AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2017GL075367

Key Points:

- MAVEN Langmuir Probe and Waves (LPW) measurements are used to study the effects of crustal magnetic fields on electron densities and temperatures
- Regions of strong crustal magnetic field feature higher electron densities and lower electron temperatures than noncrustal field regions
- Neutral densities and temperatures are not significantly affected

Correspondence to:
P. Withers,
withers@bu.edu

Citation:
Flynn, C. L., Vogt, M. F., Withers, P., Andersson, L., England, S., & Liu, G. (2017). MAVEN observations of the effects of crustal magnetic fields on electron density and temperature in the Martian dayside ionosphere. *Geophysical Research: Letters*, *44*. https://doi.org/10.1002/2017GL075367

Received 18 AUG 2017
Accepted 20 OCT 2017
Accepted article online 26 OCT 2017

MAVEN Observations of the Effects of Crustal Magnetic Fields on Electron Density and Temperature in the Martian Dayside Ionosphere

Casey L. Flynn[1], Marissa F. Vogt[2], Paul Withers[1,2], Laila Andersson[3], Scott England[4], and Guiping Liu[5]

[1]Department of Astronomy, Boston University, Boston, MA, USA, [2]Center for Space Physics, Boston University, Boston, MA, USA, [3]Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO, USA, [4]Department of Aerospace and Ocean Engineering, Virginia Tech, Blacksburg, VA, USA, [5]Space Sciences Laboratory, University of California Berkeley, Berkeley, CA, USA

Abstract Mars lacks a global magnetic field but possesses concentrated regions of crustal magnetic field that influence the planet's interaction with the solar wind and the structure of the Martian ionosphere. In this study we survey 17 months of MAVEN Langmuir Probe and Waves dayside electron density and temperature measurements to study how these quantities are affected in regions with strong crustal magnetic fields. Above 200 km altitude, we find that regions of strong crustal magnetic fields feature cooler electron temperatures and enhanced electron densities compared to regions with little or no crustal magnetic field. Neutral densities and temperatures are not significantly affected. Closed field lines on which electrons can be trapped are more prevalent in strong crustal field regions than elsewhere. Trapped on closed field lines, electrons are protected against loss processes involving the solar wind. This would lead to longer plasma lifetimes, higher densities, and lower temperatures.

1. Introduction

At Earth, the planet's strong, global-scale, dipolar magnetic field plays a major role in influencing the interaction of the planet with the surrounding space environment (e.g., Cravens, 2004; Gurnett & Bhattacharjee, 2005; Kivelson & Russell, 1995). Moreover, Earth's magnetic field strongly affects ionospheric processes and properties (e.g., Kelley, 1989; Schunk & Nagy, 2009). Is the same true at Mars, which has a very different magnetic environment?

Mars is unique among the solar system's planets: it lacks a global intrinsic magnetic field but possesses concentrated regions of strong crustal magnetic field. The crustal magnetic fields are primarily radial in direction, have magnitudes up to several hundred nanotesla (nT) at 400 km altitude, and are strongest at southern latitudes and longitudes ~140°E–240°E (Brain et al., 2003; Connerney et al., 2001).

The question of how Mars's unique magnetic field affects the planet's interaction with the space environment is important for the disciplines of planetary science and plasma science. In planetary science, this interaction affects the present-day behavior of the atmosphere-ionosphere-magnetosphere system. It also affects the climate of Mars by its long-term effects on escape processes. In plasma science, Mars offers a unique laboratory for probing conditions not found elsewhere in the solar system, such as variations in magnetic field strength, direction, and connectedness to the solar wind on small length scales.

Previous work has established that Mars' crustal magnetic fields, although spatially restricted, do have significant effects on the planet's interaction with the solar wind (e.g., Edberg et al., 2008; Mitchell et al., 2001).

It is also clear that Mars' crustal magnetic fields have important effects on the structure of the Martian ionosphere (e.g., Gurnett et al., 2008; Withers et al., 2005). The presence of strong crustal magnetic fields can influence the ionospheric electron density on regional scales. The ionosphere of Mars is summarized in Withers (2009). The key aspects for this paper are that dayside conditions are dominated by photoionization and associated chemical processes below ~200 km, while transport processes are significant above ~200 km. Andrews, Andersson, et al. (2015) compared dayside electron densities above 300 km measured by Mars Express to an empirical model of the Martian ionosphere and found that the measured values exceeded the model predictions in regions of strongest crustal fields. The magnetic field orientation and topology can influence the local electron density. Nielsen et al. (2007) reported enhanced peak electron densities in magnetic cusps or regions of strongly vertical magnetic field that are likely connected to the solar wind. However, the large-scale effects of crustal magnetic fields on ionospheric conditions have not been fully characterized by previous work.

The purpose of this paper is to report on the influence of crustal fields on electron densities and temperatures in the dayside Martian ionosphere as observed by NASA's Mars Atmospheric and Volatile EvolutioN (MAVEN) mission. MAVEN entered Mars orbit in September 2014 and provides the best opportunity to date for studying the effects of crustal magnetic fields on the Martian ionosphere. The spacecraft is equipped with a Langmuir Probes and Waves (LPW) instrument (Andersson et al., 2015) that provides electron density measurements over a larger altitude range than was possible with Mars Global Surveyor or Mars Express radio occultations. LPW also provides the first electron temperature measurements in the Martian ionosphere since the single profile measured by the Viking landers (Hanson & Mantas, 1988).

An initial survey of MAVEN data showed that regions of strong crustal fields have increased electron densities compared to surrounding regions (Andrews, Edberg, et al., 2015). Here we expand on that study by adding roughly one Earth year of additional electron density data, considering dependence on altitude, and also examining the effects of crustal fields on the electron temperature.

This paper is organized as follows. Section 2 presents the MAVEN observations used in this study and an analysis of how the electron density and temperature are affected by strong crustal magnetic fields. Section 3 discusses the implications of our findings and possible mechanisms to explain the influence of crustal fields on the ionospheric density and temperature. Section 4 summarizes the findings of this project.

2. Observations

MAVEN is located in a 4.5 h elliptical orbit around Mars, with periapsis typically at ~150 km, apoapsis at ~6,200 km, and a 75° inclination (Jakosky et al., 2015). We have surveyed MAVEN LPW measurements of electron density and temperature from October 2014 through the end of April 2016. This interval includes four "deep dips" in which the spacecraft orbital periapsis was lowered to ~120–130 km for about a week. The interval also covers most of a Mars year, starting in northern fall (L_s ~206°) and going through northern late summer (L_s ~145°). We have restricted our analysis to data assessed by the LPW team to be suitable for scientific interpretation and to solar zenith angles less than 90° because the dayside and nightside ionospheres are controlled by different physical processes (e.g., Withers, 2009). We shall examine the effects of crustal magnetic field using maps of how dayside electron density and temperature vary with areographic latitude and longitude (defined positive eastward throughout).

Figure 1 shows how the median LPW electron density and temperature vary with areographic latitude and longitude at three different altitude ranges: 180–200 km, 240–260 km, and 300–320 km. The conclusions of this work are the same whether considering the median or mean electron density or temperature. In each panel the color of each 10° latitude by 10° longitude bin indicates the median electron density or electron temperature in each bin. Contours of crustal magnetic field as predicted by the Cain et al. (2003) model are overplotted in each panel and show that regions of strongest crustal magnetic fields are largely confined to southern latitudes, particularly at longitudes ~140°–240°. Each 10° latitude by 10° longitude bin in Figure 1 typically contains at least 50 data points at altitudes above 300 km and more than 100 data points per bin at altitudes below 200 km.

Inspection of Figure 1 leads to two immediate impressions. First, there are substantial differences between observed conditions in the northern and southern hemispheres. Second, observed conditions at high altitudes, southern latitudes, and longitudes near 180° are noticeably different from observed conditions at the same altitudes and latitudes but different longitudes.

The first impression, hemispheric asymmetry, is not significant for this work. The hemispheric asymmetry that is visible is simply caused by variations in the Mars-Sun distance and solar zenith angle between northern and southern observations. We do not discuss these further in this work.

The second impression, variations in ionospheric conditions with longitude, is the focus of this work. The Mars-Sun distance, season, and the latitude, local time, solar zenith angle of MAVEN's periapsis change

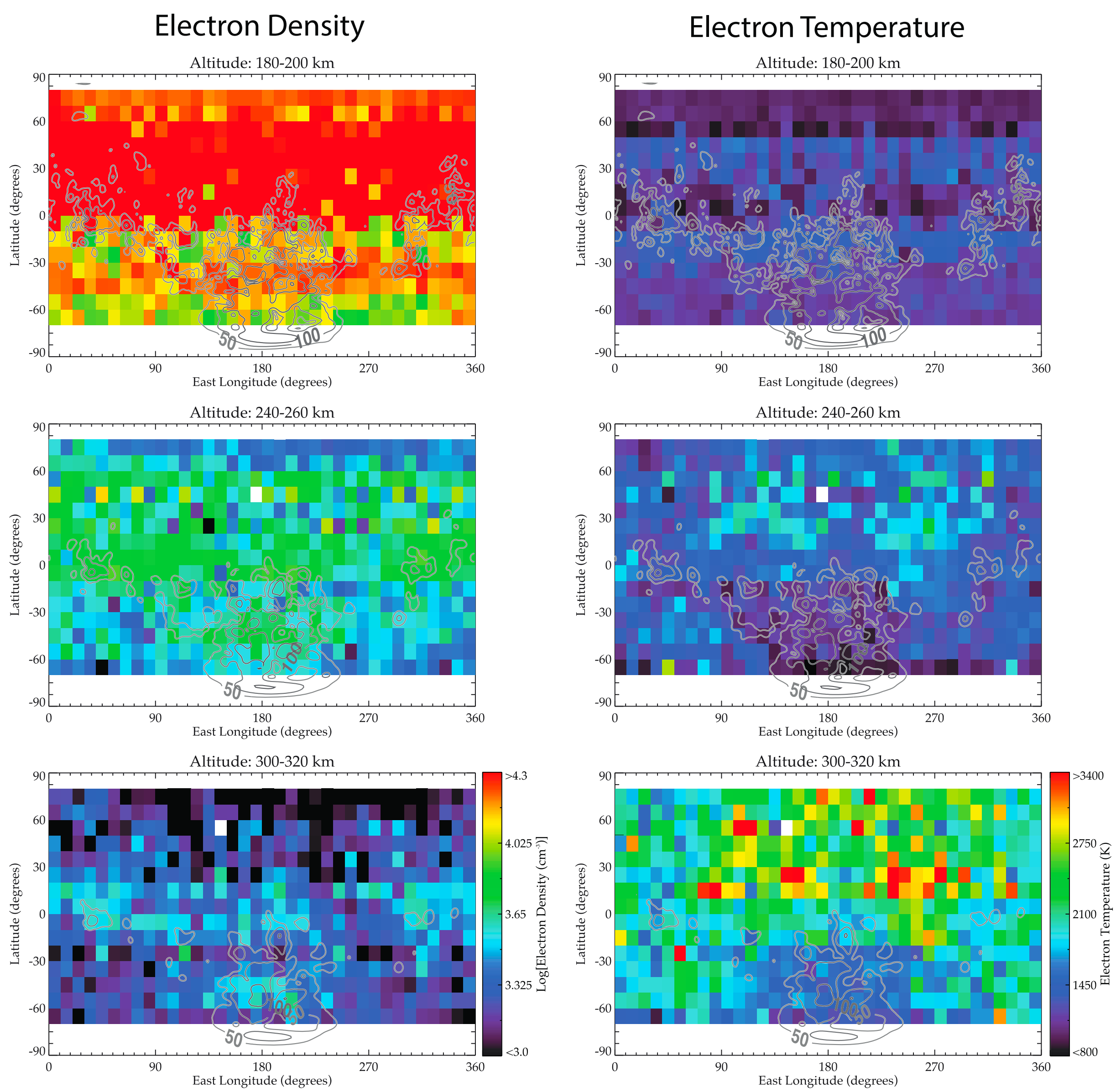

Figure 1. MAVEN LPW (left column) electron density and(right column) temperature as a function of areographic latitude and longitude, plotted for three different altitude ranges. The color indicates the median (left) electron density or (right) electron temperature in each 10° latitude by 10° longitude bin. The white bins indicate those with fewer than five available data points. The contours of the Cain et al. (2003) model for magnetic field magnitude 50, 100, and 200 nT, evaluated in the middle of each altitude range (e.g., at 190 km for the 180–200 km altitude), are overplotted in gray.

slowly and systematically between successive orbits. Longitude, on the other hand, changes appreciably between successive orbits. Differences in ionospheric conditions at two different longitudes and the same latitude cannot be caused by changes in Mars-Sun distance, season, latitude, local time, or solar zenith angle. Only factors fixed with respect to the solid body of Mars can do so—such as crustal magnetic fields.

Temporal variations in solar forcing, such as the solar ionizing flux or external solar wind conditions, could, in principle, cause variations in ionospheric conditions with longitude. However, any such temporal variations in solar forcing are unlikely to occur with a periodicity commensurate with the periodicity of MAVEN's longitudinal sampling. MAVEN completes approximately five orbits in each Martian day (sol). Occasional extreme solar events, such as solar flares, which occur on timescales of minutes to hours, could perhaps create longitudinal structure in observed ionospheric conditions. Since the MAVEN observations come from a very weak solar cycle with few solar flares, we deem this unlikely (e.g., Thiemann et al., 2017). We conclude that variations with longitude in this set of ionospheric observations cannot be caused by external factors.

Figure 1 shows that the electron density and temperature are largely unaffected by the presence or absence of strong crustal magnetic fields at low altitudes (180–200 km panel). At higher altitudes (240–260 km and 300–320 km) the strong crustal magnetic field regions feature larger electron densities and smaller electron temperatures than the surrounding regions. This is most noticeable in the largest region of strong crustal fields, located at southern latitudes and longitudes ~140°–240°, but is also noticeable in the more equatorial crustal field regions (e.g., latitudes ±~15°, longitudes ~10–50°, and ~300–360°). At these higher altitudes, the electron density increases by ~25–30% and the electron temperature decreases by ~10–15% in regions of strong crustal fields compared to other regions. For example, we can compare the electron density and temperature at 240–260 km altitude in a region of weak crustal field, southern latitudes between $-30°$ and $-60°$, and longitudes 0–140°, to the electron density and temperature in the nearby region of strong crustal field, southern latitudes between $-30°$ and $-60°$, and longitudes 140–240°. In this weak crustal field region the electron density is typically ~3.5–3.6 × 10^3 cm^{-3} compared to ~4.4 × 10^3 cm^{-3} in the strong crustal field region, while the electron temperature is typically ~1,750 K in the weak crustal field region compared to ~1,950 K in the strong crustal field region.

Next, we focus on the southern hemisphere only and consider how the electron density and temperature change with longitude. This approach allows us to continue to examine the effects of crustal fields on the ionosphere, since the regions of strongest crustal fields are located in the southern hemisphere and the crustal fields not only are most longitudinally constrained in the southern hemisphere but also remove the observational bias and other factors that contribute to the north-south hemispheric asymmetry in both the electron density and electron temperature.

Figures 2a and 2b show how the electron density and temperature vary with altitude and longitude for latitudes poleward of 30°S. This latitude restriction highlights latitudes where the crustal magnetic fields are the most longitudinally restricted, though we note that expanding the analysis to data at all southern latitudes shows similar trends to those seen in Figure 2. Below ~200 km altitude both the electron density and temperature are uniform with longitude, while above ~200 km altitude, both quantities show a dependence on longitude. At a given altitude above ~200 km, the electron densities are increased and electron temperatures are decreased at longitudes ~110–250° compared to values for noncrustal field regions, as seen in Figure 1.

Figures 2c and 2d show how the median electron density and electron temperature in four different 20 km altitude bins vary with longitude poleward of 30°S. At 160–180 km altitude (black line) the electron density and temperature are independent of longitude. As in Figures 2a and 2b, a longitudinal dependence is evident for both the electron density and temperature at higher altitudes. For example, in Figure 2c, at altitudes 320–340 km (red line), the median electron density increases from values of ~1.7 × 10^3 cm^{-3} in noncrustal field regions to ~2.0 × 10^3 cm^{-3} in the strong crustal field regions at longitudes 110–250°. In Figure 2d, at altitudes 320–340 km (red line), the median electron temperature decreases from values of ~2,400 K in noncrustal field regions to ~2,100 K in the strong crustal field regions at longitudes 110–250°.

Upper and lower quartiles are shown for data from 160–180 km and 220–240 km. The median value for all longitudes is generally within those quartiles, so the statistical significance of the putative variations with longitude is not immediately clear. Further inspection, however, of the data at 220–240 km shows that the 24 of the 26 median values of electron density in 5° longitude bins between 120° and 250° are greater than the zonal average. Such a high proportion of observed values exceeding the median is extremely unlikely to have occurred by chance. By contrast, 10 of the 26 median values at 160–180 km exceed the zonal average, close to the half expected when longitude has no effect on electron density. Similarly, 1 of 26 electron temperature values exceeds the zonal average at 220–240 km.

Based on Figure 2, we conclude that the longitudinal dependence of dayside electron density and electron temperature at high altitudes and southern latitudes is due to the presence of strong crustal magnetic fields at longitudes ~110–250°.

In Figure 3 we present median altitude profiles of the electron density and temperature in the southern hemisphere for five different longitude regions. Electron density and temperature measurements are typically presented as altitude profiles, so it is interesting to compare median profiles in strong crustal field regions to profiles from regions without strong crustal fields. The two green lines represent longitudes with strong

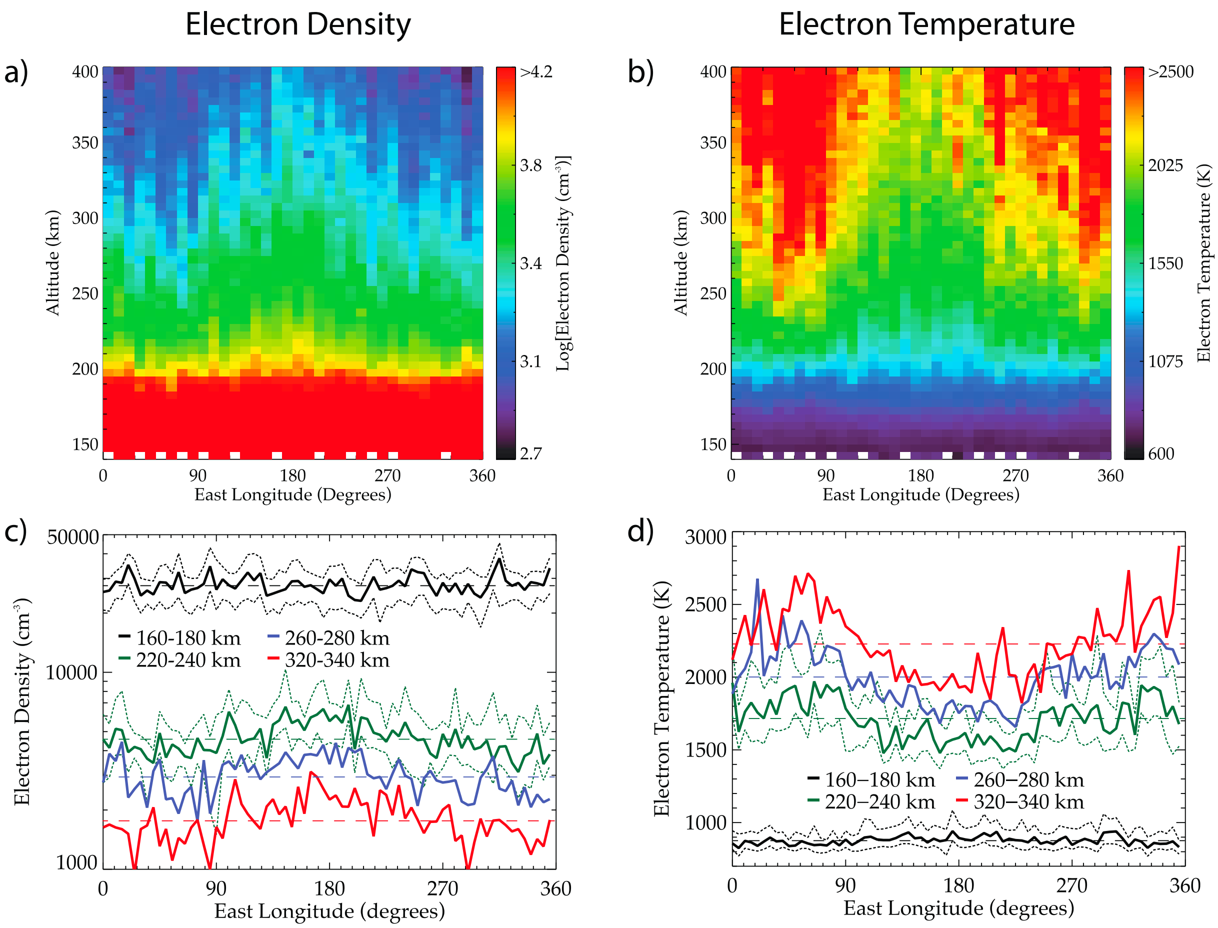

Figure 2. (a) MAVEN LPW electron density measurements as a function of altitude and longitude from latitudes poleward of 30°S and solar zenith angles less than 90°. The color indicates the median electron density in each 5 km altitude by 10° longitude bin. The white bins indicate those with fewer than five available measurements. (b) As in Figure 2a but for electron temperature. (c) Median MAVEN LPW electron density as a function of longitude, calculated using data from latitudes poleward of 30°S and solar zenith angles less than 90° at four different altitude ranges: 160–180 km (black), 220–240 km (green), 260–280 km (blue), and 320–340 km (red). The black dashed horizontal line shows the median value of all densities at 160–180 km, and so on for other altitude ranges. The two dotted black (green) lines show lower and upper quartiles for 160–180 km (220–240 km). (d) As in Figure 2c but for electron temperature.

crustal magnetic fields (160–180° in dark green, 180–200° in light green), while the other colored lines represent longitudes without crustal fields. Each point in this figure below (above) 380 km is the median of over 200 (over 100) measurements.

For both the electron density and temperature the green crustal field-influenced profiles diverge from the other three profiles at altitudes ~200 km. The electron density in the green crustal field-influenced profiles is ~30% larger than in the noncrustal field profiles at ~200–250 km altitude, ~40% larger at ~250–350 km altitude, and ~50–60% larger at ~350–500 km altitude. The electron temperature in the green crustal field-influenced profiles is ~95% of the electron temperature in the noncrustal field profiles at ~200–250 km altitude, ~90% at ~250–320 km altitude, and ~85% at ~320–500 km altitude. This represents a temperature difference of ~250 K at ~250–320 km altitude and ~450 K above 320 km altitude.

Upper and lower quartiles are shown for data at 60°–80° (weak crustal fields) and 160°–180° (strong crustal fields). Median electron densities in the strong crustal field region are not generally larger than the upper quartile densities in the weak crustal field region, so the statistical significance of the putative variations with longitude is not immediately clear. Further inspection, however, of the data shows that each of the 60 median electron density values reported at 5 km intervals between 200 km and 500 km is greater for the strong crustal field longitudes than for the weak crustal field longitudes. That is extremely unlikely to have occurred by chance. Similar trends are seen for electron temperature.

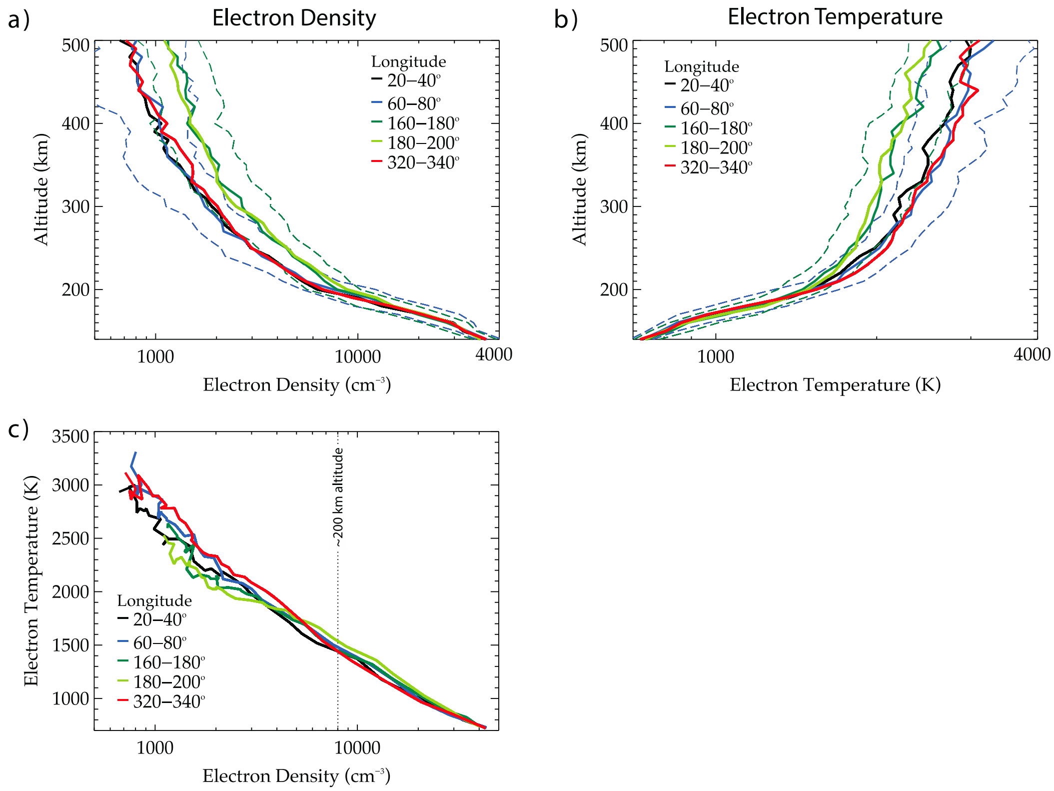

Figure 3. (a) Median MAVEN LPW electron density altitude profiles, calculated using data from latitudes poleward of 30°S and solar zenith angles less than 90°, and five different longitude ranges: 20–40° (black), 60–80° (blue), 160–180° (dark green), 180–200° (light green), and 320–340° (red). The dashed lines show upper and lower quartiles for data at 60°–80° (weak crustal fields) and 160°–180° (strong crustal fields). (b) As in Figure 3a but for electron temperature. (c) Electron temperature profiles from Figure 3b as a function of electron density profiles from Figure 3a.

Figure 3c shows electron temperature as a function of electron density for the five sets of results shown as vertical profiles in Figures 3a and 3b. Strikingly, the five profiles are very similar. The two profiles from strong crustal field regions do not appear different from the other three profiles in this representation.

Overall, Figures 1–3 show that above 200 km altitude in the dayside Martian ionosphere, regions of strong crustal magnetic fields feature larger electron densities and colder electron temperatures than regions without crustal magnetic fields. The influence of the crustal fields on both density and temperature increases with altitude, but between ~200 and ~400 km altitude, the presence of strong crustal fields typically increases the electron density by ~30% from values in noncrustal field regions and decreases the electron temperature by ~10–15% from values in noncrustal field regions, or about ~250–450 K.

3. Discussion

Our survey of dayside MAVEN LPW data shows how the electron density and temperature changes in regions of strong crustal fields, which provides useful information for determining the processes by which crustal fields influence the structure of the dayside Martian ionosphere. The key finding is that electron densities are larger but electron temperatures are smaller, in regions of strong crustal field than in regions of weak crustal field.

Our findings for electron density are consistent with the results of previous work. For example, using Mars Express MARSIS AIS measurements, Andrews, Andersson, et al. (2015) reported that the dayside electron density at altitudes 350–400 km was ~40% larger in regions of strong crustal magnetic fields compared to average values. Similarly, we found that the green crustal field-influenced median profiles in Figure 3 are ~50% larger than noncrustal field profiles at altitudes 350–400 km.

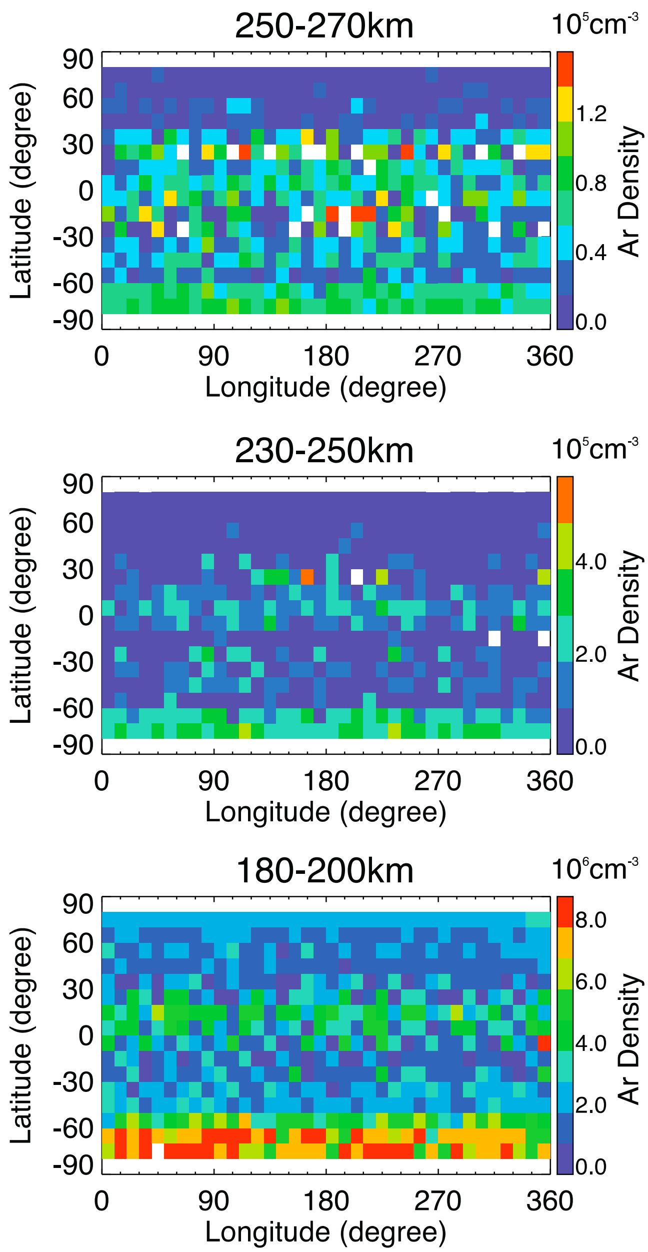

Figure 4. MAVEN NGIMS Ar number density as a function of areographic latitude and longitude, plotted for three different altitude ranges. Bin sizes are 10° in both latitude and longitude. The data span from February 2015 to October 2016.

Our most significant result concerns the influence of crustal fields on the electron temperature, as MAVEN's electron temperature measurements are the first since Viking's single vertical profile. This work shows that Mars's crustal magnetic fields affect its ionospheric electron temperature. We found that regions of strong crustal magnetic field feature electron temperatures that are ~10–15%, or ~250–400 K, cooler than regions without strong crustal fields at altitudes between ~200 and ~400 km.

One hypothesis for the observations presented in this work is that ionospheric properties, including density and temperature, track fixed pressure levels. This hypothesis is suggested by Figure 3c, which shows that electron temperature is fixed with respect to electron density regardless of crustal magnetic field strength. This hypothesis is reasonable at low altitudes, where the ionosphere is photochemically controlled (Bougher et al., 2001), but questionable at high altitudes, where transport plays a significant role. Nevertheless, if that supposition were true, then the longitudinal variations in ionospheric properties could simply be a consequence of longitudinal variations in the neutral atmosphere associated with crustal magnetic fields. To test this hypothesis, we examined MAVEN Neutral Gas and Ion Mass Spectrometer (NGIMS, Mahaffy et al., 2015) data from a period that overlaps the period from which LPW data were selected. Figure 4 shows the number density of neutral argon in a format equivalent to the display of electron density and temperature in Figure 1. In order to reach the highest altitudes possible, the inert species argon is selected as it is the species whose density is measured most reliably by NGIMS. As in Figure 1, the variations with latitude that are visible in Figure 4 are caused by variations in periapsis latitude, the Mars-Sun distance, and solar zenith angle over the observing period. Our interest is in whether the neutral measurements show longitudinal variations similar to those displayed by the plasma measurements. They do not, so the hypothesis is not supported. Electron temperature is fixed with respect to electron density in these observations, but these ionospheric properties are not fixed with respect to neutral density.

To interpret the finding that regions of strong crustal field feature larger electron densities and smaller electron temperatures than regions of weak crustal field, we consider two idealized end-member scenarios.

First, in photochemically controlled regions like the lower ionosphere, if the electron temperature is isothermal, electron densities decrease exponentially with altitude with a plasma scale height that is twice the neutral scale height (e.g., Withers, 2009, and references therein). This behavior is modified if the electron temperature is not isothermal, because the electron temperature controls the main plasma loss process, the dissociative recombination of the dominant O_2^+ ion species. The dissociative recombination coefficient for O_2^+ is proportional to $T_e^{-0.7}$ (Schunk & Nagy, 2009) so that the electron density is proportional to $T_e^{0.35}$, where T_e is the electron temperature (e.g., Withers, 2009, and references therein). Higher electron temperatures should be associated with higher electron densities.

Second, in transport-controlled regions like the high-altitude ionosphere, electron temperature may also affect electron densities. Hotter electron temperatures create larger pressure gradients, which lead to larger electron densities at high altitude as plasma flows upward more strongly. In the idealized case of diffusive equilibrium, the plasma scale height H_p is proportional to the sum of the ion and electron temperatures. Since the electron temperature is much greater than the ion temperature (Schunk & Nagy, 2009), the plasma scale height is effectively proportional to the electron temperature. Again, higher electron temperatures should be associated with higher electron densities.

Thus, changes in electron temperature may significantly and directly affect electron density. So if the crustal magnetic fields somehow change electron temperatures, then they will also change electron densities. However, in both these idealized end-member scenarios, higher electron temperatures are associated with higher electron densities. In the observations, higher electron temperatures are associated with low electron densities. It appears that processes associated with the crustal magnetic fields are directly affecting both the densities and temperatures of ionospheric electrons.

What processes could explain the observed changes in the electron density and electron temperature in regions of strong crustal field? Models and data suggest that the transition between the low-altitude photochemically controlled region and the high-altitude transport controlled region in the Martian ionosphere occurs at ~200 km altitude (Barth et al., 1992; Nagy & Cravens, 2002; Withers et al., 2012). The observation that ionospheric effects of strong crustal fields are noticeable only above ~200 km altitude on the dayside, along with the fact that the changes in electron density and temperature are inconsistent with photochemical equilibrium theory, suggests that the processes by which crustal magnetic fields influence the Martian ionosphere over spatially extended regions have minimal effect on photochemical production and loss processes in the dayside ionosphere. This conclusion does not necessarily apply to localized regions of cusp-like magnetic field.

In previous studies that reported enhanced electron densities at the ionospheric peak in cusp-like magnetic fields, Nielsen et al. (2007) and Gurnett et al. (2008) suggested that the electron density enhancement was due to plasma heating by either the two-stream plasma instability driven by the solar wind induced electric field or by solar wind electrons that can access the lower ionosphere along open magnetic field lines. This mechanism cannot explain the observations reported here, which concern higher altitudes and are not focused solely on cusp-like regions.

Andrews, Andersson, et al. (2015) suggested that the electron density increase observed in regions of strong crustal fields at altitudes 350–400 km is caused by changes to the magnetic field inclination, or the angle that a field line makes with respect to the planetary surface. The field is, on average, less horizontal in strong crustal field regions than elsewhere, which affects the vertical and horizontal transport of plasma. It is unclear whether this can explain the observed behavior of electron temperatures.

The ionospheric magnetic field lines in regions of strong crustal field may also have a different field topology, indicating whether one, neither, or both ends of a field line are rooted in the planet, compared to the magnetic field lines in the surrounding areas. Recent analysis by Xu et al. (2017) suggests that the magnetic fields at dayside altitudes where we have observed enhanced electron densities are most likely to be closed, or have both ends rooted in the planet, rather than having one or both ends open to the solar wind. They studied electron energy and pitch angle distributions measured by the MAVEN Solar Wind Electron Analyzer instrument from December 2014 through the beginning of May 2016, a similar interval to the one we have used here, and created 3-dimensional maps of how the magnetic topology varies with altitude and Mars latitude and longitude. They found that at altitudes between 200 and 400 km, the most common field line topology was closed (occurrence rate greater than 50%) but also that, at these altitudes, field lines were even more likely to be closed and less likely to be open in regions of strong crustal fields than in regions of weak crustal fields.

The enhanced electron densities in regions of strong crustal fields could then be explained by the fact that electrons in these regions are trapped on closed field lines, with relatively little loss to the solar wind compared to on open or draped field lines. Low electron temperatures in strong crustal field regions could perhaps be caused by the longer lifetime of plasma trapped on closed field lines. Electrons, when first generated, are hotter than neutrals and ions and therefore cool over time (e.g., Schunk & Nagy, 2009). This hypothesis predicts that ion temperatures are also relatively cool in regions of strong crustal field, which can be tested using data from the MAVEN SupraThermal and Thermal Ion Composition instrument (McFadden et al., 2015). Further work is necessary to test whether this hypothesis can explain the fixed density/temperature relationship illustrated by Figure 3c.

4. Conclusions

We have surveyed MAVEN LPW measurements of the electron density and temperature in the dayside Martian ionosphere and studied how these quantities change in response to the presence of strong crustal magnetic fields. Specifically, we have studied how the electron density and temperature vary with planetary latitude and longitude, which are excellent proxies for the spatially restricted crustal fields. We found that the presence of strong crustal fields has no effect on the electron density or temperature below 200 km altitude. Above 200 km altitude, areas with strong crustal fields feature enhanced electron density and cooler electron temperature than in surrounding regions. The effect of crustal fields on the electron density and temperature increases with increasing altitude, but it typically represents about a ~30% increase in the electron density and a ~10–15% decrease in the electron temperature, corresponding to ~250–400 K colder temperatures.

Our finding with respect to the electron density is consistent with previous studies that reported enhanced electron densities in magnetic cusps, as well as larger surveys that showed enhanced electron densities in regions of strong crustal fields at high altitudes. However, our finding that electron temperatures are coolest in regions of strong crustal fields is both new and surprising, since MAVEN provides the first electron temperature measurements in the Martian ionosphere since the single profile measured by the Viking lander and previous studies have attributed the increase in electron density near crustal fields to plasma heating.

The observed anticorrelation of electron densities and temperatures is not consistent with explanations based on idealized photochemical equilibrium, which is anyway unlikely to apply at the relevant altitudes, or idealized plasma diffusion. However, processes associated with plasma transport are favored by the fact that these effects of crustal fields are observed only above 200 km, which is the altitude at which plasma transport becomes significant. One possible explanation for the observations is that closed field lines on which electrons can be trapped are more prevalent in strong crustal field regions than elsewhere. Trapped on closed field lines, electrons are protected against loss processes involving the solar wind. This would lead to longer plasma lifetimes, higher densities, and lower temperatures.

Acknowledgments
C.F. acknowledges support from Boston University's Undergraduate Research Opportunities Program (UROP). M.V., P.W., and C.F. acknowledge support from NASA awards NNX13AO35G and 80NSSC17K0735. S.E and G.L acknowledge support from NASA award NNX16AJ42G. M.V. acknowledges helpful discussions with Kathryn Fallows and Zachary Girazian. The authors thank the MAVEN NGIMS team. MAVEN data are available via the Planetary Plasma Interactions node of NASA's Planetary Data System at https://pds-ppi.igpp.ucla.edu/.

References

Andersson, L., Ergun, R. E., Delory, G. T., Eriksson, A., Westfall, J., Reed, H., … Meyers, D. (2015). The Langmuir probe and waves (LPW) instrument for MAVEN. *Space Science Reviews*, *195*(1–4), 173–198. https://doi.org/10.1007/s11214-015-0194-3

Andrews, D. J., Andersson, L., Delory, G. T., Ergun, R. E., Eriksson, A. I., Fowler, C. M., … Jakosky, B. M. (2015). Ionospheric plasma density variations observed at Mars by MAVEN/LPW. *Geophysical Research Letters*, *42*, 8862–8869. https://doi.org/10.1002/2015GL065241

Andrews, D. J., Edberg, N. J. T., Eriksson, A. I., Gurnett, D. A., Morgan, D., Němec, F., & Opgenoorth, H. J. (2015). Control of the topside Martian ionosphere by crustal magnetic fields. *Journal of Geophysical Research: Space Physics*, *120*, 3042–3058. https://doi.org/10.1002/2014JA020703

Barth, C. A., Stewart, A. I. F., Bougher, S. W., Hunten, D. M., Bauer, S. J., & Nagy, A. F. (1992). Aeronomy of the current Martian atmosphere. In H. H. Kieffer, et al. (Eds.), *Mars* (pp. 1054–1089). Arizona: University of Arizona Press.

Bougher, S. W., Engel, S., Hinson, D. P., & Forbes, J. M. (2001). Mars Global Surveyor Radio Science electron density profiles: Neutral atmosphere implications. *Geophysical Research Letters*, *28*, 3091–3094. https://doi.org/10.1029/2001GL012884

Brain, D. A., Bagenal, F., Acuña, M. H., & Connerney, J. E. P. (2003). Martian magnetic morphology: Contributions from the solar wind and crust, *Journal of Geophysical Research*, *108*(A12), 1424. https://doi.org/10.1029/2002JA009482

Cain, J. C., Ferguson, B. B., & Mozzoni, D. (2003). An n = 90 internal potential function of the Martian crustal magnetic field, *Journal of Geophysical Research*, *108*(E2), 5008. https://doi.org/10.1029/2000JE001487

Connerney, J. E. P., Acuña, M. H., Wasilewski, P. J., Kletetschka, G., Ness, N. F., Rème, H., … Mitchell, D. L. (2001). The global magnetic field of Mars and implications for crustal evolution. *Geophysical Research Letters*, *28*, 4015–4018. https://doi.org/10.1029/2001GL013619

Cravens, T. E. (2004). *Physics of solar system plasmas*. New York: Cambridge University Press.

Edberg, N. J. T., Lester, M., Cowley, S. W. H., & Eriksson, A. I. (2008). Statistical analysis of the location of the Martian magnetic pileup boundary and bow shock and the influence of crustal magnetic fields. *Journal of Geophysical Research*, *113*, A08206. https://doi.org/10.1029/2008JA013096

Gurnett, D. A., & Bhattacharjee, A. (2005). *Introduction to plasma physics*. New York: Cambridge University Press. https://doi.org/10.1017/CBO9780511809125

Gurnett, D. A., Huff, R. L., Morgan, D. D., Persoon, A. M., Averkamp, T. F., Kirchner, D. L., … Picardi, G. (2008). An overview of radar soundings of the Martian ionosphere from the Mars Express spacecraft. *Advances in Space Research*, *41*(9), 1335–1346. https://doi.org/10.1016/j.asr.2007.01.062

Hanson, W. B., & Mantas, G. P. (1988). Viking electron temperature measurements: Evidence for a magnetic field in the Martian ionosphere. *Journal of Geophysical Research*, *93*, 7538–7544. https://doi.org/10.1029/JA093iA07p07538

Jakosky, B. M., Lin, R. P., Grebowsky, J. M., Luhmann, J. G., Mitchell, D. F., Beutelschies, G., … Zurek, R. (2015). The Mars Atmosphere and Volatile Evolution (MAVEN) mission. *Space Science Reviews*. https://doi.org/10.1007/s11214-015-0139-x

Kelley, M. (1989). *The Earth's ionosphere*. New York: Academic Press.

Kivelson, M. G., & Russell, C. T. (1995). *An introduction to space physics*. New York: Cambridge University Press.

Mahaffy, P. R., Benna, M., King, T., Harpold, D. N., Arvey, R., Barciniak, M., … Thomas Nolan, J. (2015). The neutral gas and ion mass spectrometer on the Mars Atmosphere and Volatile Evolution mission. *Space Science Reviews*, *195*, 49–73.

McFadden, J. P., Kortmann, O., Curtis, D., Dalton, G., Johnson, G., Abiad, R., … Jakosky, B. (2015). MAVEN SupraThermal and Thermal Ion Composition (STATIC) Instrument. *Space Science Reviews*, *195*, 199–256.

Mitchell, D. L., Lin, R. P., Mazelle, C., Rème, H., Cloutier, P. A., Connerney, J. E. P., … Ness, N. F. (2001). Probing Mars' crustal magnetic field and ionosphere with the MGS Electron Reflectometer. *Journal of Geophysical Research*, *106*, 23,419–23,427. https://doi.org/10.1029/2000JE001435

Nagy, A. F., & Cravens, T. E. (2002). Solar system ionospheres. In M. Mendillo, A. F. Nagy, & J. H. Waite (Eds.), *Atmospheres in the solar system: Comparative aeronomy* (pp. 39–54). Washington, DC: American Geophysical Union. https://doi.org/10.1029/130GM04

Nielsen, E., Fraenz, M., Zou, H., Wang, J.-S., Gurnett, D. A., Kirchner, D. L., … Lundin, R. (2007). Local plasma processes and enhanced electron densities in the lower ionosphere in magnetic cusp regions on Mars. *Planetary and Space Science*, *55*(14), 2164–2172. https://doi.org/10.1016/j.pss.2007.07.003

Schunk, R. W., & Nagy, A. F. (2009). *Ionospheres* (2nd ed.). New York: Cambridge University Press. https://doi.org/10.1017/CBO9780511635342

Thiemann, E. M. B., Chamberlin, P. C., Eparvier, F. G., Templeman, B., Woods, T. N., Bougher, S. W., & Jakosky, B. M. (2017). The MAVEN EUVM model of solar spectral irradiance variability at Mars: Algorithms and results. *Journal of Geophysical Research: Space Physics*, *122*, 2748–2767. https://doi.org/10.1002/2016JA023512

Withers, P. (2009). A review of observed variability in the dayside ionosphere of Mars. *Advances in Space Research*, *44*(3), 277–307. https://doi.org/10.1016/j.asr.2009.04.027

Withers, P., Fallows, K., Girazian, Z., Matta, M., Häusler, B., Hinson, D., … Witasse, O. (2012). A clear view of the multifaceted dayside ionosphere of Mars. *Geophysical Research Letters*, *39*, L18202. https://doi.org/10.1029/2012GL053193

Withers, P., Mendillo, M. J., Rishbeth, H., Hinson, D. P., & Arkani-Hamed, J. (2005). Ionospheric characteristics above Martian crustal magnetic anomalies. *Geophysical Research Letters*, *32*, L16204. https://doi.org/10.1029/2005GL023483

Xu, S., Mitchell, D., Liemohn, M., Fang, X., Ma, Y., Luhmann, J., … Jakosky, B. (2017). Martian low-altitude magnetic topology deduced from MAVEN/SWEA observations. *Journal of Geophysical Research: Space Physics*, *122*, 1831–1852. https://doi.org/10.1002/2016JA023467