MAVEN and the Mars Initial Reference Ionosphere model

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Abstract The Neutral Gas and Ion Mass Spectrometer (NGIMS) on the Mars Atmosphere and Volatile Evolution (MAVEN) satellite measured the distribution of thermal ions (2–150 amu) at ionospheric heights (~130–400 km) under midday conditions during the “Deep-Dip” orbit campaign from 17 to 22 April 2015. Assuming charge neutrality, we use the sum of NGIMS ions as a proxy for electron density (Ne) and compare results with a new version of the Mars Initial Reference Ionosphere (MIRI) developed for this study. At altitudes where the transition between photochemical and dynamical processes occurs (130–200 km), the NGIMS results agree with the shape of the MIRI-predicted Ne(h) profiles, but the model predictions are a factor of 2 higher. Above 200 km, the NGIMS gradients of total ions versus height diverge even more from MIRI’s Ne(h) predictions for reasons that may involve crustal-B field effects, ionopause-like boundaries, and horizontal plasma transport away from the noon sector—factors not yet included in MIRI.

1. Introduction

The Mars Atmosphere and Volatile Evolution (MAVEN) mission [Jakosky et al., 2015] offers an unprecedented opportunity to study the ionosphere of Mars—a key component of MAVEN’s goal to determine the current modes of atmospheric escape. Plasma in the Martian ionosphere experiences upward diffusion and solar wind capture on the dayside hemisphere of the planet. At night, the Martian ionosphere is orders of magnitude lower in density, and thus initial studies of escape will focus on the more robust daytime parameters. The Mars Initial Reference Ionosphere (MIRI) model [Mendillo et al., 2013a] for solar zenith angles (SZAs) in the range 0°–90° is a useful tool for placing the new observations made by MAVEN within the context of previous data sets. The initial MAVEN observations can be used as validation targets for such a predictive model (the topic of this paper), with later, multiyear MAVEN data sets a vital asset for improving MIRI.

2. Observations

MAVEN’s Neutral Gas and Ion Mass Spectrometer (NGIMS) provides data on the thermal ionic species along an orbit [Mahaffy et al., 2014]. In its standard “mapping orbit” the MAVEN spacecraft has a periapsis altitude of ~150 km, and thus in situ instruments sample the topside ionosphere. During MAVEN’s Deep-Dip observing campaigns, the periapsis is lowered to ~130 km, providing the mission’s main opportunity to sample the ionosphere at the typical heights of maximum plasma density (hm,ap), and perhaps below. The 27 orbits used in this study are from campaign #2, which spanned the days 17–22 April 2015. The MAVEN convention is to change orbit numbers when the satellite begins its outbound pass from periapsis. NGIMS typically alternates between its ion and neutral measurement modes for a full orbit around the planet, starting at apoapsis. Thus, for each MAVEN orbit designation used here, ion data are typically available on either the inbound or outbound segment.

NGIMS measures the abundances of ions with masses between 2 and 150 amu. The NGIMS conversion of count rates to absolute ion densities is achieved by normalizing the sum of all ions to the electron density measured by the Langmuir Probe and Waves (LPW) instrument on MAVEN [Andersson et al., 2015]. The initial calibration between NGIMS and LPW was done in the first few weeks of the mission [Benna et al., 2015], and those results were used for the data set analyzed here. The assessment of any possible drifts from the initial NGIMS-LPW calibration is an ongoing activity, and the results offered here may help in such determinations.

Ionospheric theory shows that singly charged ion-electron pairs are produced at Mars [Schunk and Nagy, 2009], and thus the summation all ions to form a proxy for the electron density value rests upon a solid...
foundation. We interpolated the time steps for each species to obtain a uniform cadence of one data point every 10 s. The measurement precision depends on the magnitudes of the ion densities. For the dominant ion (\(\text{O}_2^+\)), the instrument precision is estimated to be 1–2% when \(\text{O}_2^+ \geq 5 \times 10^7/\text{cm}^3\), 5–10% when \(\text{O}_2^+ = 2 \times 10^7/\text{cm}^3\), and ~15% when \(\text{O}_2^+\) is in the \(10^7/\text{cm}^3\) domain. Added to these is a ~ ±15% systematic error for the uncertainties of the LPW electron density data used for cross calibration. Finally, we confined our study to daytime conditions (SZA < 90°) when the satellite was below ~400 km. The satellite moves about 35 km between data points, mostly horizontal, with altitude changing by ~5 km.

3. Model

3.1. Background

The Mars Initial Reference Ionosphere (MIRI) model \cite{Mendillo et al., 2013a} is a semiempirical model that relates the maximum electron density \(N_{\text{max}}\) in the Martian ionosphere to solar zenith angle (SZA) and solar flux \(F_{\text{Sun}}\). It was developed using 112,718 observed \(N_{\text{max}}\) values spanning the years 2005–2012 that were parameterized into a semiempirical model using photochemical-equilibrium equations. The observational peak densities were obtained by the active ionosphere sounding mode of the radar instrument (Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS)) on board the European Space Agency Mars Express mission \cite{Gurnett et al., 2005}. Validations for MIRI-mark-1 were conducted using \(N_{\text{max}}\) values measured by both Viking landers and by radio occultation experiments on flyby and orbital missions at Mars \cite{Mendillo et al., 2013a, Table 1 and Figures 2–4}. MIRI agreed with the Viking data to within ±3% and ±8–10% for radio occultation case studies.

The MIRI-mark-1 model for \(N_{\text{max}}\) is of limited direct use for MAVEN simply because the in situ observations are made throughout the topside ionosphere, i.e., not just at \(h_{\text{max}}\) (assumed to coincide with periapsis for Deep-Dip Campaign #2). In addition, the observations are not in the vertical direction (but along an orbital track) and therefore do not share a common SZA. This was not the case for earlier radio occultation experiments on various satellites at Mars. The radio occultation technique derives vertical \(N_e(h)\) profiles under the assumption of uniform morphology over spatially confined regions (i.e., narrow ranges of latitudes and longitudes). These yield electron density profiles but ones limited almost exclusively to near-sunrise and near-sunset conditions at high latitudes (SZA > ~70°, latitude > ~60°). The only other type of \(N_e(h)\) profiles available came from the in situ probes on the two Viking landers \cite{Hanson et al., 1977} that provided pre-MAVEN vertical profiles of ion densities (with their sum assumed to be the electron density). The Viking observations occurred near 1400 LT with SZA ~ 45°.

MAVEN’s highly elliptical orbit provides a remarkably new diagnostic capability that samples a more global range of daytime and nighttime ionospheric conditions. Yet MAVEN/NGIMS data present a significant challenge for modelers due to the extended horizontal space traversed by the satellite as its sensors sample a few hundred kilometers of vertical ionospheric structure. There are three approaches that can be used (1) run a global (3-D) theoretical model and sample its output along a MAVEN trajectory, (2) run 1-D theoretical model many times along a MAVEN trajectory and extract the electron density at the orbital heights sampled as a function of latitude, longitude, and local time, and (3) modify the semiempirical MIRI-mark-1 model (parameterized for SZAs at \(h_{\text{max}}\)) to include altitudes above and below the height of maximum density—and then extract the local plasma density at varying heights and SZAs along the trajectory. We decided to take option (3) to create a MIRI-mark-2 that could provide electron densities both above and below \(h_{\text{max}}\). Building upon existing techniques keyed to \(N_{\text{max}}\) offered the shortest development time and allowed for the most computer efficient way to make model \(N_e(h)\) results available on the MIRI website.

3.2. Model Development

The extension of MIRI from a single output value \(N_{\text{max}}\) for a fixed SZA and \(F_{\text{Sun}}\) to a full vertical profile, \(N_e(h)\), can be achieved by determining the shape of the electron profile to be used for those conditions. At altitudes below \(h_{\text{max}}\), the expectation is one of full photochemical equilibrium. Yet MAVEN rarely, if ever, gets below \(h_{\text{max}}\) and thus the theoretical model needed is one that addresses, in a comprehensive fashion, altitudes above ~170 km where plasma diffusion becomes an important process. The \cite{Matta et al., 2013} model was selected for use because it includes plasma diffusion dependent upon both ion-neutral and...
ion-ion collisions, and a neutral atmosphere with hydrogen (H and H₂) that leads to a broad range of ion-neutral chemistry (e.g., hydrogenated ions). Such processes are highly relevant to MAVEN data sets because most of the observations by NGIMS and other instruments sampling the ionosphere will do so in the topside altitude range ~200–400 km.

3.3. Model Runs

Our goal for MIRI-mark-2 was to create a family of ionospheric profiles for nine bins of solar zenith angles (0°–10°, 10°–20°, ..., 80°–90°) that can be normalized by the N_max value predicted by MIRI-mark-1 for that day’s solar flux condition. For MAVEN applications, the resultant N_e(h) profiles can then be sampled at satellite heights along an orbital track where the NGIMS observations are made. For the simulations using the Matta et al. [2013] model, we selected neutral atmospheres at 37 latitudes (90°S to 90°N in 5° steps) from the Mars Climate Data Base (http://www-mars.lmd.jussieu.fr/mcd_python/) for conditions of average solar flux (F_10.7 = 130 units at 1 AU = 56 units at 1.524 AU), no dust, Mars at spring equinox (Ls = 0), and 1500 LT for stable daytime conditions. A compatible solar irradiance model at Mars was derived from Earth-based measurements using the Solar Irradiance Platform [Tobiska, 2004]. For the ionospheric calculation, 17 height levels were used between 80 and 400 km. At each of the 37 latitudes, a diurnal run was made to yield a distribution of N_e(h) profiles versus local time. With 5° latitude resolution and 1 h increments in local time, a total of 888 N_e(h) profiles were available for characterization. We sorted them into the 10° SZA bins and computed an average <N_e(h)> profile for each bin. This <N_e(h)> was then divided by that bin’s N_max to obtain the average profile shape to be calibrated by the MIRI-mark-1 prediction. Figure 1 shows the nine daytime normalized profiles that, when calibrated by a daily N_max versus SZA value from MIRI-mark-1, now comprise the MIRI-mark-2 model. This paper deals with the first attempt at validation for MIRI-mark-2 using newly available MAVEN observations. Fortunately, solar flux conditions were stable during MAVEN’s 6 day Deep-Dip #2 campaign, thereby having one less source of variability to consider; the Deep-Dip orbits of April 2015 also had excellent coverage at small SZAs—rarely found in previous missions. Additional MIRI validations of profile shapes will be possible using pre-MAVEN radio occultation data closer to the solar terminator and from MARSIS topside sounder observations under various SZA conditions.

Figure 1. (top) Illustration of MIRI’s use of theoretical electron density profiles to form normalized profile shapes ordered by solar zenith angles. Validation of N_e(h) profiles generated by the BU Mars Ionosphere Model appears in Mendillo et al. [2011] and Matta et al. [2015]. The <N_e(h)> profile for each 10° bin of SZA comes from a different number of theoretical model simulations. For the daytime bins shown, these were 4, 14, 24, 29, 47, 60, 76, 111, and 79 for a total of 444 profiles. The model-mean N_e(h) profiles shown were calibrated by the MIRI-mark-1 daily values for N_max (with their σ#2) within each SZA bin from the theoretical profiles to yield the total uncertainty in a MIRI-mark-2 prediction (see text). (bottom) N_e(h) profiles using the α-Chapman layer formula for the <SZA> = 5°–45° and h_max conditions shown in Figure 1 (top), and a neutral scale height (H) of 14 km.
To estimate the uncertainty values associated with MIRI-mark-2 predictions, we considered two sources of model variability. First is the variability associated with the profile’s normalization by $N_{\text{max}}$ ($\sigma_1$ from MIRI-mark-1). As described in Mendillo et al. [2013a], this could be characterized using the magnitudes of $N_{\text{max}}$ and $\sigma_1$ ranged from 5% (midday $N_{\text{max}}$) to 30% (near-terminator $N_{\text{max}}$). For the MAVEN data set used here (low SZAs and therefore large $N_{\text{max}}$ values), the calibration uncertainty was ±5%. A second source of variability comes from the standard deviations ($\sigma_2$) at each altitude in each bin of the averaged theoretical profiles. These were about half the values of $\sigma_1$ for the small range of SZAs used and were treated as independent contributors to the overall uncertainty. MIRI-mark-2 results shown below will include total uncertainty estimates as shadings about the predicted curves.

The attention to model variability is driven by the fact that the Martian ionosphere (and in particular its topside structure) is not always in full photochemical equilibrium (e.g., as portrayed by Chapman Theory profiles) throughout a diurnal simulation. If that were the case, all of the $N_e(h)$ patterns for a given SZA and neutral atmosphere would be identical. There are several reasons why this is not the case for the theoretical profiles computed for MIRI. Most important, the inclusion of a sophisticated treatment of plasma diffusion leads to the same zenith angle having different topside profile shapes. Thus, it matters if a specific SZA (e.g., 35°) occurs after sunrise or prior to sunset at the subsolar latitude or at local noon from a higher latitude. There are also latitude differences in the background neutral atmosphere that lead to different $N_e(h)$ profile shapes for the same SZA. Figure 1 (bottom) gives Chapman shapes for the SZA and height ranges encountered during Deep-Dip #2 campaign—clearly inadequate for topside ionosphere studies.

4. Data-Model Comparisons

In the course of the 6 day MAVEN Deep-Dip campaign in April 2015, the orbits were essentially fixed in space, with the planet rotating below. This results in a fairly consistent pattern of height, latitude, and local time (and thus SZA) along the trajectory segments below 400 km. Longitudes, of course, change with each satellite pass.

Figure 2 shows how we relate the MAVEN orbit to the observations as a function of SZA and height below 400 km. In Figure 2 (middle), a sample Deep-Dip pass on 17 April 2015 is shown with the latitudes, longitudes, and local times of the NGIMS observational start and end times noted. The NGIMS sampling of vertical structure along the outbound orbit segment (#1060, red) was for neutrals and thus Figure 2 (right) does not show ion data; the subsequent inbound orbit segment (#1060, blue) occurred ~4 h later, and...
NGIMS was then in ion mode. Note that the observations below 400 km in each segment were acquired over a short orbital time (~10 min). These brief samples encompass broad spatial portions of each hemisphere and significant SZA changes (0°–50°), yet within a narrow band of local times; this is typical of all passes (see Figures 3 and 4).

In Figure 2 (left), the NGIMS total ion densities are indicated by the solid squares. The solid colored line in each panel gives the MIRI-mark-2 predicted $N_e$ value, and the shading gives the MIRI uncertainties (typically 5–6%). There are several things to note in this first comparison of NGIMS and MIRI values: (1) the model values are all higher than the data, (2) considerable topside variability in total ion density, and (3) the gradient with altitude above ~240 km diverges markedly from model predictions.

![Figure 3](image1.png)

**Figure 3.** Same format as Figure 2 but using continuous orbit segments (#1080 inbound and #1081 outbound) from 21 April 2015. The steep topside gradients suggestive of ionopause-like boundaries near 240 km are not included in MIRI predictions (see text).

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![Figure 4](image2.png)

**Figure 4.** Same format as Figures 2 and 3 but for the total NGIMS data set in comparison to MIRI’s average of all predictions (with standard deviation) for the period 17–22 April 2015. Different symbols and colors are used to indicate the seven NGIMS data sets showing ionopause-like topside gradients (purple triangles), the nine NGIMS data sets obtained above regions of strong crustal-B fields in the southern hemisphere (green circles), and the three NGIMS ionopause cases above crustal-B regions (orange asterisks). The remaining eight NGIMS profiles without ionopauses and not above strong crustal B (e.g., the one shown in Figure 2) are shown as black squares. Average patterns are given in the supporting information.
Figure 3 presents observations from 21 April 2015, in the same format as Figure 2, to illustrate a more dramatic case of item (3)—a significant difference in the topside structure between data and model. Here we show continuous orbit segments: for the inbound trajectory of orbit #1080 (Figure 3, left), there is a steep altitude gradient to $N_e \sim 2 \times 10^3$ e/$\text{cm}^3$ near 240 km, with irregular recovery and decrease to $\sim 10^{-3}$ e/$\text{cm}^3$ above. This is followed (Figure 3, right) by another steep gradient above $\sim 240$ km on the outbound segment of orbit #1081. Taken together, these suggest “ionopause-like” behavior for the 11:00–12:30 local time sector. Abrupt terminations of the Martian dayside ionosphere due to solar wind interactions have been described in Nagy et al. [2004] and Duru et al. [2009]. Detections of such “ionopause” signatures using MAVEN data are described by Vogt et al. [2015]. Of the 27 orbit segments examined, 10 had patterns of ionopause-like structures not included in MIRI predictions. We examined the longitudes of these orbit segments at latitudes in the southern hemisphere to see if they coincided with areas of strong crustal magnetic fields, i.e., if they occurred in the longitude range 130°–260° east [Withers et al., 2005; Mendillo et al., 2011, 2013b]. Of the 13 orbit segments within crustal-B longitudes, only three of the 10 ionopause-like patterns occurred there.

Figure 4 summarizes the total NGIMS data set in comparison to the MIRI-mark-2 predictions. In the central panel, all 27 orbit segments from MAVEN’s second Deep-Dip campaign are shown. There are clearly consistent patterns of heights and SZAs sampled during the inbound and outbound orbit segments of this 6 day period. The MIRI-predicted electron densities for each type of orbit segment (inbound and outbound) were averaged, and those mean $N_e$ values are shown (with their small variabilities) in Figure 4 (right and left). The total number of NGIMS data points, sorted by height and SZA, is given using symbols and color coding to indicate the subsets of observations showing ionopause-like gradients and smoother topside patterns near and away from strong crustal-B fields. There is more variability with the green points (above crustal B), but their mean values (shown in Figure S1 of the supporting information) are essentially the same as obtained with the less-variable black points (away from crustal B). The topside gradients showing ionopause-like characteristics above and away from crustal-B locations (orange asterisks and purple triangles, respectively) are similarly consistent and show the greatest departures from MIRI predictions (see supporting information). An overall summary of observations, together with MIRI input/output values at $h_{\text{max}}$ (assumed to be periapsis), appears in Table S1 of the supporting information.

5. Interpretation and Conclusions

We have used the MAVEN Deep-Dip campaign of 17–22 April 2015 to compare the total ion density from the NGIMS sensor with the electron density patterns predicted by a new version of the Mars Initial Reference Ionosphere (MIRI) model. The observations do not give vertical profiles, but rather provide data that span the 130–400 km altitude range while traversing broad horizontal distances in both hemispheres (at 130°–260° east) and corresponding to $\sim 2200$ km and 610 km, respectively, near the equator), SZA conditions varying between 0° and 50°. The MIRI-mark-2 model—developed to cope with such data sets by using theoretical $N_e(h)$ profile shapes calibrated by daily solar flux, $N_{\text{max}}$, and SZA conditions—resulted in the following set of preliminary conclusions:

1. At all ionospheric heights treated, the NGIMS data are consistently lower in magnitude than the MIRI predictions. In the altitude range where the transition occurs between photochemical-only processes and plasma diffusion conditions (130–200 km), the morphology patterns between data and model are fairly consistent (while differing by a factor of 2 in absolute magnitudes). This difference might be due to calibration uncertainties for these initial NGIMS data sets, and thus altitude gradient comparisons constitute success criteria. As such, the visual agreement of $N_e(h)$ gradients above $h_{\text{max}}$ is encouraging for this first test of a semiempirical ionospheric model with MAVEN’s observed plasma densities at Mars.

2. At altitudes above $\sim 200$ km, the NGIMS values of total ion density versus height diverge considerably from the MIRI $N_e(h)$ predictions derived only for photochemistry and vertical diffusion processes. In some cases, differences may be due to horizontal transport away from the noon sector not included in the semiempirical MIRI model. Moreover, MIRI does not yet treat a high-altitude cutoff associated with “ionopause” conditions, and it appears that NGIMS detected many such patterns [Vogt et al., 2015].

3. MIRI predictions do not yet take into consideration electron density deviations associated with crustal-B fields at latitudes in the southern hemisphere in the longitude sector 130° to 260° E. A total of 13 orbit segments occurred above crustal-B regions, and only 3 of the 10 detected ionopause-like gradients occurred in their vicinity.
This preliminary analysis of MAVEN’s Deep-Dip Campaign #2 focused on initial comparisons between in situ observations of total ion density by the NGIMS instrument and the latest version of MIRI for electron density. The results obtained point to the contributions MAVEN observations will make to modeling efforts, initially as validation targets (as shown here) and later as data inserted into the model to improve semiempirical predictions. The initial MAVEN/NGIMS observations from the single Deep-Dip orbit campaign used in this study represent an extraordinary set of new results (recalling that only two VIKING observations of ion composition existed prior to these observations). Additional data sets and semiempirical model development (how to include effects caused by horizontal transport and crustal-B fields) will further MAVEN’s exploration of the Martian ionosphere and its key relationships to atmospheric escape.

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