Mars’ Ionopause: A Matter of Pressures

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Abstract This study assesses under what circumstances the Martian ionopause is formed on the dayside, both in regions where there are strong crustal magnetic fields and areas where these fields are small (<30 nT). Multiple data sets from three MAVEN dayside deep dip campaigns are utilized between perijapsis and 600–1,000 km, as well as solar wind observations from Mars Express. The ionopause is identified as a sudden decrease of the electron density with increasing altitude and a simultaneous increase of the electron temperature and variability below 400 km. This is a physically robust approach as the electron temperature is a key parameter in determining the structure of the ionospheric profile, and, therefore, also a strong indicator of the ionopause location. We find that 36% (54%) of the electron density profiles over strong (weak) crustal magnetic field regions had an ionopause event. We also evaluate the roles of ionospheric thermal and magnetic pressures on the ionopause formation as well as the presence of solar wind particles, H+, down to the location of the ionopause. We found that the topside ionosphere is typically magnetized at mostly all altitudes. The ionopause, if formed, occurs where the total ionospheric pressure (magnetic + thermal) equals the upstream solar wind dynamic pressure. Moreover, the lower edge of the ionopause coincides with the altitude where the solar wind flow stops: The thermal pressure suffers a significant reduction with increasing altitude and the solar wind proton density has a prominent increase.

Plain Language Summary The ionosphere of Mars is the layer of its atmosphere where gases are separated into ions and electrons by solar radiation. The ionopause is the uppermost region where the ionosphere terminates. However, the Martian ionopause is not well-understood because it does not always form, and when it does, it is located over a large range of altitudes, varies rapidly, and is highly structured. This paper does a statistical analysis of the different parameters that play a role in ionopause formation, both over and far from the strong Martian crustal magnetic field regions. The study focuses on observations from the dayside of Mars, and analyzes several data sets from the MAVEN and Mars Express missions. It is found that the ionosphere almost always contains magnetic fields within it and that there is a pressure balance at its upper boundary (the ionopause) between the solar wind and the ionosphere. Moreover, there are more ionopause events far from the surface magnetic field regions than over them.

1. Introduction

An ionopause is a tangential discontinuity in a planet’s thermal plasma density profile, N_e(h), that marks the end of the ionosphere for unmagnetized planets. Across an ionopause the total pressure is constant and the normal components of the velocity and magnetic field are zero (Schunk & Nagy, 2009). Ionopauses thus identify the interface between the shocked solar wind and the ionospheric plasma (Russell & Vaisberg, 1983). Venus and Mars are the only planets in our solar system that do not have global “dipole” magnetic fields, and that fact alone makes ionopauses a unique dual-planet feature.

Despite Venus and Mars not having global magnetic fields, their ionospheres can be found in either a magnetized or unmagnetized state depending on the degree to which the solar wind draped magnetic field is able to penetrate into the ionosphere. This is a well-known scenario for Venus’ ionosphere, where thanks to the Pioneer Venus Orbiter (PVO) mission, the ionopause formation is well characterized (Russell & Vaisberg, 1983). The Venusian ionosphere is found to be unmagnetized when it does not have any
significant large-scale solar wind-induced magnetic field, as the thermal plasma pressure is larger than the solar wind dynamic pressure. In this case, the ionopause is found where the thermal pressure of the ionosphere balances the magnetic pressure of the magnetic pileup boundary (MPB) within a few tens of kilometers (Cravens, 1997; Schunk & Nagy, 2009). The Venusian ionosphere is found in a magnetized state, however, when the solar wind dynamic pressure is comparable to, or greater than the maximum thermal pressure of the ionosphere (i.e., at the peak of the ionosphere). In this case, magnetic fields are induced throughout the dayside ionosphere (Cravens, 1997) and the Venusian ionopause is located at lower altitudes, that is, ~100–150 km lower than in the previous case, and the ionopause thickness is much broader (Schunk & Nagy, 2009).

In the case of Mars, however, the ionosphere is mostly always found to be in a magnetized state because the maximum thermal pressure of the ionosphere is usually insufficient to balance the total pressure in the overlying MPB (e.g., Nagy et al., 2004). Therefore, solar wind-induced magnetic fields are usually present in Mars’ ionosphere. Previous studies suggested that this overpressure situation occurs ~85% of the time at Mars (Phillips et al., 1984; Zhang et al., 1990). Figure 1 shows a schematic of the expected solar wind-Mars plasma system interaction. The dynamic pressure \( P_{\text{dyn}} \) and the magnetic pressure \( P_B \) coming from the solar wind are plotted, as well as the magnetic pressure in the magnetosheath \( P_{\text{Bmag}} \) and ionosphere \( \Pi \). The ionospheric \( P_B \) and magnetosheath \( P_{\text{Bmag}} \) thermal pressures are also indicated. The ionopause (black dashed line) is formed when a balance of these pressures occurs. In general, the component of the solar wind dynamic pressure normal to the boundary is largest at the subsolar point of the planet and diminishes toward the flanks. Therefore, the ionopause should be expected to be at lower altitudes at the subsolar point and at higher altitudes toward the dawn/dusk terminators. The main difference from the case at Venus is that solar wind-induced magnetic fields at Mars (typically horizontal fields) are usually found well inside the Martian ionosphere for most of the entire dayside because of the overpressure situation. Moreover, Mars has some regions of its surface where crustal magnetic fields (with different orientations) are important, and so, they contribute to the pressure balance with their own associated magnetic pressure \( P_B \). As a consequence, the pressure balance at Mars is more complex than for Venus, resulting in sporadic Martian ionopauses, and, when it is present, its identification is not always straightforward.

The topside ionosphere of Mars is characterized by small irregularities and large-scale variability caused by different factors, such as photoionization, recombination, heating, transport, waves, etc., (e.g., Bouger et al., 2015; Mayyasi et al., 2019; Mendillo et al., 2017a). These features do not identify ionopause-like electron density gradients. Similarly, the magnetization of the Martian ionosphere causes the ionopause transition to be an extended region (Schunk & Nagy, 2009), which also makes its identification difficult. Studies based on the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) on board Mars Express suggest that an ionopause in Mars’ ionosphere occurs between 9–18% of the time (Chu et al., 2019; Duru et al., 2009), while studies based on the Neutral Gas and Ion Mass Spectrometer (NGIMS) from the Mars Atmosphere and Volatile Evolution (MAVEN) mission indicate that ionopause-like density gradients are observed in 54% of ion density profiles (Vogt et al., 2015). Moreover, the Martian ionopause is not a static boundary, as it is often highly structured and varies with rapid motions of ~1 km s\(^{-1}\) (Mitchell et al., 2001).

The ionopause altitude is also variable, occurring between 180 and 800 km, being generally higher near the terminator (Schunk & Nagy, 2009), although on average it is found to occur at 363 ± 65 km (Chu et al., 2019). While all these studies agree that the Martian ionopause should be considered as a sharp decrease in the total ion and electron densities, the magnitudes and altitudes of that decrease vary in each study. For example, Chu et al. (2019) and Duru et al. (2009) identify the ionopause as a horizontal line at frequencies below...
0.4 MHz (~2 × 10⁹ m⁻³) in the MARSIS radar observations, while Han et al. (2014) consider a total electron density drop below a threshold of 10⁹ m⁻³ on the same data set. Other criteria are used by Vogt et al. (2015) who consider the ionopause as a sharp decrease in the total ion density by at least a factor of 10 over an altitude range of at most 30 km, and Mendillo et al. (2015, 2017b) who consider the ionopause as sharp topside gradients and/or transitions to electron densities lower than 10⁹ m⁻³ below 300 km. Although a density decrease to around 10⁹ m⁻³ seems to be the general rule, this criterion cannot be applied to profiles near the terminator where the maximum electron density is about an order of magnitude lower than at the subsolar point (~10¹⁰ m⁻³ at terminator and ~10¹⁴ m⁻³ at subsolar point, e.g., Sánchez-Cano et al., 2013). In addition, ionopause identifications are even more complex over regions of crustal magnetic fields (e.g., Nagy et al., 2004). Mitchell et al. (2001) and Ma et al. (2002) found that the ionopause height positively correlates with the strength of the magnetic field, although Vogt et al. (2015) found that neither the crustal magnetic field strength nor solar wind dynamic pressure seems to influence the altitude of the ionopause.

Since many aspects of the Martian ionopause formation and identification are still uncertain, and are currently topics of debate, the objective of this paper is to offer a new assessment of the circumstances leading to an ionopause, both over and far from strong crustal magnetic fields. We identify the ionopause based on different features of the electron density and electron temperature parameters, as both are closely related. Then, its formation is investigated from the point of view of the different pressures. The goal is to explore whether Mars' ionopause formation follows the same rules as for the Venus case; that is, the ionopause is the region where the total pressure of the ionosphere (thermal pressure plus magnetic pressure in the ionosphere) balances the solar wind ram pressure (e.g., Luhmann et al., 1987; Schunk & Nagy, 2009). This is a coherent and a more universal approach that only now can be investigated at Mars thanks to the in situ plasma and magnetic field observations from the MAVEN mission.

2. Data Sets and Data Processing

This work utilizes several data sets from the MAVEN mission (Jakosky et al., 2015) while it was sampling the ionosphere and was far from the solar wind, as well as near simultaneous Mars Express in situ observations in the solar wind (Chicarro et al., 2004). In particular, we use the MAVEN Langmuir Probe and Waves (LPW) (Andersson et al., 2015) instrument that is designed to measure the cold, thermal electron population within the Martian ionosphere with densities above ~20 cm⁻³ and temperatures ~<20,000 K (Ergun et al., 2015). We also use the MAVEN Magnetometer (MAG) (Connerney, Espley, Lawton, et al., 2015; Connerney, Espley, DiBraccio, et al., 2015) instrument that consists of two fluxgate magnetometers that measure the vector magnetic field at a rate of 32 Hz with an accuracy better than 0.05%. Finally, dynamic pressure observations within the solar wind come from the Analyser of Space Plasmas and Energetic Atoms (ASPERA-3) instrument on board Mars Express (Barabash et al., 2004).

In order to give context to our results, we also use to a lesser extent data from the MAVEN Solar Wind Ion Analyzer (SWIA) (Halekas et al., 2015), which is an energy and angular ion spectrometer covering an energy range between 25 eV/q to 25 keV/q, with a broad 360° × 90° field-of-view. We also use the Suprathermal and Thermal Ion Composition (STATIC) instrument, which measures the ion composition and distribution function of the cold Martian ionosphere, the heated suprathermal plasma in the upper ionosphere, and the pickup ions accelerated by solar wind electric fields in the energy range of 0.1 eV to 30 keV (McFadden et al., 2015). The instrument field of view is 360° × 90°, provided by electrostatic deflectors. STATIC can determine ion mass via time of flight capabilities.

All the calculations performed in this study are in Gaussian units. For universality, the figures show our results also in SI units. For consistent visualization and data interpretation, all figures use the same colors for the same parameters. Finally, we obtain the various pressures at every 5 km along each orbit.

The thermal pressure of the ionosphere, \( P_{th} \), is obtained by

\[
P_{th} = N_e k_B (T_e + T_i)
\]

where \( N_e \) is the electron density, \( k_B \) is the Boltzmann constant, \( T_e \) is the electron temperature and \( T_i \) is the ion temperature. \( N_e \) and \( T_e \) come from the LPW instrument (Level 2 data). MAVEN \( T_i \) observations are currently not available (e.g., Wu et al., 2019). Instead, we derive \( T_i \) using the \( T_e/T_i \) parametrization.
scheme depicted in Figure 9b of Mendillo et al. (2011). The ratio is assumed to be 1 for heights below 120 km and above 400 km, with \( T_e > T_i \) between those heights.

The magnetic pressure, \( P_B \), is obtained using

\[
P_B = \frac{B^2}{2\mu_0} \quad [\text{dyn} \cdot \text{cm}^{-2}]
\]

where \( \mu_0 \) is the magnetic permeability in a vacuum, and \( B \) is the magnetic field magnitude obtained from the averaged magnetic field vector that comes from the MAG instrument. We note that the direction of the magnetic field may be important in this study as vertical fields in the ionosphere do not exert an effective pressure normal to the ionopause boundary. However, as discussed in section 6, we consider that this situation is not common (at least far from strong crustal magnetic fields) because only horizontal components of the interplanetary magnetic field (IMF) typically drape about the planet (Fang et al., 2018). As seen in Figure 1, several types of magnetic pressure are present in the Martian system. Since our observations come from low altitude, for simplicity, we use the term \( P_B \) for the magnetic pressure measured by MAVEN within the ionospheric region. We do not distinguish between magnetic pressure induced by the solar wind in the ionosphere and crustal magnetic fields, but as explained later, we separate our observations between regions close to and far from strong crustal magnetic fields. The solar wind magnetic pressure is considered negligible when compared to the solar wind dynamic pressure because it is typically 1 to 2 orders of magnitude smaller.

The solar wind dynamic pressure taken in situ in the solar wind \( (P_{\text{dyn}}) \) comes from the Mars Express ASPERA-3 instrument and is calculated using:

\[
P_{\text{dyn}} = \rho_{\text{sw}} u_{\text{sw}}^2 \cos^2 \chi \quad [\text{dyn} \cdot \text{cm}^{-2}]
\]

where \( \rho_{\text{sw}} \) is the solar wind mass density calculated as \( \rho_{\text{sw}} = n \cdot m \), \( n \) and \( m \) are the solar wind proton density and mass, respectively, \( u_{\text{sw}} \) is the speed of the solar wind, and \( \chi \) is the solar zenith angle (SZA) corresponding to the altitude of the ionopause (see section 4).

We note that all the calculated quantities with Equations 1–3 agree very well with the recent MAVEN estimates by Holmberg et al. (2019).

For contextual purposes in section 4, the solar wind dynamic pressure measured within the magnetosheath \( (P_{\text{dyn,ms}}) \) (MAVEN was not in the solar wind during the periods of this study) is obtained from the SWIA key parameter in the MAVEN Science Data Center. Dunn, (2017) indicates that \( P_{\text{dyn,ms}} \) is computed from SWIA’s density and velocity moments, assuming 100% protons. Similarly, for contextual purposes in section 5, solar wind proton density observations from STATIC between periapsis and 1,000 km have been used in order to assess the altitude to which the solar wind is able to penetrate into the ionosphere (section 5). Calculated proton densities were included when the attenuator state was zero (i.e., no attenuation), which occur when MAVEN samples the solar wind, magnetosheath and upper ionosphere. Higher level attenuator states occur in the ionosphere, where heavy planetary ions dominate the composition and solar wind protons are no longer present. Density moments during the higher attenuator states are currently unavailable due to ongoing calibration work.

Three MAVEN deep dip (DD) campaigns with periapsis on the dayside of Mars are selected to ensure inclusion of maximal thermal pressure observations close to the peak of the ionosphere. During a DD campaign, the periapsis is lowered from \(-150 \) to \(-130 \) km, which gives the opportunity to sample the ionosphere close to the altitude of the maximum plasma density. These campaigns are the DD2 (17–22 April 2015, orbits 1,058–1,086), DD8 (14–23 October 2017, orbits 5,903–5,952) and DD9 (23 April to 1 May 2018, orbits 6,935–6,978). We note that we have only chosen data from dayside DD campaigns because this study investigates the altitude in which the different pressures have a role on the ionopause formation. This includes the photochemical region that can only be investigated when MAVEN is on a DD campaign. However, this decision constrains the higher-altitude observations because during all the time that MAVEN is in the DD orbits, it does not enter the solar wind. These DD orbits have a good coverage of latitudes and longitudes, including regions over strong crustal fields and far from them. The SZA coverage of DD2, DD8, and the
inbound-orbit profiles of DD9 goes from near the subsolar point to SZA ~ 45°, a region not widely available in many earlier studies, which ensures observations from the region where \( P_{\text{dynsw}} \) has the largest effect on the ionopause formation (see Figure 1). Outbound profiles from DD9 cover larger SZAs at high altitude, and they correspond to ~ 10% of the observations. We note that the profiles of this study are not vertical, but as Mendillo et al. (2017a) evaluated, for low solar zenith angles (SZA), the shapes and magnitudes of the electron density profiles have a small variation, making it possible to use the MAVEN measurements along slanted orbit segments as vertical profiles. Furthermore, the three DD campaigns are representative of a variety of different solar conditions such as moderate to high (DD2) and low (DD8 and DD9) solar activity, as well as solar wind calm conditions (DD9). Moreover, a few moderate solar flares and SEPs (DD2 and DD8) and even a few moderate coronal mass ejections (DD2 and DD8) hit Mars (as seen in the Space Weather Database Of Notifications, Knowledge, Information (DONKI) catalog, https://kauai.ccmc.gsfc.nasa.gov/DONKI/search/).

There are a total of 119 DD orbits from which five orbits were subsequently excluded as they have incomplete data sets. Thus, there is a total of 228 profiles, one inbound and one outbound for each of the remaining 114 orbits. We note that five profiles from DD9 (all of them outbound) were excluded because they had SZA near 90°. Since DD profiles are not totally vertical, we only identify ionopauses below 400 km to ensure that the spacecraft traversed the lowest possible SZAs. Thus, these portions of the orbits can be considered vertical-like (Mendillo et al., 2017a). We adopted this low limit in order to avoid false ionopause detections caused by horizontal irregularities at high altitudes, and because previous studies found that the ionopause is formed, on average, below 400 km (e.g., Chu et al., 2019; Mendillo et al., 2017b; Mitchell et al., 2001; Vogt et al., 2015).

Finally, the location of the orbits with respect to the crustal magnetic fields is taken into account by considering the relative position of the ionopause location with respect to the strength of the crustal fields as seen by the Arkani-Hamed (2004) model at 150 km altitude. In particular, profiles over strong crustal fields are considered when they cross the most intense areas of crustal magnetization. The limit of these areas is considered where the magnitude of magnetic crustal field model at 150 km is larger than 30 nT. For the sake of brevity in the subsequent text, we refer to those events where the magnetic field magnitude is measured to be >30 nT as “over” crustal fields, and those where the measured magnetic field magnitude is <30 nT as “far from” the crustal fields. For those orbits without ionopauses, the same criteria has been applied but at the altitude of 310 km that corresponds to the average altitude where an ionopause is found (see next section). We have divided our set of profiles into four groups, hereinafter called ionospheric groups, as follows.

1. Profiles far from strong crustal fields with ionopause detections (58 in total).
2. Profiles far from strong crustal fields without ionopause detections (50 in total).
3. Profiles over strong crustal fields with ionopause detections (43 in total).
4. Profiles over strong crustal fields without ionopause detections (77 in total).

### 3. Ionopause Characterization

#### 3.1. Ionopause Identification Method

Figure 2 shows four characteristic examples of profiles from the ionospheric groups described in section 2. For each group, the electron density, electron temperature, magnetic field, and thermal and magnetic pressure profiles are plotted, respectively. For spatial context, trajectories for these examples are shown in Figure 3a.

Our criteria to identify the ionopause are based on simultaneous changes in both the electron density and the electron temperature, as both parameters are related via the electron recombination rate (section 3.4). As seen in Figures 2a and 2c, an ionopause is identified (dashed-line) following three simultaneous criteria: (1) the onset of a sudden electron density, \( N_e(h) \), negative gradient (reduction), coincident with (2) the onset of a sudden electron temperature, \( T_e(h) \), increase (from ~2,000–3,000 K to ~8,000 K), and (3) with the onset of large electron temperature fluctuations. This is, therefore, a physical and quantitative robust approach. Thus, the ionopause at Mars divides the plasma into two different regimes: below there is a mild \( N_e(h) \) negative slope typical of the photo-chemical-equilibrium and plasma diffusion regions, to a more severe negative
slope that implies a region of stronger convection/stripping by the solar wind where wave heating and transport dominates.

Several attempts at an automated definition were tried but no scheme worked for all three DD campaigns. Thus, all the ionopause events are determined visually (by multiple authors) with the above criteria. The systematic error of this selection is considered to be 5 km, which is the distance between two consecutive data points (see section 2), and the uncertainty caused by the manual selection can be up to 15 km, which corresponds to 3 data points that are needed to identify the electron density reduction. Although the width of the ionopause can be of several tens of km, we mark the ionopause as the last point in the electron density before the reduction starts (bottom-edge of the ionopause). The individual results for each orbit are shown in the Supporting Information.

In a few exceptional cases, the ionopause identification was not straightforward due to several factors. For example, 31 profiles had a small electron density decrease, sometimes even recovering at higher altitude. In those cases, we relied on an increase in fluctuations in the electron temperature (similar to the levels described above) to classify them as ionopauses. Another example is when there were changes in electron temperature (as described above) but no notable changes in electron density. Those cases, 39 in total, were identified as nonionopause detections.

### 3.2. Ionospheric Regions

Multiple regions within the ionosphere can be identified in the four cases shown in Figure 2. Figure 2a shows a constant and horizontal magnetic field with a magnitude of 20 nT that is found within the ionosphere in regions far from strong crustal magnetic fields (Figures 2a and 2b), which is most likely diffused from the solar wind. The magnitude of this field may vary from one orbit to another, but as can be seen in the supporting information and later in section 5, this orbit is representative of the magnetic field magnitude found within the ionosphere far from strong crustal fields during the three DDS. Over strong crustal magnetic field regions (Figures 2c and 2d), the magnetic field magnitude is larger with a pronounced variation that corresponds to the different crustal magnetic field areas traversed by MAVEN. Consequently, the fields have notable fluctuations in orientation. The total magnetic pressure, in these cases is on average, one order of magnitude larger than that encountered far from strong crustal fields.

The lowest part of the ionosphere (below ~200 km) corresponds to the photochemical-equilibrium region (PCE). This is the densest part of the ionosphere, where the coldest electron temperatures are found, and less variability is observed. Within the PCE domain, the thermal pressure equals the total magnetic pressure at a small altitude range in those regions far from strong crustal fields, as previously studied by Ramírez-Nicolás et al. (2016). However, in some cases over strong crustal magnetic fields (e.g., Figure 2c), we do not have observations low enough to assess whether both pressures are equal at altitudes closer to the peak of the ionosphere. This arises from the finding that in this study, over strong crustal fields, the magnetic pressure is stronger than the thermal pressure at all altitudes sampled by MAVEN.

The region above the PCE is the so-called diffusion region of the ionosphere, where plasma transport occurs. The PCE-diffusion limit is typically characterized by a moderate increase in the electron temperature that remains near constant at ~2,000–3,000 K for several hundreds of kilometers, and by a simultaneous change in the slope of the electron density (e.g., at ~220 km in Figures 2a and 2b). At the diffusion region, both the electron density and electron temperature profiles show large irregularities. If there is no ionopause detection (Figures 2b and 2d), the diffusion region expands up to the lower boundary of the magnetosheath, at ~1,000 km (e.g., Dubinin et al., 2008; Holmberg et al., 2019). However, if there is an ionopause detection (dashed line in Figures 2a and 2c), the ionopause marks the end of the ionosphere, and so, of the diffusion region. In these cases, the sudden decrease in the electron density coincides with a sudden increase in the electron temperature that we have used in section 3.1 as a marker for the ionopause identification. This is a similar behavior to that observed at Venus (Luhmann et al., 1987).

### 3.3. Ionopause Distribution

Figure 3b shows the ionopause distribution (white dotted circles) upon a Martian planetographic map where the magnetic field strength is indicated in colors. It also shows those orbits with no ionopause detections (black circles) at 310 km, which corresponds to the average altitude where an ionopause is found. Of the 228 profiles used in this study, 101 had an ionopause signature. This is a rate of occurrence of 45%,
similar to the Vogt et al. (2015) findings. Regarding the locations of the ionopause detections, we find that only 36% of the crossings over strong crustal fields have an ionopause, while far from strong crustal fields, this percentage is 54%.

Figure 2. Electron density (in blue), electron temperature (in pink), total magnetic field (in black), magnetic field components (in yellow, orange, and purple, MSO coordinates), and thermal (in green) and magnetic (in red) pressure profiles, respectively, for (a) an orbit far from strong crustal fields and with an ionopause detection; (b) an orbit far from strong crustal fields and without ionopause detection; (c) an orbit over strong crustal fields with ionopause detection; (d) an orbit over strong crustal fields without ionopause detection. The ionopause detection (bottom edge) is marked with a black dashed line, and the solar zenith angle (SZA) at the ionopause (or at 400 km when no ionopause) and at periapsis is also indicated.
Figures 3c and 3d shows the distribution of the altitudes of the ionopause detections with respect to local time and SZA (red dots), respectively. The observations are binned every hour and every 10° of SZA, respectively, and their means and standard deviations are plotted as black dots with errorbars, respectively. In general, the variability of the ionopause altitudes is notably large. The lower-altitude ionopauses are found in the noontime sector, while somewhat higher ionopauses occur at morning and afternoon local times. The same pattern is observed using SZAs. The lowest altitude ionopauses are found closer to zero (noon), while the higher altitude ones appear at higher SZA values. The exception to this overall trend occurs for SZA ~30–40° where the average altitude of the ionopause is lower than the surrounding SZA. The message of these figures is not a symmetrical parabolic morphology from noon to dawn/dusk, but rather a highly variable pattern. Although not shown here, no relationship with solar radiation flux has been found. We use the three DD campaigns because they have relatively narrow SZA and local time intervals, conditions not widely available in many earlier studies. The variability of the ionopause altitude with respect to these parameters might be considerably larger than the range demonstrated in this study.

3.4. Electron Temperature Control of the Ionospheric Profile

Figure 4 shows profiles of the median (solid lines) and median absolute deviation (MAD, shaded areas) every 5 km of the electron density and electron temperature of all the profiles in each ionospheric group defined above. We have chosen the MAD parameter over other robust measures of scale such as the interquartile range because the MAD better represents the variability of the data sample with respect to the median value. The PCE region (up to ~200 km) is similar for the four ionospheric groups, all having small variability as seen with the MAD (note that the left panel of each pair of plots, the electron density, is on a logarithmic scale). This is a well-known fact as the electron density and electron temperature are fundamentally related quantities as the electron recombination rate is proportional to $T_e^{-0.7}$ (Schunk & Nagy, 2009). Within the...
diffusion region (above ~200 km), transport processes dominate and the electron temperature generally increases to 2000–3000 K, and the slope of the electron density profile becomes steeper than within the PCE domain. The variability of both parameters is larger than at PCE heights, but still rather small. In panels (a) and (c), the ionopause regions are clearly visible at ~350–400 km (the dashed line marks the beginning of the boundary). They perfectly match a significant increase in the electron temperature up to a median value of ~6,000 K. Above the ionopause, the electron temperature exhibits the largest variability. Panels (b) and (d) do not exhibit any ionopause-like structure and the electron temperature remains nearly constant at 2,000–4,000 K. We note that the average profile in panel (d), which correspond to profiles over strong crustal magnetic fields, has lower electron temperature and variability than found far from strong crustal fields (panel b). As a consequence, the electron density median profile is also denser and less variable, which could be a direct effect of the solar wind suprathermal electron shielding by the crustal fields.

This figure demonstrates that the selection criteria in section 3.2 capture correctly the important signatures of an ionopause, and that this method could be used systematically to determine ionopauses for any SZA, local time or planetographic conditions. It also shows the key role that the electron temperature has over the ionospheric profile.

4. Pressure Balance at the Ionopause

At Venus, the ionopause is found to be the region where the total pressure of the ionosphere balances the solar wind ram pressure. In order to assess whether this is also the case at Mars, Figure 5a displays a comparison between the ram pressure of the solar wind and the total pressure of the ionosphere at the altitude of the lower edge of the ionopause. It shows solar wind dynamic pressure, $P_{\text{dyn,sw}}$, measured by ASPERA-3/ Mars Express (MEX) in situ in the solar wind and the total ionospheric pressure ($P_{\text{th}} + P_{\text{Bi}}$ at the lower-edge ionopause altitude) for the three MAVEN DD campaigns (green dots) for profiles where an ionopause was detected (both over and far from strong crustal fields). To obtain $P_{\text{dyn,sw}}$, the density and velocity of the solar wind need to be multiplied by the cosine of the solar zenith angle (Equation 3), which has been obtained from the SZA at the ionopause height in the MAVEN data set. Since Mars Express only takes measurements in the solar wind for part of its orbit and MAVEN was never in the upstream solar wind during the DD campaigns, there are no precisely simultaneous observations of solar wind and ionospheric pressure at the ionopause altitude for most of the cases. In order to make the best possible comparison between MAVEN and MEX observations, only ionopause events within 10 hr of simultaneity (MAVEN and MEX) are used in the comparison. The 10 hr limit corresponds to roughly 1.5 MEX orbits and it is a time-limit compromise in order to have enough data points to balance the statistics. Under certain circumstances solar wind variability can be large during 10 hr, especially with space weather activity. For solar wind dynamic pressure values lower than 2 nPa, Marquette et al. (2018) have shown that the pressure parameter is correlated over intervals of roughly 20 hr with better error reduction within 10 hr. This good correlation applies to 57% of observations in our study, while the other 43% occurred during larger solar wind dynamic pressures, which have an effect on the variability of our results. For a better visualization of the data trends, the median values of the solar wind dynamic pressure for four equidistant total ionopause pressure intervals (plotted at the data median of the interval) are also plotted in Figure 5a as red squares. Taking into consideration that Figure 5a only compares observations at “nearly” the same time, the median values seem to follow the 1:1 ratio similar to what was observed at Venus by the PVO mission (Phillips et al., 1988). Yet the data variability is larger in our case.

Figure 5b confirms this trend with the same data plotted (from the three DDs) in the form of a histogram of the ratio of solar wind and total ionospheric pressure at the ionopause height. The histogram indicates that 73% of the cases are close to a ratio of 1.0 ± 0.5, meaning that both pressures have a similar magnitude. The 27% of the cases with a ratio larger than 1.5, which have no physical meaning, could be a consequence of the data dispersion observed in Figure 5a, which in turn may be caused by additional solar wind variability not taking into account by the nonsimultaneity of the observations. Moreover, a two-sample t-test analysis also indicates that both pressures for the 3 DD campaigns are statistically similar at the 95% significance level.

Figure 5c shows the same observations in panels a and b in the form of time series. We only show here the DD8 data as an example of the three campaigns but the other two campaigns have similar results and can be found in the supporting information file. For temporal context purposes, the dynamic pressure observed by MAVEN-SWIA in the magnetosheath, $P_{\text{dyn,sw}}$, has been added, providing an improved temporal coverage.
and higher data cadence than the MEX data set. $P_{\text{dynmash}}$ comes from a mixed source between the solar wind and the magnetosheath regions as solar wind particles are rapidly decelerated inside the magnetosheath (e.g., Sánchez-Cano et al., 2017). Only data above 1,000 km and on the dayside have been plotted to ensure observations at (or close to) the magnetosheath. The regularly-spaced spikes of this data set are caused by the MAVEN orbit evolution, such that the pressure is larger when MAVEN is in the magnetosheath closer to the solar wind and at the flanks. The lowest pressure values occur when MAVEN is closer to the ionosphere. Therefore, it should only be considered as a proxy for the dynamic pressure of the solar wind (e.g., Holmberg et al., 2019; Witasse et al., 2017) and its maximum magnitude per orbit should be smaller than the actual solar wind dynamic pressure measured by MEX, $P_{\text{dynsw}}$ (e.g., Ma et al., 2017). Note that at the subsolar point, the solar wind dynamic pressure in the sheath has a drastic reduction (e.g., Dubinin et al., 2008), which is not the case toward the flanks (e.g., Holmberg et al., 2019). In our case, due to orbit evolution, SWIA observations in the sheath come from regions far from the subsolar point. Figure 5c shows that the agreement between ASPERA-3 and SWIA is very good, except for some observations during 20 October in which ASPERA-3 shows a rise in the dynamic pressure not observed by SWIA. This discrepancy on 20 October is most probably caused by an orbit phase difference, as MAVEN was in the Martian nightside while MEX observed this apparently rapid and short increase in the dynamic pressure. In some particular cases, such as at the end of 15 October, $P_{\text{dynmash}}$ seems larger than $P_{\text{dynsw}}$ while it should be the opposite. This is another case mostly likely caused by orbit phase differences, as both spacecraft have different orbits that transit different local times, longitudes and latitudes. As observed in Figure 5c, the total ionospheric pressure at the ionopause height follows very well the pattern of both ASPERA-3 and SWIA observations, with similar increases and decreases at the same time. The magnitude is also very similar taking into consideration the limitations previously described of both data sets.

Figure 4. Median (solid lines) and median absolute deviation (MAD, shadow areas) of the electron densities (left panels) and electron temperature (right panels) of (a) all the orbits far from strong crustal fields and with ionopause detections; (b) all the orbits far from strong crustal fields and without ionopause detections; (c) all the orbits over strong crustal fields with ionopause detection; (d) all the orbits over strong crustal fields without ionopause detection. The average location of the bottom-edge of the ionopause is marked with a black dashed line.
Figure 5. (a) Solar wind dynamic pressure from the ASPERA-3 instrument on board Mars Express of the three DD campaigns of this study versus the total ionospheric pressure (thermal plus magnetic pressure) at the ionopause altitude measured by MAVEN for those cases in which both pressures could be retrieved in a time range of less than 10 hr (green dots). The median values of the solar wind dynamic pressure for four equidistant total ionopause pressure intervals (or bins) plotted at the data median of the interval are plotted as red squares. The 1:1 ratio is plotted for reference. (b) Histograms of the ratio of solar wind dynamic pressure and total ionospheric pressure at the ionopause height of the three DD campaigns. The percentage of observations per histogram bar and the results of a two-sample t test are also indicated. A 1% outlier-bar is missing (not shown for visualization purposes) at a higher value in x axis. (c) Time series of the solar wind dynamic pressure from ASPERA3-Mars Express (blue dots), magnetosheath dynamic pressure from MAVEN-SWIA (only dayside and data above 1,000 km, solid blue line), and total ionospheric pressure at the ionopause altitude (pink squares) for DD8 (DD2 and DD9 can be found in the supporting information file). The regularly-spaced MAVEN-SWIA spikes are related to the MAVEN orbit evolution, being largest when MAVEN was in the magnetosheath closer to the solar wind. We remark that only Mars Express took data in the solar wind during the time periods of this study. The SZA effect is included in the three panels, see Equation 3.

Figure 5 confirms, therefore, that for those cases with an ionopause, the upstream solar wind dynamic pressure outside the system, $P_{\text{dyn,up}}$, is approximately equal to the pressure inside the system ($P_{\text{th}} + P_B$) at the bottom-edge of the ionopause.

5. Statistical Analysis of the Magnetic, Thermal, and Dynamic Pressure Roles

In order to understand the general role of the magnetic and thermal pressures on the ionopause formation, we have performed a statistical analysis of their effects for the four ionospheric groups (Figure 6). Since the data distributions are skewed, the median value every 5 km is plotted for each of the four cases (solid line). The variability of the sample is robustly evaluated through the median absolute deviation that is plotted as shaded areas. For context purposes, Figure 7 shows the density of protons measured by STATIC from 1,000 km to periapsis. Since proton densities are proportional to the dynamic pressure (see Equation 3), we consider that, in a first-order, a rise in solar wind dynamic pressure is associated with a rise in proton density at lower altitudes. This is a first order approximation that we consider adequate to satisfy the statistical analysis context of this study, by assuming there are only solar wind protons and no changes in the upstream solar wind speed.

For profiles far from strong crustal fields, Figures 6a and 6b confirm that the ionosphere of Mars is typically found in a magnetized state, with a nearly constant magnetic pressure magnitude of $\sim 3 \times 10^{-9}$ dyn·cm$^{-2}$. In
Figure 6. Median (solid lines) and median absolute deviation (MAD, shadow areas) of the thermal (in green), and magnetic (in red) pressures, for (a) all the orbits far from strong crustal fields with ionopause detections; (b) all the orbits far from strong crustal fields without ionopause detections; (c) all the orbits over strong crustal fields with ionopause detection; (d) all the orbits over strong crustal fields without ionopause detection. The average location of the bottom-edge of the ionopause (from Figure 4) is marked with a black dashed-line.
both panels, the magnetic pressure is larger than the thermal pressure for most altitudes except below ~180 km, where the thermal pressure dominates. The altitude in which both thermal and magnetic pressures are equal tends to occur ~20 km higher for those profiles without an ionopause because the magnetic pressure tends to be smaller. The variability of the magnetic pressure in both cases is relatively small for all altitudes, while the thermal pressure variability is minor at lower altitudes (the PCE region) and increases at higher altitudes.

The main differences between the magnetic and thermal pressures appear, however, at greater altitudes. Figures 6a and 7a show that the lower-edge of the ionopause occurs at the onset of the thermal pressure.

**Figure 7.** Median (solid lines) and median absolute deviation (MAD, shadow areas) of proton densities measured by the MAVEN-STATIC instrument, for (a) all the orbits far from strong crustal fields with ionopause detections; (b) all the orbits far from strong crustal fields without ionopause detections; (c) all the orbits over strong crustal fields with ionopause detection; (d) all the orbits over strong crustal fields without ionopause detection. The average location of the bottom edge of ionopause from Figures 4 and 6 is marked with a black dashed-line.
large reduction (see dashed line) coinciding with the altitude in which the proton density measured by STATIC also starts a significant change, increasing by a factor of 5 from the ionopause altitude to 1,000 km, a change which is not seen in those cases without ionopauses (Figures 7b–7d). Moreover, it also perfectly matches with the average altitude in which the lower edge of the electron temperature has a drastic rise (Figure 4a). The proton density and electron temperature increases at ~400 km altitude might be an indicator of MAVEN probably sampling the lower edge of the induced magnetosheath. On the contrary, Figures 6b and 7b, as well as 4b, show that when the level of hot protons within the ionosphere is very low at all altitudes (<1/cc on average), the thermal pressure expands in altitude, the electron temperature remains at cooler values, and no signs of an ionopause are found.

Figures 6c, 6d and 7c, 7d show similar observations but over regions of intense crustal magnetic fields. The main difference of Figures 6c and 6d with respect to Figures 6a and 6b is the larger magnitude of the magnetic pressure that oscillates between ~half and one order of magnitude more. However, the thermal pressure has a very similar behavior. Consequently, both thermal and magnetic pressure are equal at much lower altitudes than in Figures 6a and 6b, possibly even below the minimum altitude sampled by MAVEN, depending on the strength of the crustal fields. As before, this point also tends to occur at higher altitudes for those profiles without an ionopause (see shaded overlay regions). Fewer ionopause detections are observed over strong crustal field regions because the magnetic pressure in the ionosphere is larger, and stands off the solar wind dynamic pressure (a low level of proton density (<1/cc on average) is observed in Figure 7d). Only large values of solar wind dynamic pressure (as seen with the proton density observations) are able to penetrate downwards and so, produce an effect on the thermal pressure profile.

In addition, if one considers that above the ionopause $P_{\text{dyn,sw}}$ and $P_{\text{g}}$ do not significantly change with altitude, and that $P_{\text{th}}$ is negligible when compared to $P_{\text{th}}$, the pressure balance for those cases with ionopauses is well satisfied at least between 400 and 600 km (Figures 6a–6c and 7a–7c). However, the altitude of the lower edge of the ionopause marks the last height in which the total pressure of the system (total ionospheric pressure) stops the incoming pressure from the flow outside the system (solar wind dynamic pressure). Below this height, the dynamic pressure is negligible, $P_{\text{g}}$ does not significantly change with altitude, and the contribution of $P_{\text{th}}$ starts to be significant. Therefore, below the lower edge of the ionopause, the total pressure of the ionosphere ($P_{\text{th}}+P_{\text{g}}$) becomes larger than the pressure above the ionopause, which is the last point at which planetary and solar wind plasmas are separated. Over crustal magnetic fields, fewer ionopauses are identified mainly because the total ionospheric pressure is larger and excludes the solar wind from penetrating into the ionosphere. This is inferred from Figure 6, where at the lower-edge ionopause altitude, the total ionospheric pressure is ~2.5 times larger than far from strong crustal fields. Therefore, only solar wind dynamic pressure values > ~2.5 times larger than for far from crustal fields can penetrate and balance the ionosphere below 400 km. Despite the fact of having less detections over strong crustal fields, the altitude of the ionopause can be found at lower altitudes than for regions far from crustal fields (Figure 6c) because the lower-edge ionopause mainly depends on the altitude where the pressure balance occurs. Figures 5 and 6 indicate that the larger the solar wind dynamic pressure, the lower the ionopause altitude. For those cases without an ionopause, the pressure balance could occur at higher altitudes than those considered in this study, or even at the lower edge of the MPB which is typically found at ~1,000 km (e.g., Dubinin et al., 2008; Holmberg et al., 2019). This should be a focus of a future study in which higher altitude pressure observations are considered.

6. Discussion

This study focuses on the characterization of ionopause formation at Mars, and our understanding of the physical processes involved. These have been long-debated areas of study. As summarized in the section 1, there have been several methods to identify this transition boundary. In our case, we take a coherent approach thanks to the well instrumented MAVEN mission. Since the ionopause separates the shocked solar wind plasma at higher altitudes from the cold ionospheric plasma at lower altitudes, our identification of an ionopause is based on simultaneous sudden onsets of three features within the Martian ionosphere: a negative electron density gradient, a positive electron temperature gradient, and the onset of dramatic variability in values of electron temperature. Previous ionopause identifications at Mars were based only on electron
density signatures, and did not consider the electron temperature as a fundamental parameter that influences the structure of the ionosphere.

We note that all of the $N_e(h)$, $T_e(h)$, and $B(h)$ profiles used in this study are not vertical as they come from in situ observations along the MAVEN orbit. To minimize that issue, we have only considered data from lower SZA, and ionopauses that occurred below 400 km and lower SZA during three DD campaigns when periapsis (~130 km) is well below possible ionopause heights and the profiles can be considered more vertical at ionopause heights (Mendillo et al., 2017a). The ionopause altitude discussed here is the lowest altitude of this boundary. Several studies have found that the ionopause can be found at altitudes above 400 km (e.g., Duru et al., 2020), as well as the magnetization of the ionosphere can make the ionopause to occupy an extensive region (Schunk & Nagy, 2009). While we concentrated on the more dramatic cases of ionopauses below 400 km, we nevertheless showed key physical parameters to 600 km. We have found that indeed, our 400 km upper boundary is a statistically appropriate altitude for this study that only considers low SZA profiles, as our four ionospheric groups have clearly well-defined properties that are not significantly affected by possible missed ionopauses at higher altitudes (see Figures 4–6).

We have shown that Mars and Venus ionopauses are similar in the sense that this boundary is a tangential discontinuity across which the total pressure is constant; that is, the total ionospheric pressure at the ionopause at both planets is equal to the upstream solar wind dynamic pressure. However, the Martian ionopause is not always formed, as its formation is less obvious and more constrained at Mars than at Venus. One possible reason can be a more robust ionosphere and stronger solar wind upstream at Venus in comparison to Mars. Another possible reason can be related to the fact that Mars’ ionosphere is typically found magnetized (both over and far from strong crustal fields), and the associated magnetic pressure in the ionosphere is always larger than the thermal pressure of the ionosphere, except at the photochemical region (near the peak of the ionosphere). The Venusan ionosphere is most of the time unmagnetized, and so, the ionopause is formed when the magnetic pressure of the magnetosheath equals the thermal pressure of the ionosphere. However, at Mars, the ionosphere is most of the time magnetized. Therefore, the Martian ionopause is formed when the upstream solar wind dynamic pressure is enough to equal the total pressure of the ionosphere (thermal + magnetic), which also coincides with the altitude at which the thermal pressure starts a significant reduction while the solar wind proton density starts a prominent increase (as seen from lower to higher altitudes). We find that magnetic and thermal pressures are only equal within the PCE region, well below the ionopause region as previously studied by Ramírez-Nicolás et al. (2016).

Previous studies have shown that the extreme ultraviolet (EUV) flux may play a long-term role on the altitude of the ionopause formation, such as on annual and solar cycle time scales (e.g., Chu et al., 2019; Duru et al., 2020). Despite the different solar activity conditions of our data set, we have not found any clear correlation with the EUV flux. This can simply be due to the relatively small size of our data sample as compared to those previous studies that used a full solar cycle of observations. On the contrary, Figure 5 shows that upstream solar wind dynamic pressure variability plays a more notable role in a short-term scale on ionopause formation.

The broad proton distributions found within the magnetosheath, combined with the (inherent) field of view limitations associated with the STATIC (and SWIA) particle instruments, can lead to large uncertainties in derived proton temperatures within this region. We have subsequently used the proton density (derived from STATIC) as a proxy for the dynamic pressure in this region and have shown that large increases in the proton density exist above the height at which the identified ionopause structures form, both over and far from strong crustal fields. Although field of view issues may lead to underestimates of the proton density on individual orbits, the robust trend observed across our full data set gives us confidence in the use of proton density as a proxy for dynamic pressure in the sheath region. Moreover, the ionopause height also coincides with the drastic change in electron temperature that we have used to identify the ionopause events. Above the ionopause, hotter particles from the solar wind and the sheath are found as well as more waves, which can heat the electrons causing that large increase in electron temperatures. The STATIC observations also indicate that solar wind particles are present at these altitudes heating the upper atmosphere. If the solar wind dynamic pressure is lower than the magnetic pressure at the top of the ionosphere, then the magnetic pressure prevents the solar wind from entering the ionosphere and the ionopause is not formed. In this case, the electron temperature is not found hot as before because the solar wind is not compressing the topside of
the ionosphere, and so, electrons are less heated than in the other case. This is one of the possible reasons for fewer ionopauses identified over strong crustal magnetic fields, as only a large solar wind dynamic pressure is able to compete with the larger magnetic pressure caused by the crustal fields. The altitude of the ionopause depends, therefore, on the balance of these pressures. Indeed, it is well-known that crustal magnetic field regions play an important role, both locally and globally, in the location of the higher-altitude plasma boundaries such as the bow shock and MPB (e.g., Crider et al., 2002; Edberg et al., 2008; Fang et al., 2017; Hall et al., 2016). Therefore, the ionopause formation and its altitude should also be affected in these regions by changes in the strength and altitude of the magnetic field at the MPB, which produces changes in the induced current system, and finally, changes in the magnetic pressure at the topside of the ionosphere.

For strong crustal fields, only very large solar wind dynamic pressure pulses can make ionopause altitudes to be lower. Our pressure balance results explain the finding of Vogt et al. (2015), who showed that the crustal magnetic field strength does not influence the altitude of the ionopause, as well as with Duru et al. (2020) that found that the altitude of the ionopause over strong crustal magnetic fields is higher.

Both dynamic and magnetic pressures are inherently directional quantities. To take into account the solar wind dynamic pressure that is normal to the surface of the planet (the one needed to be balanced by ionospheric pressure), we have considered the term \( \cos^2 \chi \) in Equation 3. Regarding the magnetic pressure, only the tangential component of the magnetic field should exert pressure on the plasma across the boundary. However, we note that the total magnitude of the field has been considered for this study because, in this study, this parameter is only used with the purpose of showing that the ionosphere is mostly always found magnetized and that the altitude in which is equal to the thermal pressure occurs well below the ionopause altitude. Moreover, Figure 5 has shown that the total ionospheric pressure at the ionopause height is very close to the value of the upstream solar wind dynamic pressure. This means, that the effect of the radial component must be small because we have considered the magnitude of the magnetic field to obtain the total ionospheric pressure. Discussing this issue more in detail, we consider that for profiles far from strong crustal field areas, this may be a negligible issue because most of the magnetic field is horizontal as it directly comes from draped IMF. The only region in which the radial component of the magnetic field could be important is over some crustal fields. In a first simple scenario, it can happen that the radial component is smaller or of the same order as the horizontal components. In this case, after removing the radial contribution, a small reduction of the magnetic pressure similar to panels 6a and 6b would result. Another possible scenario is that the draped IMF is of the same order as the radial component of the crustal fields. If we remove the radial contribution, again, the resultant magnetic pressure should be similar again to panels 6a and 6b. However, over strong/moderate radial crustal fields, the magnetic pressure would not exert any pressure at the ionopause, which is another possible reason for finding less ionopauses over crustal fields. Finally, another possible scenario to consider is that the radial crustal fields are reconnected to the IMF. This is the most complex case because other phenomena would also play a role, such as solar wind particles moving along the field lines and heating the ionosphere. Moreover, the IMF orientation should also play a role in the ionopause formation. Unfortunately, of the two spacecraft used for this study, MAVEN is the only spacecraft with an onboard magnetometer and, it could never be in the solar wind during the three DD campaigns where periapsis is close to the subsolar regions, and hence apoapsis is in the tail. A more detailed study of the crustal field orientations and of their effects on the ionopause formation is needed, but this is beyond the current scope of this paper. Future numerical modeling simulations could also help to understand the role of the IMF orientation on the ionopause formation.

7. Conclusions

Using three MAVEN DD campaigns on the dayside of Mars, we have done a statistical analysis of the ionopause formation. We have found:

1. In regions where there are no strong crustal fields (i.e., \( B \ < \ 30 \text{ nT} \)), the thermal pressure of the ionosphere near the maximum ionization altitude is larger than the magnetic pressure of the ionosphere (at the altitudes sampled by MAVEN).
2. The topside ionosphere is typically magnetized.
3. The altitude at which the thermal and magnetic pressure are equal is between the peak of the ionosphere and ~180–200 km, that is, in the PCE region, well below the region of the ionopause formation.
4. The ionopause is the lowest altitude boundary that separates the cold planetary plasma from the shocked solar wind plasma.

5. For those cases in which an ionopause is formed, the altitude of the lower-edge of the ionopause is the last height at which the upstream solar wind dynamic pressure (pressure outside the system) is comparable to the total pressure of the ionosphere (pressure inside the system). Below the ionopause, the total pressure of the ionosphere is larger than the dynamic pressure of the solar wind.

6. The ionopause is less often formed over strong crustal magnetic field regions, and higher (54%) far from these regions.

7. We found that 45% of MAVEN $N_h(h)$ profiles exhibited an ionopause. The occurrence was lower (36%) over strong crustal magnetic field regions, and higher (54%) far from these regions.

8. Over strong crustal magnetic field regions, only the largest solar wind dynamic pressure values are able to produce an ionopause event because the ionospheric total pressure (thermal + magnetic) at the height of the lower-edge ionopause is ~2.5 times larger than far from strong crustal fields.

Future studies should explore the entire MAVEN data set in order to understand the ionopause formation with other factors that are well-known to affect the ionosphere, such as the solar cycle, seasons, and solar zenith angle (e.g., Sánchez-Cano et al., 2015, 2016, 2018). This also includes the hundreds of $N_h(h)$ obtained from the Radio Occultation Science Experiment (ROSE) (Withers et al., 2018). Also, a full assessment of the IMF and crustal field orientation roles on the ionopause development either with other MAVEN observations in the solar wind, or with numerical simulations should be done.

Data Availability Statement

All MAVEN data can be downloaded from the NASA Planetary Data System (https://pds-atmospheres.nmsu.edu/data_and_services/atmospheres_data/MAVEN/maven_main.html) and the MAVEN Science Data Center (https://lasp.colorado.edu/maven/sdc/public/), and ESA data from the Planetary Science Archive (https://www.cosmos.esa.int/web/psa/mars-express).

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