



Influence of plasma ions on source rates for the lunar exosphere during passage through the Earth's magnetosphere

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[1] The total electron flux in the lunar exosphere, measured by the Electron Reflectometer onboard the Lunar Prospector during its passage through the Earth's magnetosphere (June 7–16, 1998), is strongly correlated with variations in the column abundance of equatorial sodium observed coincidentally with the McMath-Pierce solar telescope at Kitt Peak. At the same time, the exospheric temperature increased from a minimum of 1200 K to a maximum of 3000 K at minimum phase angle. A comparison of different source mechanisms, using the measured electron flux as the proxy for the ion flux, provides strong evidence that ion impact enhances the photon-stimulated desorption yield. At the Moon photon-stimulated desorption is shown to be the dominant source of exospheric sodium outside the magnetosphere. Inside the magnetosphere, where the ion flux and the associated photon-stimulated desorption yield decrease, the contributions from impact vaporization to the observed column abundance and temperature are found to be substantial. **Citation:** Sarantos, M., R. M. Killen, A. S. Sharma, and J. A. Slavin (2008), Influence of plasma ions on source rates for the lunar exosphere during passage through the Earth's magnetosphere, *Geophys. Res. Lett.*, 35, L04105, doi:10.1029/2007GL032310.

1. Introduction

[2] The lunar exosphere is exposed to the magnetospheric plasma during its passages through the magnetosphere. During such a period (7–16 June, 1998) the lunar sodium emission was measured above the equator at a range of altitudes from 100 to 4000 km using the McMath-Pierce solar telescope [Potter *et al.*, 2000], while the electron flux onto the Moon was measured *in-situ* with Lunar Prospector [Lin *et al.*, 1998]. These data are analyzed to develop a model for the interaction between the lunar exosphere and the magnetospheric plasma. Using for the first time simultaneous ground and *in-situ* spacecraft observations we obtain limits on the sodium vapor production by photon-stimulated desorption (PSD), impact vaporization and ion sputtering.

2. Emission Data and Lunar Prospector Measurements

[3] During the period, 7–16 June, 1998, the lunar sodium emission data showed a decline in the exospheric column

abundance during the ingress phase of the passage through the magnetotail, and subsequently increased after zero phase angle until the Moon moved out of the Earth's magnetotail back into the magnetosheath [Potter *et al.*, 2000]. The temperature increased from 1200 K to 3000 K during ingress and decreased at a slower rate during egress. The data were interpreted to indicate that the primary production mechanism for the lunar atmosphere is photon-stimulated desorption (PSD), but that ion bombardment is an important process contributing indirectly by producing defects through which sodium atoms diffuse to the surface and are desorbed.

[4] Lunar Prospector (LP) orbited the Moon in a ~40–100 km polar orbit from January 1998 to June 1999. The Magnetometer/Electron Reflectometer experiment (MAG/ER) onboard LP measured the magnetic field and the flux of electrons in the energy range 40 eV–20 keV [Lin *et al.*, 1998]. The spacecraft data for the period June 7–16, 1998, are shown in Figure 1 along with the lunar sodium column density and its temperature [Potter *et al.*, 2000]. The magnetopause crossings, marked in Figure 1 by dotted lines, are obtained from the magnetic field orientations measured by the spacecraft and indicate the residence time in the magnetosphere.

[5] The electron flux measured by LP/ER increased by an order of magnitude from a minimum of $2 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ in the magnetosphere (June 8) to a maximum of $3 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ (June 15) in the magnetosheath. The first two panels of Figure 1 show a correlation between the observed sodium column abundance and the total electron flux measured by the Electron Reflectometer onboard LP. When the electron flux is high, the column density increases and vice versa. However, electrons do not lead to significant sputtering [Ageev *et al.*, 1998]. It is assumed herein that the electron flux can be used as a proxy for the ion flux. The temperature of the exospheric sodium and the flux of energetic (>3 keV) electrons are shown in the next two panels of Figure 1. The increase in temperature approximately coincided with multiple injections of energetic electrons, which are indicative of magnetotail plasma sheet crossings. However, ion sputtering leads to an energetic component that largely escapes the exosphere [Wurz *et al.*, 2007] and heating of the residual exosphere is not believed to result from ion-neutral interactions in a collisionless exosphere.

3. Lunar Sodium Production and Loss Mechanisms

[6] Ion impact on the surface can lead to changes in the lunar exosphere through sputtering processes, or by creating defects in surface crystals which enhance other processes

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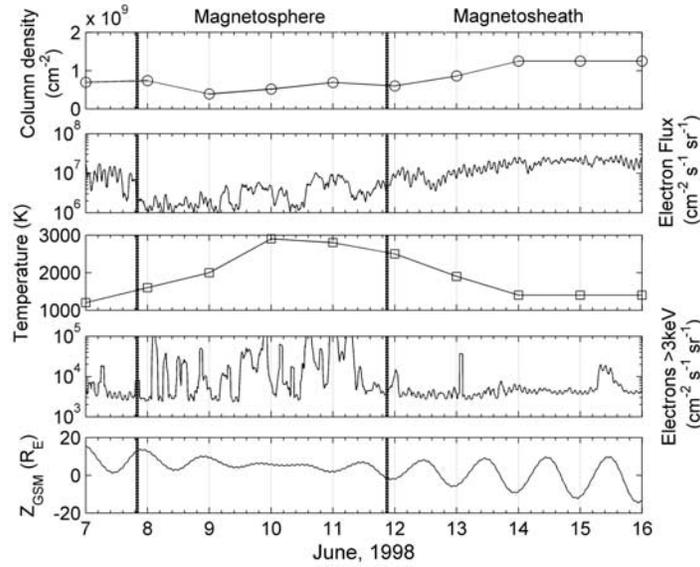


Figure 1. Correlation of ground-based sodium emission measurements from June 7–16, 1998 [Potter *et al.*, 2000], to L P Electron Reflectometer (LP/ER) in-situ data: (top to bottom) column density of sodium in the Moon’s equatorial exosphere; total electron flux onto the Moon measured by L P; the temperature of the exosphere; the high-energy electron flux ($E > 3$ keV); and the spacecraft Z_{GSM} location. The LP/ER data have been smoothed using a 1-hr moving window average.

(“priming” of the surface). In this section we estimate the relative contributions to the lunar exospheric sodium from three processes: sputtering, impact vaporization, and photon stimulated desorption.

[7] For kinetic sputtering, the energy of the sputtered ejecta depends on ion impact energy and follows the Sigmund-Thompson distribution [e.g., Wurz *et al.*, 2007],

$$f(E) = \frac{6E_b}{3 - 8\sqrt{E_b/E_{\text{Max}}}} \frac{E}{(E + E_b)^3} \{1 - \sqrt{(E + E_b)/E_{\text{Max}}}\}, \quad (1)$$

where the binding energy for sodium is assumed to be $E_b = 1.85$ eV, E is the ejecta energy and E_{Max} , the maximum energy that can be transferred to the sputtered atom by the projectile, is given by

$$E_{\text{Max}} = E_i \frac{4m_{\text{ion}}m_N}{(m_{\text{ion}} + m_N)^2}. \quad (2)$$

For protons with energy E_i incident on sodium targets ($m_N = 23$ amu), $E_{\text{Max}} = 0.15E_i$. In the plasma sheet at $X = -60 R_E$ the protons have kinetic energy of 2.6 keV, while in the magnetosheath they have properties typical of the solar wind, viz. kinetic energy of 0.96 keV [Slavin *et al.*, 1985]. Using impact energies of 1 keV and 3 keV in the magnetosheath and plasma sheet, respectively, the maximum energy of the ejected atoms is computed to be ~ 150 eV (magnetosheath) and ~ 500 eV (plasma sheet). On integrating the distribution function of equation (1) with these limits, the resulting mean energy of sputtered atoms are found to be ~ 7.5 eV in the magnetosheath and ~ 10 eV in the plasma sheet. In either plasma regime $\sim 92\%$ of sputtered particles are above the escape velocity (>2.38 km/s).

[8] The contribution to the lunar exosphere from sputtering caused by solar wind ions was recently computed to be approximately two orders of magnitude smaller than the total observed column for volatiles [Wurz *et al.*, 2007]. In order to estimate sputtering from LP measurements, the ion flux is averaged over 24 hours prior to a measurement. We assume a sputtering yield of 0.05 per impact, and lifetime = 6000 sec (D. H. Crider, personal communication, 2007), resulting in contribution to the zenith column ≤ 4000 km by 56% of the sputtered population. The averaged LP ion flux and the standard deviation for each day are shown in the top plot of Figure 2.

[9] Estimates of the lunar sodium production due to micrometeoroid impact vaporization have some uncertainty due to uncertainties in the physical properties of the regolith and the impactors, and the micrometeoritic flux. Three estimates of the steady-state sodium vapor flux are: 3×10^4 atoms $\text{cm}^{-2} \text{s}^{-1}$ [Morgan and Killen, 1997], $2-3 \times 10^4$ atoms $\text{cm}^{-2} \text{s}^{-1}$ [Smyth and Marconi, 1995], and $3-4.9 \times 10^4$ atoms $\text{cm}^{-2} \text{s}^{-1}$ [Bruno *et al.*, 2006]. Sporadic variability of this source on time intervals comparable to the observations can be attributed to impactors in the range $10^{-3}-0.15$ m, which contribute $\sim 6-10$ per cent of the total vaporized sodium, while the flux of micrometeoroids $<10^{-3}$ m is a constant source providing $\sim 90-94$ per cent of the daily neutral sodium vapor [Bruno *et al.*, 2006].

[10] We estimate the probability of an impulsive event required to double the exosphere during the Potter *et al.* [2000] observations. Assuming that the total number of atoms in the lunar atmosphere is 7.6×10^{28} , and that the average atomic mass is 24 amu, an upper limit for the total mass of the exosphere is about 3000 kg. Assuming that the average impactor has density of 1.8 g/cm^3 and produces twice its mass in vapor, the mass and radius required to double the lunar exosphere are ~ 1500 kg and ~ 0.5 m,

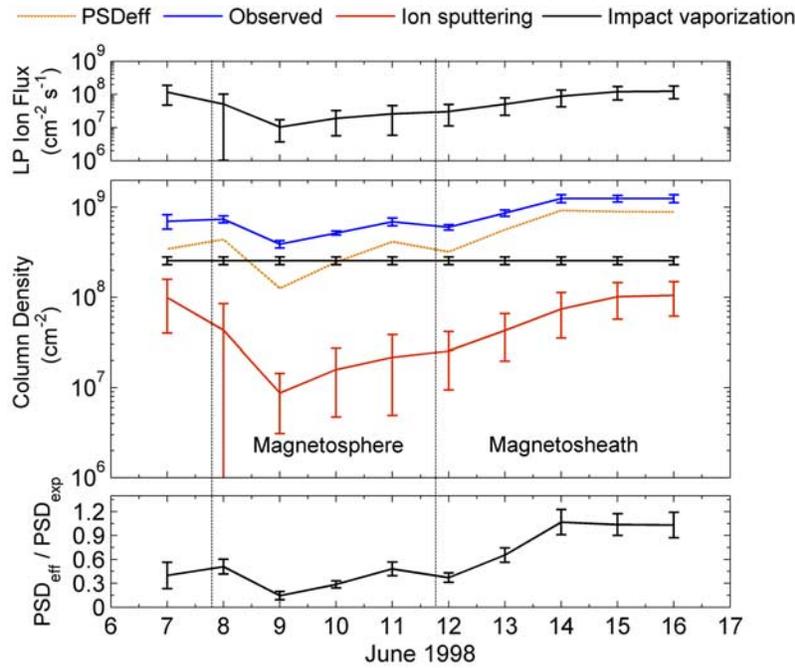


Figure 2. (top) Daily average of the LP electron flux, which is assumed equal to the precipitating ion flux; (middle) sodium column density from competing source processes during passage through the magnetotail; and (bottom) the ratio of effective PSD yield, determined from the observations, to the theoretically expected PSD yield [Yakshinskiy and Madey, 1999]. The temporal variability of each source on a daily basis is indicated by bars.

respectively. The time between impacts of a 1 m diameter object with the Earth is estimated to be 1.7 weeks (30 impacts/year) [Brown *et al.*, 2002]. Since the impact flux onto the moon is about 4% that onto the Earth, it is implied that a 0.5 m radius particle hits the moon once per year. Thus the probability of a medium-sized impact within any given week that would double the lunar atmosphere is $\sim 2\%$. Note that rapid increase of column abundance due to hot, impulsive impacts is unlikely since the observed column abundance and temperature were anticorrelated.

[11] The production rate due to impact vaporization is assumed to be $5 \times 10^4 \text{ cm}^{-2} \text{ s}^{-1}$ (the upper limit by Bruno *et al.* [2006]). With a lifetime of 6000 sec, and escape fraction = 0.15 (using a Maxwellian with $T \sim 3000 \text{ K}$) this yields a column of $2.5 \times 10^8 \text{ cm}^{-2}$. The expected daily temporal variability is $\pm 10\%$ [Bruno *et al.*, 2006].

[12] When the impact vaporization and sputtering contributions are subtracted from the observed column abundance, the residual column is presumed to indicate the effective PSD contribution. Figure 2 (middle) summarizes these calculations of the exospheric column density from competing source processes. Inside the magnetosphere, impact vaporization compares to or surpasses the effective PSD and consequently the exosphere has a higher temperature. Elsewhere, the PSD source dominates and the exosphere has a lower temperature. Thus, the increase of the exospheric temperature seen in the Potter *et al.* [2000] measurements can be explained as seeing the “hot” impact vaporization source ($T \sim 3000 \text{ K}$) when the Moon is in the magnetosphere. The cooling of the exosphere as the Moon re-emerged in the magnetosheath is consistent with a

transition from impact vaporization to dominant PSD ($T \sim 1100 \text{ K}$).

[13] The cross section for sodium desorption via PSD has been determined from laboratory measurements of thin films simulating lunar soils as $Q_{\text{Na}} = 1-3 \times 10^{-20} \text{ cm}^2$ [Yakshinskiy and Madey, 1999]. However, the actual yield from a porous regolith is reduced by an estimated factor of three [Cassidy and Johnson, 2005]. Additionally, the PSD yield depends on surface temperature and scales as the square root of the cosine of the azimuthal angle, or by approximately a factor of one-half over the equatorial zone. A realistic yield of $Q_{\text{Na}}/6 = 3 \times 10^{-21} \text{ cm}^2$ gives a sodium PSD production rate of $1.563 \times 10^5 \text{ cm}^{-2} \text{ s}^{-1}$. With a lifetime of 6000 sec and an escape fraction of 0.08 the theoretically expected contribution to the column abundance PSD_{exp} is $8.627 \times 10^8 \text{ cm}^{-2}$. The effective PSD values derived above are factors of 0.16–1.14 of the theoretical values (Figure 2, bottom). The theoretically expected PSD yield is shown to over predict the column abundance inside the magnetosphere up to a factor of six. The effective PSD yield is related to the ion flux: when the ion flux increases, the computed PSD rate is higher and approaches the experimental PSD rate reduced by a factor of six.

[14] The ion-enhanced PSD is shown to be the dominant process supplying the lunar exosphere in the magnetosheath and the solar wind. Inside the magnetosphere, where the ion flux is low, the PSD yield decreases and impact vaporization becomes comparable to PSD. A statistical correlation of the ion flux to the observed column abundance has not been attempted due to the limited sample of observations and

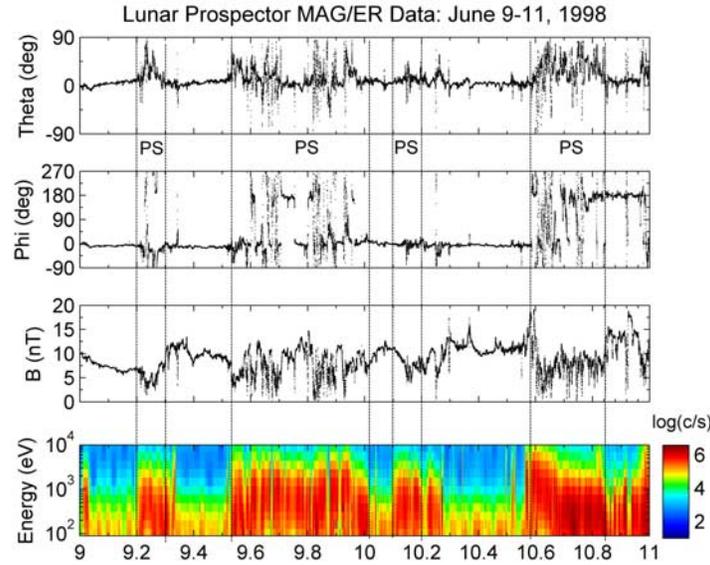


Figure 3. An example of two days of LP plasma and magnetometer measurements in the cis-lunar magnetotail during the sodium observations on June 9–11, 1998. Plasma sheet crossings (PS) with residence time >1 hr are indicated within dashed lines.

must await publication of more spectrographic observations that were obtained while LP was in orbit around the Moon.

4. Lunar Projector Trajectory and Plasma Sheet Location

[15] As the Moon orbits around the Earth, LP samples two broad regions of the magnetosphere, the magnetotail lobe and the plasma sheet. The lobes are characterized by a relatively strong, steady magnetic field pointing toward (north lobe) or away (south lobe) from the Earth. The plasma sheet can be identified from the electron energy spectrum and the magnetic field data. MAG/ER measurements are shown in Figure 3 for the period between 0000 UT on June 9 to 0000 UT on June 11. It is seen that plasma sheet signatures (low magnetic field magnitude and high field latitude accompanied by electron flux peaking at ~ 1 keV) were repeatedly encountered during this time. Changes in the magnetic field polarity indicate crossings of the neutral sheet inside the plasma sheet. The first clear lobe signature in MAG/ER data is observed around ~ 2000 UT on June 7 while the last is seen at ~ 1700 UT on June 11.

[16] These magnetopause crossings deduced from magnetometer data are consistent with the LP trajectory (Figure 4), keeping in mind that the statistical radius of the tail is 30–35 Earth radii (R_E) [e.g., Slavin *et al.*, 1985]. The LP trajectory is viewed from the tail in GSE (\bar{x} : Earth-Sun line; \bar{z} : ecliptic North Pole), GSM (\bar{x} : Earth-Sun line; \bar{z} : projection of dipole axis on GSE yz plane) and Geocentric Solar Wind (GSW) (\bar{x} // $-\vec{V}_{SW}$; xy : plane of the solar wind) coordinates, respectively. The trajectory in the solar wind frame (Figure 4, bottom right) is incomplete due to gaps in ancillary ACE data. The approximate motion of the neutral sheet in GSM and GSW coordinates is shown (Figure 4, bottom plots).

[17] The average location of the neutral sheet is determined by the seasonal and diurnal variations of the geomagnetic dipole tilt and by the “hinging”, or the alignment

of the distant tail with the plane of the ecliptic, caused by the solar wind. Assuming that the tail axis remains parallel to the ecliptic beyond $X_{GSM} = -8 R_E$, the neutral sheet displacement from the GSM X - Y plane is $Z_n [R_E] = 8 \cdot \tan \phi$, where ϕ is the dipole tilt in the GSM X - Z plane. Under these simplifications the neutral sheet lies 2–5 R_E above the $Z_{GSM} = 0$ plane during June 7–16, 1998. The spacecraft moves with the plasma sheet for extended periods of time during June 8–11 (Figure 4, bottom left). Tail

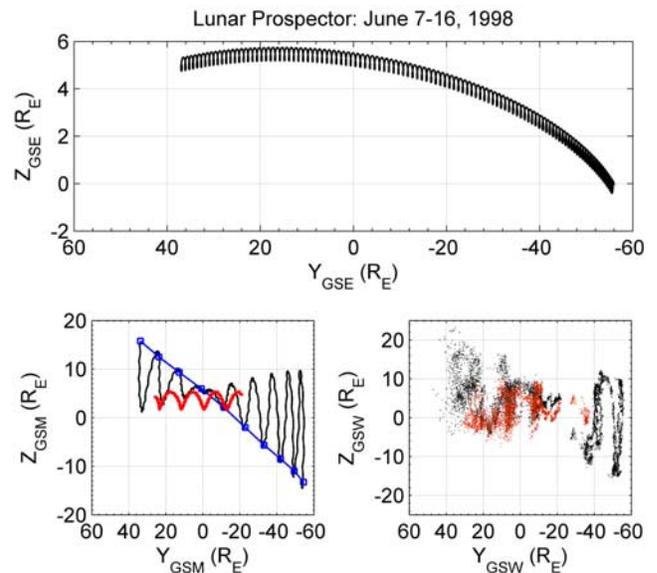


Figure 4. The trajectory of LP during the 10-day period of observations is shown in the Y - Z plane in the GSE, GSM and GSW coordinates viewed from the tail. The estimated location of the neutral sheet (red line) and the location of LP at 0000 UT each day (blue squares; 7 June is on the upper left) indicate their relative locations.

deflections due to abrupt changes in the solar wind direction and speed, which were observed by ACE during 7–16 June, 1998, “scatter” the actual trajectory of LP in the GSW frame increasing the residence time in the magnetotail lobes (Figure 4, bottom right).

5. Discussion and Conclusions

[18] The observations of lunar sodium during a passage of the Moon through the Earth’s magnetosphere [Potter *et al.*, 2000] and the concurrent plasma and magnetometer data obtained by LP are used to study the contributions to the lunar exosphere. The in-situ LP data show that the Moon entered the magnetosphere late on June 7, 1998, and reemerged into the magnetosheath late on June 11, 1998. The electron flux varied by an order of magnitude during the observations, consistent with the typical order of magnitude increase in plasma density in going from the tail to the magnetosheath at lunar distances [Slavin *et al.*, 1985]. We find that the observed sodium column density correlates with the total electron flux measured by the LP Electron Reflectometer, which we use as a proxy for the ion flux.

[19] The exospheric temperature is an additional clue to the relative importance of each process, and constrains the nature of the correlation between the column abundance and plasma flux. The expected temperature of a PSD source is about 1200 K, ignoring the high energy tail [Yakshinskiy and Madey, 1999]. The exosphere observed as the Moon entered the magnetosphere is consistent with this source. Two mechanisms may be invoked to explain the high exospheric temperature observed inside the magnetosphere: an energetic ion sputtering source associated with plasma sheet encounters [e.g., Wilson *et al.*, 2006] or a prominent impact vaporization contribution. Multiple crossings of the Earth’s plasma sheet were, in fact, observed by the LP Magnetometer/Electron Reflectometer between June 8–12, 1998. Plasma sheet crossings contribute to an enhanced scale height and lead to increased escape of the lunar exosphere. However, our analysis shows small contribution from direct ion sputtering ($\leq 10\%$ of total column out to 4000 km) and high escape from lunar gravity ($>90\%$) of the sputtered ejecta (in agreement with Wurz *et al.* [2007]), leading to the conclusion that plasma sheet crossings cannot explain the coincident column abundance and temperature data in the lower exosphere. The role of plasma sheet crossings in supporting an extended lunar alkali corona remains important as noted by Wilson *et al.* [2006], who observed the sodium emission out to about ten lunar radii, or 17400 km.

[20] In the range of heights monitored spectroscopically by Potter *et al.* [2000] (≤ 4000 km, or 2.5 lunar radii), the exosphere seen at minimum column abundance (June 9, 1998) coincident with the highest exospheric temperature (June 9–11, 1998), is consistent with a large contribution from an impact vaporization source. We have shown that model estimates of sodium vapor production from micrometeoroid impact ($4.5\text{--}5 \times 10^4$ atoms $\text{cm}^{-2} \text{s}^{-1}$) can account for $\sim 50\%$ of the column inside the magnetosphere assuming the expected neutral sodium lifetime to be $\sim 6 \times 10^3$ s.

[21] The decrease in column abundance and increase in temperature when the Moon enters the magnetosphere

imply a variable efficiency for photon-stimulated desorption. We have demonstrated that the only parameter changing rapidly is the ion flux. However, the relatively inefficient ion sputtering source cannot explain the evident correlation of column abundance to ion flux. The effective photon-stimulated desorption yield is found to increase when the LP ion flux is high, thus showing that the primary effect of ions is to augment the PSD yield, as proposed by Potter *et al.* [2000]. Laboratory evidence exists for the validity of defect-mediated sputtering in alkali halides, SiO_2 and Al_2O_3 [Aumayr and Winter, 2004]. The same, or a similar, mechanism could enhance PSD. We conclude that in the magnetosheath and solar wind ion-enhanced PSD dominates the exosphere, whereas shielding of precipitating ions by the terrestrial magnetosphere emphasizes the role of impact vaporization.

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