The influence of magnetic field topology and orientation on the 1 distribution of thermal electrons in the Martian magnetotail 2

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Abstract

Thermal (<1 eV) electron density measurements, derived from the Mars Atmosphere and Volatile Evolution's (MAVEN) Langmuir Probe and Waves (LPW) instrument, are analyzed to produce the first statistical study of the thermal electron population in the Martian magnetotail. Coincident measurements of the local magnetic field are used to demonstrate that close to Mars, the thermal electron population is most likely to be observed at a cylindrical distance of ~1.1 Mars radii (Rm) from the central tail region during times when the magnetic field flares inward toward the central tail, compared to ~1.3 Rm during times when the magnetic field flares outward away from the central tail. Similar patterns are observed further down the magnetotail with greater variability. Thermal electron densities are highly variable throughout the magnetotail; average densities are typically ~20-50 /cc within the optical shadow of Mars and can peak at ~100 /cc just outside of the optical shadow. Standard deviations of 100% are observed for average densities measured throughout the tail. Analysis of the local magnetic field topology suggests that thermal electrons observed within the optical shadow are likely sourced from the dayside ionosphere. Finally, thermal electrons within the optical shadow of Mars are up to 20% more likely to be observed when the strongest crustal magnetic fields point sunward than when they point tailward.

The influence of magnetic field topology and orientation on the distribution of thermal electrons in the Martian magnetotail

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Key Points:

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11	•	The local magnetic topology and flaring direction play an important role in determin-
12		ing the thermal electron structure in the magnetotail
13	•	Thermal electrons are most likely to be observed just outside of the optical shadow in
14		the magnetotail, at peak likelihoods of $\sim 35\%$
15	•	The likelihood of observing thermal electrons does not appear to be influenced by the
16		location of the strongest crustal magnetic fields

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17 Abstract

Thermal (<1 eV) electron density measurements, derived from the Mars Atmosphere 18 and Volatile Evolution's (MAVEN) Langmuir Probe and Waves (LPW) instrument are ana-19 lyzed to produce the first statistical study of the thermal electron population in the Martian 20 magnetotail. Coincident measurements of the local magnetic field are used to demonstrate 21 that close to Mars, the thermal electron population is most likely to be observed at a cylindri-22 cal distance of ~1.1 Mars radii (R_M) from the central tail region during times when the mag-23 netic field flares inward, compared to ~1.3 R_M during times when the magnetic field flares 24 outward. Similar patterns are observed further down the magnetotail with greater variability. 25 Thermal electron densities are highly variable throughout the magnetotail; average densities 26 are typically \sim 20-50 cm⁻³ within the optical shadow of Mars and can peak at \sim 100 cm⁻³ just 27 outside of the optical shadow. Standard deviations of 100% are observed for average den-28 sities measured throughout the tail. Analysis of the local magnetic field topology suggests 29 that thermal electrons observed within the optical shadow of Mars are likely sourced from 30 the nightside ionosphere, whereas electrons observed just outside of the optical shadow are 31 likely sourced from the dayside ionosphere. Finally, the location of the strongest crustal mag-32 netic fields with respect to the Sun appears to only slightly affect the likelihood, location and 33 mean densities at which thermal electrons are observed in the magnetotail region. 34

35 **1 Introduction**

Mars lacks an intrinsic dipole magnetic field and the interaction between the planet's 36 atmosphere, ionosphere and extended exosphere results in the formation of a partially in-37 duced magnetosphere that acts to stand off and deflect the supersonic solar wind flow around 38 the planetary obstacle [Luhmann et al., 1991; Brain et al., 2003; Bertucci et al., 2011]. The 39 interplanetary magnetic field (IMF) drapes about the planet's dayside, leading to a forma-40 tion of a flared "wake" behind the planet, similar to Venus, comets, and other unmagnetized 41 bodies (e.g. Vaisberg and Smirnov 1986; Luhmann et al. 1991; Zakharov 1992; Israelevich 42 et al. 1994). Analysis of the structure and dynamics of the magnetotail region inform us of 43 the interaction between the planet and the supersonic solar wind. Planetary ions have also 44 been observed traveling tailward within the wake [Lundin and Dubinin, 1992], and thus un-45 derstanding magnetotail dynamics is essential to understanding the global structure of the 46 induced Martian magnetosphere and ion loss to space. 47

Early Mars orbiters, such as the Phobos spacecraft, demonstrated that the Martian tail is a two-lobe structure whose polarity and orientation depends on the upstream solar wind orientation [*Yeroshenko et al.*, 1990], similar to the Venusian magnetotail [*Vaisberg and Smirnov*, 1986]. Data from the Mariner 4, Mars 2, 3, 5, Phobos and Mars Global Surveyor (MGS) spacecraft missions show the shape and extent of the Martian magnetotail is highly variable (e.g. *Slavin et al.* 1991; *Vignes et al.* 2000), and the flaring angle of the tail depends on the upstream solar wind pressure [*Zhang et al.*, 1994].

Later spacecraft, including MGS, Mars Express (MEX) and the Mars Atmosphere and Volatile EvolutioN (MAVEN) mission, have enhanced these early observations, demonstrating that a current sheet separates both tail lobes, as expected for an induced magnetotail produced by the draping of the IMF about the dayside of the planet [*Ferguson et al.*, 2005].

Halekas et al. 2006 have also shown that MGS current sheet crossings at 400 km al-59 titude occur everywhere except over the strong Martian crustal magnetic fields, and such 60 crossings occur at locations that vary with Mars season and upstream IMF orientation. The 61 magnetotail region has been observed to be at times highly dynamic. Evidence of magnetic 62 reconnection occurring in the tail region has been reported using both MGS and MAVEN 63 data (e.g. DiBraccio et al. 2015; Halekas et al. 2009; Eastwood et al. 2012; Harada et al. 64 2015a), while the repetitive loading and unloading of magnetic flux in the magnetotail region 65 is akin to sub-storm activity within intrinsic magnetospheres (e.g. DiBraccio et al. 2015). 66

DiBraccio et al. 2018 also demonstrated that the magnetotail lobes typically exhibit a 45 67 degree twist relative to upstream IMF orientations, a characteristic thought to be strongly 68 influenced by dayside reconnection between the draped IMF and planetary crustal magnetic 69 fields. Xu et al. 2020 compared the tail topology determined from magnetohydrodynamic 70 simulations to that inferred from MAVEN data and how each topology responds to the up-71 stream IMF orientation. Their results support the hypothesis that magnetic reconnection be-72 tween crustal magnetic sources and the solar wind is responsible for the observed twist in 73 Mars's tail lobes. 74

Planetary ions have been observed in the magnetotail by multiple spacecraft, and have 75 been used to infer the existence of various plasma acceleration mechanisms and subsequent 76 plasma outflow from Mars. Ion data from the Analyzer of Space Plasmas and Energetic 77 Atoms (ASPERA) instruments on Phobos 2 and MEX show highly variable O⁺ fluxes, par-78 ticularly in the central tail region, and these fluxes are likely driven by a variety of ion accel-79 eration mechanisms; some of which are similar to those that exist in the terrestrial magne-80 totail [Lundin et al., 1989; Kallio et al., 1995; Lundin and Barabash, 2004; Fedorov et al., 81 2006; Lundin et al., 2008]. Magnetic field and suprathermal electron measurements from the MGS spacecraft show that detached magnetic structures intermittently exist in the Mar-83 tian tail region and contain planetary plasma. Such structures are thought to be caused by 84 the stretching of crustal magnetic fields via their interaction with the solar wind in the tail 85 region, until magnetic reconnection occurs, detaching part of the crustal field, which is then 86 convected down the tail region [Brain et al., 2010]. 87

Initial MAVEN estimates of planetary ion escape rates for ions with energies > 25 eV88 from Mars generally agree with earlier studies, demonstrating that tailward ion escape in 89 the magnetotail region can contribute significantly to the total escaping flux from the planet 90 [Brain et al., 2015]. MAVEN observations of enhanced ionospheric electron temperatures 91 above the exobase region suggest that ambi-polar electric fields can be an important ion ac-92 celeration mechanism at Mars, providing up to $\sim 1 \text{ eV}$ of energy to planetary ions [Xu et al., 93 2018a; Collinson et al., 2019; Akbari et al., 2019]. Such energy represents a significant 94 amount (~ 50% for O^+) of the total needed for these heavy ions to overcome Mars' relatively 95 weak gravitational potential and drive ion outflow on open magnetic field lines that connect 96 the ionosphere to the solar wind. Numerical simulations have explicitly shown that ion out-97 flow can be significantly enhanced by such ambi-polar electric fields at Mars [Ergun et al., 98 2016]. Magnetohydrodynamic (MHD) modelling of the Martian magnetosphere, for exam-99 ple, has shown that such field lines exist in abundance in the magneotail region [Ma et al., 100 2002, 2004; Fang et al., 2018]. 101

The instrument limitations and difficulties associated with observing low energy ions 102 at just above escape energy (a few eVs at Mars) mean that detailed studies of this low energy 103 ion escape component were not possible before the arrival of MAVEN at Mars [Inui et al., 104 2018]. MAVEN entered Mars orbit in September 2015 and carries two instruments capable 105 of measuring low energy thermal plasma: the SupraThermal And Thermal Ion Composi-106 tion (STATIC) instrument - an electrostatic top hat analyzer with time of flight capabilities 107 [McFadden et al., 2015]; and the Langmuir Probe and Waves (LPW) instrument - consisting 108 of two Langmuir Probes that perform current-voltage sweeps [Andersson et al., 2015]. This 109 study focuses on data from the LPW measurements, from which the local thermal (<1 eV) 110 electron density and temperature are derived. We provide, to our knowledge, the first statis-111 tical analysis of the thermal electron population in the Martian magnetotail. We demonstrate 112 that the location at which thermal electrons are observed within the magnetotail is highly de-113 pendent upon the orientation of the local magnetic field and whether it connects to the day or 114 night side ionosphere. Section 2 describes the dataset and analysis methods utilized in this 115 study; results are presented in Section 3 and discussed in 4. We conclude in Section 5. 116

117 2 Data and Methodology

2.1 Instruments

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The MAVEN spacecraft entered into an elliptical orbit about Mars in September 2014 119 [Jakosky et al., 2015]. The orbit precesses such that MAVEN samples all local times, longi-120 tudes, and latitudes. The rate of orbital precession results in coverage of the Martian magne-121 totail roughly every 3-4 months, for about one month each time. The data used in this study 122 are taken from such "tail seasons." Data from several instruments were utilized in this study. 123 These include the Langmuir Probe and Waves (LPW) [Andersson et al., 2015], Magnetome-124 ter (MAG) [Connerney et al., 2015], and Solar Wind Electron Analyzer (SWEA) [Mitchell 125 et al., 2016]. 126

LPW consists of two Langmuir probes, each mounted on the end of \sim 7m booms and 127 separated by an angular distance of 110 degrees. The instrument can operate as both a Lang-128 muir probe ("when in LP mode") or as an electric field instrument ("when in waves mode"). 129 During LP mode, the Langmuir Probes measure (alternating in time) the current-voltage 130 (I-V) characteristics of the local plasma environment. The density and temperature of lo-131 cal thermal (< 1eV) electrons and the spacecraft potential are derived from the I-V curve by 132 using an enhanced fitting method [Ergun et al., 2015]. During waves mode, the instrument 133 measures—as a time series— the potential difference between the two sensors, from which 134 electric field power spectra are derived [Andersson et al., 2015; Fowler et al., 2017]. Only 135 data obtained from LPW's LP mode were used in this study. 136

The LPW instrument is designed to measure thermal (<1 eV), high density (>1000's cm⁻³) dayside ionospheric plasma. However, there are times when the local thermal electron density is low (~< 15 cm⁻³) and the electron temperature is relatively high (approaching l eV or larger). During such conditions the LPW instrument is operating beyond its design specifications and at times may not be capable of measuring a significant current. The derived thermal electron density can subsequently be zero, and this limitation (during very low density conditions) should be kept in mind when interpreting the results of this study.

The local three-dimensional magnetic field vector is measured by the MAG instrument at a sampling rate of 32 Hz. The instrument consists of two fluxgate magnetometers which allow for hardware redundancy, calibration, and removal of the spacecraft generated magnetic fields. The magnetic field is measured to an accuracy of about 0.01 nT [*Connerney et al.*, 2015].

The SWEA instrument is an electrostatic top-hat analyzer that measures electron fluxes within the 3 eV to 5 keV energy range. The instrument has a field of view of $360^{\circ} \times 120^{\circ}$ provided by electrostatic deflectors and an energy resolution ($\Delta E/E$) of 17% [*Mitchell et al.*, 2016]. SWEA operates at a cadence of 2-4 seconds. As described in section 2.2, SWEA shape parameters were used to determine magnetic field topology.

In this study, the data were analyzed in the Mars Solar Orbital (MSO) coordinate system, where the x-axis points from Mars to the Sun, the y-axis is anti-parallel to Mars' instantaneous orbital velocity, and the z-axis completes the right-handed coordinate system.

2.2 Methodology

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The goal of this study is to investigate the effects of the local magnetic field topology on the spatial distribution of the thermal electron population in the Martian magnetotail. To this end, we analyze MAVEN data from periods when the spacecraft was present in the magnetotail region between 01-01-2015 to 12-31-2019.

Every LPW observation for which the I-V curve fitting technique detected a thermal electron density in the magnetotail was binned according to its observed location within the magnetotail region and the associated local magnetic field orientation and topology—this is

further described below. The magnetotail region was defined as all post-terminator locations 165 (X (MSO) < 0) with altitudes greater than 600 km. All LPW I-V sweep measurements were 166 then binned into two spatial regions of the tail—called regions X1 and X2—and separated by 167 their associated local magnetic field orientation and topology. Region X1 enclosed -1.5 R_M $< X < 0 R_M$ and region X2 enclosed $-3 R_M < X < -1.5 R_M$, where $R_M = 1$ Mars radius (3396) 169 km). Splitting the tail region into two regions provides the opportunity to observe the evo-170 lution of the spatial distribution of thermal plasma down the tail. However, spatial coverage 171 at this time in the MAVEN mission means the tail region could not be split into additional 172 regions while maintaining adequate sample numbers. 173

¹⁷⁴ Data were also analyzed with respect to the parameter ρ , the cylindrical distance of ¹⁷⁵ MAVEN from the center of the tail region, defined as $\rho = \sqrt{Y^2 + Z^2}$, in the MSO coordinate ¹⁷⁶ system. To first order, $\rho < 1$ lies within the planet's optical shadow and $\rho > 1$ lies outside the ¹⁷⁷ optical shadow (ignoring atmospheric effects). These constraints ensured MAVEN was sam-¹⁷⁸ pling the magnetotail region and not the nightside ionosphere, which is typically observed ¹⁷⁹ below altitudes of 600 km (e.g. *Fowler et al.* 2015). A cartoon diagram showing regions X1 ¹⁸⁰ and X2, and ρ is shown in Figure 1.

Two distinct datasets were utilized in this study. The first are dubbed "measurement 181 points" which represent all measurements made by LPW regardless of whether sufficiently 182 large currents were observed such that a density could be derived from the measured I-V 183 curve or not. The second, "derived data points," represent measurements from which densities were derivable, corresponding to times when the thermal electron density was larger 185 than ~ 15 cm⁻³. Dividing the number of derived data points by the number of measurement 186 points provides a percentage of how often a density can be derived from the measured I-V 187 curves. The 4-year-long dataset consisted of 10⁵ measurement points in the tail region. Of 188 these 10⁵ measurement points, ~ 6×10^4 are derived data points. Since LPW is sensitive 189 down to densities of a ~ 15 cm⁻³, we may lack measurements of the lowest densities. 190

Furthermore, each MAG and SWEA measurement were paired to a corresponding LPW measurement in time. Both MAG and SWEA operate at significantly faster cadences than LPW at high altitudes within the magnetotail region (128 s, compared to 2 s for SWEA and 32 s⁻¹ for MAG).

Suprathermal electron energies and pitch-angle distributions measured by SWEA allow 195 for the inference of magnetic topology based on three principles. First, the presence of a loss 196 cone in one or both field-aligned directions indicates a magnetic field line intersects the colli-197 sional atmosphere once or twice. Thus, the field line is considered open or closed (e.g. Brain 198 et al. 2007; Xu et al. 2018b; Weber et al. 2017). Second, ionospheric photoelectrons are ob-199 served in one or both field-aligned directions. This implies one or both footpoints of a field 200 line are embedded in the dayside ionosphere, corresponding to either open or closed field topology (e.g. Xu et al. 2017). Finally, strong depletion of suprathermal electron flux, called 202 "suprathermal electron voids," signifies closed field lines with both footpoints intersecting 203 the nightside ionosphere (e.g. Mitchell et al. 2001; Steckiewicz et al. 2015). Note, magnetic 204 topology or footpoint(s) of a field line is defined with respect to the suprathermal electron 205 exobase (~ 160 km, Xu et al. 2016). If none of the above is observed, then the field line is 206 draped. The methodology of identifying photoelectrons and loss cones through MAVEN 207 data are described in further detail in Xu et al. [2017] and Weber et al. [2017], respectively. 208 This study infers thermal electron origin (dayside versus nightside ionosphere) based on the 209 magnetic topology identification method described by [Xu et al., 2016, 2019]. 210

2.3 Example Data

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Example MAVEN data are shown as a time series in Figure 2. The time series data span a period of 6 hours, which includes two periapsis passes at ~15:00 and 19:30 UTC. These periapsis passes are located on the dayside of the planet and are characterized by typical peak electron densities $\leq 10^5$ cm⁻³ (Figure 2B). Apoapsis occurs just after 17:00 UTC in the magnetotail region. MAVEN crosses into the planet's optical shadow between 16:00
and 17:30, as enclosed by the two vertical solid blue lines. The effect of the optical shadow is
observed as a reduction of photoelectron-current in the LPW I-V sweeps (negative voltages,
panel A) and a reduction of SWEA suprathermal electron flux (due to negative spacecraft
potentials within the optical shadow, energies less than ~20 eV, panel D).

MAVEN crosses the magnetotail current sheet at about 17:00, as indicated by the change in sign of the magnetic field's B_X component (panel C) (e.g. *DiBraccio et al.* 2015). Thermal ionospheric electrons are observed in the magnetotail region, as shown in panel B. The vertical dashed green lines mark an altitude of 600 km, the minimum altitude above which data were analyzed in this study. At high altitudes, the LPW data are measured at lower time cadences. This results in fewer I-V sweeps and density measurements at higher altitudes, as shown in panels A and B.

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2.4 Removal of LPW Photoelectron signatures from LPW Densities

During LP operation mode, the Langmuir Probe sensor measures electrical current from a variety of sources, including thermal electrons, ions and photoelectrons emitted by 230 the sensor when in sunlight. In sunlit conditions, the photoelectron current emitted by the 231 LPW sensors can dominate the collected current, when the local thermal electron density 232 is small. This results in a "background" derived thermal electron density of $\sim 10 \text{ cm}^{-3}$. An 233 example of this background density influenced by photoelectrons is shown in Figure 3 (A). 234 The panel shows the number of LPW measurement points as functions of radial distance (ρ) 235 from the center of the tail and their respective derived densities. Radial distances less than 236 1 denote measurements made within Mars' optical shadow, while measurements made at radial distances greater than 1 are made in sunlight. Within the optical shadow region (ρ 238 <1), an "artificial cutoff" at densities below $10^{0.5}$ cm⁻³ demonstrates the lower measurement 239 limit of the LPW instrument, when photo electrons are not present. Outside of the optical 240 shadow ($\rho > 1$), there is a clear "background" of measured densities at $\sim 10 \text{ cm}^{-3}$, which are 241 a result of photoelectron currents dominating the collected current. The LPW instrument 242 team previously investigated such cases in detail (not shown here) and confirmed that the 243 photoelectron "background current" is equivalent to a density of about 10 cm^{-3} .

We correct the LPW thermal electron densities for this background photoelectron current before performing the analysis in Section 2.2. Derived densities measured in sunlight ($\rho > 1 R_M$) have 10 cm⁻³ subtracted from their derived values, and the results of this correction are shown in Figure 3 (B). The format is the same as for panel (A). For radial distances greater than 1, the transition to density values below 10 cm⁻³ is now much smoother, indicating that this background correction is successful.

251 3 Results

This study analyzes the spatial distribution of thermal electrons with respect to the flaring angle of the magnetic field and the magnetic field topology, in the magnetotail region. The flaring angle of the magnetic field was calculated based upon the relative angle between the local magnetic field vector and the anti-solar vector (-X) in the three-dimensional MSO coordinate system. The dashed red line and solid blue line in Figure 1 depict outward and inward flaring field, respectively (as projected onto the two-dimensional plane).

When combined with LPW density measurements, the flaring angle and topology provide insight into the origin of the electrons measured on the field line, i.e. the nightside vs the dayside ionosphere. This study utilizes three primary magnetic field orientations: closed, open and draped, as described in section 2.2.

In addition to the magnetic field topology in the tail region, the effect of the Martian crustal magnetic field (e.g. *Acuna et al.* 1999) on the distribution of the thermal electrons

in the tail was also investigated. The location of the region which contains the strongest 264 field (e.g. planetary longitudes of 180 degrees in the southern hemisphere - see Acuna et al. 265 1999) with respect to the tail was analyzed when the thermal electron population was ob-266 served. To achieve this, the planetary longitude at which the sub-solar point is located at each MAVEN data point was calculated. Sub-solar longitude values close to 0 degrees indicate 268 the strongest crustal fields are pointing sunward and sub-solar longitudes close to 180 de-269 grees indicate they are pointing tailward. Similarly, intermediate sub-solar longitude values 270 of 90 degrees and 270 degrees, signify the strongest crustal fields are located at dawn and 271 dusk, respectively. 272

Derived data points and measurement points were further binned based on sub-solar longitude into four sub-solar longitude bins $(0^{\circ} \pm 45^{\circ}, 90^{\circ} \pm 45^{\circ}, 180^{\circ} \pm 45^{\circ}$ and $270^{\circ} \pm 45^{\circ}$), corresponding to strong crustal fields located at midnight, dawn, noon, and dusk. This was done regardless of whether the measurements belong to region X1 or X2 to ensure adequate sampling statistics.

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3.1 Statistics and the Influence of the Magnetic Field Flaring Angle

3.1.1 Region X1: -1.5 < X < 0

The statistics of the data and measurement points in region X1 of this study are presented in Figure 4. Plotted against ρ , panel (A) shows the number of derived data points, panel (B) shows the number of measurement points, panel (C) shows the percent likelihood of observing a density, i.e. panel (A) divided by panel (B), and panel (D) shows the mean densities for times when densities are observed, i.e. panel (A). The solid blue line indicates an inward flaring field and the dashed red line indicates an outward flaring field.

²⁸⁶ LPW sampled the tail up to 10^4 times during the observed time interval, depending ²⁸⁷ on ρ , and the largest number of data points are made for $\rho > 1$. A significant number of de-²⁸⁸ rived data points are still observed in the central tail region (Figure 4A), and the likelihood of ²⁸⁹ LPW observing thermal electrons is roughly constant at ~ 30% for 0.5 < $\rho < 1$ (Figure 4C). ²⁹⁰ Thermal electrons are most likely to be observed near the optical shadow ($\rho ~ 1$), and this ²⁹¹ likelihood then decreases with increasing ρ .

Figure 4D shows mean electron density (when electrons are observed, i.e. Figure 4A) peaks at ~100 cm⁻³ just outside of the optical shadow, $\rho \sim 1.2$. Densities within the optical shadow ($\rho < 1$) are typically a few 10's to 50 cm⁻³. The error bars in panel (D) show the standard deviation of each bin's measurements; they demonstrate high measurement variability, with standard deviations of ~ 100% in most bins. Standard deviations were calculated by calculating the standard deviation of all the measurements in each ρ bin.

The red and blue lines in Figure 4 show that the magnetic field orientation does not significantly affect the likelihood of LPW observing electrons in region X1 (4C), nor does it affect the observed average densities in each bin (4D).

301 3.1.2 Region X2: -3 < X < -1.5

The statistics for region X2 are shown in Figure 5, which shows distinct differences to region X1. The likelihood of observing thermal electrons is roughly constant for $\rho < 1$, compared to a decreasing likelihood for $\rho < 0.5$ in region X1. Average densities are typically smaller in X2 than X1 (not exceeding ~30 cm⁻³ on average), and are roughly constant as ρ increases.

In general, a greater number measurement and derived data points occur when the field flares outward, suggesting that (as expected) the field tends to be in an outward flaring configuration more often than an inward one, particularly at greater distance down the tail (i.e. region X2). Within $\rho < 1$, densities are more likely to be observed when the magnetic field flares inward (blue line, Figure 5C), though this difference is small, $\sim 10\%$, between outward and inward flaring fields.

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3.2 The Influence of Magnetic Field Topology

Figures 6-7 show the likelihood of MAVEN observing thermal electrons as functions of the magnetic field flaring direction and magnetic topology. Note that the sum of all panels for a given ρ is less than one hundred percent because the SWEA analysis routine cannot always reliably determine the topology. These "unknown" topologies were excluded in this section of analysis.

319 3.2.1 Region X1: -1.5 < X < 0

The flaring direction and topology of the magnetic field influences the location where 320 thermal electrons are observed, as shown in Figure 6. Panels A-C show that thermal elec-321 trons on an outward flaring field are most likely to observed at the largest values of ρ , re-322 gardless of field topology. For inward pointing, open and closed field lines (panels A and B), 323 electrons are most likely observed at and just past the optical shadow ($\rho \sim 1-1.2$), observed at 324 a peak of 25% of the time. Electrons on open, inward pointing field lines are observed more frequently for $\rho < 1$ (panel 6A). Electrons are most consistently observed on outward draped field lines at the largest values of ρ (panel 6C), although they are also observed for a signifi-327 cant fraction of the time on an inward pointing, draped field for $\rho < 1$. 328

The magnetic field flaring angle and source region for observed thermal electrons (e.g. 329 day or nightside ionosphere) also strongly influence where such electrons are observed, as shown in Figure 7. Electrons observed on open field lines originating from the dayside iono-331 sphere (panel A) are most likely to be observed at $\rho > -1$, particularly when the field is flared 332 outward. In contrast, electrons sourced from the nightside ionosphere (panel B) are most 333 likely to be observed at ρ <1. Electrons observed on closed field lines (panel C) demonstrate 334 similar patterns to those on open field lines (panel A). Electrons on an inward pointing field 335 are most likely to be observed just past the optical shadow at $\rho = 1-1.2$, while electrons on an 336 outward flaring field are observed at equal likelihood for all large values of ρ . Electrons ob-337 served on closed field lines originating from the nightside ionosphere (panel D) show similar 338 behavior to panel B, albeit at much smaller likelihoods of observation. 339

340 3.2.2 Region X2: -3 < X < -1.5

Figure 8 demonstrates that the flaring direction of the magnetic field can significantly 341 influence where thermal electrons are observed on open field lines in region X2. Panel A 342 shows that electrons are observed with \sim 30-40% likelihood at ρ > \sim 0.8 when the field flares 343 outward, compared to a peak of $\sim 20\%$ at the center of the tail when the field flares inward. 344 Electrons are less likely to be observed on closed field lines in general in region X2 com-345 pared to X1 (Figure 8B versus 6B), which is perhaps not unexpected given that region X2 346 lies further downtail away from the closed crustal magnetic fields whose influences are stronger 347 closer to the planet. The presence of outward flared field in region X2 still leads to a greater 348 likelihood of observation at higher ρ . Electrons observed on draped field lines in region X2 349 (Figure 8C) are observed at similar likelihoods (as a function of ρ) to region X1 (Figure 6C). 350

Investigating the source regions for thermal electrons observed in region X2 further 351 demonstrates the clear impact that the magnetic field flaring direction has on the likelihood 352 of observing these electrons. Figure 9 A and B show that thermal electrons are more likely 353 to be observed at large ρ when the field flares outward, for field lines connected to the day or 354 nightside ionosphere. Inward field connected to the nightside ionosphere (panel B) clearly 355 influences where thermal electrons are likely to be observed, with electrons most likely to be 356 observed in the central tail region, similar to region X1. Figure 9C and D again show that 357 electrons are not often observed on closed field lines in region X2 (\sim <10% of the time). 358

³⁵⁹ When such conditions exist, electrons are more likely to be observed at larger ρ when on ³⁶⁰ outward flared field.

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3.3 The Influence of Strong Crustal Magnetic Fields

The influence of the location of the strongest crustal magnetic fields on the likelihood 362 of observing thermal electrons in the magnetotail is shown in Figure 10. For simplicity, we 363 define the strongest crustal fields simply as those located at 180 degrees planetary longitude 364 in the southern hemisphere (e.g. Acuna et al. 1999). Panel (A) shows the likelihood of LPW 365 observing thermal electrons, while panel (B) shows the mean densities observed; both as a 366 function of ρ . The green (yellow) line denotes when the strongest crustal fields are located at 367 a sub solar longitude of 0 (180) degrees - pointing sunward (tailward) on the day (night) side 368 of the planet. The gray lines denote sub solar longitudes of 90 or 270 degrees, i.e. dawn or 369 dusk. Data are combined for regions X1 and X2 to ensure adequate sampling statistics. 370

The location of the strongest crustal fields does not appear to drastically alter the loca-371 tion, likelihood nor mean densities at which thermal electrons are observed in the magneto-372 tail. Panel (A) shows that for all crustal field locations, thermal electrons are most likely to 373 be observed just outside of the optical shadow, for ρ between $\sim 1R_M$ and $1.3R_M$. The panel 374 shows that when the strongest crustal fields are located on the dayside (green line), electrons 375 are observed at slightly greater likelihoods outside of the optical shadow (ρ >1), but con-376 versely at lesser likelihoods for $\rho < 1$. These differences in likelihood are however small, usu-377 ally less than 5%. The average thermal electron densities observed as a function of ρ (panel 378 B) are also similar for each crustal field location. Large variations are again observed within 379 each bin, similar to Figures 4D and 5D.

381 4 Discussion

The LPW observations analyzed in this study show that thermal electrons are observed 382 with relatively high frequency in the magnetotail region of Mars: with typical likelihoods of 383 $\sim 40\%$ in region X1 close to Mars, and likelihoods of $\sim 20\%$ further down the tail in region X2. These thermal electrons originate from the planetary ionosphere, and their presence in the magnetotail is suggestive that they may be contributing to ionospheric escape. The like-386 lihood of LPW observing thermal electrons within the Martian magnetotail varies as a func-387 tion of both distance down the tail, and cylindrical distance from the center of tail. Figure 4 388 shows that closer to the planet in region X1, thermal electrons are most likely to be observed 389 just outside of the optical shadow, at ρ values $\sim 1R_M - 1.3R_M$. Magnetic field topology in-390 formation in Figure 6 shows that electrons observed just past the optical shadow are equally 391 likely to be on open or closed magnetic field lines close to the planet. In contrast, thermal electrons are most likely to be observed inside of the optical shadow in region X2 ($\rho < 1$) 393 (Figure 5). 394

Within the optical shadow region (ρ values < 1), thermal electrons are observed at 395 roughly constant likelihood as a function of ρ for both tail regions, although thermal elec-396 trons are roughly twice as likely to be observed in region X1 compared to X2 (Figures 4 and 397 5). Additionally, electron densities are on average factors of \sim 2-5 larger in region X1 com-398 pared to region X2, depending upon the ρ values being considered. One possible explanation 399 for these differences is that as thermal electrons move tailward, they can be energized to ener-400 gies greater than ~ 1 eV, and subsequently cannot be measured by the LPW instrument. Var-401 ious ion acceleration mechanisms are known to act in the Martian magnetotail (for example, 402 ambi-polar fields [Collinson et al., 2015; Ergun, 2016; Xu et al., 2018b], JxB forces [Halekas 403 et al., 2017], and magnetic reconnection[Harada et al., 2015b; Harada, 2017]). It is not unlikely that a range of mechanisms also exist that accelerate electrons in the tail region. Such suprathermal electrons can be measured by the SWEA instrument on board MAVEN, and we 406 leave it to future work to examine the specific electron acceleration mechanisms active within 407 the magnetotail region at Mars. 408

The local magnetic field direction plays an important role influencing where thermal electrons are likely to be observed, regardless of distance down the tail. When the local magnetic field flares outward compared to inward (red vs blue lines, Figures 4-9), thermal electrons are more likely to be observed at large values of ρ (>1) for all magnetic field topologies. This behavior can be explained by the fact that the magnetotail plasma environment is collisionless and electron motion is subsequently dominated by the local magnetic field direction.

The ionospheric source regions that the local magnetic fields connect to also play an 416 important role in driving the spatial distribution of observed thermal electrons. When ther-417 mal electrons are observed on open or closed magnetic field lines, they are sourced primarily 418 from the dayside ionosphere when observed outside of the optical shadow ($\rho > 1$), while they 419 are sourced primarily from the nightside ionosphere within the optical shadow ($\rho < 1$). This 420 behavior is observed in regions X1 and X2 (Figures 7 and 9). Such a dependence on source 421 region demonstrates that open and closed magnetic fields anchored in the dayside ionosphere 422 "drape" across the terminator into the magnetotail region, such that ionospheric thermal elec-423 trons are able travel along these fields lines into the magnetotail region. This behavior likely explains why the largest thermal electron densities are observed at $\rho \sim 1$ -1.3. This region 425 is where the magnetic field is most likely to be connected to the dayside ionosphere, where 426 ionospheric densities are large. Open and closed magnetic fields anchored to the nightside 427 ionosphere extend tailward within the shadow of the planet, leading to the observed spatial 428 distributions of thermal electrons. These interpretations are consistent with magnetohydro-429 dynamic (MHD) simulations of the Martian magnetosphere (e.g. Fang et al. 2018) and its 430 magnetic environment. 431

Interestingly, and somewhat surprisingly, the locations of the strongest crustal magnetic fields do not appear to strongly influence the spatial distribution nor average densities of thermal electrons in the magnetotail region. It is well known that the strongest crustal fields influence the structure and density of the ionosphere at low altitudes (e.g. *Withers et al.* 2005; *Andrews et al.* 2015). A possible explanation for the lack of clear crustal field influence in this study is that the crustal field strengths are significantly reduced at the altitudes studied here (greater than 600 km), and effects are either negligible, or are "smeared" out over the larger volume of the magnetotail region, compared to the lower ionosphere.

An important caveat to bear in mind when considering the interpretations and implications of this study is that the LPW instrument is only sensitive to electron populations with densities greater than about 15 cm⁻³ and temperatures less than about 1 eV. As such, the very lowest density populations may not be included here. Furthermore, the LPW instrument is not capable of determining the bulk flow direction of measured thermal electrons; therefore, we cannot produce an estimate of thermal electron escape rates without assuming a flow direction and speed.

447 **5** Conclusions

This study presents the first detailed analysis of the spatial distribution of thermal (<1 eV) electrons in the Martian magnetotail as observed by the Langmuir Probes and Waves instrument on the MAVEN spacecraft. The thermal nature of the observed electrons means that they are sourced from the planetary ionosphere. The presented analysis yields insight into the thermal plasma structure of the Martian magnetotail region and electron source regions.

The spatial distribution of observed thermal electrons varies with both distance down the tail and cylindrical distance from the center of the tail. We have shown that the local magnetic field flaring direction plays an important role in driving the spatial distribution, with thermal electrons more likely to be observed at greater cylindrical distances for outward flaring field. Additionally, we have shown that the ionospheric regions to which the

local magnetic field connects to also drives the spatial distribution of thermal electrons in the 459 magnetotail. Broadly speaking, thermal electrons observed within the optical shadow behind 460 Mars are typically sourced from the nightside ionosphere, while thermal electrons observed 461 outside of the optical shadow region tend to be sourced from the dayside ionosphere. The lo-462 cations of the strongest crustal magnetic fields (i.e. sunward or tailward pointing) do not ap-463 pear to significantly influence the distribution of thermal electrons, a somewhat unexpected 464 result that may be related to the relatively high altitude range covered by this study. The ob-465 servations presented here demonstrate the importance of the magnetic field in structuring the 466 plasma environment of the Martian magnetotail, a characteristic that is likely applicable to 467 other unmagnetized bodies such as Venus and comets. 468



Figure 1. Cartoon depicting the tail region. ρ is the cylindrical distance from the center of the tail, defined as $\rho = \sqrt{Y^2 + Z^2}$ in the MSO coordinate system. The relative angle between the magnetic field vector and the anti-solar vector determines the flare orientation, as described in sections 2.2 and 3.



Figure 2. One MAVEN orbit while the spacecraft was present in the tail region. The top panel (A) shows
LPW I-V sweeps with voltage on the Y-axis and the log of the absolute value current in the Z-axis. thermal
electron densities derived from the I-V sweeps are in panel (B). The 3D MAG data in the MSO frame (C).
SWEA suprathermal electron spectrum (D). MAVEN position and altitude (black line) in the MSO frame;
altitudes values (km) printed underneath (E). The dashed green lines mark altitudes of 600 km and the solid

 $_{\rm 477}$ $\,$ blue lines enclose the optical shadow, which extends to $\rho \sim 1.$



Figure 3. The number of LPW derived data points as a function of radial distance (ρ) from the center of the tail and their respective derived densities. Panel (A) shows the measurement points without the photoelectron correction and panel (B) shows the measurement points with the 10 cm^3 photoelectron current correction applied.



Figure 4. The number of derived data points (A) and measurement points (B), the likelihood of observing a density– (panel (A) / panel (B)), (C) and the mean densities (D) for all ρ in region X1. The blue line indicates the magnetic field flares inward and the dashed red line indicates the field flares outward. Error bars on (D)

are the standard deviations of each bin.



Figure 5. The number of derived data points (A) and measurement points (B), the likelihood of observing a density– (panel (A) / panel (B)), (C), and the mean densities (D) for all ρ in **region X2**. The blue line indicates the magnetic field flares inward and the dashed red line indicates the field flares outward. Error bars on (d) are the standard deviations of each bin.



Figure 6. The likelihood of observing electrons on open (A), closed (B), and draped (C) field lines in region X1. Red lines indicate the magnetic field lines flare outward and blue lines indicate the field flares inward. Error bars represent the counting uncertainties in each bin (i.e. \sqrt{N} , where N is the number of measurements in each bin).



Figure 7. The likelihood of observing electrons on open and closed field lines in region X1 that are con nected to the dayside (A and C) and nightside (B and D) of Mars in region X1. Red lines indicate the mag netic field lines flare outward and blue lines indicate the field flares inward. Error bars represent the counting
 errors in each bin.



Figure 8. The likelihood of observing electrons on open (A), closed (B), and draped (C) field lines in
 region X2. Red lines indicate the magnetic field lines flare outward and blue lines indicate the field flares
 inward. Error bars represent the counting errors in each bin.



Figure 9. The likelihood of observing electrons on open and closed field lines in region X2 that are connected to the dayside (A and C) and nightside (B and D). Red lines indicate the magnetic field lines flare
 outward and blue lines indicate the field flares inward. Error bars are the counting errors in each bin.



Figure 10. The likelihood of observing thermal electrons in the southern hemisphere tail region (Z MSO <0) based on the location of the strongest crustal fields (A). Yellow lines and dots correspond to the strongest crustal fields pointing tailward (subsolar longitude = 180°), green corresponds to the strongest crustal fields pointing sunward (subsolar longitude = 0°), and gray corresponds to dawn and dusk-ward orientation of the crustal fields. Mean densities are presented for each crustal field orientation (B).

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are available on the NASA Planetary Data System, via https://pds.nasa.gov/. 512

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The influence of magnetic field topology and orientation on the distribution of thermal electrons in the Martian magnetotail

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Key Points:

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9	• The local magnetic topology, flaring angle, and location of the crustal fields influence
10	the thermal electron structure in the magnetotail
11	• Close to the planet, thermal electrons are most likely observed just outside the optical
12	shadow in the magnetotail, peaking at $\sim 35\%$
13	• Thermal electrons are 10-20% more likely to be observed, in the central tail, when the
14	strongest crustal fields point sunward than tailward

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15 Abstract

Thermal (<1 eV) electron density measurements, derived from the Mars Atmosphere 16 and Volatile Evolution's (MAVEN) Langmuir Probe and Waves (LPW) instrument, are an-17 alyzed to produce the first statistical study of the thermal electron population in the Martian 18 magnetotail. Coincident measurements of the local magnetic field are used to demonstrate 19 that close to Mars, the thermal electron population is most likely to be observed at a cylin-20 drical distance of ~1.1 Mars radii (R_M) from the central tail region during times when the 21 magnetic field flares inward toward the central tail, compared to ~1.3 R_M during times when 22 the magnetic field flares outward away from the central tail. Similar patterns are observed 23 further down the magnetotail with greater variability. Thermal electron densities are highly 24 variable throughout the magnetotail; average densities are typically $\sim 20-50$ cm⁻³ within the 25 optical shadow of Mars and can peak at ~100 cm⁻³ just outside of the optical shadow. Stan-26 dard deviations of 100% are observed for average densities measured throughout the tail. 27 Analysis of the local magnetic field topology suggests that thermal electrons observed within 28 the optical shadow of Mars are likely sourced from the nightside ionosphere, whereas elec-29 trons observed just outside of the optical shadow are likely sourced from the dayside iono-30 sphere. Finally, thermal electrons within the optical shadow of Mars are up to 20% more 31 likely to be observed when the strongest crustal magnetic fields point sunward than when 32 they point tailward. 33

34 1 Introduction

Mars lacks an intrinsic dipole magnetic field and the interaction between the planet's 35 atmosphere and solar wind results in the formation of a partially induced magnetosphere 36 that acts to stand off and deflect the supersonic solar wind flow around the planetary obstacle 37 [Luhmann et al., 1991; Brain et al., 2003; Bertucci et al., 2011]. The interplanetary mag-38 netic field (IMF) drapes about the planet's dayside, leading to a formation of a flared "wake" 39 behind the planet, similar to Venus, comets, and other unmagnetized bodies (e.g. Vaisberg 40 and Smirnov 1986; Luhmann et al. 1991; Zakharov 1992; Israelevich et al. 1994). Analysis 41 of the structure and dynamics of the magnetotail region inform us of the interaction between 42 the planet and the supersonic solar wind. Planetary ions have also been observed traveling 43 tailward within the wake [Lundin and Dubinin, 1992], and thus understanding magnetotail 44 dynamics is essential to understanding the global structure of the induced Martian magneto-45 sphere and ion loss to space. 46

Early Mars orbiters, such as the Phobos spacecraft, demonstrated that the Martian tail
 is a two-lobe structure whose polarity and orientation depends on the upstream solar wind
 orientation [*Yeroshenko et al.*, 1990], similar to the Venusian magnetotail [*Vaisberg and Smirnov*, 1986]. Data from the Mariner 4, Mars 2, 3, 5, Phobos and Mars Global Surveyor
 (MGS) spacecraft missions show the shape and extent of the Martian magnetotail is highly
 variable (e.g. *Slavin et al.* 1991; *Vignes et al.* 2000), and the flaring angle of the tail depends
 on the upstream solar wind pressure [*Zhang et al.*, 1994].

Later spacecraft, including MGS, Mars Express (MEX) and the Mars Atmosphere and Volatile EvolutioN (MAVEN) mission, have enhanced these early observations, demonstrating that a current sheet separates both tail lobes, as expected for an induced magnetotail produced by the draping of the IMF about the dayside of the planet [*Ferguson et al.*, 2005].

Halekas et al. 2006 have also shown that MGS global current sheet crossings at 400
 km altitude occur everywhere (including the dayside) except over the strong Martian crustal
 magnetic fields. Such crossings occur at locations that vary with Mars season and upstream
 IMF orientation. The magnetotail region has been observed to be at times highly dynamic.
 Evidence of magnetic reconnection occurring in the tail region has been reported using both
 MGS and MAVEN data (e.g. *DiBraccio et al.* 2015; *Halekas et al.* 2009; *Eastwood et al.* 2012; *Harada et al.* 2015a), while the repetitive loading and unloading of magnetic flux in

the magnetotail region is akin to sub-storm activity within intrinsic magnetospheres (e.g. Di-65 Braccio et al. 2015). DiBraccio et al. 2018 also demonstrated that the magnetotail lobes typ-66 ically exhibit a 45 degree twist relative to upstream IMF orientations, a characteristic thought 67 to be strongly influenced by dayside reconnection between the draped IMF and planetary 68 crustal magnetic fields. Xu et al. 2020 compared the tail topology determined from mag-69 netohydrodynamic (MHD) simulations to that inferred from MAVEN data and how each 70 topology responds to the upstream IMF orientation. Their results support the hypothesis that 71 magnetic reconnection between crustal magnetic sources and the solar wind is responsible 72 for the observed twist in Mars's tail lobes. 73

Planetary ions have been observed in the magnetotail by multiple spacecraft, and have 74 been used to infer the existence of various plasma acceleration mechanisms and subsequent 75 plasma outflow from Mars. Ion data from the Analyzer of Space Plasmas and Energetic 76 Atoms (ASPERA) instruments on Phobos 2 and MEX show highly variable O⁺ fluxes, par-77 ticularly in the central tail region, and these fluxes are likely driven by a variety of ion accel-78 eration mechanisms. Some processes are similar to those that exist in the terrestrial magne-79 totail and others are different [Lundin et al., 1989; Kallio et al., 1995; Lundin and Barabash, 80 2004; Fedorov et al., 2006; Lundin et al., 2008]. Magnetic field and suprathermal electron 81 measurements from the MGS spacecraft show that detached magnetic structures intermit-82 tently exist in the Martian tail region and contain planetary plasma. Such structures are thought 83 to be caused by the stretching of crustal magnetic fields via their interaction with the solar 84 wind in the tail region, until magnetic reconnection occurs, detaching part of the crustal field, 85 which is then convected down the tail region [Brain et al., 2010]. 86

Initial MAVEN estimates of planetary ion escape rates for ions with energies > 25 eV 87 from Mars generally agree with earlier studies, demonstrating that tailward ion escape in 88 the magnetotail region can contribute significantly to the total escaping flux from the planet 89 [Brain et al., 2015; Dong et al., 2015]. MAVEN observations of enhanced ionospheric elec-90 tron temperatures above the exobase region suggest that ambi-polar electric fields can be an 91 important ion acceleration mechanism at Mars, providing up to ~1 eV of energy to planetary 92 ions [Xu et al., 2018a; Collinson et al., 2019; Akbari et al., 2019]. Such energy is close to the 93 escape energy for heavy ions to overcome Mars' relatively weak gravitational potential and 94 drive ion outflow on open magnetic field lines that connect the ionosphere to the solar wind. 95 Numerical simulations have explicitly shown that ion outflow can be significantly enhanced 96 by such ambi-polar electric fields at Mars [Ergun et al., 2016]. MHD modelling of the Mar-97 tian magnetosphere, for example, has shown that draped field lines exist in abundance in the 98 magneotail region [Ma et al., 2002, 2004; Fang et al., 2018]. 99

Instrument limitations make it difficult to study the thermal (< few eV energy) plasma 100 environment in the Martian magnetotail with electrostatic analyzers. The arrival of the MAVEN 101 spacecraft at Mars in September 2014 [Jakosky et al., 2015] presented an additional method 102 to observe the planet's low energy thermal plasma environment, in the form of the Langmuir 103 Probe and Waves (LPW) instrument. LPW measurements enable a derivation of the local, 104 thermal (<1 eV) electron density, and this study presents, to our knowledge, the first statisti-105 cal analysis of the thermal electron population in the Martian magnetotail. We demonstrate 106 that the location at which thermal electrons are observed within the magnetotail is highly 107 dependent upon the orientation of the local magnetic field, whether it connects to the day 108 or night side ionosphere, and the location of the strongest crustal fields. Section 2 describes 109 the dataset and analysis methods utilized in this study; results are presented in Section 3 and 110 discussed in 4. We conclude in Section 5. 111

112 **2 Data and Methodology**

2.1 Instruments

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The MAVEN spacecraft entered into an elliptical orbit about Mars in September 2014 114 [Jakosky et al., 2015]. The orbit precesses such that MAVEN samples all local times, longi-115 tudes, and latitudes. The rate of orbital precession results in coverage of the Martian magne-116 totail roughly every 3-4 months, for about one month each time. The data used in this study 117 are taken from such "tail seasons." Data from several instruments were utilized in this study. 118 These include the Langmuir Probe and Waves (LPW) [Andersson et al., 2015], Magnetome-119 ter (MAG) [Connerney et al., 2015], and Solar Wind Electron Analyzer (SWEA) [Mitchell 120 et al., 2016]. 121

LPW consists of two Langmuir probes, each mounted on the end of ~7m booms and 122 separated by an angular distance of 110 degrees. The instrument can operate as a Langmuir 123 probe ("when in LP mode") or as an electric field instrument ("when in waves mode"). Dur-124 ing LP mode, the Langmuir Probes measure (alternating in time) the current and voltage 125 (I-V) characteristics of the local plasma environment. The density and temperature of lo-126 cal thermal (< 1eV) electrons and the spacecraft potential are derived from the I-V curve by 127 using an enhanced fitting method [Ergun et al., 2015]. During waves mode, the instrument 128 measures—as a time series— the potential difference between the two sensors, from which 129 electric field power spectra are derived [Andersson et al., 2015; Fowler et al., 2017]. Only 130 data obtained from LPW's LP mode were used in this study. 131

The LPW instrument is designed to measure thermal (<0.1 eV), high density (>1000's 132 cm^{-3}) dayside ionospheric plasma. However, there are times when the local thermal electron 133 density is low (≤ 15 cm⁻³) and the electron temperature is relatively high (approaching 1 eV 134 or larger). During such conditions the LPW instrument is operating beyond its design speci-135 fications and at times may not be capable of measuring a significant thermal electron current. 136 Additionally, if the probe and/or spacecraft are sunlit, photoelectron currents can dominate 137 the thermal electron current, when the thermal electron density is below $10-15 \text{ cm}^{-3}$. Con-138 sequently, when the thermal electron density is below ~ 15 cm⁻³, derived thermal electron 139 densities can be close to or equal to zero, and have large uncertainties associated with them. 140 These limitations should be kept in mind when interpreting the results of this study. 141

The local three-dimensional magnetic field vector is measured by the MAG instrument at a sampling rate of 32 Hz. The instrument consists of two fluxgate magnetometers which allow for hardware redundancy, calibration, and removal of the spacecraft generated magnetic fields. The magnetic field is measured to an accuracy of about 0.01 nT [*Connerney et al.*, 2015].

The SWEA instrument is an electrostatic top-hat analyzer that measures electron fluxes within the 3 eV to 5 keV energy range. The instrument has a field of view of $360^{\circ} \times 120^{\circ}$ provided by electrostatic deflectors and an energy resolution ($\Delta E/E$) of 17% [*Mitchell et al.*, 2016]. SWEA operates at a cadence of 2-4 seconds. As described in section 2.2, SWEA shape parameters were used to determine magnetic field topology.

In this study, the data were analyzed in the Mars Solar Orbital (MSO) coordinate system, where the x-axis points from Mars to the Sun, the y-axis is anti-parallel to Mars' instantaneous orbital velocity, and the z-axis completes the right-handed coordinate system.

2.2 Methodology

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The goal of this study is to investigate the effects of the local magnetic field topology on the spatial distribution of the thermal electron population in the Martian magnetotail. To this end, we analyze MAVEN data from periods when the spacecraft was present in the magnetotail region between 01-01-2015 to 12-31-2019.

Every LPW observation for which the I-V curve fitting technique detected a thermal 160 electron density in the magnetotail was binned according to its observed location within the 161 magnetotail region and the associated local magnetic field orientation and topology. This 162 is further described below. The magnetotail region was defined as all post-terminator loca-163 tions (X (MSO) < 0) with altitudes greater than 600 km. All LPW I-V sweep measurements 164 were then binned into two spatial regions of the tail—called regions X1 and X2—and sepa-165 rated by their associated local magnetic field orientation and topology. Region X1 enclosed 166 $-1.5R_M < X < 0R_M$ and region X2 enclosed $-3R_M < X < -1.5R_M$, where $R_M = 1$ 167 Mars radius (3396 km). Splitting the tail region into two regions provides the opportunity to 168 observe the evolution of the spatial distribution of thermal plasma down the tail. However, 169 spatial coverage at this time in the MAVEN mission means the tail region could not be split 170 into additional regions while maintaining adequate sample numbers. 171

¹⁷² Data were also analyzed with respect to the parameter ρ , the cylindrical distance of ¹⁷³ MAVEN from the center of the tail region, defined as $\rho = \sqrt{Y^2 + Z^2}$, in the MSO coordinate ¹⁷⁴ system. To first order, $\rho < 1$ lies within the planet's optical shadow and $\rho > 1$ lies outside the ¹⁷⁵ optical shadow (ignoring atmospheric effects). These constraints ensured MAVEN was sam-¹⁷⁶ pling the magnetotail region and not the nightside ionosphere, which is typically observed ¹⁷⁷ below altitudes of 600 km (e.g. *Fowler et al.* 2015). A cartoon diagram showing regions X1 ¹⁷⁸ and X2, and ρ is shown in Figure 1.

Two distinct datasets were utilized in this study. The first are dubbed "measurement 179 points" which represent all measurements made by LPW regardless of whether sufficiently 180 large currents were observed such that a density could be derived from the measured I-V 181 curve or not. The second, "derived data points," represent measurements from which den-182 sities were derivable, corresponding to times when the thermal electron density was larger 183 than $\sim 15 \text{ cm}^{-3}$. Dividing the number of derived data points by the number of measurement 184 points provides a percentage of how often a density can be derived from the measured I-V 185 curves. The 4-year-long dataset consisted of 10⁵ measurement points in the tail region. Of 186 these 10^5 measurement points, ~ 6×10^4 are derived data points. Since LPW is sensitive down to densities of ~ 15 cm⁻³, we may lack measurements of the lowest densities. 188

Furthermore, each MAG and SWEA measurement were paired to a corresponding LPW measurement in time. Both MAG and SWEA operate at significantly faster cadences than LPW at high altitudes within the magnetotail region (128 s, compared to 2 s for SWEA and 32 s⁻¹ for MAG).

The flaring angle of the magnetic field was calculated based upon the relative angle between the local magnetic field vector and the anti-solar vector (-X) in the three-dimensional MSO coordinate system. The dashed red line and solid blue line in Figure 1 depict outward and inward flaring field, respectively (as projected onto the two-dimensional plane). When combined with LPW density measurements, the flaring angle and topology provide insight into the origin of the electrons measured on the field line, i.e. the nightside vs the dayside ionosphere. This study utilizes three primary magnetic field orientations: closed, open and draped.

Suprathermal electron energies and pitch-angle distributions measured by SWEA allow 201 for the inference of magnetic topology based on three principles. First, the presence of a loss 202 cone in one or both field-aligned directions indicates a magnetic field line intersects the colli-203 sional atmosphere once or twice. Thus, the field line is considered open or closed (e.g. Brain 204 et al. 2007; Xu et al. 2018b; Weber et al. 2017). Second, ionospheric photoelectrons are ob-205 served in one or both field-aligned directions. This implies one or both footpoints of a field 206 line are embedded in the dayside ionosphere, corresponding to either open or closed field 207 topology (e.g. Xu et al. 2017). Finally, strong depletion of suprathermal electron flux, called "suprathermal electron voids," signifies closed field lines with both footpoints intersecting 209 the nightside ionosphere (e.g. Mitchell et al. 2001; Steckiewicz et al. 2015). Note, magnetic 210 topology or footpoint(s) of a field line is defined with respect to the suprathermal electron 211

exobase (~ 160 km, *Xu et al.* 2016). If none of the above is observed, then the field line is
draped. The methodology of identifying photoelectrons and loss cones through MAVEN
data are described in further detail in *Xu et al.* [2017] and *Weber et al.* [2017], respectively.
This study infers thermal electron origin (dayside versus nightside ionosphere) based on the
magnetic topology identification method described by *Xu et al.* [2016, 2019].

In addition to the magnetic field topology in the tail region, the effect of the Martian 217 crustal magnetic fields (e.g. Acuna et al. 1999) on the distribution of the thermal electrons in 218 the tail was also investigated. The location of the region which contains the strongest fields 219 (e.g. planetary longitudes of 180 degrees— Acuna et al. 1999) with respect to the sub-solar point was analyzed when the thermal electron population was observed. These "relative sub-221 solar longitudes" are the difference between the position of the strongest crustal fields and the 222 sub-solar point. Relative sub-solar longitude values close to 0 degrees indicate the strongest 223 crustal fields are pointing sunward and values close to 180 degrees indicate they are pointing 224 tailward. Similarly, intermediate relative sub-solar longitude values of 90 degrees and 270 225 degrees, signify the strongest crustal fields are located at dawn and dusk, respectively.

Derived data points and measurement points were further binned based on relative subsolar longitude bins $(0^{\circ} \pm 45^{\circ}, 90^{\circ} \pm 45^{\circ}, 180^{\circ} \pm 45^{\circ}$ and $270^{\circ} \pm 45^{\circ}$), corresponding to strong crustal fields located at noon, dawn, midnight, and dusk. This was done regardless of whether the measurements belong to region X1 or X2 to ensure adequate sampling statistics.

231 **2.3 Example Data**

Example MAVEN data are shown as a time series in Figure 2. The time series data 232 span a period of 6 hours, which includes two periapsis passes at ~15:00 and 19:30 UTC. 233 These periapsis passes are located on the dayside of the planet and are characterized by typ-234 ical peak electron densities $\leq 10^5$ cm⁻³ (Figure 2B). Apoapsis occurs just after 17:00 UTC 235 in the magnetotail region. MAVEN crosses into the planet's optical shadow between 16:00 236 and 17:30, as enclosed by the two vertical solid blue lines. The effect of the optical shadow is observed as a reduction of photoelectron-current in the LPW I-V sweeps (negative voltages, 238 panel A) and a reduction of SWEA suprathermal electron flux (due to negative spacecraft 239 potentials within the optical shadow, energies less than ~ 20 eV, panel D). 240

MAVEN crosses the magnetotail current sheet at about 17:00, as indicated by the change in sign of the magnetic field's B_X component (panel C; e.g. *DiBraccio et al.* 2015). Thermal ionospheric electrons are observed in the magnetotail region, as shown in panel B. The vertical dashed green lines mark an altitude of 600 km, the minimum altitude above which data were analyzed in this study. At high altitudes, the LPW data are measured at lower time cadences. This results in fewer I-V sweeps and density measurements at higher altitudes, as shown in panels A and B.

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2.4 Removal of LPW Photoelectron signatures from LPW Densities

During LP operation mode, the Langmuir Probe sensor measures electrical current 249 from a variety of sources, including thermal electrons, ions and photoelectrons emitted by 250 the sensor when in sunlight. In sunlit conditions, the photoelectron current emitted by the 251 LPW sensors can dominate the collected current, when the local thermal electron density 252 is small. This results in a "background" derived thermal electron density of ~ 10 cm⁻³. An 253 example of this background density influenced by photoelectrons is shown in Figure 3 (A). 254 The panel shows the number of LPW measurement points as functions of radial distance (ρ) 255 from the center of the tail and their respective derived densities. Radial distances less than 1 256 R_M denote measurements made within Mars' optical shadow, while measurements made at 257 radial distances greater than 1 are made in sunlight. Within the optical shadow region ($\rho <$ 258 1), an "artificial cutoff" at densities below $10^{0.5}$ cm⁻³ demonstrates the lower measurement 259 limit of the LPW instrument, when photoelectrons are not present. Outside of the optical 260

shadow ($\rho > 1$), there is a clear "background" of measured densities at ~10 cm⁻³, which are a result of photoelectron currents dominating the collected current. The LPW instrument team previously investigated such cases in detail (not shown here) and confirmed that the photoelectron "background current" is equivalent to a density of about 10 cm⁻³.

We correct the LPW thermal electron densities for this background photoelectron cur-265 rent before performing the analysis mentioned in Section 2.2. Derived densities measured 266 in sunlight ($\rho > 1R_M$) have 10 cm⁻³ subtracted from their derived values, and the results 267 of this correction are shown in Figure 3 (B). The format is the same as for panel A. For ra-268 dial distances greater than 1, the transition to density values below 10 cm^{-3} is now much smoother, indicating that this background correction is successful. We note here that the 270 photo electron current correction of 10 cm⁻³ is only significant when derived thermal elec-271 tron densities are less than $\sim 50 \text{ cm}^{-3}$. As shown in Figure 2, the majority of derived density 272 values are greater than 100 cm^{-3} , and this correction is negligible for most data points. 273

274 **3 Results**

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3.1.1 Region X1: -1.5 < X < 0

The statistics of the data and measurement points in region X1 of this study are presented in Figure 4. Plotted against ρ , panel A shows the number of derived data points, panel B shows the number of measurement points, panel C shows the percent likelihood of observing a density, i.e. panel A divided by panel B, and panel D shows the mean densities for times when densities are observed, i.e. panel A. The solid blue line indicates an inward flaring field and the dashed red line indicates an outward flaring field.

3.1 Statistics and the Influence of the Magnetic Field Flaring Angle

The LPW observations analyzed in this study show that thermal electrons are observed with relatively high frequency in the magnetotail region of Mars, with typical likelihoods of ~30% in region X1 close to Mars, $0.5 < \rho < 1$, (Figure 4C). Thermal electrons are most likely to be observed just outside the optical shadow (ρ slightly greater than 1 R_M), and this likelihood then decreases with increasing ρ . The near imperceptible error bars in 4C represent the counting errors (i.e. \sqrt{N} , where N is the number of derived data points).

Figure 4D shows mean electron density (when electrons are observed, i.e. Figure 4 A) peaks at ~100 cm⁻³ just outside of the optical shadow, $\rho \sim 1.2$. Densities within the optical shadow ($\rho < 1$) are typically a few 10's to 50 cm⁻³. The error bars in panel D show the standard deviation of each bin's measurements. They demonstrate high measurement variability, with standard deviations of ~ 100% in most bins.

The red and blue lines in Figure 4 show that the magnetic field orientation does not significantly affect the likelihood of LPW observing electrons in region X1 (panel C), nor does it affect the observed average densities in each bin (panel D).

3.1.2 Region X2: -3 < X < -1.5

The statistics for region X2 are shown in Figure 5, which shows distinct differences to region X1. The likelihood of observing thermal electrons is roughly constant for $\rho < 1$, compared to a decreased likelihood for $\rho < 0.5$ in region X1. Average densities are typically smaller in X2 than X1 (not exceeding ~30 cm⁻³ on average), and are roughly constant as ρ increases.

In general, a greater number of measurement and derived data points occur when the field flares outward, suggesting that (as expected) the field tends to be in an outward flaring configuration more often than an inward one, particularly at greater distance down the tail (i.e. region X2). Within $\rho < 1$, densities are more likely to be observed when the magnetic field flares inward (blue line, Figure 5C), though this difference is small, ~10%, between outward and inward flaring fields.

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3.2 The Influence of Magnetic Field Topology

Figure 6 shows the likelihood of MAVEN observing thermal electrons as functions 310 of the magnetic field flaring direction and magnetic topology. We considered measurement 311 points on each specific topology as a fraction of measurement points on all topologies. We 312 divide the instances when a thermal electron is observed on a specific topology by the sum 313 of all measurement points for all topologies to make these calculations. Note that the sum of 314 all panels for a given ρ is less than one hundred percent because the SWEA analysis routine 315 cannot always reliably determine the topology. These "unknown" topologies were excluded 316 in this section of analysis. 317

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3.2.1 Region X1: -1.5 < X < 0

Magnetic field topology information in Figure 6 A-D shows that electrons observed 319 just past the optical shadow are approximately equally likely to be on open or closed mag-320 netic field lines in region X1. Panels A-C show that thermal electrons on an outward flaring 321 field are typically most likely to be observed at the largest values of ρ , regardless of magnetic 322 field topology. An interesting caveat to this includes panels 6 B and G, where for $\rho < 1$, elec-323 trons are most likely to be observed in the central tail even for an outward flaring field. The 324 cause of this is not immediately clear, but the observations in panels 6 B and 6 G suggest that 325 an outward flaring magnetic field has a greater influence on thermal electrons in region X2 326 compared to X1, whereas the blue and red lines show similar behavior for $\rho < 1$. 327

For an inward pointing field originating from the dayside, open and closed field lines (panels A and C), electrons are most likely observed at and just past the optical shadow ($\rho \sim 1$ -1.2), observed at a peak of ~25% of the time. Electrons on open, inward pointing field lines are observed more frequently for $\rho < 1$ than electrons on open, outward pointing field lines (panel 6A). Electrons are most consistently observed on outward draped field lines at the largest values of ρ (panel 6 E), although they are also observed for a significant fraction of the time on an inward pointing, draped field for $\rho < 1$.

The magnetic field flaring angle and source region for observed thermal electrons (e.g. 335 day or nightside ionosphere) also strongly influence where such electrons are observed, as 336 shown in Figure 6 A - D. Electrons observed on open field lines originating from the day-337 side ionosphere (panel A) are most likely to be observed at $\rho \gtrsim 1$, particularly when the field is flared outward. In contrast, electrons sourced from the nightside ionosphere (panel B) 339 are most likely to be observed at $\rho < 1$. Dayside originating electrons observed on closed 340 field lines (panel C) demonstrate similar patterns to those on open field lines (panel A). The 341 dayside electrons on inward pointing field are most likely to be observed just past the optical 342 shadow at $\rho = 1 - 1.2$, while those on an outward flaring field are observed at equal likeli-343 hood for all large values of ρ . Electrons observed on closed field lines originating from the 344 nightside ionosphere (panel D) are more likely to be attached to an inward pointing field than 345 outward pointing field. 346

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3.2.2 Region X2: -3 < X < -1.5

Thermal electrons are most likely to be observed inside of the optical shadow in region X2 ($\rho < 1$), as shown in Figure 5 C. Panels F - I of Figure 6 demonstrate that the flaring direction of the magnetic field can significantly influence where thermal electrons are observed in region X2. Panel F shows that electrons are observed with ~30-40% likelihood at $\rho \ge 1.5$ when the field flares outward, compared to a peak of ~5% at the center of the tail when the field flares inward. Electrons are less likely to be observed on closed field lines in general in region X2 compared to X1 (Figure 6 H and I versus Figure 6 C and D). This is perhaps not ³⁵⁵ unexpected given that region X2 lies further down-tail away from the closed crustal magnetic ³⁵⁶ fields whose influences are stronger closer to the planet. The effect of an outward flared field ³⁵⁷ is observed for $\rho \ge 1$, but the inward and outward flaring directions do not seem to influence ³⁵⁸ the spatial distribution of thermal electrons for $\rho < 1$. The presence of an outward flared ³⁵⁹ field in region X2 still leads to a greater likelihood of observation at higher ρ .

Electrons observed on draped field lines in region X2 (Figure 6 J) are observed at similar likelihoods (as a function of ρ) to region X1 (Figure 6 E). On draped field lines, thermal electrons are most likely to be observed at small or large values of ρ (panels E and J) for both regions. It is not immediately clear why the likelihood of observing thermal electrons on draped field increases at the smallest values of rho in panels 6 E and 6 J. Comparison with global MHD simulations of the Martian magnetosphere may provide answers to this, although such a study is outside the scope of this work. In general, thermal electrons are roughly half as likely to be observed in region X2 compared to X1 (Figures 4 and 5).

Investigating the source regions for thermal electrons observed in region X2 further 368 demonstrates the clear impact that the magnetic field flaring direction has on the likelihood 369 of observing these electrons. Figure 6 panels F-I show that thermal electrons are typically 370 more likely to be observed at large ρ when the field flares outward, for field lines connected 371 to the day or nightside ionosphere when compared to thermal electrons in X1. Inward point-372 ing field connected to the nightside ionosphere (Figure 6 G) clearly influences where thermal 373 electrons are likely to be observed, with electrons most likely to be observed in the central 374 tail region, similar to region X1. Figure 6 H and I show that electrons are not often observed 375 on closed field lines in region X2 ($\leq 15\%$ of the time). When such conditions exist, electrons 376 are more likely to be observed at larger ρ when on outward flared field. 377

378

3.3 The Influence of Strong Crustal Magnetic Fields

The influence of the location of the strongest crustal magnetic fields on the likelihood 379 of observing thermal electrons in the magnetotail is shown in Figure 7. For simplicity, we define the strongest crustal fields as those located at 180 degrees planetary longitude (e.g. Acuna et al. 1999). The parameter "relative sub-solar longitude" is defined as the longitude 382 difference between the location of the strongest crustal fields (180 degrees planetary longi-383 tude) and the sub-solar point. When the relative sub-solar longitude equals 0 (180) degrees, 384 the strongest crustal fields are on the dayside (nightside) of Mars pointing sunward (tail-385 ward). Values of 90 and 270 degrees denote dawn and dusk locations (90 ± 45 and 270 ± 45 386 degrees, respectively). Figure 7 A shows the likelihood of LPW observing thermal electrons, 387 while 7 B shows the median densities observed; both as a function of ρ . The green (yellow) line denotes when the relative sub-solar longitude equals 0 ± 45 degrees (180 ± 45 degrees). 389 The gray lines denote dawn and dusk locations. Data are combined for regions X1 and X2 to 390 ensure adequate sampling statistics. 391

The location of the strongest crustal fields drastically alters the location and likelihood 392 of observing thermal electrons, despite showing similar median densities. The peak likeli-393 hood of observation occurs at $\rho \sim 1.2 R_M$ for each relative sub-solar longitude bin; however, 394 the distributions vary significantly. When the strongest crustal fields point sunward (0 de-395 grees, green line in Figure 7A), LPW observes a thermal electron density 10-20% more often 396 than when the strongest crustal fields point tailward (180 degrees, yellow line in Figure 7 A), 397 within the optical shadow for $\rho < 1.2R_M$. Beyond $\rho \sim 1.2R_M$, thermal electrons are ~5% 398 more likely to be observed when the strongest crustal fields point sunward compared to when 399 they point tailward. 400

401 **4 Discussion**

Thermal electron densities are on average factors of ~2-5 larger in region X1 compared to region X2, depending upon the ρ values being considered. These electrons originate

from the planetary ionosphere, and their presence in the magnetotail is suggestive that they 404 may be contributing to ionospheric escape. One possible explanation for the differences be-405 tween the two regions is that, as thermal electrons move tailward, they can be accelerated to 406 energies greater than ~ 1 eV, and subsequently cannot be measured by the LPW instrument. Various ion acceleration mechanisms are known to act in the Martian magnetotail (for exam-408 ple, ambi-polar fields [Collinson et al., 2015; Ergun, 2016; Xu et al., 2018b], $J \times B$ forces 409 [Halekas et al., 2017], and magnetic reconnection [Harada et al., 2015b; Harada, 2017]). 410 It is not unlikely that a range of mechanisms also exist that accelerate electrons in the tail 411 region. Such suprathermal electrons can be measured by the SWEA instrument on board 412 MAVEN, and we leave it to future work to examine the specific electron acceleration mecha-413 nisms active within the magnetotail region at Mars. 414

The local magnetic field direction plays an important role in influencing where thermal electrons are likely to be observed, regardless of distance down the tail. When the local magnetic field flares outward compared to inward (red vs blue lines, Figure 6), thermal electrons are typically more likely to be observed at $\rho > 1$ for all magnetic field topologies. This behavior can be explained by the fact that the magnetotail plasma environment is collisionless and electron motion is subsequently dominated by the local magnetic field direction.

The ionospheric source regions to which the local magnetic fields connect also play an 421 important role in driving the spatial distribution of observed thermal electrons. When ther-422 mal electrons are observed on open or closed magnetic field lines, they are sourced primarily 423 from the dayside ionosphere when observed outside of the optical shadow ($\rho > 1$), while they are sourced primarily from the nightside ionosphere when observed within the optical 425 shadow ($\rho < 1$). This behavior is observed in regions X1 and X2 (Figure 6 A-D and F-I). 426 Such a dependence on source region demonstrates that open and closed magnetic fields an-427 chored in the dayside ionosphere "drape" across the terminator into the magnetotail region, 428 such that ionospheric thermal electrons are able travel along these field lines into the mag-429 netotail region. This behavior likely explains why the largest thermal electron densities are 430 observed at $\rho \sim 1.2$. This region is where the magnetic field is most likely to be connected to the dayside ionosphere, where ionospheric densities are large. Open and closed magnetic 432 fields anchored to the nightside ionosphere extend tailward within the shadow of the planet, 433 leading to the observed spatial distributions of thermal electrons. These interpretations are 434 consistent with MHD simulations of the Martian magnetosphere (e.g. Fang et al. 2018) and 435 its magnetic environment. 436

The locations of the strongest crustal magnetic fields drastically affect the spatial dis-437 tribution of thermal electrons in the magnetotail region. Since the strongest crustal fields 438 influence the structure and density of the topside ionosphere [Andrews et al., 2015], this re-439 sult is expected. Thermal electrons are less likely to be observed in the tail region (within 440 the optical shadow) when the strongest crustal fields are also located on the nightside. Such 441 conditions suggest that the crustal fields may act to "trap" ionospheric thermal electrons at 442 lower altitudes there. Thermal electrons are also more likely to be observed at $\rho > 1$ when 443 the strongest crustal fields are on the dayside. This configuration likely "puffs up" the dayside ionosphere (as observed by Flynn et al. 2017 and Matta et al. 2015), resulting in draped 445 and dayside open magnetic fields draping about the terminator region at higher altitudes, as 446 observed in Figure 7 A. 447

An important caveat to bear in mind when considering the interpretations and implications of this study is that the LPW instrument is only sensitive to electron populations with densities greater than about 15 cm⁻³ and temperatures less than about 1 eV. As such, the very lowest density populations may not be included here. Furthermore, the LPW instrument is not capable of determining the bulk flow direction of measured thermal electrons; therefore, we cannot produce an estimate of thermal electron escape rates without assuming a flow direction and speed, which is beyond the scope of this study.

455 **5** Conclusions

This study presents the first detailed analysis of the spatial distribution of thermal (<1 eV) electrons in the Martian magnetotail as observed by the Langmuir Probes and Waves instrument on the MAVEN spacecraft. The thermal nature of the observed electrons means that they are sourced from the planetary ionosphere. The presented analysis yields insight into the thermal plasma structure of the Martian magnetotail region and electron source regions.

The spatial distribution of observed thermal electrons varies with both distance down 462 the tail and cylindrical distance from the center of the tail. We have shown that the local 463 magnetic field flaring direction plays an important role in driving the spatial distribution, 464 with thermal electrons more likely to be observed at greater cylindrical distances for outward 465 flaring field. Additionally, we have shown that the ionospheric regions to which the local 466 magnetic field connects also drive the spatial distribution of thermal electrons in the magne-467 totail. Broadly speaking, thermal electrons observed within the optical shadow behind Mars 468 are typically sourced from the nightside ionosphere, while thermal electrons observed out-469 side of the optical shadow region tend to be sourced from the dayside ionosphere. When the 470 strongest crustal fields point sunward, thermal electrons are much more likely to be observed 471 in the tail region than when they point tailward. The observations presented here demon-472 strate the importance of the magnetic field in structuring the plasma environment of the Mar-473 tian magnetotail, a characteristic that is likely applicable to other unmagnetized bodies such 474 as Venus and comets. 475



Figure 1. Cartoon depicting the tail region. The cylindrical distance from the center of the tail is given by $\rho = \sqrt{Y^2 + Z^2}$ in the MSO coordinate system. The relative angle between the magnetic field vector and the anti-solar vector determines the flare orientation, as described in section 2.2.



Figure 2. One MAVEN orbit while the spacecraft was present in the tail region. The top panel (A) shows LPW I-V sweeps with voltage on the Y-axis and the log of the absolute value of the current as color. Log current has units of $\log_{10}(A)$. Thermal electron densities derived from the I-V sweeps are in panel B. The 3D MAG data in the MSO frame are in panel C. The SWEA suprathermal electron spectrum is shown in panel D, where "Eflux" has units of $\frac{eV}{eV \ s \ sr \ cm^2}$. Panel E shows MAVEN position and altitude (black line) in the MSO frame; altitude values (km) are printed underneath. The dashed green lines mark altitudes of 600 km and the solid blue lines enclose the optical shadow, which extends to $\rho \sim 1$.



Figure 3. The number of LPW derived data points as a function of radial distance (ρ) from the center of the tail and their respective derived densities. Panel A shows the measurement points without the photoelectron correction and panel B shows the measurement points with the 10 cm⁻³ photoelectron current correction applied.



Figure 4. The number of derived data points (A), the number of measurement points (B); the likelihood of observing a density, (panel A / panel B), (C); and the mean densities (D) for all ρ in **region X1**. The blue line indicates the magnetic field flares inward and the dashed red line indicates the field flares outward. Error bars in C are counting errors and error bars in D are the standard deviations of each bin.



Figure 5. The number of derived data points (A), the number of measurement points (B); the likelihood of observing a density, (panel A / panel B), (C); and the mean densities (D) for all ρ in **region X2**. The blue line indicates the magnetic field flares inward and the dashed red line indicates the field flares outward. Error bars in C are counting errors and error bars in D are the standard deviations of each bin.



Figure 6. The likelihood of observing electrons in both regions for multiple magnetic field configurations. In region X1 the likelihood of observing electrons in <u>open</u> (A,B), closed (C,D), and draped (E) field lines is shown. In region X2 the likelihood of observing electrons in open (F,G), closed (H,I), and draped (J) field lines is shown. The red lines indicate the magnetic field lines flare outward and blue lines indicate the field flares inward. Error bars (shaded regions) represent the counting errors in each bin.



Figure 7. The likelihood of observing thermal electrons based on the location of the strongest crustal fields relative to the sub-solar point (A). The yellow line and dots correspond to the strongest crustal fields pointing tailward (180°), green line and dots corresponds to the strongest crustal fields pointing sunward (0°), and gray corresponds to dawn and dusk-ward orientation of the crustal fields. Median densities are presented for each crustal field orientation (B).

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