An Automatic Identification Method for the Photoelectron Boundary at Mars

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Abstract

The photoelectron boundary (PEB) at Mars is defined to be the boundary separating the photoelectron-dominated ionosphere from the external plasma environment. Extensive studies have been presented to analyze the PEB variation in the Martian dayside ionosphere. However, the PEB was identified manually in previous studies because of the difficulty in detecting the faint photoelectron features at high altitudes. In this study, we develop an algorithm to detect these faint features and identify the location of PEB from energetic electron measurements automatically. We apply the algorithm to the measurements by the Solar Wind Electron Analyzer instrument on board the Mars Atmosphere and Volatile Evolution mission and identify a total number of 15,681 PEB crossing events accumulated from 2015 January to 2019 October, of which 9169 PEB are on the dayside and 6912 are on the nightside. Our analysis indicates that the altitude of the identified PEB tends to increase with solar extreme ultraviolet radiation and crustal magnetic field strength, in agreement with previous findings. By contrast, the PEB altitude on the nightside tends to increase dramatically with solar zenith angle but is found to be weakly influenced by the crustal magnetic field strength.

Unified Astronomy Thesaurus concepts: Mars (1007); Planetary ionospheres (2185)

1. Introduction

Photoelectrons, generated by the solar Extreme Ultraviolet (EUV) and X-ray ionization of atmospheric neutrals, are a significant component of planetary ionospheres that plays a crucial role in ionization, heating, radiation, and escape (e.g., Fox et al. 2008; Frahm et al. 2010; Coates et al. 2011; Gu et al. 2020). At Mars, the photoelectrons are characterized by several distinctive peaks at 22–27 eV in the energy distribution due to the ionization of CO2 and O by the intense He II 30.4 nm line in the solar EUV radiation (e.g., Frahm et al. 2006a, 2006b). In addition, these photoelectrons are characterized by a reduction in intensity that occurs around 60–70 eV, which is related to the rapid drop in solar radiation at wavelengths shorter than 17 nm (e.g., Sakai et al. 2015; Peterson et al. 2016). The above spectral characteristics have been extensively observed by several instruments and the photoelectrons in the Martian ionosphere have been well studied over the past four decades (e.g., Manta & Hanson 1979; Frahm et al. 2006a, 2006b, 2010; Trantham et al. 2011; Peterson et al. 2016; Wu et al. 2020a). For instance, Lienhoep et al. (2007) proposed that photoelectrons in the Martian tail regions were magnetically connected to the dayside ionosphere and the photoelectron intensity could be used as a proxy of the ion escape rate. In a more recent study, Wu et al. (2020b) reported that the intensity of photoelectrons at 10–15 eV could be viewed as a good tracer of the atmospheric CO abundance in the Martian upper atmosphere. In addition, the shift of a distinctive peak in the photoelectron energy distribution has been used to characterize the ambipolar electric field at Mars, and Xu et al. (2018) proposed that the field-aligned potential had average values ranging from 0 to −1.5 V, an order of magnitude lower than that measured at Venus (Collinson et al. 2019). In another study, Wu et al. (2019a) reported that the shape of the photoelectron distribution over the energy range of 10–50 eV was strongly related to the inelastic collisions between photoelectrons and atmospheric neutrals.

In addition, the observation of photoelectrons in the vicinity of Mars has been frequently used to characterize the ambient magnetic field topology as these photoelectrons are typically magnetized and gyrate around the magnetic field lines. Photoelectrons at Mars, therefore, have been observed not only on the dayside but also on the nightside where photoelectrons are unlikely produced locally due to the lack of solar radiation (e.g., Xu et al. 2016; Cao et al. 2021). Frahm et al. (2006a, 2010) also reported the detection of photoelectrons in the Martian magnetotail, far away from the Martian ionosphere.

The photoelectron boundary (PEB) is defined to be the interface separating the photoelectron-dominated ionosphere from the external plasma environment, which is typically identified as the altitude where the photoelectron spectral features disappear. Garnier et al. (2017) presented a detailed statistical analysis of the location and properties of the PEB at Mars, based on the energetic electron measurements made by the Solar Wind Electron Analyzer (SWEA) on board the Mars Atmosphere and Volatile Evolution (MAVEN) mission. The PEB altitude in the Martian dayside ionosphere was reported to vary between 186 and 1931 km, with an average altitude of 573 km (Garnier et al. 2017). They also proposed that the PEB altitude increased with increasing solar EUV radiation and decreased with increasing upstream solar wind dynamic pressure, density, and velocity. Meanwhile, the PEB altitude was found to be elevated near the strong crustal magnetic field.
regions over the Martian southern hemisphere (Garnier et al. 2017). In addition to the location of the PEB, extensive studies have been devoted to understanding the relationship between the PEB and the ionopause (e.g., Han et al. 2014, 2019; Duru et al. 2020). With the aid of the measurements made by the Mars Advanced Radar for Subsurface and Ionospheric Sounding and the Electron Spectrometer on board the Mars Express, Duru et al. (2020) reported the coincidence of the ionopause and PEB altitudes in 89% of the cases, of which the former was identified as where the ionospheric electron density manifested a steep altitudinal gradient. Han et al. (2019) confirmed that the ionopause and PEB were collocated as long as they were simultaneously identified by the MAVEN Langmuir Probe and Waves instrument and the SWEA instrument, respectively.

Previous studies of the Martian PEB were based on visual inspection because of the difficulty in identifying the faint energy peaks near 22–27 eV, the main diagnostic of photoelectrons. With the accumulation of more energetic electron spectral data, an automatic procedure is required for distinguishing between photoelectrons and solar wind electrons, which serves as the main motivation of the present study. Meanwhile, previous studies of the Martian PEB focus exclusively on the dayside where they are produced by EUV ionization, but it is well known that these electrons are also present in the deep nightside owing to the cross-terminator transport along large scale magnetic fields (e.g., Han et al. 2014; Cao et al. 2021). This implies that the nightside measurements should also be examined for a thorough understanding of the PEB variations. For illustrative purposes, the PEB identified on the nightside by our automatic procedure is denoted as the nPEB, to be distinguished from the PEB on the dayside. We expect that the distribution of the nPEB may have important implications on the day–night magnetic connectivity in the vicinity of Mars, which serves as another motivation for the present study.

The analysis presented here relies exclusively on the MAVEN SWEA data set. The layout of the paper is as follows. A brief description of the SWEA data set and a detailed description of the PEB identification algorithm are provided in Section 2. We then present the temporal and spatial variations of the dayside PEB under the influences of both the crustal magnetic field and the solar EUV radiation in Section 3. This is followed by Section 4 where we discuss the nPEB distribution. Finally, we end with concluding remarks in Section 5.

2. Data Set and Methodology

The SWEA is a symmetric hemispheric electrostatic analyzer that measures the energetic electron flux as a function of the energy per charge and direction of arrival (Mitchell et al. 2016). During the instrument operation, the voltage is varied in order to sweep through a 64 level energy spectrum every 2 s, covering the energy range of 3 eV–4.6 keV with a resolution of 17% ($\Delta E/E$). The SWEA has a field of view of 360° × 120° (azimuth × elevation) of which 8% is blocked by the spacecraft body. In this work, we use the SWEA level 2 data, which consists of the omnidirectional electron intensity values averaged over all angles within the instrument field of view, accumulated from 2015 January to 2019 October.

For the purpose of the present study, we identify a PEB as the altitude where the photoelectron features start to disappear from below, specifically the photoelectron energy peak at 22–27 eV and the reduction in intensity at 60–70 eV. Xu et al. (2017) designed a shape parameter to automatically identify the photoelectron energy spectra with a manually selected template over the energy range of 20–80 eV. Cao et al. (2021) used a similar method to identify photoelectron observations in the nightside Martian ionosphere. However, the above methods are unsatisfactory when used for detecting photoelectrons near the PEB where the photoelectron features are faint and the whole energetic electron spectrum becomes quite different from the selected template. In general, we design a Peak Parameter (PP) in this work to characterize the presence of a photoelectron energy peak in an SWEA spectrum. It is notable that the observed photoelectron spectra are shifted in the instrument frame by both the spacecraft potential and the field-aligned ambipolar electric potential. The field-aligned potential ranges from 0 to −1.5 V (Xu et al. 2018) and without showing the details, we mention that the typical spacecraft potential measured by the MAVEN Langmuir Probe and Waves (Andersson et al. 2015) varies from 0 to −2.7 V over the altitude range of interest here. We, therefore, examine a spectrum over the energy range of 19–30 eV, specifically the 19.4, 21.7, 24.4, and 27.5 eV SWEA energy channels. If there is a peak structure over the selected energy range, which means that the energy flux measured at one energy bin is higher than the fluxes measured at the two adjacent energy bins, we set the PP value of the spectrum as 1. Comparisons of the observed photoelectron energy spectrum with the selected template suggest that photoelectron energy peaks are sometimes manifest as a sharp transition in spectral slope rather than a local maximum in flux (see below for details). To account for such circumstances with no apparent peaks, we further define the additional parameter $k_i$ for the energy flux measured at the $i_{th}$ energy channel centered at $E_i$ to identify the presence of a faint peak. This parameter is defined as

$$k_i = \frac{\phi_{i+1} - \phi_i}{E_{i+1} - E_i} \frac{\phi_i - \phi_{i-1}}{E_i - E_{i-1}},$$

where $\phi_i$ is the energy flux at $E_i$. If the maximum $k_i$ over the energy range of 19–30 eV is larger than 2.0 and meanwhile both $\phi_{i+1} - \phi_i$ and $\phi_i - \phi_{i-1}$ values are negative, we regard the spectrum as a photoelectron spectrum and set PP to be 1 as well. Otherwise, PP is set as 0, indicating that there is no peak in the spectrum.

Because the photoelectron flux drops rapidly at 60–70 eV due to the reduction in solar radiation at wavelengths shorter than 17 nm (to be distinguished from the solar wind/magnetosheath electrons which are much hotter than the photoelectrons), we design a Drop Parameter (DP) to characterize the contribution of photoelectrons at high energies. To derive the DP of a spectrum, we determine the fractional contribution from high energy electrons to the total electron energy flux over the full SWEA energy range, denoted as $r$ and expressed as

$$r = \frac{\int_{4.6 \text{ keV}}^{50 \text{ eV}} \phi dE}{\int_{5 \text{ keV}}^{4.6 \text{ keV}} \phi dE}.$$  

In this work, if $r > 0.2$, the measured energetic electrons are thought to be contributed mainly by the solar wind/magnetosheath electrons and we set DP as 0. Otherwise, the
measured energetic electrons are thought to be contributed mainly by ionospheric photoelectrons, and DP is set to be 1.

In this study, we classify a spectrum as a photoelectron spectrum if both PP and DP of the spectrum are 1. For illustrative purposes, we present in Figure 1 a typical PEB crossing event during MAVEN orbit #1944 on 2015 September 29. During this orbit, the spacecraft passed by the periapsis, located at 146 km, at 04:03:40 UT. We present in Figure 1(a) the suprathermal electron energy spectra measured from 03:32:00 UT to 04:15:00 UT. The variations of the solar zenith angle (SZA) and altitude at the spacecraft location are provided in Figures 1(b), (c), respectively. In Figure 1(d) we present the variations of PP and DP of the spectra with time. It is noteworthy that PP = 0 and PP = 1 cannot appear at the same time according to the definition, though panel (d) presents a visual misleading after 04:10:00 UT.

We further provide in Figure 2 three typical electron energy spectra measured during MAVEN orbit #1944 and the color of each spectrum is the same as the color of the dashed line in Figure 1(a), which marks the location where the spectrum is extracted. The orange spectrum measured at 03:41:40 UT shows no peak signature at 19–30 eV and is thought to be observed in the Martian magnetosphere. Around 03:44:22 UT, the energy flux of these hot electrons dropped rapidly and the distinctive photoelectron energy peak at 22–27 eV became visible in the spectra, when both PP and DP turned to 1, implying PEB crossing by the spacecraft. The spacecraft was located in the Martian dayside ionosphere between 03:44:22 UT and 04:08:52 UT, as the SWEA continuously observed clear photoelectron peaks in the spectra during this time interval. After 04:08:52 UT, the SZA at the spacecraft location was beyond 90°, indicating that the spacecraft was entering the nightside; meanwhile, the photoelectron energy peak became faint in the spectra, but the PP and DP values remained 1 until 04:13:14 UT.

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According to the algorithm described above, the black and magenta spectra are both identified as photoelectron spectra. The PEB is, then, identified as photoelectron spectra. The respective PP and DP values are quoted in the parentheses (see text for more details).

To identify the PEB, we apply the above algorithm to the SWEA suprathermal electron data measured from the apoaapsis to the periapsis for both the inbound and outbound portions of each orbit, respectively. Because the SWEA is expected to observe ionospheric photoelectrons continuously after crossing the PEB and entering the Martian ionosphere, an additional requirement for identifying the PEB is that after the PEB crossing, both PP and DP of the observed electrons are 1 for at least 20 measurements out of the following 30 continuous measurements. The PEB is, then, identified when this requirement is first met.

It is notable that the values of the threshold of $k_i$ and $r$ strongly affect the identification of ionospheric photoelectrons, and the requirement for continuous photoelectron measurements also affects the accuracy of the identified PEB with our algorithm. To evaluate the accuracy of our algorithm, 110 orbits are randomly selected from 2015 January to 2019 December as a test subset, from which we are able to visually determine 159 PEB/nPEB crossing events. Our algorithm identifies all these 159 PEB/nPEB crossings and 137 events that share exactly the same timings, indicating that the efficiency of our algorithm is 86%. The remaining 22 PEB/nPEB crossings have to be shifted in time by a few minutes. In addition, our automatic procedure identifies 41 additional PEB/nPEB crossing events that are difficult to be visually determined. We further compare our results to the previous works, and 92.4% of the photoelectrons classified here (with both PP and DP being 1) are identical to the photoelectron classification of Cao et al. (2021), which also confirms the effectiveness of our algorithm. To identify the PEB, we apply the above algorithm to the SWEA suprathermal electron data measured from the apoaapsis to the periapsis for both the inbound and outbound portions of each orbit, respectively. Because the SWEA is expected to observe ionospheric photoelectrons continuously after crossing the PEB and entering the Martian ionosphere, an additional requirement for identifying the PEB is that after the PEB crossing, both PP and DP of the observed electrons are 1 for at least 20 measurements out of the following 30 continuous measurements. The PEB is, then, identified when this requirement is first met.

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### 3. PEB Variations with Internal and External Conditions

With the aid of the algorithm outlined above, we are able to identify 14,520 PEBs from a total number of 9807 MAVEN orbits, of which 8979 PEBs are identified on the dayside (SZA < 90°) and 4727 (4252) PEBs are identified during the inbound (outbound) passes, respectively. We present in Figure 3 the geographical distributions of the PEB (shown as gray dots) in MSO cylindrical coordinates, where $R_m$ is the average Martian radius and $\rho = \sqrt{Y^2 + Z^2}$ is the distance to the X-axis. The cyan/yellow/red solid lines indicate the northern/southern/global median locations of the PEB, respectively (for 5° SZA bin).

**Figure 3.** The geographical distribution of the PEBs (shown as gray dots) in MSO cylindrical coordinates. $R_m$ is the average Martian radius and $\rho = \sqrt{Y^2 + Z^2}$ is the distance to the X-axis. The cyan/yellow/red solid lines indicate the northern/southern/global median locations of the PEB, respectively (for 5° SZA bin).
solid lines, respectively. On the dayside, the southern median location of the PEB is always at higher altitudes than the northern median location, with the median PEB altitudes at 705 and 560 km over the southern and northern hemispheres, respectively. Such a hemispheric difference in PEB altitude is likely caused by the strong crustal anomalies over the Martian southern hemisphere, as explained by Garnier et al. (2017). For illustrative purposes, we present in Figure 4 the variation of the dayside PEB altitude with geographic longitude and latitude, by dividing the surface of Mars into continuous regions each with a size of 1° in latitude and 2° in longitude. The crustal magnetic field intensity model of Gao et al. (2021) is superimposed at a reference altitude of 400 km.

Figure 4 reveals a strong tendency of PEB elevation over strong crustal magnetic anomalies. For comparison, the average PEB altitude is 805 km over the strong crustal field region, located at east longitude from 120° to 240° and northern latitude from −90° to 0°, but decreases to 603 km outside the strong crustal magnetic anomalies. Such an observation clearly supports that the presence of localized crustal magnetic anomalies, as a Martian internal condition, plays an important role in raising the Martian PEB altitude on the dayside, presumably attributed to the upward transport of photoelectrons since the magnetic field lines tend to be more vertical within strongly magnetized regions (e.g., Wu et al. 2019b).

In addition to the crustal magnetic field strength, the solar EUV radiation is another important factor that affects the altitude of the dayside PEB (Garnier et al. 2017). Because Mars experiences all four seasons, which affects the plasma density and temperature in the Martian ionosphere (e.g., Valeille et al. 2009; H alekas et al. 2017; Girazian et al. 2019), we further present in Figure 5 the seasonal variation of the PEB altitude. Due to Mars’s orbit, the seasonal variations of the PEB altitude include significant variations in the Mars–Sun distance as well as the EUV flux level. We, therefore, present the annual variation of the PEB altitude with solar longitude (Ls) and the daily PEB altitude variation with time, respectively.

In Figure 5(a), we present the PEB altitude variations as a function of Ls, in which a given radial direction is associated with a given Ls bin and the radius indicates the PEB altitude. The median and average PEB altitudes are shown in green and yellow, respectively, with the standard deviation of the average PEB altitude shown in orange. Figure 5(a) shows that the PEB altitude varies by ~160 km throughout one Martian year. The average PEB altitude reaches a minimum of 521 km near the aphelion and increases with increasing Ls, reaching 681 km near the perihelion. From the aphelion to the perihelion, the solar EUV radiation increases prominently, which is naturally accompanied by an increase in the PEB altitude, as reported by Garnier et al. (2017).

To demonstrate the influence of the solar EUV radiation on the PEB, we present in Figure 5(b) the daily PEB altitude variation and the solar EUV flux variation as a function of time. The solar EUV flux is obtained from the level 3 solar spectral model, constructed from the Flare Irradiance Spectral Model—Mars (Thiemann et al. 2017) and calibrated with the MAVEN EUV Monitor band irradiance data (Eparvier et al. 2015). In this study, we use the solar EUV flux integrated over the wavelength range of 0.5–100 nm as a proxy of the input solar EUV energy, shown as the light green dots in Figure 5(b). The dark green line is the spline fitting of the measured EUV flux to better illustrate the variation of the solar EUV input with time. The black dots are the daily averaged PEB altitudes with the solid red circles giving the median values for every 4 months and the error bars encompassing the ranges from 25% to 75% quartiles.

Figure 5(b) reveals a strong coincidence between the variation of the EUV flux and the PEB altitude. For instance, from 2017 March to 2018 July the EUV flux at Mars decreased from 1.2 to 0.9 mW m$^{-2}$ and then increased to 1.2 mW m$^{-2}$. Analogous to the EUV flux variation, the PEB altitude decreased from 688 to 487 km, followed by an increase to 679 km during the same period. Such an observation further confirms that the PEB altitude increases with increasing solar EUV radiation.

In addition, it is notable that from 2018 to 2019 July, when the EUV flux was significantly lower than the EUV flux measured from 2015 to 2016 March, the PEB altitude measured during the former period was higher than the PEB altitude measured during the latter period. We caution that such a difference may result from the global dust storm in the second half of 2018. Previous studies have shown that large dust
storms can cause a sudden increase in ionospheric peak altitude (e.g., Hantsch & Bauer 1990; Withers & Pratt 2013; Withers et al. 2018; Girazian et al. 2020). From 2018 June to 2018 October, an intense global dust storm was observed on Mars, during which the Martian ionospheric peak increased by 10–15 km (Felici et al. 2020). Using the MAVEN Imaging Ultraviolet Spectrograph observations (Gröller et al. 2015, 2018), Chaufray et al. (2020) revealed an increase in CO\textsubscript{2} density by a factor of ∼2 at 110 km due to the heating of the lower atmosphere and Niu et al. (2021) also reported the enhancement of the CO\textsubscript{2} density during the global dust storm. We, therefore, propose that the global dust storm on Mars may also increase the altitude of the PEB, but a detailed study is beyond the scope of this work and will be left for future works.

4. Discussion

With the aid of our automatic algorithm, we identify 8979 PEB crossings from a total number of 9807 MAVEN orbits in the dayside Martian ionosphere. The statistical studies of the dayside PEB altitude presented in this work not only support previous results that the PEB altitude increases with increasing solar EUV radiation and increasing crustal magnetic field strength (e.g., Garnier et al. 2017; Duru et al. 2020) but also highlight the performance of our algorithm. In addition, the method developed in this study helps to distinguish effectively photoelectrons with faint peaks from the solar wind/magnetosheath electrons at high altitudes.

We apply our algorithm further to the suprathermal electrons measured on the nightside, where the photoelectron features are faint due to the lack of photoionization. A total of 5541 nPEB crossings are identified on the nightside, shown as the gray dots in Figure 6, and the solid red line shows the median nPEB altitude within each 5° SZA bin, with the error bars encompassing the ranges from 25% to 75% quartiles. The median nPEB altitude first decreases from 724 km to 553 km with increasing SZA from 90° to 105°. Over this SZA range, the Martian ionosphere is not completely in the shadow, with the sunlit portion continuously shrinking as SZA increases. Therefore, such a decrease in nPEB altitude near the terminator may result from the decrease of local photoelectron production with increasing SZA. When the SZA is over 105°, the nPEB altitude increases significantly with increasing SZA, reaching a median altitude of 2177 km at the SZA of 135°. One obvious interpretation is that the EUV terminator that defines the sunlit limit tends to increase with increasing SZA (Lillis et al. 2018), which is naturally responsible for the elevation of the nPEB altitude toward the nightside. However, the Martian atmosphere at such altitudes is very tenuous, indicating that the local production of photoelectrons in these regions should be fairly low and as a consequence, it is more likely that the observed photoelectrons are populated by field-aligned transport from the sunlit low altitude regions. Furthermore, a small yet non-negligible portion of the nPEB events shown in Figure 6 is identified at low altitudes where photoionization is certainly switched off, implying that day-to-night transport provides the only viable interpretation for these observations.

To demonstrate the role of magnetic field configuration on the nPEB, we further present in Figure 7 the variation of the nPEB altitude with geographic longitude and latitude, in the same format as in Figure 4. Similarly, the crustal magnetic field intensity model of G90 is superimposed for reference. Compared to the PEB geographic variation on the dayside, the nPEB geographic variation appears to be more uniform, indicating that the nPEB location is weakly influenced by the
Martian crustal magnetic anomalies. We, therefore, speculate that the nPEB is more likely formed by the transport of dayside photoelectrons along the draped magnetic field lines, which originate from the solar wind interactions with Mars. Some draped solar wind field lines can dip below the electron exobase at low SZA, along which the photoelectrons produced on the dayside can travel to the deep nightside and be identified by our method. Indeed, the realistic shape of any given Martian draped magnetic field line suggests a pattern of increasing altitude with increasing SZA, which naturally explains the observed SZA variation of the nPEB altitude beyond the EUV terminator.

It is notable that on the dayside the PEB is the boundary below which the observed suprathermal electrons are mainly produced by photoionization. On the nightside, however, the observed nPEB is a diagnostic of day-to-night magnetic connectivity near Mars. Though we can still identify the nPEB based on our algorithm, it is no longer an indicator of a boundary that separates the photoelectron-dominated ionosphere from the external environment. In practice, suprathermal electrons observed below the nPEB are still dominated by precipitating solar wind electrons (e.g., Cui et al. 2019), which is different from the situation on the dayside that regions below the dayside PEB are nearly exclusively dominated by photoelectrons. This can also be inferred from Figure 6 that at SZA < 110° the nPEB observations tend to be uniformly distributed around the median nPEB altitudes, whereas beyond the SZA of 110°, the distribution of nPEB observations becomes more widespread.

5. Conclusions

The Martian PEB is a well-known interface that separates the photoelectron-dominated ionosphere from the external environment and has been extensively studied (e.g., Han et al. 2014, 2019; Garnier et al. 2017). However, the PEB crossings were identified visually in previous studies, which lacks a generally accepted criterion and is difficult to be applied to a large data set. In this study, we develop an automatic algorithm to identify the possible presence of a PEB from the suprathermal electron flux measurements. We then apply the method to the MAVEN SWEA data set accumulated from 2015 January to 2019 October, from which we are able to identify a total of 14,520 PEBs from 9807 orbits, including 8979 PEBs on the dayside and 5541 nPEBs on the nightside.

We further present statistical analyses of the PEB location, including the geographical distribution and the seasonal variation. The PEB on the dayside is found to be controlled by both internal and external conditions. For instance, the PEB altitude increases significantly near the strong crustal magnetic anomalies over the Martian southern hemisphere. Over the northern hemisphere, the PEB is at lower altitudes during the summer when Mars is located at the aphelion and reaches higher altitudes during the winter when Mars is located at the perihelion. The above analyses not only confirm existing statistical results but also support the effectiveness of our algorithm. We also report an abnormal increase in PEB altitude in the second half of 2018, which may be related to the global dust storm on Mars. We, therefore, propose that the presence of the global dust storm may increase the PEB altitude.

In addition, we apply our algorithm to the nightside SWEA measurements to investigate, for the first time, the statistical properties of the nPEB altitude in the Martian ionosphere. Our analyses indicate a surprisingly significant trend in the SZA variation of the nPEB altitude, which is restricted within a narrow range of 550–720 km over the SZA range from 90° to 105° but then increases substantially to near 2200 km as approaching 140°. Despite a possible role played by the known SZA variation of the sunlit limit (Lillis et al. 2018), we propose that field-aligned photoelectron transport from the sunlit source regions is primarily responsible for such an observation. The observed absence of any correlation between the crustal magnetic field strength and the nPEB altitude further implies that the photoelectron transport should preferentially occur along draped magnetic field lines as the outcome of solar wind interactions with Mars. The results presented here, especially in terms of a comparison between the dayside and nightside behaviors of the PEB variation, strongly support a scenario that the dayside PEB represents the interface between ionospheric and external plasma environments, whereas the nightside PEB is instead a diagnostic of day-to-night magnetic connectivity.
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