Dayside electron temperature and density profiles at Mars: First results from the MAVEN Langmuir probe and waves instrument


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Abstract We present Mars’ electron temperature ($T_e$) and density ($n_e$) altitude profiles derived from the MAVEN (Mars Atmosphere and Volatile EvolutionN) mission deep dip orbits in April 2015, as measured by the Langmuir probe instrument. These orbits had periapsides below 130 km in altitude at low solar zenith angles. The periapsides were above the peak in electron density at Mars: First results from the MAVEN Langmuir probe and waves instrument, Geophys. Res. Lett., 42, doi:10.1002/2015GL065280. We present Mars’ electron temperature ($T_e$) and density ($n_e$) altitude profiles derived from the MAVEN (Mars Atmosphere and Volatile EvolutionN) mission deep dip orbits in April 2015, as measured by the Langmuir probe instrument. These orbits had periapsides below 130 km in altitude at low solar zenith angles. The periapsides were above the peak in $n_e$ during this period. Using a Chapman function fit, we find that scale height and projected altitude of the $n_e$ peak are consistent with models and previous measurements. The peak electron density is slightly higher than earlier works. For the first time, we present in situ measurements of $T_e$ altitude profiles in Mars’ dayside in the altitude range from ~130 km to ~500 km and provide a functional fit. Importantly, $T_e$ rises rapidly with altitude from ~180 km to ~300 km. These results and functional fit are important for modeling Mars’ ionosphere and understanding atmospheric escape.

1. Introduction

The primary science goal of the Mars Atmosphere and Volatile EvolutionN (MAVEN) mission is to understand the loss of Mars’ atmosphere and water, in particular the loss of O. There is substantial evidence of loss to space in the ratios of isotopic abundances [Pepin, 1994]. Mars’ gravitational acceleration is such that Jeans escape can explain the loss of H, but O is bound by ~2 eV (depending on altitude) and requires an additional energy source for escape. The primary escape mechanism of O is believed to be from dissociative recombination of O$_2^+$ [e.g., McElroy, 1972; Rohrbaugh et al., 1979; Barth, 1985; Nagy and Cravens, 1988; Zhang et al., 1993; Fox and Hac, 2009]:

$$O_2^+ + e^- \rightarrow O + O$$

This process can impart sufficient kinetic energy into the O products for escape, up to 6.99 eV, depending on excitation state. The reaction rate is proportional to the product of the O$_2^+$ density with $n_e$ and depends on $T_e^{-0.7}$ [Alge et al., 1983, and references therein]. Thus, $T_e$ and $n_e$ can strongly influence atmospheric escape through O$_2^+$ dissociative recombination.

The exobase is typically defined as the altitude above which the vertical column density is equal to the inverse of the collisional cross section, which is tantamount to the boundary where collisions no longer dominate photochemistry. This region is particularly important for the O escape process via dissociative recombination of O$_2^+$ [e.g., Fox and Hac, 2009]. If the dissociative recombination reaction occurs above the exobase, at least one of the O atoms is likely to escape, since it is unlikely to suffer a collision. However, $n_e$ and the density of O$_2^+$ rapidly decrease with increasing altitude, so the reaction rate is low at the exobase and rapidly falls with altitude. Below the exobase, the reaction rate dramatically increases with increased electron and O$_2^+$ densities, but the escape efficiency falls significantly due to collisions, which are dominated by the neutral atmosphere. As a result, the region within a several scale heights (roughly 50 km) of the exobase (roughly 180 km for O) is critical to O escape. The $n_e$ and $T_e$ profile in this region is essential for determining O escape via dissociative recombination of O$_2^+$. Measurements of $n_e$ have been made of the Martian ionosphere over range of solar zenith angles and altitudes using a variety of techniques. Near the peak in $n_e$, the Martian ionosphere is reasonably well...
approximated by a Chapman layer with peak densities in the range \(1.5\times10^5\) cm\(^{-3}\) at altitudes of \(125\)–\(130\) km. Scale heights are less well constrained with values ranging from \(-5\) to \(-25\) km [Morgan et al., 2008; Némec et al., 2011; Fallows et al., 2015a, 2015b].

The altitude profile of \(T_e\) at Mars, which is critical to modeling efforts [e.g., Fox and Yeager, 2006; Withers et al., 2014; Cui et al., 2015; Fallows et al., 2015a, 2015b], is not well established. The only previous in situ measurements of \(T_e\) and ion temperatures were from the Viking landers [Hanson et al., 1977; Hanson and Mantas, 1988]. Indirect estimates of \(T_e\), for example, from the vertical \(n_e\) gradient, vary significantly [e.g., Cui et al., 2015], which makes in situ measurements of \(T_e\) valuable. A more general description of Mars’ ionosphere and discussion on the importance of \(T_e\) and \(n_e\) altitude profiles are provided by Nagy et al. [2004]; Witasse et al. [2008], and Withers et al. [2012].

In this article, we present the measurements of \(n_e\) and \(T_e\) during the MAVEN deep dip campaign [Jakosky et al., 2015] from 15 April 2015 to 22 April 2015 from the Langmuir probe and waves instrument (LPW). These data summarize 28 orbits in which MAVEN probed altitudes just below 130 km in Mars’ dayside ionosphere, which is a critical region for modeling Mars’ atmospheric photochemistry. Our data include altitudes up to 500 km and contains the region critical for \(O_2^+\) dissociative recombination. Several of the orbits showed unusual density structure, which is the focus of several future articles.

## 2. Instrument

The MAVEN LPW instrument is described by Andersson et al. [2015], so our description here is brief. The LPW has two independent cylindrical Langmuir Probes (LPs), each sensor being 0.0625 cm in diameter and 40 cm long. The sensors are mounted at the end of 7 m booms resulting in excellent isolation from spacecraft disturbances of the electron distribution and limited photoelectron fluxes emitted by the spacecraft.

During the deep dip campaign, the Langmuir probes made a 128-step sweep, stepping the voltage from +5.4 V to −5.4 V with respect to an estimated plasma potential [see Andersson et al., 2015 for details] while measuring the current with \(-1\) nA accuracy, resulting in a current-voltage (I/V) characteristic. A sweep is made over a 1 s period. Each of the two probes is swept every 4 s, resulting in 2 s time resolution when combined.

The electron density, ion density, electron temperature, and spacecraft potential are derived from the I/V characteristics via a fitting process enhanced from that of, e.g., Allen [1992] or Brace [1998]. The \(n_e\) also is derived from wave sounding [Andersson et al., 2015]. The sensors, coated with TiN, have undergone some contamination from atomic oxygen (AO). Starting January 2015, the LPW sensors display a deviation from the expected I/V characteristic in regions of high density \((n_e > 10^4\) cm\(^{-3}\)) and low temperatures \((T_e < 0.15\) eV\). This deviation is shown in Figure 1 (left). The deviation appears as the probe potential is positive with respect to the plasma \((V_{sweep} > -V_{SC}\) where \(V_{SC}\) is the spacecraft potential) and persists until \(V_{sweep} > -V_{SC} + 1.3\) V. The AO contamination does not appear to influence the electron retardation region of the I/V curve, so \(T_e\) and \(n_e\) are derived to be better than 20% accuracy in most conditions. In addition to the AO contamination, the RAM ions can distort the sheath around the sensor and cause deviations from the expected I/V characteristic in high plasma densities if \(V_{sweep} > -V_{SC}\).

To ensure an accurate fit, the electron current \((I_e)\) is separated from the sensor-emitted photoelectron current \((I_{PheSens})\), the spacecraft photoelectron current \((I_{PheSC})\), and the ion current \((I_i)\)

\[
I_e = I_m - I_{PheSens} - I_{PheSC} - I_i
\]

Here \(I_m\) is the measured current and \(I_i\) is optimized so that \(I_e\) is near zero at negative sweep voltages. \(I_{PheSens}\) and \(I_{PheSC}\) are established by examining I/V characteristics in low-density plasmas. \(I_{PheSens}\) is typically between 10 and 20 nA (depending on the spacecraft orientation) in \(V_{sweep} < -V_{SC}\). \(I_{PheSC}\) reaches \(-30–50\) nA if \(V_{sweep} >> -V_{SC}\).

Figure 1 (center) shows the separated electron current. \(T_e\) is derived from an isolated region of the I/V characteristic where \(7.5\) nA < \(I_e\) < 1000 nA to avoid effects of AO contamination. This region can contain as few as six points in the highest densities but contains more than 10 points in most cases. \(T_e\) is also derived from the slope of \(dI_e/dV\) (Figure 1, right), which requires no modification of \(I_m\) since \(I_i\) is nearly constant through the electron retardation region [see example in Andersson et al., 2015]. In almost all (>95%) of the derivations with \(n_e > 10^4\) cm\(^{-3}\) reported here, the two derivations of \(T_e\) agree to within 20% on a given sensor. For each sensor, the reported values of \(T_e\) are a weighted average of two \(T_e\) values.
The value of $T_e$ derived from $dI_m/dV$ receives a lower weighting in lower densities since the derivative amplifies measurement error. A difference between the two derived values results in a larger uncertainty in $T_e$. The isolation procedure is not needed if $n_e < 10^4 \text{ cm}^{-3}$ or if $T_e > 0.15$ eV.

Surface resistance or capacitance on the sensor appears to prevent a measurement of $T_e$ below 0.045 eV (~525°K) on sensor 1 and below 0.60 eV (~700°K) on sensor 2. As a result, the lowest temperature measurements, those below ~0.1 eV, have larger uncertainties and are systematically biased to yield a higher measurement of $T_e$ than the actual value. Furthermore, $T_e$ from sensor 1 and sensor 2 can disagree by ~20%. Surface resistance, surface capacitance, and other measurement errors can be estimated from hysteresis in $I/V$ characteristics (the difference between a positive-stepped sweep and a negative-stepped sweep). Regular hysteresis tests show that the hysteresis in LPW sensor 1 is very small (and lower than that of sensor 2), which allows us to estimate a lower bound of $T_e$. Sensor 1 is given higher weight if $T_e < 0.1$ eV in the reported average altitude profile. We present $T_e$ data as derived from the slope of $I_e$ and from the slope of $dI_m/dV$ (weighted average) from the LPs with these known uncertainties and include estimates of lower and upper uncertainties. At low values of $T_e$, the reported value of $T_e$ is near the upper bound.

The density is measured on both sensors using ion current and electron current, resulting in four measurements of plasma density from the two sensors. The density from the ion current is derived assuming the ion ram velocity is from the spacecraft motion. The ion-derived density is systematically lower than the electron-derived density by ~15% when $n_e > 10^5 \text{ cm}^{-3}$; the ion-derived density is used primarily to verify the electron-derived density.

The wave sounding can allow for an accurate determination of $n_e$ at times when valid returns can be identified. However, stimulated Langmuir waves from sounding appear to reside in density cavities created by the spacecraft suggestive of Langmuir eigenmodes [Ergun et al., 2008; Malaspina and Ergun, 2008; Andrews et al., 2015]. Thus, sounding returns are best considered a lower bound of $n_e$. The LPs and wave sounding agree within ~5% when $n_e > 10^5 \text{ cm}^{-3}$. The LPs systematically underestimate $n_e$ from that of wave sounding by as much as ~25% when $n_e < 10^5 \text{ cm}^{-3}$ or lower. The LP-derived density is systematically higher (by a factor of ~1.33, causing a 25% uncertainty) from that wave sounding when $2 \times 10^4 \text{ cm}^{-3} < n_e < 5 \times 10^4 \text{ cm}^{-3}$. Wave sounding is not available if $n_e > 5 \times 10^4 \text{ cm}^{-3}$ (frequency limit of wave receiver) and is highly unreliable/variable when $2 \times 10^3 \text{ cm}^{-3} < n_e < 2 \times 10^4 \text{ cm}^{-3}$, presumably because of eigenmode formation in the spacecraft wake. At this time, we are unable to determine if the wave sounding is underestimating $n_e$ (eigenmode formation) or if the LPs are overestimating $n_e$ in regions of high density.
In this article, we present uncorrected LP measurements with appropriate uncertainties (typically $-25\% + 10\%$) assigned.

3. Coverage

Figure 2 (left) displays the tracks of 28 orbits of the MAVEN deep dip campaign from 17 April 2015, 05:43:08 UT, until 22 April 2015, 06:45:33 UT. The horizontal axis represents the $Y$ position, and the vertical axis represents the $Z$ position in Mars-centered Solar Orbital (MSO) coordinates. The red circle outlines Mars. The orbital tracks run from the bottom right to top left, and the color represents the altitude. We confine this study to altitudes below 500 km. The periapsis line is just north and east of the subsolar point of Mars. The inbound leg (below 500 km to periapsis) of the orbits has the lower solar zenith angles, whereas the outbound legs (from periapsis to 500 km) show strong variation in $n_e$ and $T_e$ (see below), so we use only inbound legs in this study. The average solar zenith angle is $\sim 12^\circ$ at periapsis, $\sim 6^\circ$ at 150 km in altitude, $\sim 15^\circ$ at 225 km in altitude, and as high as $40^\circ$ at 500 km. The MAVEN orbital period (~4 h) results in broad coverage in longitude.

4. Results

Figure 2 (right) displays $n_e$ and $T_e$ as a function of time for a single periapsis pass as MAVEN descended from 500 km in altitude to ~130 km and then ascended back 500 km over a ~24 min period. The blue lines are $n_e$ and $T_e$ values derived from sensor 1, and the black lines represent values from sensor 2. The two sensors have excellent agreement in $n_e$ but occasionally display differences in $T_e$ as large as 20%. The inbound (descending) leg shows a nearly steady increase in $n_e$ and a mostly steady decline in $T_e$. The outbound (ascending) leg shows interesting structure that is seen on many orbits. At ~1100 s into the pass, $T_e$ sharply rises to nearly 0.4 eV as $n_e$ decreases by roughly an order of magnitude. This event is followed at 1150 s by a sharp decrease in $T_e$ and increase in $n_e$, then at ~1210 s there is another sharp increase in $T_e$ and decrease in $n_e$. The MAVEN spacecraft (velocity of ~4.1 km/s) travels ~400 km during this period. It is unclear at the time of this writing if these abrupt changes are due to changes in altitude, due to horizontal motion, or are temporal variations.

Figure 3 displays the altitude profile of $n_e$ and $T_e$ over 28 orbits. These data have several interesting features. The density profiles show large variation at altitudes above ~180 km, sometimes in individual passes and sometimes from orbit to orbit. On the other hand, the variation is <10% below 150 km in altitude, indicating that this part of the ionosphere was stable for the 6 day deep dip campaign.
The density profile at the lowest altitudes was fit to a Chapman function for comparison to previous works [e.g., Fallows et al., 2015a]:

\[ N_e = N_{e1} + N_{e2} \]
\[ N_{e1} = N_i \exp \left( 1 - \frac{z - Z_i}{H_i} - \exp \left( \frac{z - Z_i}{H_i} \right) \right) \]

Here \( z \) is the altitude, \( N_{e1} \) is the density of the M1 layer, and \( N_{e2} \) is the density of the M2 layer. Since the MAVEN spacecraft does not probe the M1 layer, we use predetermined values for \( N_i \) (peak density), \( Z_i \) (altitude of the peak density), and \( H_i \) (the scale height), which are on Figure 3 [e.g., Fox and Yeager, 2006; Liao et al., 2006; Fallows et al., 2015a, 2015b]. We include the M1 contribution to improve the M2 fit.

The values of \( N_{e2}, Z_{e2}, \) and \( H_{e2} \) are determined by fit to the average measured value of \( n_e \) (red line in Figure 3, left). The fit included a weighting function proportional to average value of the measured \( n_e \), so measurements above \( \sim 180 \) km have little influence. The fits indicate that MAVEN periapsides (~130 km) were just above \( Z_{e2} \), the altitude of the M2 density peak, at 124 km (±2.5 km/±5 km); the uncertainty is dominated by the altitude binning of the data (5 km). Since MAVEN did not penetrate below the M2 peak, there is a larger uncertainty to the lower bound. \( Z_e \) at 124 km is consistent with \( Z_e \) in most Mars models [Hantsch and Bauer, 1990; Zhang et al., 1990; Fox and Weber, 2012], consistent with that determined by the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) instrument [Gurnett et al., 2005; Nielsen et al., 2006; Morgan et al., 2008; Némec et al., 2011], but slightly below of that derived by the Mars Global Surveyor (MGS) radio occultation [Fallows et al., 2015a]. Given differences in solar zenith angle coverage and possible variation in \( Z_e \), we find the results from MAVEN, MARSIS, and MGS to be generally consistent.

The peak density of the M2 layer \( (N_{e2}) \) is projected by fit to be \( 2.6 \times 10^5 \text{ cm}^{-3} \) with a lower limit of \( 1.95 \times 10^5 \text{ cm}^{-3} \) and an upper limit of \( 2.86 \times 10^5 \text{ cm}^{-3} \). The lower limit reflects the uncertainty in the comparison of density from wave sounding and LP-derived densities. These values are higher than most model-predicted values but very near of that derived from the Mars Global Surveyor (MGS) radio occultation \( (1.97 \times 10^5 \text{ cm}^{-3}) \) [Fallows et al., 2015a, 2015b]. The peak \( n_e \) is somewhat higher than that determined...
by MARSIS [Nielsen et al., 2006; Morgan et al., 2008; Němec et al., 2011]. Considering that the MAVEN data are limited to a 6 day period and that seasonal variation, magnetic fields, and solar output have not been accounted for, we see good agreement with previous observations and modeling.

The scale height, $H_2$, at 12.6 km, is relatively accurately measured at $\pm 1$ km. It is generally consistent with that determined from measurements made by MARSIS [Němec et al., 2011] but somewhat higher than that reported by MGS radio occultations and many models [e.g., Fox and Weber, 2012; Fallows et al., 2015a, 2015b]. Figure 3 (right) reports the first in situ measurements of the $T_e$ profile near the subsolar ionosphere at Mars. Above ~300 km, $T_e$ is highly variable both within a single orbit and from orbit to orbit. The mean value of $T_e$ (300 km $< z <$ 500 km) is 0.270 eV (3130°K) with an uncertainty range of 0.216 eV to 0.301 eV, considering the standard deviation and possible systemic errors from the measuring technique.

The mean value of $T_e$ at 200 km is 0.084 eV (−0.017 eV, +0.010 eV). In this region, sensor 2 is near its lower limit, so the uncertainty, particularly of the lower limit of $T_e$, increases. This region is critical to dissociative recombination of $O_2^+$ and subsequent escape of O. The dramatic change in $T_e$ with altitude increases the importance of the region just below the exobase for O escape since $O_2^+$ dissociative recombination reaction rate is proportional to $T_e^{-0.7}$. For example, at ~225 km, the mean value of $T_e$ is 0.135 eV (−0.027 eV, +0.014 eV) reducing the $O_2^+$ dissociative recombination rate, whereas at 175 km, the mean value of $T_e$ reduces to 0.062 eV (−0.015 eV, +0.006 eV), greatly increasing the $O_2^+$ dissociative recombination rate.

In the region below ~200 km, we rely on more heavily on sensor 1, which has reported temperatures as low as 0.045 eV. The mean value of $T_e$ continues to decrease with a decrease in altitude. At the lowest altitudes measured by MAVEN, sensor 1 indicates a mean value of $T_e$ of 0.052 eV. From our best estimates of surface irregularities, surface resistance, and capacitance of sensor 1, we estimate a lower bound of 0.026 eV and an upper bound of 0.060 eV. At these low temperatures, the LP measuring technique can overestimate $T_e$, whereas an underestimation can only come from current measurement error, which is very low in such high densities.

5. Discussion

The measured $T_e$ altitude profiles from the MAVEN LPW instrument are consistent with that observed by the Viking 1 lander [Hanson and Mantas, 1988] given the large variability above 200 km. The Viking 1 lander did not measure $T_e$ at altitudes below 200 km. Modeling efforts [e.g., Matta et al., 2014] expect $T_e$ to be close to the neutral temperature (~0.02 eV; ~200°K) below ~125 km in altitude but rise quickly with altitude above ~125 km. An additional heat source is required to reach the Viking lander temperatures (~0.3 eV; ~3000°K).
The MAVEN LPW results indicate $T_e$ rises relative slowly from ~130 km to ~180 km in altitude, with a dramatic rise in temperature from ~180 km to 300 km in altitude. The high values of $T_e$ (0.271 eV; 3140°K) above 300 km in altitude require a substantial energy source.

Since an analytic equation for $T_e$ could be most useful in modeling efforts, we attempted to fit the measured profile to an analytic form. The $T_e$ profile as measured during this period, fits surprisingly well to a simple hyperbolic tangent in altitude:

$$T_e = \frac{T_H + T_L}{2} + \frac{T_H - T_L}{2} \tanh \left( \frac{z - Z_0}{H_0} \right)$$

While there is no theoretical justification for this functional form, the parameters are useful to describe the $T_e$ profile. $T_L$ (0.044 eV; 510°K) represents the asymptotic value of $T_e$ at the lowest altitudes, $T_H$ (0.271 eV; 3140°K) is the high-altitude asymptotic value of $T_e$, $Z_0$ (241 km) is the altitude of the most rapid change in $T_e$, and $H_0$ (60 km) is the scale height of the rapid change. Figure 4 displays the mean values of $T_e$ as a function of altitude (identical to those in Figure 3) and the fit.

The measured $T_e$ profile is suggestive of plasma heating in the topside ionosphere [e.g., Ergun et al., 2006; Andersson et al., 2010]. Plasma waves and fluctuations from the solar wind boundaries appear to be absorbed as they propagate toward the lower ionosphere, heating the topside of the ionosphere but having relatively little effect below ~150 km. The value of $T_H$ is such that the ambipolar electric field, needed to retain the electron population, could result in a potential on the order of 1 V (3 to 4 times $T_H$). This potential alone supplies nearly one half of the escape energy needed for O$^+$ and a forth of that needed for O$_2^+$. A reinvestigation of the Mars ionosphere in the light of new data should prove interesting.

6. Conclusions

We report in situ measurements of $n_e$ and $T_e$ from the LPW during the MAVEN deep dip campaign from 15 April 2015 to 22 April 2015. At the lowest altitudes, MAVEN was within ~15° solar zenith angle during the campaign. The $n_e$ altitude profiles show a slightly higher than expected M2 peak $n_e$. Given the measurement uncertainties, possible seasonal variation, magnetic fields, and solar output are not accounted for; we find that MAVEN primarily confirms the peak $n_e$ and the location of the peak $n_e$ in models and in previous observations. The MAVEN LPW reports a Chapman scale height of 12.6 km ± 1 km during this 6 day period. The MAVEN LPW instrument presented the first in situ measurements of $T_e$ at low solar zenith angles. We find that $T_e$ rises with altitude from ~0.052 eV (~0.026 eV, +0.008 eV) at 130 km in altitude to 0.084 eV (~0.017 eV, +0.010 eV) at 200 km. From ~180 km in altitude to ~300 km in altitude, $T_e$ rapidly rises to 0.239 eV (~0.042 eV, +0.027 eV) at 300 km. The $T_e$ profile fits well to a hyperbolic tangent, which may be useful to modeling. Above 300 km, $T_e$ is highly variable both within a single pass (~24 min) and from orbit to orbit (~4 h). It is not known at the time of this writing if the $T_e$ variation within an orbit is due to horizontal motion of the MAVEN spacecraft, if it reflects $T_e$ variation in altitude or if it is temporal variation. Future work includes careful examination and modeling of the LPW sensor response to reduce the uncertainty in these observations.

References


Andersson, L., R. E. Ergun, and A. I. F. Stewart (2010), The combined atmospheric photochemistry and ion tracing code: Reproducing the Martian upper atmosphere in the light of new data should prove interesting.


