Ionopause-like density gradients in the Martian ionosphere: A first look with MAVEN

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Abstract For unmagnetized planets, the top of the ionosphere is often marked by a sharp change in electron density and other plasma properties, called an ionopause. Here we present a statistical study of dayside ionopause-like density gradients observed in 54% of ion density profiles from the Mars Atmosphere and Volatile Evolution (MAVEN) mission spacecraft at Mars. Prior studies of the Martian ionopause have lacked simultaneous comprehensive measurements of plasma and magnetic field properties. Therefore, we use MAVEN observations of the electron density, magnetic field, and ion and electron energy spectra to study the factors that influence properties of the ionopause. On average, profiles with an ionopause are accompanied by a higher energy flux of protons at high altitudes and stronger magnetic field at low altitude than profiles without an ionopause. At altitudes above ~300 km, the O⁺/O₂⁺ ratio is significantly larger for profiles with an ionopause than those without an ionopause. These findings enhance our understanding of this important plasma boundary at Mars.

1. Introduction

The interaction between Mars and the solar wind is similar to the solar wind interaction with Venus in that the ionosphere provides the primary obstacle to the solar wind flow, though in the case of Mars there is added complexity due to the presence of strong crustal magnetic fields. Several physical boundaries defining transitions in the plasma and magnetic field properties arise as a result of the solar wind interaction. For example, at the base of the magnetosheath is a region marked by a transition from solar wind to planetary plasma. This boundary is sometimes referred to as the Induced Magnetosphere Boundary (IMB) or the Magnetic Pileup Boundary (MPB) [e.g., Nagy et al., 2004]. The transition from the induced magnetosphere to the ionosphere is sometimes identified by the photoelectron boundary, which marks the transition from shocked solar wind electrons in the induced magnetosphere to electrons produced by the ionization of atmospheric neutrals at lower altitudes [e.g., Mitchell et al., 2001] or a sharp and substantial decrease in electron density [Duru et al., 2009], sometimes called an ionopause.

At Venus, the ionopause marks the altitude at which the external magnetic and solar wind dynamic pressure balances the ionospheric thermal pressure. Currents flowing on the ionopause typically shield the ionosphere and atmosphere from the interplanetary magnetic field. During intervals of high solar wind dynamic pressure or during solar minimum when the peak ionospheric density is low, the solar wind plasma and interplanetary magnetic field can penetrate into the atmosphere, magnetizing the ionosphere [e.g., Zhang et al., 1990; Luhmann et al., 2004]. At Mars, the ionopause altitude is influenced by the solar wind [e.g., Ma et al., 2014] and also by crustal fields [e.g., Mitchell et al., 2001].

The Mars Atmosphere and Volatile Evolution (MAVEN) mission spacecraft has been in orbit around Mars since September 2014. It is equipped with a suite of particle and field instruments, the Neutral Gas and Ion Mass Spectrometer (NGIMS) [Mahaffy et al., 2014], and an imaging ultraviolet spectrograph [McClintock et al., 2014]. To date, most electron density measurements from the Martian ionosphere have been obtained with remote radio occultation observations [e.g., Kliore, 1992]. More recently, the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) instrument on Mars Express has provided both in situ (above ~275 km) and remote radar sounding electron density data [Gurnett et al., 2005].
but the spacecraft lacked a magnetometer. Therefore, MAVEN provides a unique opportunity to examine the Martian ionopause in the context of magnetospheric conditions like the presence of strong crustal magnetic fields, the position of magnetospheric boundaries, and the upstream solar wind conditions. The goal of this study is to use MAVEN data from the Martian upper ionosphere to identify signatures of an ionopause and determine how the presence or absence of an ionopause, and its altitude, depend on factors like solar zenith angle, crustal magnetic field strength, ionospheric currents, and solar wind drivers.

Section 2 of this paper describes the data used in this study. Section 3 reviews the methods we used to identify ionopause-like signatures in the NGIMS ion densities. Section 4 presents our results, including statistics on the ionopause altitude and its position with respect to relevant magnetospheric boundaries, and the ionospheric composition. We conclude with a summary and discussion of topics for future study.

2. Overview of MAVEN Observations Used in This Study

MAVEN is located in a 4.6 h elliptical orbit around Mars, with periapsis at 150 km (~120 km during the week-long "deep dip" campaigns), apoapsis at ~6200 km, and a 75° inclination [Jakosky et al., 2015]. Historically, the presence of an "ionopause" at Mars or Venus has been inferred from sharp decreases in the electron density over, at most, a few tens of kilometers in altitude [Brace et al., 1983; Kliore and Luhmann, 1991; Kliore, 1992]. At the time of submission, direct electron density measurements from MAVEN’s Langmuir Probe and Waves (LPW) instrument were still undergoing validation. During the manuscript revision process, LPW electron densities became available. A preliminary comparison between these data and the total ion densities measured by NGIMS showed good qualitative agreement for the intervals considered in our study (see section 3), both overall and with respect to the visual identification of an ionopause-like density gradient. Therefore, we use NGIMS ion density as a proxy for the electron density and search for an ionopause-like density gradient in the NGIMS total ion density, which we obtain by summing the densities of all ion species. NGIMS measures ion densities with masses from 2 to 150 amu collects data from 150 to 500 km, typically alternating between neutral and ion modes on each periapsis pass. NGIMS does not measure protons (see discussion in section 3). Figure 1 shows an example of six total ion density profiles measured by NGIMS, including three—from orbits 108, 1233, and 1263—which feature density gradients that meet our criteria, described in section 3, to be labeled as an "ionopause."

Figure 1. NGIMS ion density profiles for six MAVEN orbit segments. Each profile after the far left one has been multiplied by $10^2$ per cm$^3$ for clarity. Horizontal lines on the profiles from orbits 108, 1233, and 1263 show the ionopause altitude identified by our automated routine (see text). Our automated criteria did not identify an ionopause in the other three orbits.
To study the factors that control the presence or absence of an ionopause and its altitude, we use data from several instruments in MAVEN’s particle and fields suite, including: the Solar Wind Ion Analyzer or SWIA [Halekas et al., 2014], an electrostatic analyzer which measures the density and velocity distributions of ions with energies from 5.1 eV to 26 keV; the Solar Wind Electron Analyzer or SWEA [Jakosky et al., 2015], an electrostatic analyzer which measures the density and velocity distributions of electrons with energies from 5 eV to 5 keV; and the magnetic field investigation [Connerney et al., 2015], which consists of two magnetometers that measure the ambient magnetic field with a time resolution of 32 vector samples per second. We use data from these instruments to identify the location of the IMB or MPB for comparison with the ionopause altitude, to examine magnetic field changes across the boundary, and to study the effects of crustal fields and the external solar wind conditions.

3. Identification of the Ionopause-Like Density Gradient

We searched for ionopause-like density gradients in each ion density profile using an automated routine that we developed and refined over several iterations. Our selection criteria require a decrease in the ion density by at least a factor of 10 over an altitude range of at most 30 km. Such a sharp density gradient is a classic signature of an ionopause, or the boundary between a low-altitude region in which the ion and electron populations are derived from ionospheric processes and a higher-altitude region in which the charged particle populations originate from the solar wind. Therefore, in the following sections we will refer to the observed sharp density gradient as the “ionopause” and refer to its altitude as the “ionopause altitude.”

Our automated routine included several additional requirements to ensure that the resulting ionopause altitude closely matched what would be identified through visual inspection. The routine required that over that 30 km altitude range, the minimum ion density be $3 \times 10^2$ per cm$^3$ or lower and the maximum density be $2 \times 10^2$ per cm$^3$ or greater to ensure that the decrease by at least a factor of 10 represents a significant decrease in absolute density. Finally, we required that the density remain below $5 \times 10^2$ per cm$^3$ at all altitudes above the 30 km altitude range in order to exclude multiple ionopause crossings. For each ion density profile, the routine began at periapsis and moved upward in altitude until, if the criteria were met, the ionopause altitude was recorded as the midpoint of the 30 km altitude range over which the ion density decreased by at least a factor of 10.

These criteria identified a sharp density gradient in orbits 108, 1233, and 1263, as marked by the horizontal line on each profile in Figure 1. Though the ion density decreases markedly near ~380 km in orbit 109, the density increases significantly above that altitude (to more than $2 \times 10^3$ per cm$^3$) so our routine does not mark this brief decrease as an ionopause-like density gradient. Figure 1 illustrates that our automated routine does an excellent job of identifying the altitude of ionopause-like sharp density gradients that can be identified by visual inspection.

We have applied our automated criteria to 84 MAVEN orbit segments (inbound or outbound pass), including the six shown in Figure 1, in which the solar zenith angle is less than 70° and varies by at most 20° at altitudes below 400 km. Because of MAVEN’s orbital trajectory, the spacecraft’s areographic position (and therefore the solar zenith angle) can change significantly during a periapsis pass. Our solar zenith angle requirement allows us to approximate the ion density from each orbit as a vertical profile. The 84 selected orbits occurred during October 2014, April 2015, and May 2015.

Overall, we identified an ionopause-like density gradient in 45 (54%) of the 84 orbits. The ionopause altitudes range from 270 to 464 km, with a mean value of 344 km. These altitudes are similar to those reported by Mitchell et al. [2001] (median 380 km), but generally lower than those of Duru et al. [2009] (450–500 km at solar zenith angles < 60°). Additionally, the frequency with which we have identified an ionopause in the ion density profiles is higher than has typically been seen in radio occultation data [e.g., Kliore, 1992], and Duru et al. [2009] reported sharp density gradients in only about 10% of MARSIS orbits. One possible explanation for the differences between our findings and previous work is that the observations were made under different conditions, for example, with respect to the external solar wind conditions or the presence of strong crustal fields, which Duru et al. [2009] reported can raise the ionopause altitude by as much as 100 km.

Finally, we note that while we refer to the sharp ion density gradient as the “ionopause,” there are some important caveats to this interpretation. One is that an ionopause-like density gradient could be observed...
in the ion density if plasma flows carry ions out of the instrument field of view [Mahaffy et al., 2014]. Another important caveat is that NGIMS does not measure protons, so that at high altitudes the total ion density measured by NGIMS may be artificially lower than the electron density. Unless the proton density increases rapidly with increasing altitude, which is not suggested by any model [e.g., Chen et al., 1978; Fox, 2015], it is unlikely that the absence of protons has led to any spurious ionopause identifications, since our automated criteria required very sharp density gradients. Furthermore, as we discuss in section 4, many of the sharp density gradients we identify in the NGIMS data are accompanied by changes in the plasma or magnetic field properties, giving us additional confidence that the ion density signatures we have identified are indicative of an ionopause.
4. Analysis

4.1. Ionopause Altitude and Its Relationship to the IMB

In order to study the ionopause altitude in the context of the relevant Martian magnetospheric boundaries and conditions, we have included data from MAVEN's magnetometer, SWEA, and SWIA instruments. Figure 2 shows time series data from these instruments, altitude profiles of the NGIMS ion density, magnetic field, crustal magnetic field magnitude predicted by the Cain et al. [2003] model, SWIA energy flux above 100 eV, and SWEA energy flux above 100 eV, averaged in bins of 20 km altitude. Averages from all 84 orbits used in this study are shown in black, while averages from orbits with (without) an identified ionopause (see text) are shown in red (blue). In Figures 2b and 2e, we plot the SWEA and SWIA energy fluxes above 100 eV so as not to include effects from ionospheric plasma [e.g., Mitchell et al., 2001] or spacecraft charging.

In the top example, from orbit 1247 on 22 May 2015, the ionopause and induced magnetosphere boundary or magnetic pileup boundary are nearly collocated. At the beginning of the interval shown in Figure 2a, MAVEN is located in a region of very strong (>200 nT) crustal magnetic fields. The magnetic field strength decreases with time and undergoes a large rotation just before MAVEN encounters the sharp density gradient in the NGIMS ions density. Our automated routine identifies the ionopause at 03:28:27, at an altitude of 362 km. The magnetic field, which is mostly produced by crustal fields, rotates from being primarily vertical below the ionopause to horizontal above, as seen by the decrease in $|B_x|$ and $|B_z|$ and increase in $|B_y|$ (all in the Mars-centered Solar Orbital coordinate system) in Figure 2a and the rotation in the field angles in Figure 2b.

The horizontal field angle is defined as $\tan^{-1}\left(\frac{B_y}{B_x}\right)$ and the vertical field angle is defined as $\tan^{-1}\left(\frac{B_z}{B_x}\right)$, where $B_x$ is the radial component of the magnetic field in cylindrical coordinates. Above the ionopause, the field remains steady except for the high-frequency oscillations that suggest that MAVEN is in the magnetosheath.

Figure 3. (a) From left to right, altitude profiles of the NGIMS ion density, magnetic field, crustal magnetic field magnitude predicted by the Cain et al. [2003] model, SWIA energy flux above 100 eV, and SWEA energy flux above 100 eV, averaged in bins of 20 km altitude. Averages from all 84 orbits used in this study are shown in black, while averages from orbits with (without) an identified ionopause (see text) are shown in red (blue). (b) Scatter plot of the ionopause altitude as a function of the average crustal field magnitude below 200 km altitude in each orbit as predicted by the Cain et al. [2003] model. (c) Scatter plot of the ionopause altitude as a function of the proxy solar wind dynamic pressure (see text). (d) Scatter plot of the ionopause altitude as a function of solar zenith angle (black dots). The red line shows the mean ionopause altitude in each 10° SZA bin.
Within roughly a minute of the ionopause encounter, the SWIA energy flux increases at energies up to ~1000 eV, and the SWEA energy flux increases at energies above ~20–30 eV, as can be seen in Figure 2a. Together, these data strongly suggest that the ionopause and IMB or MPB are nearly collocated in this case.

By comparison, in the second example, from orbit 984 on 3 April 2015, there is a ~3–6 min gap, corresponding to ~300 km in altitude, between when MAVEN crosses the IMB or MPB and when it encounters the ionopause. For example, our automated routine identifies the ionopause at 07:37:51 and 298 km altitude. However, MAVEN exits the magnetosheath as early as ~07:32, when the SWEA energy flux below ~100 eV begins to decrease. MAVEN’s position at this time, marked by a blue star in Figure 2f, is noticeably below the average IMB / MPB locations of both Vignes et al. [2000] and Trotignon et al. [2006]. About a minute later, at ~07:33, the SWIA energy below ~1000 eV begins to decrease and the magnetic field ceases its oscillations and begins to pile up. Overall, data from the MAVEN particle and fields instruments suggest that the magnetospheric conditions for orbits with an ionopause are different than for orbits in which we did not identify an ionopause. For example, Figure 3a shows altitude profiles of the average NGIMS total ion density, magnetic field magnitude, and SWIA and SWEA energy fluxes for energies above 100 eV. On average, orbits with an ionopause (red line) have a higher ion and electron energy flux at high altitudes and higher magnetic field magnitude at low altitudes, due largely to crustal fields, than orbits without an ionopause (blue line). In fact, both the magnetic field magnitude and SWEA energy flux have nearly vertical altitude profiles for the orbits without an ionopause.

We do not find any systematic trend between the ionopause altitude and solar zenith angle (SZA), as shown in Figure 3d, consistent with the results of Duru et al. [2009] for SZA < 60°.

### 4.2. Magnetic Field Changes at the Ionopause

In roughly half of the orbits with an ionopause, the magnetic field changes noticeably within a couple of tens of kilometers of the ionopause altitude. Typically, the magnetic field magnitude increases at altitudes below the ionopause, such as in the two examples in Figure 2. The examples in Figure 2 also display a significant horizontal field rotation near the ionopause altitude, as shown by the field angles plotted in Figure 2b and 2e. A similar rotation is seen in roughly half of the orbits with an ionopause, with the horizontal field direction changing by an average of 37° over altitudes within 20 km of the ionopause. By comparison, at similar altitudes (within 20 km of 350 km, the average ionopause altitude), the average field rotation is only 25° in orbits without an ionopause. Magnetic field rotations have been reported at the Venusian ionopause [Law and Cloutier, 1995] and in Mars Global Surveyor observations of the Martian ionopause [Cloutier et al., 1999] and are attributed to the magnetic field draping around the ionopause and a shear in the horizontal plasma flow across the boundary.

The presence of strong crustal fields appears to heavily influence the presence of an ionopause but not its altitude. As shown in Figure 3, the average magnetic field magnitude at altitudes below 200 km is higher for orbits with an ionopause than for those without an ionopause. Much of this difference is due to larger vertical magnetic fields for the orbits with an ionopause than for those without: the mean crustal field below 200 km, according to the Cain et al. [2003] model, is ~56 nT for orbits with an ionopause and ~39 nT for orbits without. We identified an ionopause in 10 of the 13 orbits in which the model crustal field reaches 150 nT or more. The scatter plot of the ionopause altitude as a function of the mean model crustal field below 200 km in Figure 3b shows that the presence of strong crustal fields does not appear to affect the ionopause altitude.

### 4.3. Influence of External Solar Wind Drivers on the Ionopause Altitude

At Venus, the ionopause is the surface where the ionospheric thermal pressure balances the external magnetic and solar wind dynamic pressure, so its altitude is strongly dependent on the solar wind dynamic pressure [e.g., Brace et al., 1983; Russell and Vaisberg, 1983; Nagy et al., 2004]. MAVEN measurements of energetic protons at periapsis can be used to compute solar wind proxies for the study of the solar wind influence on the ionopause altitude. These energetic protons originate from charge exchange of solar wind protons upstream of the bow shock, producing energetic hydrogen Energetic Neutral Atoms (ENAs) that penetrate to low altitude and subsequently undergo electron stripping in the atmosphere below altitudes of ~250 km. MAVEN observations show that this penetrating population retains the same velocity as the upstream solar wind and has a density that depends on the upstream solar wind density and velocity [Halekas et al., 2015]. By utilizing an empirical scaling of the periapsis measurements, we
can therefore obtain proxy values for both solar wind density and velocity and therefore also the solar wind dynamic pressure.

As with the crustal field strength, the proxy solar wind conditions appear to influence whether or not an ionopause is detected but have little or no effect on the ionopause altitude. Figure 3c shows a scatter plot of the ionopause altitude as a function of the proxy solar wind dynamic pressure. The linear correlation coefficient is 0.07, or −0.08 if the outlier point with a dynamic pressure of 16.6 nPa is excluded, suggesting effectively no relationship between the ionopause altitude and the solar wind dynamic pressure. Similar plots for the proxy solar wind velocity and density (not shown) also did not show a clear link between the solar wind drivers and the ionopause altitude. However, it is worth noting that we detected an ionopause in 11 of 15 orbits with $P_{\text{Dyn}} > 2$ nPa. (A nominal solar wind density of 3 protons/cm$^3$ and velocity of 400 km/s is ~0.8 nPa.) Additionally, the mean proxy solar wind dynamic pressure for orbits with an ionopause is 1.81 nPa, compared to 1.07 nPa for orbits without an ionopause. Therefore, we conclude that the presence of an ionopause is most likely for high solar wind dynamic pressure conditions, which would lead to a lower IMB/MPB in orbits with an ionopause than without an ionopause. This is consistent with the observation in Figure 3a, that orbits with an ionopause have a higher average ion and electron energy flux at high altitudes than orbits without an ionopause.

4.4. Composition of the Upper Ionosphere

MAVEN’s NGIMS provides the first opportunity since the Viking landers to measure the in situ composition of the Martian atmosphere and ionosphere and therefore the first opportunity to determine the composition of the ionosphere at or near the ionopause. The NGIMS data collected from the dayside ionosphere so far show that, as in the Viking profiles, $O_2^+$ is the dominant ion below ~300 km, while above this altitude the $O^+$ density matches or even exceeds that of $O_2^+$ [Benna et al., 2015].

Figure 4 shows the median fractional abundance of $O_2^+$ (top) and $O^+$ (middle) binned by altitude and the total ion density and the ratio of the $O^+$ to the $O_2^+$ abundance (bottom). This figure illustrates several trends
in the ion composition as a function of altitude. Below ~300 km, O$_2^+$ is more abundant than O$^+$ by as much as an order of magnitude, while O$^+$ is the dominant ion above 300 km. It is also immediately apparent that when the ion density is less than 10$^2$ per cm$^3$ at 300–400 km altitude, which is the case for most of the orbits in which we identified an ionopause, O$_2^+$ represents only a few percent of the total ion density, and O$^+$ is the dominant ion. By comparison, when the total ion density at 300–400 km altitude is ~10$^3$ per cm$^3$ or larger, O$_2^+$ represents about 20–30% of the total and O$^+$ represents about 50% of the total. Above 300 km, the median ratio of the O$^+$ to the O$_2^+$ abundance is significantly higher for orbits with an ionopause (red) than for all orbits (black) or those orbits without an ionopause (blue), suggesting a loss of O$_2^+$ in the orbits with an ionopause. One scenario that could explain these observations is that whatever process is responsible for the presence of an ionopause preferentially removes O$_2^+$.

5. Conclusions

An ionopause-like feature is a common feature in dayside plasma density profiles acquired by the MAVEN NGIMS instrument, occurring in 54% of ion density profiles. On average, plasma density profiles with an ionopause are accompanied by a higher energy flux of protons and electrons at high altitudes and stronger magnetic field at low altitude than profiles without an ionopause. The correlation with strong magnetic fields occurs because ionopauses occur preferentially above regions of strong crustal field [e.g., Duru et al., 2009]. In some instances, the ionopause occurs within a few tens of kilometers of the IMB/MPB, which indicates that the induced magnetosphere or magnetic pileup region can be extremely compressed. Accordingly, we find that most orbits with a high solar wind dynamic pressure exhibit an ionopause. Surprisingly, the available evidence does not suggest that the crustal magnetic field strength or solar wind dynamic pressure influences the altitude of the ionopause, though these factors both appear to influence the presence or absence of an ionopause. However, variations in magnetic field strength, which were not accounted for in this analysis, may have obscured the expected influence.

Analysis of the relative abundances of O$^+$ and O$_2^+$ ions near the ionopause suggests that the ionopause can be an ion composition boundary as well as an electron density boundary. At altitudes above ~300 km, the relative abundance of O$^+$ is significantly larger for profiles with an ionopause than those without.

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