (Since they also exhibit the $180^\circ$ symmetry, only one A and one B open zone are shown). Both Figures 3-5a and 3-5b were calculated by D. L. Reasoner [private communication, 1974], by numerical trajectory tracing using a spherical moon. The bars are the numerical solution; the solid curves are the appropriate analytical solution. We see that the electron shadow zones agree quite well, and that the proton zones are quite similar, although larger, and flipped in equatorial asymmetry for the B analyzer.

These open and shadow zones will be valid for lunar locations where there are no large local magnetic fields (e.g. at the Apollo 15 site) in particle populations where there are
Figure 3-4. The regions inside the closed curves are the open zones for Analyzers A, B, and "C" (described in text). For protons, change the sign of theta.
Figure 3-5a. Open zones for 100 eV electrons in a 5 γ field (bars). The solid curves are the corresponding analytical solution. In this no-local-field case, the curves are symmetric, and two identical open zones are separated 180° apart in longitude. Therefore, only one A and one B open zone are shown.
Figure 3-5b. Same as Figure 3-5a, but for 100eV protons.
no large scale electric fields. They are also a good approximation to the open zones for high-rigidity particles in regions where the local magnetic field is moderate in strength and extent (e.g. protons at the Apollo 14 ALSEP, with energies \( \geq 200 \text{ eV} \)).

Isotropic fluxes of all energies are allowed to the surface only for magnetic fields perpendicular to the surface. Thus it is only for that special field orientation that current-balance equations yield the correct lunar surface potential. For fields at a large angle to the surface normal, much of the incoming flux is shadowed and the potential is underestimated. We may use the shadowing solution to find the region of magnetic field directions for which isotropic flux to the surface is approximately correct: the "golden zone". Imagine a circular array of detectors, each of whose look directions is at a 60° angle to the surface normal. If each of these detectors is not shadowed, then at least half of the sky is open, and at least three-fourths of the incident downward flux reaches the surface, from

\[
\Omega = \int d\Omega = \int_0^{\pi/3} \int_0^{2\pi} \cos \theta \sin \theta \, d\theta \, d\phi = \pi \tag{3-19a}
\]

\[
\frac{\% \text{ flux}}{\Omega} = \frac{\int_0^{\pi/3} \int_0^{2\pi} \cos \theta \sin \theta \, d\theta \, d\phi}{\int_0^{2\pi} \int_0^{\pi} \cos \theta \sin \theta \, d\theta \, d\phi} = \frac{.75\pi}{\pi} = .75 \tag{3-19b}
\]

where in these equations only are \( \theta, \phi \) defined as standard polar angles with the polar axis (\( \theta = 0, \phi \) undefined) equal to
the surface normal.

From symmetry, it is easy to see that the "golden zone" (here defined as the region of external magnetic field direction for which the external fluxes can reach at least 60° to the surface normal on all sides) should be a cone around the local surface normal. This corresponds to approximately a circle on the Mercator plots we have been using [Figures 3-4, 3-5]. We may exploit the symmetries of the solution to find that circle. We may define a dummy analyzer "C" with a $\beta = 60°$ (i.e. the same angle to the vertical as analyzer B, but pointing east instead of west), and calculate its open zones [Figures 3-4]. The golden zones will lie in the intersections of the open zones of analyzers A, B and C, and will be the largest circle centered on ($\theta = 0°$, $\phi = 0°$) (and $\theta = 0°$, $\phi = 180°$) wholly contained within that intersection [Figure 3-4]. It is only for external field orientations in the golden zones that the surface potentials calculated by most workers are approximately valid. For other field orientations the flux to the surface cannot be considered isotropic and thus the equilibrium surface potential is underestimated.

In summary, analytical solutions to particle shadowing by the lunar surface in uniform external magnetic fields have been found. These solutions, however, explicitly ignore the effect of local magnetic fields. Local fields, which have been measured to be quite strong [Dyal et al., 1972], do have an important effect which will be discussed in the next section. It should be noted, however, that even in the absence of local fields, the direction of the external magnetic field
has an important influence on the access of external plasma to the surface, and therefore a modulating effect on the equilibrium surface potential of the moon.
Local Magnetic Fields

The assumption of uniform magnetic fields, used in the shadowing solution above, explicitly neglects lunar magnetic fields at the surface. Strong magnetic fields have been detected on the lunar surface, up to 313 γ at one Apollo 16 site [Dyal et al., 1972]. Although the remanent field was not measured at the Apollo 14 ALSEP site, Dyal et al. [1971] did report magnetic field measurements at two Apollo 14 locations, sites A and C' (Figure 3-6). Given 3 components of magnetic field measured at two sites, one can determine, in principle, all six degrees of freedom for a buried dipole (3 of location, 3 of moment), and use ALSEP's location relative to that dipole to estimate the remanent field at CPLEE. As there is no assurance that in fact a single buried dipole is responsible for the remanent fields at the three locations, we feel justified in simplifying the problem by assuming that the dipole is oriented vertically. The validity of this assumption can be checked later.

The lack of an azimuthal component of magnetic field allows, assuming vertical alignment, easy location of a dipole's projection onto the surface. Vectors representing the direction of the horizontal component of the magnetic field are drawn from the two sites at which the field was measured, and the point where the two lines cross is the surface projection of the dipole. This method was done graphically, with the dipole located 586 m east and 125 m south of CPLEE, at an unknown depth [Figure 3-6].
Figure 3-6. Magnetic fields measured at Apollo 14 sites A and C', and computed for the ALSEP site. The horizontal components are plotted on a map of the region.
The depth of the dipole, \( h \), can be determined by the field magnitudes at the two locations. The dipole field in a spherical coordinate system aligned antiparallel to the dipole is given by:

\[
B_{\text{dipole}} = -\frac{M}{r^3} (2 \cos \theta \hat{r} + \sin \theta \hat{\theta}) \quad (3-20)
\]

If the distance from the site to the surface projection of the dipole is \( d \) (= 336 m for A, 934 m for C', 599 m for ALSEP), then

\[
B = -\frac{M}{(d^2 + h^2)^{3/2}} \left(2 \frac{h}{(h^2 + d^2)^{1/2}} \hat{r} + \frac{d}{(h^2 + d^2)^{1/2}} \hat{\theta} \right)
\]

\[
B = \frac{M}{(d^2 + h^2)^{1/2}} \left(\frac{4h^2 + d^2}{d^2 + h^2} \right)
\]

\[
\begin{align*}
B_A &= \frac{(4h^2 + (336)^2)^{1/2}}{(h^2 + (336)^2)^2} \quad \frac{(h^2 + (934)^2)^2}{(4h^2 + (934)^2)^{1/2}} = 103 \\
B_{C'} &= \frac{(4h^2 + (336)^2)^{1/2}}{(h^2 + (336)^2)^2} \quad \frac{(h^2 + (934)^2)^2}{(4h^2 + (934)^2)^{1/2}} = 43
\end{align*}
\]

This fifth-order algebraic equation can be solved iteratively for \( h \), yielding a value of 1095 m. The value of \( M \) can be found from the magnitude of the field at A or C', yielding

\[
M = \frac{(d^2 + h^2)^2}{(4h^2 + d^2)^{1/2}} \quad B = 8.00 \times 10^{10} \quad \gamma - m^3. \quad (3-22)
\]

One check of the validity of the vertical alignment assumption is to now compare the individual components of a vector measurement (say, at site A), with the components predicted from the dipole. Expressing \( B \) in \( \gamma \) (1\( \gamma \) = 1 nanotesla), we have
\[ \theta_A = \tan^{-1} \left( \frac{336}{1095} \right) = 17.16^\circ; \quad \theta_{C'} = 40.5^\circ \]

\[ B_A \text{ (measured)} = -102 \hat{r} - 16 \hat{\theta} \]

\[ B_A \text{ (calculated)} = \frac{-8 \times 10^{10}}{1.5 \times 10^9} \left( 2 \cos 17^\circ \hat{r} + \sin 17^\circ \hat{\theta} \right) = -102 \hat{r} - 16 \hat{\theta} \]

\[ B_{C'} \text{ (measured)} = -38 \hat{r} - 21 \hat{\theta} \]

\[ B_{C'} \text{ (calculated)} = -41 \hat{r} - 17 \hat{\theta} \quad (3-23) \]

The agreement is good; the vertical alignment assumption is justified. These determined dipole parameters can be used to approximate the remanent field at CPLEE.

\[ \theta_{\text{CPLEE}} = \tan^{-1} \left( \frac{599}{1095} \right) = 28.7^\circ \]

\[ B_{\text{CPLEE}} = \frac{-8 \times 10^{10}}{(1248)^3} \left( 2 \cos 28.7^\circ \hat{r} + \sin 28.7^\circ \hat{\theta} \right) \]

\[ = -41.15 \left( 1.75 \hat{r} + 0.48 \hat{\theta} \right) \]

\[ = -72.01 \hat{r} - 19.75 \hat{\theta} \]

\[ = 74.67 \left( \cos 46.0 \text{ horiz} - \sin 46.0 \text{ vert} \right) \]

\[ = 51.89 \text{ horiz} - 53.71 \text{ vert} \quad (3-24) \]

Referring back to Figure 3-6 to return to local lunar coordinates,

\[ B_{\text{CPLEE}} = 10.0 \gamma \text{ south} \]

\[ 50.8 \gamma \text{ east} \]

\[ 53.7 \gamma \text{ down} \quad (3-25) \]
Putting this back into shadowing coordinates, this becomes

\[ B = 74.7 \]
\[ \theta = -8^\circ \]
\[ \phi_a = 137^\circ \]  
(3-26)

The uncertainty in the components would be of the order of the uncertainty in the original measurements, i.e. \( \pm 5\gamma \). Such a large field would have a marked effect on the observed fluxes, deflecting the plasma [Clay et al., 1975], or perhaps even setting up a shock wave [Siscoe and Goldstein, 1971].

Particle trajectories have been computed in this dipolar magnetic field, both with no external magnetic field, and with external fields of 5 and 10 gamma. The results are summarized in Tables 3-1 through 3-4.

Table 3-1 is merely a reminder of the cyclotron radii in a 75 gamma field. For comparison, the scale size of the field, by 1/e falloff with height either above the dipole or above CPLEE, is near .5km. Thus we expect electrons below about 100 eV to be severely affected by the field, whereas only extremely low-energy protons would be significantly affected. This is borne out in Table 3-2. The deflection is calculated by following the appropriate antiparticle trajectory for \( \sim 6 \) km, and noting its final velocity. Actual trajectories for these conditions are shown in Figures 3-7 through 3-11. The 0 initial angle corresponds to the CPLEE A analyzer; -60, to the CPLEE B analyzer; and +20, to the SIDE
TABLE 3-1

Cyclotron Radii in a 75 $\gamma$ field (km)

<table>
<thead>
<tr>
<th>Perpendicular Energy (eV)</th>
<th>1</th>
<th>2</th>
<th>10</th>
<th>50</th>
<th>100</th>
<th>500</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron</td>
<td>.05</td>
<td>.07</td>
<td>.15</td>
<td>.33</td>
<td>.47</td>
<td>1.0</td>
<td>2.1</td>
</tr>
<tr>
<td>proton</td>
<td>2.0</td>
<td>3.1</td>
<td>6.8</td>
<td>15.</td>
<td>21.</td>
<td>48.</td>
<td>96.</td>
</tr>
</tbody>
</table>
TABLE 3-2

Particle Deflection in Lunar Dipole

<table>
<thead>
<tr>
<th>Energy</th>
<th>Detector, Particle type*</th>
<th>W</th>
<th>N</th>
<th>W</th>
<th>N</th>
<th>W</th>
<th>N</th>
<th>W</th>
<th>N</th>
<th>W</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ae, Ap = CPLEE analyzer A electrons, protons</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Be, Bp = CPLEE analyzer B electrons, protons</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sp = SIDE protons</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>S</td>
<td>11</td>
<td>-1.5</td>
<td>73</td>
<td>-33</td>
<td>-11</td>
<td>-11</td>
<td>96</td>
<td>-32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>60 10</td>
<td>9</td>
<td>28</td>
<td>31</td>
<td>-38</td>
<td>-4.0</td>
<td>-.44</td>
<td>52</td>
<td>-51</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>71 20</td>
<td>-8</td>
<td>22</td>
<td>16</td>
<td>-30</td>
<td>-2.1</td>
<td>.24</td>
<td>28</td>
<td>-41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>70 38</td>
<td>-10</td>
<td>7.4</td>
<td>6.7</td>
<td>-20</td>
<td>-.86</td>
<td>.37</td>
<td>11</td>
<td>-28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>49 42</td>
<td>-6.6</td>
<td>2.2</td>
<td>3.4</td>
<td>-14</td>
<td>-.44</td>
<td>.32</td>
<td>5.8</td>
<td>-21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>28 37</td>
<td>-3.7</td>
<td>.3</td>
<td>1.7</td>
<td>-10</td>
<td>-.15</td>
<td>.24</td>
<td>2.9</td>
<td>-15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>15 29</td>
<td>-1.9</td>
<td>-.3</td>
<td>.85</td>
<td>-7.3</td>
<td>-.16</td>
<td>.18</td>
<td>1.5</td>
<td>-10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>6.1 19</td>
<td>-0.8</td>
<td>-.4</td>
<td>.34</td>
<td>-4.7</td>
<td>-.04</td>
<td>.11</td>
<td>.62</td>
<td>-6.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>1.6 9.9</td>
<td>-0.1</td>
<td>-.2</td>
<td>.09</td>
<td>-2.3</td>
<td>-.04</td>
<td>.06</td>
<td>.13</td>
<td>-3.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 3-7. Analyzer A trajectories for electrons of various energies in the computed dipolar magnetic field (no external fields). The abscissa is horizontal distance from the dipole; the ordinate, vertical. For scale, the dipole is 1.1 km below the surface. Energies are in eV.
Figure 3-8. Same as Figure 3-7, but for Analyzer B.
Figure 3-9. Same as Figure 3-7, but for protons.
Figure 3-10. Same as Figure 3-7, but for Analyzer B protons.
Figure 3-11. Same as Figure 3-7, but for SIDE protons.
analyzer. The deflection is separated into $W$ (in the plane of the dipole and ALSEP, with positive towards the west) and N (perpendicular to that plane, positive towards north). We see that significant deflections ($10^\circ$ or more - above the underline) occur up to higher energies for electrons than for protons. For example, 2000 eV is the cutoff for A electrons; 100 eV for A protons. For a given particle type, detectors more nearly perpendicular to the field show significant deflections up to higher energies than for detectors more nearly parallel to the field. For example, the B analyzer, $-16^\circ$ away from the local field, has a cutoff in significant proton deflections between 1 and 5 eV, whereas the SIDE analyzer (64$^\circ$ to the field) has $10^\circ$ deflections up to a particle energy of 200 eV. Both of these general results are due to the longer amount of time that the particle spends in the magnetic field.
Combined Effects of the Local and External Magnetic Fields

Tables 3-3 and 3-4 summarize the effect on electron trajectories if a uniform field is superposed on the local dipolar field. The external field is assumed in the ecliptic plane, with azimuth $\phi_A$ as defined earlier ($0^\circ = $ look direction of the A analyzer, positive values towards the east). The A analyzer is used; therefore $\phi_A$ is the pitch angle that one would observe with the A analyzer had there been no local field (first column). The second column uses the analytic solution to assay whether the particle would have been shadowed without the local dipole. The remaining columns are the actual pitch angles observed for electrons of the given energies of the sub-columns: 25, 50, 100, 200, and 500 eV. The difference between the first column and the appropriate subcolumn, therefore, is an indication of the deflection in the local magnetic field. The fact that, in general, one can \textit{not} estimate the pitch angle at infinity by $\sin^2\alpha/\sin^2\beta = \sin^2\alpha/\sin^2\beta$ is a consequence of the non-adiabatic nature of the interaction. That is, the lunar magnetic field changes over length scales smaller than the cyclotron radii of the particles in question.

We note that the shadow zones are strongly energy dependent (for this 30° grid) for energies up to \textasciitilde 100 eV, where they stabilize. As most plasma sheet electrons at lunar distance have energies \textgreater 100 eV, it becomes reasonable to redo the shadowing solution for the whole ($\phi, \theta$) plane with an energy typical of the plasma sheet. We choose 200 eV, for two
TABLE 3-3

Effect of Dipole on Pitch Angle Distribution, 5 γ External Field, A analyzer electrons

<table>
<thead>
<tr>
<th>$\phi_A$ (1)</th>
<th>Status (2)</th>
<th>(a_\infty) (degrees) (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>if no dipole</td>
<td>Energy (eV)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>180</td>
<td>C</td>
<td>129</td>
</tr>
<tr>
<td>210</td>
<td>C</td>
<td>110</td>
</tr>
<tr>
<td>240</td>
<td>BS</td>
<td>S</td>
</tr>
<tr>
<td>-90</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>-60</td>
<td>BS</td>
<td>40</td>
</tr>
<tr>
<td>-30</td>
<td>C</td>
<td>60</td>
</tr>
<tr>
<td>0</td>
<td>C</td>
<td>M</td>
</tr>
<tr>
<td>+30</td>
<td>C</td>
<td>S</td>
</tr>
<tr>
<td>+60</td>
<td>BS</td>
<td>S</td>
</tr>
<tr>
<td>+90</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>+120</td>
<td>BS</td>
<td>BC157</td>
</tr>
<tr>
<td>+150</td>
<td>C</td>
<td>146</td>
</tr>
</tbody>
</table>

(1) $\phi_A \equiv$ Ecliptic plane longitude of external magnetic field rotated so that $0^\circ$ = local lunar vertical (+ = east). External fields in ecliptic plane only ($\theta = 0$), so that $\phi_A$ would equal the pitch angle observed by the CPLEE $A'$ A analyzer, were there no local field.

(2) S = Shadowed
C = clear (understood if omitted)
BC = borderline clear (returns within 500 m of surface)
BS = borderline shadowed
M = particle mirrors and returns
<table>
<thead>
<tr>
<th>$\phi_A$</th>
<th>Status if no dipole</th>
<th>$\alpha_\infty$</th>
<th>Energy (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>180</td>
<td>C</td>
<td>131</td>
<td>133</td>
</tr>
<tr>
<td>210</td>
<td>C</td>
<td>125</td>
<td>113</td>
</tr>
<tr>
<td>240</td>
<td>BS</td>
<td>B108</td>
<td>107</td>
</tr>
<tr>
<td>-90</td>
<td>S</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-60</td>
<td>BS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-30</td>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+30</td>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+60</td>
<td>BS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+90</td>
<td>S</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+120</td>
<td>BS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+150</td>
<td>C</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
reasons: 1) for both hot and cool plasma sheet fluxes, there exist significant fluxes in the 200 eV range [Fig. 4-4], and 2) CPLEE has an energy channel centered at that energy.

The results of this calculation for 200 eV electrons in a 5 γ field are shown in Figure 3-12. Here we have calculated the open zones for analyzers A, B, and "C", to determine their open zones and the "golden zone". Note the distortion in the open zones of analyzers A and C from the no-local-field case of Figure 3-4. Analyzer B shows much less distortion, as it more nearly parallels the local field direction. The analyzer A open zones for a 70 eV electron are shown in Figure 3-13. Here again the energy dependence is underscored, as the open zones are smaller and more distorted.

Figure 3-14 displays the equatorial zone boundaries for the A analyzer as a function of energy, for a 5 γ external field. Thus we see that for certain external magnetic field orientations we can arrive at a cutoff energy of 70 eV without any surface potential at all (e.g. for $\phi_A = 40^\circ$, $\theta = 0^\circ$), as electrons below that energy would be in shadow zones for analyzer A and electrons above that energy would be in open zones. However, the region of ($\phi_A$, $\theta$) space for which that is true is fairly small, compared to the abundance of different field conditions for which a cutoff energy ≥ 70 eV is observed (two such cases are shown in the next chapter). Also, the cutoff energy derived in this way would show no dependence on the external plasma temperature, whereas such a dependence is observed. Lastly, the cutoff energy would be
Figure 3-12. Open zones (bars) for the Apollo 14 ALSEP field plus an external field of 5 $\gamma$. The solid curve for the B analyzer is the analytic solution.
Figure 3-13. The open zones for a 70 eV analyzer A electron. Note the distortion both from Figure 3-12 (200 eV) and Figure 3-4 (analytic solution).
Figure 3-14. Zone boundaries in the equatorial plane as a function of particle energy (eV).
vastly different between the two CPLEE analyzers (since their zone boundaries are far apart) - yet the cutoff (or crossover) energy is generally quite comparable. Thus we look for electric fields which may also affect the crossover energy.
The Photoelectric Field

The sunlit lunar surface emits photoelectrons. This would lead to unlimited surface charging, except that the charging creates an electric field that returns the photoelectrons. In a steady-state situation, no net current exists, and an equilibrium surface potential exists. Immersion of this surface in a dilute plasma will, in general, reduce the equilibrium potential, as the net flux of ambient electrons into the surface generally exceeds the flux of ambient protons into the surface.

Estimates of the equilibrium surface potential in the plasma sheet at lunar distance have been made by several workers, both for potentials that fall monotonically to zero with height above the surface [Grobman and Blank, 1969; Rich, 1973]; and those that include the possibility that the potential distribution is non-monotonic: that is, the potential falls from some positive value at the lunar surface to some negative value above the lunar surface, returning to zero at infinite height [Guernsey and Fu, 1970; Burke et al., 1975]. In each of these models the potential varies with the photoemissivity and the flux of incoming particles, yet each calculates potentials of the order of ten volts.

Reasoner and Burke [1972] have shown that this potential has a scale height on the order of meters. The scale height of the electric field determines the effect it has on observed particle distributions. An electric field with an extent larger than the largest gyroradius in question will
cause the particles within it to accelerate along the field lines and $E \times B$ drift across the field lines. For fields having a scale size comparable to or smaller than the gyro-radius, the effect is merely to add the energy corresponding to the potential drop to the particle's incident energy. Thus a detector viewing an accelerated incident particle population will see no fluxes up to the cutoff energy $E_c$, and accelerated fluxes above that energy. If the incident population is isotropic, the observed distribution function is particularly simple, from Liouville's theorem:

$$f(E, \mu) = \begin{cases} f_{\text{old}}(E_{\text{old}}) & , \ E \geq E_c \\ 0 & , \ E < E_c \end{cases}$$

(3-26)

where $\mu$ is the angle between the look direction and the electric field, and $E_c$ is the cutoff energy for that look direction. As the minimum velocity parallel to the electric field is $\sqrt{2e \phi/m}$, which equals $\sqrt{2E_c/m} \cos \mu$, we find $E_c = e\phi/\cos^2 \mu$, where $\phi$ = potential drop. $E_{\text{old}}$ equals the energy before the potential drop = $E - e \phi$.

For an initially isotropic flux distribution and short-scale fields, we can use the cutoff energy observed in the two CPLEE analyzers to assess both the total potential drop $\phi$ incurred by the incident particles and the direction of the electric field (at least its projection in the plane containing the two analyzers). This is another clue that the cutoff energy observed by CPLEE cannot be due only to a small-scale electric field perpendicular to the lunar surface, as
the cutoff energies observed in the two analyzers are generally quite similar. This implies that either the electric field is pointed between the two analyzer directions (and hence not perpendicular to the surface), or else some large-scale effect is at work.
Charge Separation Region

The most dramatic implication of shadowing is the formation of a charge separation region [Figure 3-15]. This effect, first described in lunar applications by Neugebauer et al. [1972], is due to the gyroradius difference between ions and electrons. The ions, having much more rigidity, are deflected less in the lunar field than the lighter electrons. The deflection of electrons creates a charge separation layer and concomitant electric field to draw the electrons to the surface (or to stand the protons off, whichever is easier). For a vertical dipole magnetic field as is assumed at CPLEE, the electron deflection currents are planar circles around the dipole projection, in the sense that the horizontal component of the local magnetic field is enhanced at the surface. This model has been discussed for the case of the solar wind by Siscoe and Goldstein [1973]. They find a critical field magnitude of about 70 \( \gamma \) for stopping solar wind flow, assuming that the scale size of the field is much larger than the penetration depth \( L_p \approx (m_e m_p)^{1/2} v_p / eB \). The penetration depth may be thought of as the gyroradius of a particle with the proton's velocity and a mass which is the geometric mean between the proton and electron masses.

Application of the charge-separation model to the plasma sheet brings two immediate difficulties. First, the magnetic field at Apollo 14 is near the minimum for stopping solar wind flow. Second, the assumption of large scale size for
Figure 3-15. Field lines near Apollo 14, showing the locations of the dipole and the charge separation region.
the field is not valid. Here $L_p$, about 1.5 km, is comparable to the scale size of the field (~.5 km), and to the radius of curvature of the field lines near CPLEE (2-3 km).

Next, the plasma parameters for the plasma sheet differ considerably from those in the solar wind. The proton thermal velocity in the plasma sheet is comparable to solar-wind bulk velocities; however, the bulk velocity in the plasma sheet is quite small in quiet times, as is the thermal velocity in the solar wind. Thus the situation changes from high Mach number flow in the solar wind to subsonic flow (if any) in the plasma sheet. The thermal energy of the electrons has also increased, from about 10 - 14 eV in the solar wind to about 200 eV in the plasma sheet. Thus the electrons are able to penetrate farther in the plasma sheet than in the solar wind.

The highly thermal fluxes in the plasma sheet necessitate examining the penetration of particles as a function of angle of entry. Trajectory calculations show that for zero external fields, normally incident protons of essentially all energies and electrons above about 40 eV are able to strike the surface. This may be understood in terms of the minimum rigidity to penetrate the field: approximately the average field times the scale length of that field. Thus, $m_e v_{\text{min}}/e = B_{\text{avg}} d$. For $d = .5$ km, $B_{\text{avg}} = 50 \gamma$, $v_{\text{min}} = 4.4 \times 10^6$ m/s, implying $E_{\text{min}} = 55$ eV. The sense of the particle deflection is to create currents that make the field more horizontal, stronger, and more nearly uniform, all tending to increase
the magnitude of $E_{\text{min}}$. The minimum energy is complicated further when angles of incidence other than normal, and external magnetic fields, are considered. Strong external fields nearly parallel to the lunar surface will shadow both ions and electrons, as we have seen earlier, leading to charge separation layers well above the lunar surface. Intermediate directions of the external magnetic field, will, in general, produce anisotropic fluxes that are both energy dependent and angle dependent. All of these factors must be brought into account before we are able to compute the strength of the charge separation potential $\phi_{\text{sc}}$ and the height of the region $h$. However, we make several general predictions:

1) the charge separation region should extend roughly from the height at which the incident electrons are reflected (approximately where the magnetic field pressure balances the incident electron pressure) to the height at which the protons are reflected, or the surface, whichever is higher.

2) the electric field should be stronger, the greater the difference between the rigidities of the electrons and protons. We define $R = \text{rigidity ratio} = m_p <v_p>/m_e <v_e> \approx 43 V_p/E_e$, where $<v>, E$ refer to the mean velocity into the surface, and the corresponding energy.

3) the charge separation region will be closer to the surface and less intense for greater electron rigidities.

4) the charge separation potential will be the greatest when the bulk of the incoming particles are shadowed, and the least when all particles have free access to the surface (i.e. in
the "golden zones" described earlier).
5) the interaction will be quite different for high Mach number flow versus low Mach number flow. In the first case, a shock wave may be necessary to deflect the incident flow; in the second case, no shock is needed.
6) charge separation regions closer to the surface are much more likely to be shorted out by photoelectrons.

Let us examine several plasma regimes to predict the characteristics of the charge separation regions corresponding to each. We shall separate the discussion into regions of high Mach number flow and low Mach number flow.

A) the solar wind. The ratio $R_L$ is here the highest ($\approx 430$ for $E_e = 8$ eV and $E_p = 800$ eV). The height of electron pressure balance $h_e$ is large: 1.6 km for densities in the range $3 - 5 \text{ /cm}^3$. The height for proton pressure balance is extraordinarily low: 200 - 100 m for densities of $3 - 5 \text{ /cm}^3$. Thus although the high rigidity ratio would demand a strong charge separation electric field, the severe compression of the field may negate this effect. In addition, the field may be shorted out by photoelectrons.

B) the magnetosheath. Here the situation is similar, with low proton pressure heights ($120 - 220$ m for $E_p = 473$ eV), fair electron pressure heights ($780 - 930$ m for $E_e = 35$ eV), and moderate rigidity ratios (about 160). Thus the potential in the magnetosheath should be smaller than that in the solar wind, and is subject to the same compression effects.

C) the boundary layer. Here the rigidity ratio is
moderate (50 for \( E_e = 50 \) eV and \( E_p = 70 \) eV), and the heights quite large (\( h_e \approx 1.7 \) km and \( h_p \approx 1.2 \) km for a density of \( 0.5 \) /cm\(^3\). Thus we predict a small potential on the basis of the rigidity ratio.

Thus for the flowing plasmas we expect the charge separation potential to be largest in the solar wind, moderate in the magnetosheath, and smallest in the boundary layer. In the solar wind and magnetosheath, however, the protons compress the magnetic field severely, which may alter the situation dramatically. Next we shall examine some non-flowing plasmas.

A) terminator solar wind or magnetosheath. At the terminators, there is very little flow into the surface. For roughly equal electron and proton temperatures, then, the rigidity ratio would be about 40. The height for pressure balance is correspondingly high (\(-1.6 \) km). Thus a small charge separation potential is predicted, and both electrons and protons may be denied the surface.

B) the plasma sheet. Here the rigidity ratio is moderate (135 for \( E_p = 10 \) \( E_e \)). The pressure is fairly low (about 250 eV/cm\(^3\) for protons, 20 eV/cm\(^3\) for electrons), leading to a high charge separation region (\( h_p \approx 1 \) km; \( h_e \approx 1.8 \) km), with fairly large electric fields possible. The plasma sheet is interesting to study because its plasma parameters vary with time over a fair range. Thus it is useful as a testing ground for the above predictions.

C) the neutral sheet. Lunar-distant neutral sheet electron characteristics are reported for the first time here,
and the predictions are, of course, dependent on the plasma parameters. In general, however, the proton flux resembles an anisotropic plasma sheet [Burke and Reasoner, 1973]. The electrons, however, have also a cold component as well as a plasma sheet component. These observations will be discussed in the light of the model in the following chapter.

The Composite Electric Field

The electrostatic potential as a function of height is shown schematically in Figure 3-15. The potential is defined to be zero at infinite height $h$. At $h_{cs}$ the electron deflection occurs, with a rise of the potential of $\phi_{cs}$. The potential will rise in a distance $L_p$, where $L_p$ is the penetration depth, as defined above. As long as both electrons and protons are reflected, i.e., $L_p < h_{cs}$, a "plateau" in the potential occurs. At several meters above the surface (the Debye length for the photoelectron layer), the potential again rises, this time by $\phi_{pe}$, the potential due to the photoelectric effect.

For the case where electrons, but not protons, are reflected (as is often the case in the plasma sheet), we may calculate the zero order potential distribution as a function of height. A certain amount of the incident electrons will be reflected at $x = h$. This will lead to a surplus positive charge density $\rho$ from $x = 0$ to $x = h$. Poisson's equation states: $\nabla^2 \phi_{cs} = -\rho/\varepsilon_0$, so that $\phi = a_0 + a_1 x - \rho/\varepsilon_0 x^2$, $0 \leq x \leq h$. We have two boundary conditions: no external electric fields (i.e. $a_1 = 0$) and $\phi = 0$ at $x = h$. Thus
Figure 3-15. Electrostatic potential as a function of height for the case in which both electrons and protons are reflected from an altitude of about 1 km.
\[ \phi(x) = \phi_{\text{cs}} (1 - \frac{x^2}{h^2}) \]. The photoelectric potential \( \phi(x) = \phi_{\text{pe}} (\exp^{-x/\lambda_{\text{pe}}}) \) is added to the charge separation potential in Figure 3-16. We see that although we do not observe so broad a plateau as in the former case (Figure 3-15), we do expect the potential to be constant to within 1% for the first \( h/10 \) m, and constant within 4% for the first \( h/5 \) m. This constancy is important to explain the SIDE data, as we shall see below.

We can do a quick check on the self-consistency of this value for \( \phi_{\text{cs}} \), using an external magnetic field of 5 \( \gamma \) normal to the surface (\( \phi_A = 0 \)). We find that normally -incident electrons above \( -35 \text{ eV} \) and virtually all protons reach the surface [Table 3-3]. Thus the surplus charge density initially should be the electron density below 35 eV or about \( (1 - e^{-35/200}) \), or 16% of the incident density. Thus, for \( n = 0.1/\text{cm}^3 \) [Rich et al., 1973], \( \rho = 2.56 \times 10^{-13} \text{C/m}^3 \). For \( h = 1 \text{ km} \), this yields \( \phi_{\text{cs}} = \rho h^2/\varepsilon_0 = 2.6 \times 10^{-13} \text{C/m}^3 \times 10^6 \text{m}^2/(10^7/4\pi \text{c}^2) = 2.9 \times 10^4 \text{ V} \), which is more than enough to draw all the external electrons in. The value of \( \phi_{\text{cs}} \) of 35 V (just enough to let most of the electrons in) corresponds to a net charge density below the separation region of \( \rho_{\text{net}} = 350/4\pi \text{c}^2 = 3.09 \times 10^{-16} \text{C/m}^3 = 1.9 \times 10^{-5} \text{ net protons/cm}^3 \), or only .02% of the incident density. Thus an equilibrium can be quickly established. The percentage of 1 keV protons reflected by a 35 eV potential would be \( 1 - e^{-35/1000} \), or about 3.4%. Thus we see that the equilibrium potential should be \( \leq 35 \text{V} \) in this case.
Figure 3-16. Zero-order analytic potential solution for a fraction of the electrons reflected, the remainder of the electrons and all of the protons reaching the surface. A constant positive charge density below 1 km is assumed.
For a steady-state equilibrium, the density of electrons reflected by the magnetic field despite the electric field must equal the density of protons reflected by the electric field. The exact value of the equilibrium potential set up in this way is critically dependent on external plasma and field parameters, and is beyond the scope of this thesis.
Summary of the Model

The model predicts shadowing of particles by the lunar surface. This effect is dependent on particle sign and energy and the magnitude and direction of the external magnetic field. The local magnetic field plays a critical role in the process, altering the "open zones" and creating a charge separation layer. The electrostatic potential due to the charge separation will be larger, the greater the difference between electron and proton rigidities, or, equivalently, the smaller the ambient electron temperature. The charge separation region is nearer the surface for greater electron rigidities. The potential, which may be "shorted out" by photoions and photoelectrons traveling up field lines, is predicted to be highest in the solar wind and magnetosheath, moderate in the plasma sheet, and lowest in the boundary layer and solar wind terminator regions. The altitude of the charge separation region will be greatest in the boundary layer and terminator regions, moderate in the plasma sheet, and lowest in the solar wind.

The next chapter examines data to test these predictions, developing tests for both the magnitude of $\phi_{cs}$ and the height of the charge separation region $h_{cs}$.
In this chapter we will examine particle data in the light of the model. In particular, first we shall examine plasma sheet fluxes to verify that shadowing does, indeed, occur. Then we shall examine particle spectra to estimate the charge separation potential $\phi_{cs}$ and determine whether the general predictions about the magnitude of the potential are substantiated by the data.

**Shadowing Observations**

Figure 4-1 presents, versus time, magnetic field and plasma parameters. This time segment, from 2000 GMT March 10, to 0300 GMT March 11, 1971, is illustrative of shadowing in both analyzers (from 2300 March 10 to nearly 0200 March 11).

The top trace in the figure is the solar ecliptic latitude of the external magnetic field. The next lower trace is the solar ecliptic longitude of the field. The next two traces are, respectively, the count rates (four cycle or 80 second averages) of the 200 eV electron channels of analyzers A and B. The bottom trace is the magnitude of the magnetic field. The magnitude is near its high-latitude field value of about 10 $\gamma$ for one period only (2130-2210 March 10). The rest of the time, the depressed field magnitude is indicative of the plasma sheet. Indeed, CPLEE proton channels (not shown here) reveal plasma sheet during the bulk of this period.
We have used the shadow zones computed for the superposition of the lunar and external fields (Figure 3-12) to predict when plasma sheet electron fluxes should not be seen (heavy shading) or unknown (light shading). The lobe magnetic field of 2140 - 2200 is used to normalize the longitude angle of the magnetic field. We see that the plasma sheet electron fluxes (operationally defined here as counting rates above 20) are not evident during all the times when the magnetic field magnitude is low. For times when the magnetic field is oriented such that an analyzer is in an open zone (no shading), the fluxes are gated by the total surface potential $\phi_O = \phi_{CS} + \phi_{pe}$. Comparison with higher-energy electron channels (not shown) indicates that the variation in fluxes is generally due to shadowing, except for near 2030 March 10 and 0230 March 11. In the former case, entry into the "golden zone" appears to lower the potential below 200 V; in the latter case, magnetic field data is unavailable.

We note that the count rates during the shadowed times do not fall below background (0-3); rather, they are significant (7-12), although slightly below typical photoelectron count rates in the high latitude tail (10-18). We interpret these fluxes to be photoelectrons being reflected to the ground by the electric and magnetic fields in the vicinity. The decrease in flux is due to the altitude of the reflecting region: in the high latitude tail, the photoelectrons are returned by the photoelectric potential, which falls off a few meters above the surface. The photoelectrons here are
reflected from about a kilometer above the surface; there
is thus more chance for magnetic field irregularities to
scatter the photoelectrons away from their field-line of ori-
gin.
Plasma Sheet Spectra

The plasma sheet yields an excellent opportunity to test the general predictions of the model. The rigidity ratio stays fairly constant, but the electron temperature has been observed to vary over a wide range, and the magnetic fields observed in the plasma sheet are quite variable. Thus we look for cases in which 1) the magnetic field is about constant, but the electron temperature varies (predicting a lower \( \phi_{cs} \) for higher electron temperatures), and 2) the electron characteristics are similar, but the magnetic field configuration is different (predicting a lower \( \phi_{cs} \) for magnetic field directions closer to the "golden zone"). Fortunately, we are able to show both effects using just three spectra.

Spectrum #1 [Figure 4-2] is a one-minute average taken from February 9, 1971, at 2343 GMT. The magnetic field magnitude was 7 \( \gamma \), longitude 170° and latitude 15°. SELODA was -240, making \( \phi_A = 194° \). This is well inside the "golden zone" [point #1 on Figure 4-3]. The electron density was near \( 1/cm^3 \) and temperature near 150 eV. The cutoff energy is estimated to be 90-100eV. As the surface potential due to photoelectrons should be about 20 V [Rich, 1973], this leaves a charge separation potential of 70 - 80 V.

Spectrum #2 [Figure 4-4] is a one-minute average taken January 20, 1973 at 0110. Here the magnetic field was about 9 \( \gamma \), longitude 190°, and latitude 13°. As SELODA was 353°, \( \phi_A = 197° \) - virtually the same magnetic field condition [point #2 on Figure 4-3]. The plasma parameters were quite
Figure 4-2. A fairly typical plasma-sheet spectrum.

The heavy diagonal line is the photoelectron average.
Figure 4-3. Reproduction of Figure 3-12 to show the magnetic field configurations for the spectra shown (V = vertical).
Figure 4-4. Spectrum #2 is taken at storm-time; the circles are more typical plasma-sheet conditions.
different, however. The density was higher (from .1 to .5 /cm$^3$) and the temperature was considerably higher (600 - 700 eV). Flux balance demands a low $\phi_{pe}$ ($\leq$ 5 - 10 V). We note that essentially no photoelectrons are present. This necessi-
tates $\phi_o < 40$ V; making $\phi_{cs} < 30$ V. Thus we verify the pre-
diction that increasing the electron temperature will lower the charge separation potential for a given field condition.

Spectrum #3 [Figure 4-5], coupled with spectrum #2, illustrates the dependence on magnetic field. Here the electron temperature and density are similar to spectrum #2 (.3 /cm$^3$, 700 eV). However, the magnetic field magnitude is 8 $\gamma$, longitude = $-90^\circ$, and latitude = 20$^\circ$. A SELODA value of $-32^\circ$ implies a $\phi_A$ of $-58^\circ$. Although A and B are both in open zones (and, indeed, both show fluxes), the magnetic field is well outside of the golden zone [point #3 on Figure 4-3]. The crossover energy of about 120 V bears this out. As the potential due to photoelectrons should be $\phi_{pe} \geq 20$ V, this implies a $\phi_{cs} \leq 100$ V. Thus the dependence of $\phi_{cs}$ on magnetic field configuration is confirmed, as well as, once again, the de-
pendence on electron temperature. Recall from Figure 4-1 that for more typical plasma-sheet electron temperatures (about 200 eV), only for fields inside the "golden zone" did the po-
tential fall below 200 V. Yet for this high-electron temper-
ature example, the potential is closer to 100 V.

We understand now why the 70 V cutoff energy reported by Rich [1973] is "typical". If one assumes that the field lines in the plasma sheet are pointed down-tail, the range
Figure 4-5. A storm-time high-flux example where photoelectrons were observed to high energies.
of $\phi_A$ across a tail passage would be $50^\circ - 0^\circ$ for the northern lobe and $230^\circ - 180^\circ$ in the southern lobe. The average latitude is near $+10^\circ$. We see from Figure 4-3 that this range is about half inside the "golden zone" and half outside. The part that is outside the "golden zone" will be also outside the open zone for the B analyzer. A "typical" plasma sheet observation is one in which significant 200 eV fluxes are observed, in either detector. However, we have seen that for "typical" plasma sheet electron energies, the crossover energy is greater than 200 V, unless the magnetic field is inside the "golden zone". Inside the golden zone, both A and B analyzers were clear, and so isotropic fluxes were reported. And, for typical electron energies, the golden zone implies crossover energies of about 70 eV. Indeed, when the magnetic field parameters were found for the "typical" plasma sheet spectrum of Rich et al. [1973], they were found to lie just on the border of the "golden zone" [point R on Figure 4-3].

Thus we see that plasma sheet observations confirm the two facets of the model: 1) external fluxes may not be observed unless the magnetic field is in an open zone for the detector in question. 2) once inside an open zone, fluxes will not be detected at energies below the cutoff energy $E_C = e(\phi_{pe} + \phi_{cs})$. The magnitude of $\phi_{cs}$ has been shown to be dependent on magnetic field orientation and electron energy, as expected.
SIDE Resonance Phenomena

SIDE observes resonances (i.e., nearby monoenergetic spikes) of photoions, under certain conditions. SIDE steps its potential relative to the surface, using a voltage supply and a spiderweb electrical contact with the surface [Freeman et al., 1973]. For certain values of the stepper voltage (which varies from -27 to +27 V), one (and only one) of the energy channels will respond to an enhanced flux of photoions, generally far above the flux at other detector energies for the same ground stepper, or the flux at that energy for other ground steps. Energy balance for the ion implies

$$K_{E_{\text{SIDE}}} + e\Phi_{\text{SIDE}} = K_{E_{\text{init}}} + e\Phi_{\text{init}}$$

where $K_E$, $e\Phi$ are the kinetic and potential energies of the ion at ionization (init) and detection (SIDE). The photoions are at surface temperature energies, i.e. only a fraction of an electron volt; thus Freeman et al. justifiably ignore $K_{E_{\text{init}}}$. The value of $\Phi_{\text{init}}$ is another problem. They assume $\Phi_{\text{init}} = 0$; in this model, $\Phi_{\text{init}} = \Phi_{cs}$ (which may, of course, have the value zero). For $\Phi_{\text{init}} = 0$, the resonant photoions may be created an indefinite height above the surface; therefore, the magnitude of their resonance should be always just about the same. In our model, only particles ionized below $h_{\text{max}}$ may participate in the resonance. Those created at higher altitudes do not have the energy to surmount the potential barrier of $\Phi_{cs}$ [Figure 4-6]. For a constant ionizing flux, the magnitude of the resonance is related to the height of the charge
Figure 4-6. Expansion of either Figure 3-15 or 3-16 to display the potential expected near SIDE. The stepper supply shifts the potential of the SIDE instrument relative to the surface by $\phi_{gs}$. 
separation layer by

\[ J_{pi} = \sum_i \int_{h_{\text{SIDE}}}^{h_{\text{max}}} \sigma_{ni} n_n(h) \phi_i(h) \, dh. \]

where \( h_{\text{max}} \) is the altitude of the top of the plateau, i.e. \( h_{cs} \) for the both-reflected case [Figure 3-15], 0.2 \( h_{cs} \) for the electrons-only-reflected case [Figure 3-16]. If the scale height of the neutral atmosphere is much larger than \( h_{cs} \), and the ionizing fluxes are nearly height-independent, this reduces to \( h_{\text{max}} \sum_i \sigma_{ni} \phi_i(0) n_n(0) \), where \( n_n \) is the neutral number density, \( \phi_i \) is the ionizing flux of the \( i \)-th species, and \( \sigma_{ni} \) is the cross-section for neutral ionization by the \( i \)-th species (e.g., UV light, photoelectron flux, or external plasma flux). The magnitude of the SIDE resonance will depend, then, on the ionizing fluxes, the height of the charge separation region, and whether the resonant energy is centered within a SIDE energy channel or not.

Freeman et al. [1973] have demonstrated the first effect, showing a correlation between solar wind density and the magnitude of the resonance. They also demonstrated the third effect in the difference between the resonances in the solar wind and magnetosheath. What remains to be tested is the prediction of this model - the variation with the height of the charge separation region. This should be most easily accomplished in the plasma sheet. One should look for times in which the magnetic field configuration was identical, the net flux to the lunar surface was identical (both solar flux and plasma flux), so that both the ionizing flux and the equilibrium
photoelectric potential are the same. The model then would predict a larger $h_{cs}$ for smaller incident electron temperatures, and therefore a larger SIDE resonance. Although this would take some searching to find appropriate times to test the model, it would be worthwhile in evaluating the model here presented. It is also advantageous as this is essentially the only way to establish the height of the charge separation region from lunar-based instrumentation. One other SIDE observation [M.Ibrahim, private communication] that is consistent with this model is that the resonances at the Apollo 15 site (where the local magnetic field is small and no charge separation predicted) are typically much stronger than at the Apollo 14 site (where the resonance should be limited by this height).

In summary, the model states that the potential that is calculated using SIDE resonance data is not the total surface potential $\phi_o$ but just the potential due to photoelectrons $\phi_{pe}$ so long as a "plateau" exists in the potential. In regions where the magnetic field is highly compressed (as is possible in the solar wind and magnetosheath) or intrinsically small (as at the Apollo 15 site), no plateau may exist (in fact, no charge separation at all may exist); in those cases, the SIDE resonance is measuring the total surface potential $\phi_o$. In a plateau situation, as is likely in the plasma sheet, neutral sheet, boundary layer, and terminator regions, the magnitude of the SIDE resonance can, in principle, be used to estimate the height of the charge separation region.
The Neutral Sheet

The neutral sheet is another population that displays cutoff energies far in excess of those calculated on the basis of the photoelectric field alone. Figure 4-7 is an electron spectrum taken just at a neutral sheet crossing. At that time the magnetic field had a magnitude of $0.88 \gamma$, $\theta = -26^\circ$, and $\phi_{SE} = 155^\circ$. As SELODA was $-12^\circ$ at the time, this implies a $\phi_A$ of $167^\circ$ (marked as point NS on Figure 4-3). We see that this is on the border of the golden zone (although the small field magnitude will expand the golden zones somewhat). We see, in addition to an extremely hot plasma-sheet type electron population (temperature $\approx 800$ eV, density $0.1$/cm$^3$), that there exists a very striking lower-energy population. This type of low-energy population is only observed for quite brief periods at the neutral sheet, and is generally associated with a southward component of the tail magnetic field.

The crossover energy in this case is fairly easy to estimate: about 60 eV for the B analyzer and about 100 eV for the A. This is often not the case. Frequently one analyzer will show a cutoff in the 40 - 200 eV range, and the other analyzer will show elevated fluxes all the way down to that analyzer's lower-energy limit ($\approx 40$ eV) [Figure 4-8]. This may be the result of shadowing - one is viewing photoelectrons from a much weaker region of the local field. Here the potential is higher, and the photoelectrons are accelerated, increasing their flux by Liouville's theorem. Or else we are viewing a neutral sheet population with a cutoff energy lower than the
Figure 4-7. A neutral-sheet spectrum taken in storm time. A hot plasma-sheet component is present.
Figure 4-8. A neutral-sheet spectrum in which no plasma-sheet component is present.
detection limit. It is virtually impossible to say which. The spatial separation between the Explorer 35 magnetometer and the Apollo 14 site is critical here, as the fields are changing direction and magnitude quite quickly.

The clear cutoffs exhibited in Figure 4-7 may be used to estimate the magnitude and direction of the total electric field. Recall from Chapter 3 the cutoff energy is related to the analyzer's angle to the electric field \( \mu \) by \( E_C = e \phi / \cos^2 \mu \). This, of course, is strictly valid only for electric fields smaller in scale than the particle's cyclotron radius, but we shall look at the result, anyway. We may then solve for the magnitude of the potential drop and the angle of the electric field in the plane of analyzers A and B. In this case, the solution is \( e \phi = 53 \) eV, and \( \phi_A = -43^\circ \). With some amazement we note that this is approximately (the opposite of) the local magnetic field direction. Certainly more examples need to be calculated to see whether this is a general result or not. In the plasma sheet, for example, the cutoff energies between the A and B analyzers are generally comparable, also compatible with a field-aligned potential drop.
Summary

Observations in the plasma sheet confirm the two basic facets of the model presented here. First, the orientation of the external magnetic field gates the fluxes of incident particles to the lunar surface. Next, the differential deflection of electrons and protons creates a charge separation potential. This potential has been shown to range from \(<30\) V in hot plasma regions to \(\approx 50\) V in normal conditions up to \(>90\) V in cold plasma conditions or when particle access is severely shadowed by external magnetic fields.

SIDE resonance data can, in principle, be used to estimate the height of the charge separation region by the magnitude of the resonance. The magnitude is, however, also dependent on the magnitude of the ionizing flux, and whether the resonant energy is centered on a SIDE energy channel.

CPL EE neutral sheet electron data show a high-flux low-energy population, which may or may not be superposed on a plasma sheet-type electron population. This steeply-falling population allows fairly accurate estimations of the cutoff energy, the energy below which one sees only photoelectrons and above which one sees an accelerated incident plasma. These cutoff energies, which may or may not be in the energy detection range of CPL EE, have implied in at least one case that the electric field is aligned with the local magnetic field. As the cutoff energies are generally comparable in the A and B analyzers, this result may be typical. As a field-aligned potential drop should be the easiest way to draw
electrons in (since the small scale length of the local magnetic field implies a small mirror force), this result is consistent with the dipole nature of the local magnetic field.

Thus, we have been able to confirm that shadowing occurs, that a charge separation region exists, and that the electric field associated with it is, at least sometimes, aligned with the local magnetic field. We have also proposed an experimental test of the height of the charge separation region, by using SIDE resonance data.

The final chapter recapitulates the model and pertinent observations, and discusses the implications of the model on particle observations at the lunar surface.
CHAPTER 5
SUMMARY AND DISCUSSION

Summary

This thesis has categorized, if not completely quantified, the effects of the interaction of incident plasmas with the lunar surface and the lunar electromagnetic environment. This interaction has several features:

1) the external magnetic field (combined with any local magnetic fields) gates the access of incident plasmas to the lunar surface. The effect is dependent on particle energy and sign, and angle of incidence with the surface. For each angle of incidence to the surface, there exist "open" and "shadowed" zones - cones of directions of the external magnetic fields such that external particles may or may not, respectively, reach the surface at that angle of incidence. In addition, there exist two "golden zones" - regions of external magnetic field directions for which essentially isotropic external fluxes may reach the surface. The open and shadowed zones have been calculated analytically for the case of no electric field in the moon's frame of reference and no lunar magnetic field. In this case, the zones are only weakly energy dependent. In the case of strong local fields (electric or magnetic), the zones become strongly energy-dependent. Open zones have been calculated for the Apollo 14 ALSEP site using a dipole fit to the local magnetic field, and again assuming no external electric field, for 200 eV electrons.
2) the gating effect of the magnetic fields will reduce the external fluxes that reach the surface. Therefore, the surface potential due to photoelectrons will, in general, be larger than that calculated assuming that incident plasma arrives isotropically over the downward hemisphere. This effect is minimized when the external field direction is in the golden zone. Since the SIDE determination measures $\phi_{pe}$ (see below), the SIDE data may be used to test this prediction. The maximum photoelectric potential they can observe is -21 V [Freeman et al., 1973]; therefore the shadowing effect should be observable as a lack of a resonance during periods when plasma-sheet fluxes are shadowed from the surface (i.e., the external field direction is far from the golden zone).

3) the differential deflection of electrons and protons will create a charge separation region. The height of the region may be estimated roughly by pressure balance. The magnitude of the charge separation potential may be roughly estimated theoretically at about 50 V for a charge separation region about 1 km above the ALSEP site at Apollo 14. The actual magnitude of this potential $\phi_{cs}$ was predicted to vary with the rigidity ratio of the incoming plasmas, the electron temperature, and the percentage of incident plasma shadowed.

Implications

There are several implications of the shadowing/charge-separation model. Some of these answer nagging questions about the proper interpretation of CPLEE results. Others make
predictions that may be testable with currently available data. These are:

a) the observed variability of lunar magnetic fields across the surface implies gradients in the local electric fields, both from the photoelectric effect and the charge separation effect.

b) the shadowing effect results in a tendency to underestimate the frequency of encounters with the plasma sheet from particle data alone. Thus Rich [1973] reported less frequent plasma-sheet occurrences than Meng and Mihalov [1972].

c) the shadowing model here presented has several advantages over the shadowing model of Anderson [1970] in explaining surface low-energy particle data. His model, that embodies flux tubes emptying of plasma as they remain in intersection with the moon, necessitates a given flux tube remaining stationary for minutes or more, which is unlikely at the moon, due to random flapping of the tail [Bowling and Wolf, 1974]. Anderson's model only allows energy-dependent shadowing as a temporal effect or an effect of the crosstail electric field. His model also does not allow differential shadowing of one angle of incidence over another, as is fairly common in CPLEE data. The present model, on the other hand, allows steady-state shadowing that is both energy- and angle of incidence-dependent, and necessitates magnetic fields that are constant for time scales of seconds or less, all of which are more in line with observations.

d) CPLEE data often show cutoff or crossover energies:
energies below which one observes only photoelectrons and above which one observes incident plasmas. A model ignoring magnetic fields would assign the crossover energy observed in the upward-looking detector to be the local surface potential energy due to the photoelectric effect. This interpretation of CPLEE data has two severe drawbacks: 1) the crossover energy observed by an analyzer 60° to the normal to the surface should be four times the crossover energy observed in the vertically-looking detector. This is never observed. The crossover energies in the two CPLEE analyzers are generally quite comparable, more often than not with the 60° detector (analyzer B) showing a smaller crossover energy (consistent with an electric field pointed somewhere between the two analyzers' look directions. 2) the surface potential calculated in this manner is larger than what would be calculated for the potential due to photoelectrons \( \phi_{pe} \) (-10 V) due to current balance. A photoelectric potential of about 10 V has also been confirmed by SIDE resonance phenomena [Freeman and Ibrhim, 1974]. This discrepancy, first noted by Rich [1973], has had no plausible resolution heretofore.

One possible resolution of the cutoff energy phenomenon is the energy-dependent boundaries of the open zones. This indeed may be possible for certain orientations of the external magnetic field, but for only one analyzer at a time (since the zone boundaries are quite different for the two analyzers). The only way one may have cutoff energies that are similar in the two analyzers is to have an electric field pointed roughly
between the two analyzers. For a case in which clear cutoffs were observed in both detectors, the electric field direction turned out to be the local magnetic field direction. As an electric field pointed in the magnetic field direction should be the easiest way to neutralize a charge excess, the electric field calculated in this way confirms not only the existence of the charge separation region but also the dipole nature of the local field, since the local field direction was calculated on the assumption that the local \( B \) field was dipolar.

Thus this thesis presents the first experimental evidence of a charge-separation region for isotropic plasmas. Siscoe and Goldstein [1973] examined charge separation for a flowing plasma. Their conclusions imply that the Apollo 14 magnetic fields are not of sufficient scale length to stop solar-wind (or magnetosheath) flow, and indeed, no detectable charge separation potential is observed with CPLEE data in the solar wind and magnetosheath [Moore, 1974; Reiff and Reasoner, 1975]. Here we have presented the first self-consistent explanation of the differences in the lunar surface potential in the plasma sheet derived from CPLEE data (around 70 V) and from current balance and from the SIDE resonance phenomenon (about 10 V). The potential distribution as a function of height falls to zero at infinite height \( x \). At \( x = h_{cs} \) (the height of the charge separation) the potential rises by about 50 V to equalize the penetration of electrons and protons. Below this height a plateau in the potential occurs, until a few meters above the surface, where the potential rises by the
photoelectric potential $\phi_{pe}$. Thus the SIDE determination calculates the photoelectric potential (as does current balance when one uses fluxes observed at the surface). The CPLEE determination, which uses the cutoff energy from plasmas incident from infinity (rather than in the lunar vicinity), measures the total potential difference between the lunar surface and infinity $\phi_{o} = \phi_{pe} + \phi_{cs}$. The SIDE determination (and the flux balance calculations) measures the difference between the potential at the surface and the potential in the region from which the fluxes come (the plateau). Thus we may derive an instantaneous value of the charge separation potential by taking the difference between the potentials measured by the CPLEE and SIDE instruments. Although the range of measurable potentials is fairly small, this would be an important experiment to perform.

Thus we see that local effects are of major importance in interpreting particle data taken on the lunar surface. Local magnetic fields (and the large size of the satellite) cause effects much more complex and far-reaching than a simple photoelectron sheath.
REFERENCES


Mihalov, J. D., D. S. Colburn, R. G. Currie, and C. P. Sonett, Configuration and reconnection of the geomagnetic tail,

Moore, P. R., Magnetosheath electrons at lunar distance, M.S. thesis, Rice University, Houston, Texas, 1974.


Reiff, P. H. and D. L. Reasoner, The magnetosheath electron population at lunar distance—general features, J.


