Regarding the possible generation of a lunar nightside exo-ionosphere

W.M. Farrell\textsuperscript{a,d,}\textsuperscript{a}, J.S. Halekas\textsuperscript{b,d,} T.J. Stubbe\textsuperscript{a,c,d}, G.T. Delory\textsuperscript{b,d}, R.M. Killen\textsuperscript{a,d}, R.E. Hartle\textsuperscript{a,b}, M.R. Collier\textsuperscript{a,d}

\textsuperscript{a}NASA Goddard Space Flight Center, Code 695, Greenbelt, MD 20771, United States
\textsuperscript{b}Space Science Laboratory, University of California at Berkeley, 7 Gauss Way, Berkeley, CA 94720, United States
\textsuperscript{c}University of Maryland/Baltimore County, 100 Hillslope Circle, Baltimore, MD 21250, United States
\textsuperscript{d}NASA's Lunar Science Institute, Ames Research Center, Moffett Field, CA 94035, United States

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ABSTRACT

The non-condensing neutral helium exosphere is at its most concentrated levels on the cold lunar nightside. We show herein that these He atoms are susceptible to impact ionization from primary and secondary electrons flowing in the vicinity of the negatively-charged nightside lunar surface. The secondary electron beams are a relatively recent discovery and are found to be emitted from the nightside surface at energies consistent with the negative surface potential. The effect is to create an electron impact-created ionosphere in nightside regions, possibly especially potent within polar craters.

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1. Introduction

The Moon possesses a tenuous surface bounded exosphere consisting primarily of argon and helium atoms, but also traces of sodium, potassium and possibly radon (see review by Stern (1990)). On the lunar dayside a fraction of these exospheric species becomes photo-ionized to create an exo-ionosphere that has been directly detected by surface packages (see Collier et al. (2011) and references therein) and orbiting spacecraft like Kaguya (Yokota et al., 2008). Such an exo-ionosphere has also been modeled by Hartle and Killen (2006). While photo-ionization is considered the dominant exo-ionosphere source process, we investigate the possibility that the lunar ionosphere extends into nightside regions; this being driven by electron impact ionization (EII) processes associated nightside wake-energized electron populations.

To make the case, we apply new knowledge of surface secondary electron emission as recently discovered by Lunar Prospector (LP) (Halekas et al., 2005; Farrell et al., 2007; Nishino et al., 2008) and Apollo-era understanding of the thermally-driven surface helium concentration variations with latitude (Hodges, 1973; Stern, 1999). While electron impact ionization is a well-known process, we now tailor calculations to include our new understanding of the nightside terminator region including ambipolar-modified primary electrons and secondary electron beam emission in the formation of He\textsuperscript{a} exo-ionosphere.

2. The He exosphere

Neutral helium is a dominant species in the lunar exosphere, with surface densities peaking at $4 \times 10^{16}$/cm$^2$ (Hodges, 1973). Typically, only argon may be found in larger concentrations but its episodic release from the sub-surface suggests a larger temporal variability for this species (Stern, 1999). In contrast, the He exosphere is believed to form from quasi-constant re-emission of solar wind implanted He ions, making it ever-present in the near-surface environment.

Unlike argon, helium does not easily condense adsorb onto the cold nightside surface instead it maintains a neutral gas exospheric density in association with a $n_{\text{He}} - \text{constant}$ relationship (Hodges and Johnson, 1968). $T$ being the temperature of the accommodating lunar surface. As the surface temperature decreases, the He exosphere becomes increasingly dense. As such, the highest near-surface He concentrations are located in the coolest nightside regions. At dawn twilight, the rising surface temperature increases the gas scale height thus reducing the daytime concentration. Instead, the plasma distribution is illustrated in Fig. 3 of Stern (1999) and Fig. 6 of Hodges (1973) shows the diurnal variation of near-surface neutral He as measured by the Lunar Atmosphere Composition Experiment (LACE). On the dayside, surface-level concentrations are below 2000/cm$^3$ but in nightside regions are at levels of $~\sim 40,000$/cm$^3$. Table 1 lists nominal He concentrations in regions across the dusk terminator (having values slowly increasing with increasing SZA).

3. Nightside plasma environment

Spatially co-located over the He neutral gas volume is a solar wind plasma-lunar surface interaction region; this being an electrostatic interaction region creating a large-scale lunar wake, surface charging, and energetic electron populations. The region is illustrated in Fig. 1. Outward flowing plasma from the Sun, called the solar wind, is incident and (mostly) absorbed on the lunar dayside, creating a trailing plasma void or wake region (Ogilvie et al., 1999; Halekas et al., 2005). Generally, the plasma expands into this trailing void via ambipolar plasma processes; low mass electrons expand into the void along solar wind magnetic field lines ahead of the ions, creating a cross-wake E-field that then forces the ions inward (Crow et al., 1979; Samir et al., 1981; Ogilvie et al., 1996). As detected by LP at 50-155 km altitude (Halekas et al., 2005), the electron density of this primary solar wind component was found to exponentially decay for solar zenith angles (SZA) beyond 90° as shown in Fig. 1.

The nightside surface will achieve an equilibrium potential based on the current balance between electrons and ions that flow into the plasma void/wake region. This effect was modeled (Farrell et al., 2007) and the electron density (above the plasma sheath) and surface potential, $\Psi_{\text{surf}}$, are both listed in Table 1. Note that the surface becomes increasingly negative beyond an SZA of 90° because the primary electrons reaching into the deeper regions of the nightside lunar surface have a steadily increasing temperature associated with energy-filtering of the tail of the solar wind kappka electron energy distribution (Halekas et al., 2005; Farrell et al.,
Table 1

The environmental parameters associated with electron impact ionization of helium near the lunar terminator. Rows 1–3 show the primary plasma electron density, temperature, and surface potential from the following solar wind; this undergoing an anisotropic expansion into nightside regions (Farrell et al., 2007). Row 4 shows the surface helium density as measured by LACE (Hodges, 1973). Rows 6 and 7 are the primary and secondary chemical reaction rates derived using Eq. (5). Row 8 is the secondary electron density using Eq. (3).

Finally, in the last row, the He ion production is quantified using the listed values in Eq. (4).

<table>
<thead>
<tr>
<th>SZA</th>
<th>85°</th>
<th>90°</th>
<th>95°</th>
<th>100°</th>
<th>105°</th>
<th>110°</th>
<th>115°</th>
<th>120°</th>
</tr>
</thead>
<tbody>
<tr>
<td>n_e (10^19/m^3)</td>
<td>2</td>
<td>1.4</td>
<td>0.8</td>
<td>0.5</td>
<td>0.2</td>
<td>0.14</td>
<td>0.09</td>
<td>0.06</td>
</tr>
<tr>
<td>T_e (eV)</td>
<td>12</td>
<td>14</td>
<td>17</td>
<td>20</td>
<td>23</td>
<td>28</td>
<td>31</td>
<td>34</td>
</tr>
<tr>
<td>Surface potential (V)</td>
<td>-10</td>
<td>-70</td>
<td>-90</td>
<td>27</td>
<td>34</td>
<td>35</td>
<td>36</td>
<td>37</td>
</tr>
<tr>
<td>n_w (10^10/m^3)</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>k_{he} (10^{-12} m^2/s)</td>
<td>1.03</td>
<td>1.6</td>
<td>2.5</td>
<td>3.3</td>
<td>4.0</td>
<td>5.1</td>
<td>5.5</td>
<td>5.9</td>
</tr>
<tr>
<td>k_{n} (10^{-12} m^2/s)</td>
<td>0.0</td>
<td>17</td>
<td>27</td>
<td>34</td>
<td>35</td>
<td>35</td>
<td>36</td>
<td>37</td>
</tr>
<tr>
<td>n_{he} (10^18/m^3)</td>
<td>163</td>
<td>100</td>
<td>110</td>
<td>120</td>
<td>130</td>
<td>140</td>
<td>150</td>
<td>160</td>
</tr>
</tbody>
</table>

He^+ production dn_{he}/dt (1/m^3/s)
21.0 23.4 41.4 34.6 16.0 14.7 15.3 10.8

Find the ionization reactions that occur at the top of the plasma D"eby sheath, in a region just above where the secondary electrons have been accelerated by the surface potential, \( \varphi_{surf} \). The sheath geometry is illustrated in Fig. 2, Halekas et al. (2002) compared L spacecraft observations of ions, \( n_{he} \), and measured primary solar wind electron density, \( n_e \), and found they should vary at the surface as \( n_{he} \propto n_e charg e \varphi_{surf} \) with \( \eta \) near 0.8 (see their Fig. 3). For kappa distributions (with \( k=1 \)), the primary ion current at the sheath top, \( I_{he}^\text{surf} \), is reduced by a factor of \( I_{he}^\text{surf}/I_{he}^\text{surf} = (1 + \varphi_{surf}/(2.5kT_e))^{-1/2} \) as it propagates to the negatively charged surface (Halekas et al., 2009). We can then express the approximate secondary electron concentration at this sheath-alarmented current as

\[
\Delta n_{e,sec} \approx \frac{\Delta n_{he}}{n_{he,sec}} \left( 1 + \varphi_{surf}/(2.5kT_e) \right)^{1/2} \tag{1}
\]

where \( T_{surf}/T_e \) is the ratio of the primary and secondary electron temperatures. These newly ejected low-energy secondary electrons are then accelerated outward via the potential, \( \varphi_{surf} \), to the topside region. For \( \varphi_{surf} > kT_e \), the secondary electron density at this topside location is estimated to be

\[
\Delta n_{e,sec} \approx \Delta n_{he} \left( \varphi_{surf}/2.5kT_e \right)^{1/2} \tag{2}
\]

with \( \varphi_{surf} \approx 2-3 \text{ eV} \) (Vokurka, 1973) such that the topside density is reduced by the repulsive electric field at the surface. Combining Eqs. (1) and (2) provides the desired expression for the topside secondary electron density.

\[
\Delta n_{e,sec} \approx \left( \varphi_{surf}/2.5kT_e \right)^{1/2} \Delta n_{he} \tag{3}
\]

Table 1 lists the values of \( \Delta n_{e,sec} \), \( \varphi_{surf} \), and \( \varphi_{surf} \), thereby allowing an easy quantification of \( \Delta n_{e,sec} \).

4. The He reaction with energetic wake electrons

In the nightside terminator region, the neutral He gas and plasma electrons interact via the EII process. In a given volume of He, there are two interflowing electron components: one warm component with a broad energy distribution flowing towards the surface and an oppositely-directed quasi-monoenergetic electron beam at energy \( \varphi_{surf} \), with beam energy determined by the surface potential at a location where the magnetic field line impacts the surface. The Debye sheath size in the nightside region is estimated to be \( 10^5 \) meters to \( 10^6 \) kilometers in size, while the scale height for the He is \( 10^{10} \) km. As such, the surface density of the neutral He (Hodges, 1973) can be used as reasonable estimate at the top of the sheath (and these concentrations are listed in Table 1). He ions produced by these two electron flows at the top of the sheath can be expressed via

\[
dn_{he}/dt = k_{he} \Delta n_{e,sec} + k_{he} \Delta n_{he} \tag{4}
\]
where $k_1$ and $k_2$ are the chemical rates for electron impact ionization. In general, the rates $k_1$ and $k_2$ can be quantified by solving the integral (Ferreira, 1983; Delory et al., 2006)

$$k_{1,2} = \frac{2 \pi m_e^2}{2 \pi m_e^2} \int_{\Phi_1}^{\Phi_2} \alpha_{1,2}(\Phi) \Phi^2 \mathrm{d} \Phi$$

where $\Phi$ is the electron energy, $\Phi_1$ is the ionization energy, $\alpha_{1,2}(\Phi)$ is the He electron impact cross section (Kieffer and Dunn, 1966) and $\Phi^2$ is the associated electron energy distribution for the primary and secondary component, respectively. The He EII cross-section is found to peak at $-135$ eV with a value of $-4 \times 10^{-17}$ m$^3$. The primary electron component is that expanding into the ambipolar region, and is in the form of a velocity-filtered kappa distribution containing only those electrons with energy, $\Phi$, exceeding $\epsilon_{\text{spatial}}$ at the observation point. In order to obtain an analytical solution to (5) we will approximate this filtered distribution with a Maxwellian distribution of the form $f_{\text{max}}(\Phi) = 2 \pi m_e^2 \Phi^2 \exp(-\Phi/k_B T_{\text{eff}})$, where $T_{\text{eff}} = T_{\text{eq}} \Phi$, where $T_q$ is the local electron temperature of the filtered electrons at the observation point. This local electron temperature is higher than that of the solar wind ions. Maxwellian distribution does not match the kappa distribution at $\Phi \gg \epsilon_{\text{spatial}}$.

To obtain $k_1$, we thus solved Eq. (5) with $\alpha_{1,2}(\Phi)$ (Kieffer and Dunn, 1966) and $f_{\text{max}}(\Phi) = 2 \pi m_e^2 \Phi^2 \exp(-\Phi/k_B T_{\text{eff}})$. The resulting values are listed in Table 1.

The quantification of $k_1$ is easily derived assuming a quasi-monenergetic secondary electron beam of the form $f_{\text{max}}(\Phi) = u_{e,1}^2 \exp(-\Phi/k_B T_{\text{eff}})$, with $u_{e,1}$ = thermal. Values of $\epsilon_{\text{spatial}}$ are also listed in Table 1.

Given the SZA profiles of the primary and secondary electrons, their density, surface potential, and chemical rates in Table 1, we can now solve Eq. (4) to derive the He II ionization associated with EII. There are three immediate conclusions from this exercise: (1) The driving contribution to create the EII He$^+$ ionsphere are the primary, ambipolar-filtered incoming electrons. However, secondary electron beams emitted from the surface do have a noticeable effect, creating additional ionization at 3–5% of the primary values at SZA of 90–105º. The secondary beam electrons near 100 eV are especially potent since they stimulate processes near the maximum EII cross-sectional values (Kieffer and Dunn, 1966). In regions where the surface potential is $-100$ V, an approximate estimate of the He$^+$ ion production is

$$dN_{\text{He}^+}/dt \approx 2.3 \times 10^{15} \left(T_e/10^4 \right)^{1/2} \Phi_{\text{flux}}$$

(6)

As indicated in Table 1, electron impact ionization has its maximum effect near an SZA of 95–100º but continues to generate He$^+$ ions deeper into nightside regions. The peak in the EII activity is consistent with regions that have surface potentials near 100 eV. (3) Electron impact ionization nightside production of He$^+$ near 100 eV and photo-ionization production of He$^+$ near 100 eV in discussing the solar wind ionization of the nightside regions. (4) Besides the nightside He$^+$ component created by EII, there may also be times when the solar wind convection E-field drives photo-ionization day-side He$^+$ in the nightside region (Hartle and Thomas, 1974). Such flows would be expected at higher altitudes on the scale size of the lunar radius, suggesting the presence of two nightside He$^+$ layers: one near surface from local generation described herein and a second higher altitude flow from convectively driven day-side photo-ionization.

5. The currents of last resort and surface erosion

The new He$^+$ ions are born in the ambipolar region where the local E-field is directed primarily downward toward the surface. As such, these new ions represent a new environmental current component in the near-surface region. As described previously (Farrell et al., 2010), in the permanently shadowed regions, the surface potential is defined by the balance of electron and ion currents that are capable of propagating through the ambipolar potential that forms along the wake fluxes:

$$J_{\text{ambipolar}} = J_{\text{electron}} - J_{\text{ion}} = 0 \tag{7}$$

where $J_{\text{ambipolar}} = J_{\text{electron}} - J_{\text{ion}}$ is the secondary electron coefficient (rejected from the surface), $J_{\text{electron}} = \epsilon_{\text{spatial}} \exp(-\Phi/k_B T_{\text{eff}})$, and $J_{\text{ion}}$ is the ion current (Equation 4). While the electrons are considered quasi-isotropic thermal flux, the solar wind ions have a directed flow at a specific angle relative to the surface normal, $\Phi$. The ambipolar E-field creates a deflection in the solar wind ion flow, pushing the ions effectively toward the surface. Thus local current balance at the surface (a solution for $\Phi$ in Eq. (7)) exists as long as the dot product ($\Phi_{\text{ion}} - \Phi_{\text{ambipolar}}$) is less than zero; in other words, at locations in a polar crater where the surface has direct access to the solar wind ion flow. However, with real topography, there are cases where the dot product ($\Phi_{\text{ion}} - \Phi_{\text{ambipolar}}$) is greater than zero and the ion flow does not have direct incidence on the surface. Candidate locations for this effect are the leeward edges of polar/terminator craters that are immersed in an electron-rich plasma, called the "electron cloud" (Crow et al., 1975; Farrell et al., 2010). Without the presence of solar wind ions, the surface would be expected to charge to anomalously large negative potentials until some other (as yet identified) remediation current forms to bring the system into current balance.

The downward directed current created by this local electron impact ionization of $\Phi$ could be a possible remediation current that occurs in polar craters/sub-structured solar wind flow to offset the loss of direct solar wind ion currents. Hence the new current balance in these strong negatively charged/electron cloud regions becomes

$$f_{\text{ion}} (\Phi_{\text{ion}} - \Phi_{\text{ambipolar}}) \exp(-\Phi/k_B T_{\text{eff}}) = \Phi_{\text{ion}}$$

(8)

where locally-created downward EII ion currents and upward negatively-charged dust flux represented by $\Phi_{\text{ion}}$ now replace the blocked flow from the sputtered solar wind ion currents in defining current balance. In essence, if the solar wind-originating ion flow becomes obstructed, secondary processes in the local environment may create alternate downward-directed currents; such currents include local ionization of He$^+$ from the expanding plasma.

These effects should become especially intense within lunar polar craters. In these very cold regions, we can expect He to be very dense. As we demonstrated previously (Farrell et al., 2010), the lack of direct access to solar wind ions makes these crater floors charge to strongly negative values (below ~100 V) and thus crater-trapped neutral He can be susceptible to the local primary and secondary (ions) electrons in flows into the region. Hence, in these craters, we may have the formation of a micro-ionosphere in association with the plasma expansion process. The downward-directed ambipolar E-field within the crater then immediately drives these new ions right back into the surface, where they then behave as the needed ion current to complete the current balance process.

We note that this accelerated He$^+$ ion flux directed into the polar crater surface by the ambipolar and sheath fields is also a source of sputtering. For an accumulated ice layer within a polar crater, the solar wind ice layer is being impacted by ~100 eV He$^+$ nearly 1 molecule/ion (Johnson, 1990), making the water molecule loss rate comparable to the incoming He$^+$ flux. As such, these newly-borne He$^+$ ions can act as a high-mass sputtering source, even at relatively low energies.

While we assume the bulk of the argon esosphere is condensed onto the cold nightside surface and thus does not contribute to the nightside electron-driven ionosphere, it is recognized that there is an argon "wind" at the sunrise terminator where desorbed species exposed to sunlight thermally-migrate back across the sunrise terminator into nightside regions (Stern, 1999). It is possible that a portion of this solar wind-sputtered flow also becomes ionized, limited only by the presence of the ionosphere. Also, Stubbs et al. (2011) recently suggested the presence of greatly enhanced electron concentrations at the terminator due to photo-electron emission from lofted dust, and the most energetic part of this population may also interact with the ambient He and Ar. There are thus other neutral-plasma processes to consider for future work.

To summarize, we demonstrate that the plasma-surface-neutral environment may be connected in a new way; this comes with the copious presence from solar wind ions, making the surface potential negative at ~100 V near SZA of 110–120º. The primary electron component along with surface-generated secondary electrons energized to ~100 eV are capable of ionizing the nightside cold, dense He neutral gas to form a near-surface He$^+$ exo-ionosphere. These interconnected plasma-surface-neutral processes could only be examined once there was a greater understanding of the solar wake processes in combination with Apollo era understanding of the exosphere He. In the future, an ion spectrometer located on the surface (an updated suprathermal ion detector experiment [SIDE, see Collier et al., 2011]) and operating through terminator passages could confirm the presence of this electron-driven He$^+$ nightside ionospheres.


