

## RESEARCH ARTICLE

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## Special Section:

Major Results From the MAVEN Mission to Mars

## Key Points:

- Pitch angle-resolved electron energy shape parameters are used to deduce magnetic topology
- Closed magnetic field lines dominate low altitudes (<400 km) of the northern hemisphere on the dayside
- The 3-D view of the Martian magnetic topology is presented for the first time

## Supporting Information:

- Supporting Information S1

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## Martian low-altitude magnetic topology deduced from MAVEN/SWEA observations

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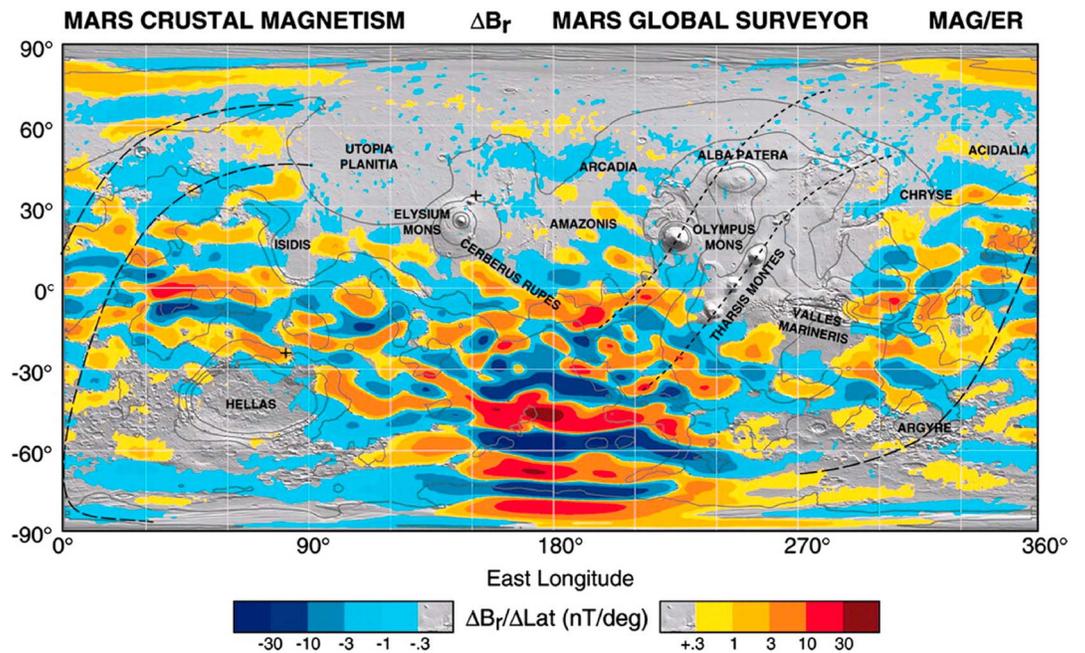
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**Abstract** The Mars Atmosphere and Volatile Evolution mission has obtained comprehensive particle and magnetic field measurements. The Solar Wind Electron Analyzer provides electron energy-pitch angle distributions along the spacecraft trajectory that can be used to infer magnetic topology. This study presents pitch angle-resolved electron energy shape parameters that can distinguish photoelectrons from solar wind electrons, which we use to deduce the Martian magnetic topology and connectivity to the dayside ionosphere. Magnetic topology in the Mars environment is mapped in three dimensions for the first time. At low altitudes (<400 km) in sunlight, the northern hemisphere is found to be dominated by closed field lines (both ends intersecting the collisional atmosphere), with more day-night connections through cross-terminator closed field lines than in the south. Although draped field lines with ~100 km amplitude vertical fluctuations that intersect the electron exobase (~160–220 km) in two locations could appear to be closed at the spacecraft, a more likely explanation is provided by crustal magnetic fields, which naturally have the required geometry. Around 30% of the time, we observe open field lines from 200 to 400 km, which implies three distinct topological layers over the northern hemisphere: closed field lines below 200 km, open field lines with foot points at lower latitudes that pass over the northern hemisphere from 200 to 400 km, and draped interplanetary magnetic field above 400 km. This study also identifies open field lines with one end attached to the dayside ionosphere and the other end connected with the solar wind, providing a path for ion outflow.

## 1. Introduction

One of the most significant findings of the Mars Global Surveyor (MGS) mission was the discovery of strong, localized crustal magnetic fields [Acuna et al., 1998]. These fields were partially mapped at altitudes ranging from 100 to 180 km during the 1.4 year aerobraking period, mostly over the North Pole and the sunlit hemisphere. The crustal field was fully sampled during >7 years in the ~400 km altitude, 02:00 A.M./02:00 P.M. circular mapping orbit (Figure 1; from Connerney et al. [2005]). These localized crustal fields strongly influence the interaction between solar wind and the Martian space environment, resulting in a complicated and dynamic magnetic topology [e.g., Brain et al., 2003; Harnett and Winglee, 2005; Liemohn et al., 2007; Y. J. Ma et al., 2014; Fang et al., 2015].

Magnetic topology is essential for understanding the Mars plasma environment, which can be categorized into three types: closed, open, and draped field lines. Closed field lines (both ends intersecting the collisional atmosphere) isolate ionospheric plasma from solar wind plasma and allow transport of ionospheric photoelectrons from one location to another. Open field lines, with one end intersecting the collisional atmosphere and the other end connected to the solar wind, permit particle/energy exchange between the Martian ionosphere and the solar wind. Energetic electron precipitation [e.g., Lillis and Brain, 2013; Xu et al., 2015a; Shane et al., 2016] through open fields can cause ionization [e.g., Lillis et al., 2009; Fillingim et al., 2007; Fillingim et al., 2010], heating [e.g., Krymskii et al., 2002, 2004], and excitation (probably aurora [e.g., Bertaux et al., 2005; Brain et al., 2006; Liemohn et al., 2007; Leblanc et al., 2008; Shane et al., 2016]). Open magnetic field lines attached to the dayside ionosphere also provide possible passages for ion escape [e.g., Lillis et al., 2015]. For example, cold ions may be accelerated by the ambipolar electric fields to reach the escape velocity [e.g., Collinson et al., 2015], resembling the polar wind at Earth [e.g., Ganguli, 1996; Khazanov et al., 1997; Glocer et al., 2009].



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**Figure 1.** The map of the derivative of the radial magnetic field along the MGS spacecraft track at a nominal 400 km altitude, also Figure 1 of Connerney et al. [2005]. Copyright (2005) National Academy of Sciences, USA.

Harada et al. [2016] investigated narrowband whistler mode waves in the Martian magnetosphere observed by Mars Atmosphere and Volatile Evolution (MAVEN), which were generated by cyclotron resonance with anisotropic electrons on open or closed field lines. These waves in return could also cause electron scattering and precipitation. Draped field lines (both ends connected to the solar wind) can dip low enough into the atmosphere to allow energy transfer through collisions [e.g., Liemohn et al., 2006a].

At Mars, superthermal electrons, mainly consisting of ionospheric photoelectrons and solar wind electrons, are typically magnetized (with the gyrocenters of their helical motion constrained to follow magnetic field lines) and are therefore useful for deducing magnetic topology. Brain et al. [2007] used electron pitch angle distributions measured by the Magnetometer/Electron Reflectometer (MAG/ER) [Acuna et al., 1992; Mitchell et al., 2001] to determine if a magnetic field is closed, open, or draped. The presence or absence of loss cones, which indicate field line intersection with the collisional atmosphere, was used to infer topology. For example, a one-sided loss cone indicates an open field line; a double-sided loss cone, an isotropic photoelectron spectrum, and a superthermal electron void (extremely low count rate) on the nightside [e.g., Mitchell et al., 2001; Steckiewicz et al., 2015; Shane et al., 2016] are all indicators of closed field lines, and a solar wind spectrum with no loss cones indicates a draped field line. Based on this technique, Brain et al. [2007] found that, at ~400 km, the dominant field topology was draped/open in the northern hemisphere and closed over the southern strong crustal field regions with cusps in between, where the field has a large radial component. Additionally, the size of loss cone can be used to derive the crustal field strength at the absorption altitude (~160 km) of these energetic electrons [Lillis et al., 2004; Liemohn et al., 2006a; Mitchell et al., 2007], also known as the superthermal electron exobase [e.g., Xu et al., 2016a].

Another way to infer magnetic topology is to use superthermal electron energy distributions to identify the source(s) of electrons traveling parallel and antiparallel to the field line. For example, Liemohn et al. [2006a] and Frahm et al. [2006] reported ionospheric photoelectrons in the high-altitude Martian tail, observed by the Analyzer of Space Plasma and Energetic Atoms version 3 experiment [Barabash et al., 2006] on board the Mars Express spacecraft. Liemohn et al. [2006b] suggested that these observed high-altitude photoelectrons escape down the tail through open field lines with one end embedded in the dayside ionosphere. Frahm et al. [2010] mapped these tail photoelectrons and estimated the escape rate. On the other hand, narrow spikes of electrons fluxes have been observed by

both MGS [e.g., Mitchell *et al.*, 2001] and Mars Express [e.g., Dubinin *et al.*, 2008] over the strong crustal regions, which are thought to be solar wind electron precipitation along open field lines. Several studies have statistically investigated the dependence of this precipitation on external conditions as well as the effects on the atmospheric target [e.g., Brain *et al.*, 2005; Lillis and Brain, 2013; Xu *et al.*, 2015a; Shane *et al.*, 2016].

Electrons can only be used to infer topology where their motion is governed by electric and magnetic fields. We define a “foot point” as the location where a magnetic field line intersects the superthermal electron exobase. Below the foot point, electron motion is dominated by collisions rather than by the magnetic field, so that we can no longer deduce topology from energy-pitch angle distributions. As a specific example, we cannot distinguish between a weak crustal magnetic field line that extends above the electron exobase and a draped solar wind field line that dips below the electron exobase at low solar zenith angles. Additional information, such as the strength and orientation of the magnetic field at the spacecraft, is needed to infer the most likely scenario. In this study, we define magnetic topology based on whether a locally measured flux tube intersects the electron exobase.

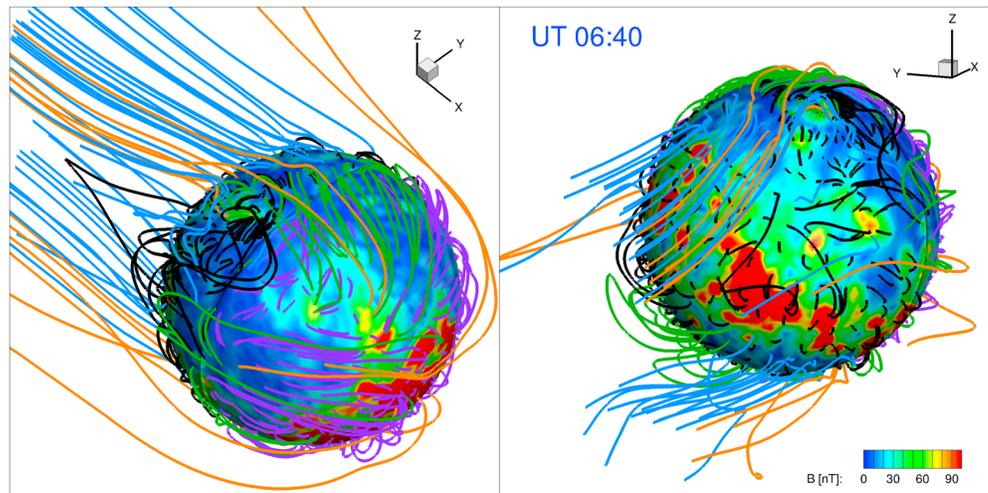
Previous missions have greatly improved our understanding of Martian magnetic topology; however, because of limitations in orbit geometry and science instrumentation, there has been no systematic mapping of magnetic topology at altitudes below 300 km until the Mars Atmosphere and Volatile Evolution (MAVEN) mission [Jakosky *et al.*, 2015]. MAVEN carries a comprehensive set of plasma and field instruments and has a periapsis as low as ~150 km (~120 km during “deep dips”), which is below the superthermal electron exobase. Xu *et al.* [2016b] reported ionospheric photoelectrons observed in the deep nightside (solar zenith angle (SZA) > 120°) below 150 km by Solar Wind Electron Analyzer (SWEA) [Mitchell *et al.*, 2016] onboard MAVEN, which indicated the existence of closed magnetic field lines that straddle the terminator in the northern hemisphere, allowing photoelectron transport from day to night. In this study, we analyze all electron energy/pitch angle distributions obtained to date by SWEA to statistically investigate Mars’ magnetic topology down to the superthermal electron exobase over wide ranges of solar zenith angle, local time, longitude, and latitude. The instrumentation is described in section 2. Then, sections 3 and 4 present how to use electron data, from which the pitch angle-resolved shape parameters are obtained, to deduce the magnetic topology, followed by the maps of different field line types in section 5. Sections 6 and 7 are the discussion and conclusions, respectively.

## 2. Instruments

The MAVEN mission aims to understand the loss of the Mars’ atmosphere to space at the current epoch and over the planet’s history. MAVEN has an elliptical orbit with an apoapsis of 2.8 Mars radii ( $R_M$ ) and a periapsis of ~150 km altitude, with several week-long deep dips, which sample key latitudes and local times down to ~120 km altitude. The inclination of the orbit is 74°, and the orbit period is 4.5 h.

SWEA is a symmetric hemispheric electrostatic analyzer with deflectors that measures the energy/angle distributions of electrons from 3 to 2000 eV over ~80% of the sky and electrons from 2000 to 4600 eV with a field of view that shrinks with energy. The 64 logarithmically spaced energy bins provide 12% ( $\Delta E/E$ ) sampling over the full range, which slightly oversamples the instrumental energy resolution of 17%. This is sufficient to distinguish ionospheric photoelectrons from (possibly energized) electrons of solar wind origin. The field view is divided into 96 solid angle bins, providing ~20° resolution. Pitch angle distributions can be obtained from the full energy/angle (3-D) distributions, but these have a low cadence (>16 s) because of telemetry rate limitations. The data described here are 2-D cuts (great circles) through the 3-D distributions that are calculated on board using real-time MAG data and designed to provide maximum pitch angle coverage, even as the magnetic field direction varies. This pitch angle distribution (PAD) data product is 6 times smaller than the 3-D product and is provided with a 2–4 s cadence, depending on altitude. See Mitchell *et al.* [2016] for a more detailed description.

The Magnetometer (MAG) is composed of two independent triaxial fluxgate sensors located on extensions (“diving boards”) at the ends of the solar panels. Each magnetometer measures the vector field with an accuracy of ~0.1 nT (including corrections for dynamic fields generated on the spacecraft) at a cadence of 1/32 s. More details about the MAG instrument are provided by Connerney *et al.* [2015].



**Figure 2.** (left and right) Field line tracing at UT 06:40 (the simulation starts at UT 00:00) from two perspectives, with the strong crustal fields on the dayside. The color on the spherical surface is the magnetic magnitude at 150 km. Different types of field lines are highlighted with colors, described in details in the text. The field lines are extracted from the simulation result in *Y. Ma et al.* [2014].

### 3. Superthermal Electrons and Magnetic Topology

The interaction of solar wind with the Martian ionosphere and crustal anomalies gives rise to several types of magnetic topology. The theoretical prediction of such a complex interaction from a time-dependent multispecies Mars magnetohydrodynamic (MHD) simulation [*Y. Ma et al.*, 2014; *Fang et al.*, 2015] is shown in Figure 2. The multispecies single-fluid MHD [*Ma et al.*, 2004] includes four continuity equations for four ion species,  $H^+$ ,  $O_2^+$ ,  $O^+$ , and  $CO_2^+$ , but assumes that all the ions share the same velocity and temperature. Details of the model are described in *Ma et al.* [2004]. This particular time-dependent run let the planet rotate for 26 h under quiet solar wind conditions, with a solar wind density of  $4\text{ cm}^{-3}$ , a velocity of 400 km/s, a Parker spiral interplanetary magnetic field (IMF) of  $-3\text{ nT}$  and  $56^\circ$  in the Mars-centered Solar Orbital (MSO)  $x$ - $y$  direction, and a plasma temperature of  $3.5 \times 10^5\text{ K}$ . The simulation was performed in the MSO coordinates; the  $x$  axis points from the center of Mars to the Sun, the  $y$  axis is opposite to the orbital motion of Mars, and the  $z$  axis is perpendicular to the Mars' orbital plane. Detailed setup of the simulation is described in *Y. Ma et al.* [2014].

Figure 2 shows an example of the field line tracing starting at 150 km in altitude at a specific time point when the strong crustal fields are on the dayside from two perspectives (left view from the Sun and right toward the Sun). The color contour on the spherical surface shows the magnetic magnitude at 150 km altitude. Different types of field lines are highlighted with colors: purple for closed field lines with both foot points on the dayside, black for closed field lines with both foot points on the nightside, green for one foot point on the dayside (solar zenith angle (SZA)  $< 90^\circ$ ) and the other on the nightside (SZA  $> 90^\circ$ ), orange for open field lines attached to the dayside ionosphere, and blue for open field lines attached to the nightside. Draped field lines are not present in this case because the tracing starts at 150 km, and according to our definition above, we are treating all field lines crossing this altitude (i.e., the electron exobase) as either open or closed. Each type of field lines has access to different electron populations, photoelectrons, or solar wind electrons, in each end. This information of electron populations in return can be utilized to retrieve the magnetic topology.

As mentioned above, SWEA has a fine energy resolution to distinguish ionospheric photoelectrons from solar wind/magnetosheath electrons based on their energy spectral shape. As noted in several studies [e.g., *Mitchell et al.*, 2000; *Liemohn et al.*, 2003; *Frahm et al.*, 2006], the Martian photoelectron energy spectrum has a several distinct features, corresponding to features in solar irradiance [e.g., *Xu et al.*, 2015b; *Peterson et al.*, 2016]: (1) a cluster of sharp peaks from 22 to 27 eV due to ionization of  $CO_2$  and O by the intense He II 30.4 nm ( $\sim 40\text{ eV}$ ) solar line, (2) a sharp drop in flux from 60 to 70 eV (the photoelectron knee) due to a corresponding sharp decrease of solar irradiance at wavelengths shorter than 17 nm, (3) a

**Table 1.** Criteria for Determining Magnetic Field Topology (Closed, Open, Draped, and Void) Based on Electron Populations Traveling Parallel and Antiparallel to the Magnetic Field on the Dayside and the Nightside, Respectively<sup>a</sup>

	Dayside (SZA < 90°)	Nightside (SZA > 110°)
Closed	Ph e <sup>-</sup> in both directions (purple)	Ph e <sup>-</sup> traveling toward the planet (green)
Open	Ph e <sup>-</sup> in one direction; SW e <sup>-</sup> in the opposite direction (orange)	Ph e <sup>-</sup> traveling away from the planet; SW e <sup>-</sup> traveling toward the planet (orange)
Draped	SW e <sup>-</sup> in both directions (draped IMF)	SW e <sup>-</sup> in both directions (blue and draped IMF)
Void (closed)	NA	Low omnidirectional electron fluxes (black)

<sup>a</sup>Photoelectron is denoted as "Ph e<sup>-</sup>" and solar wind/sheath electron as "SW e<sup>-</sup>." The colors in the parenthesis indicate the field lines in Figure 2.

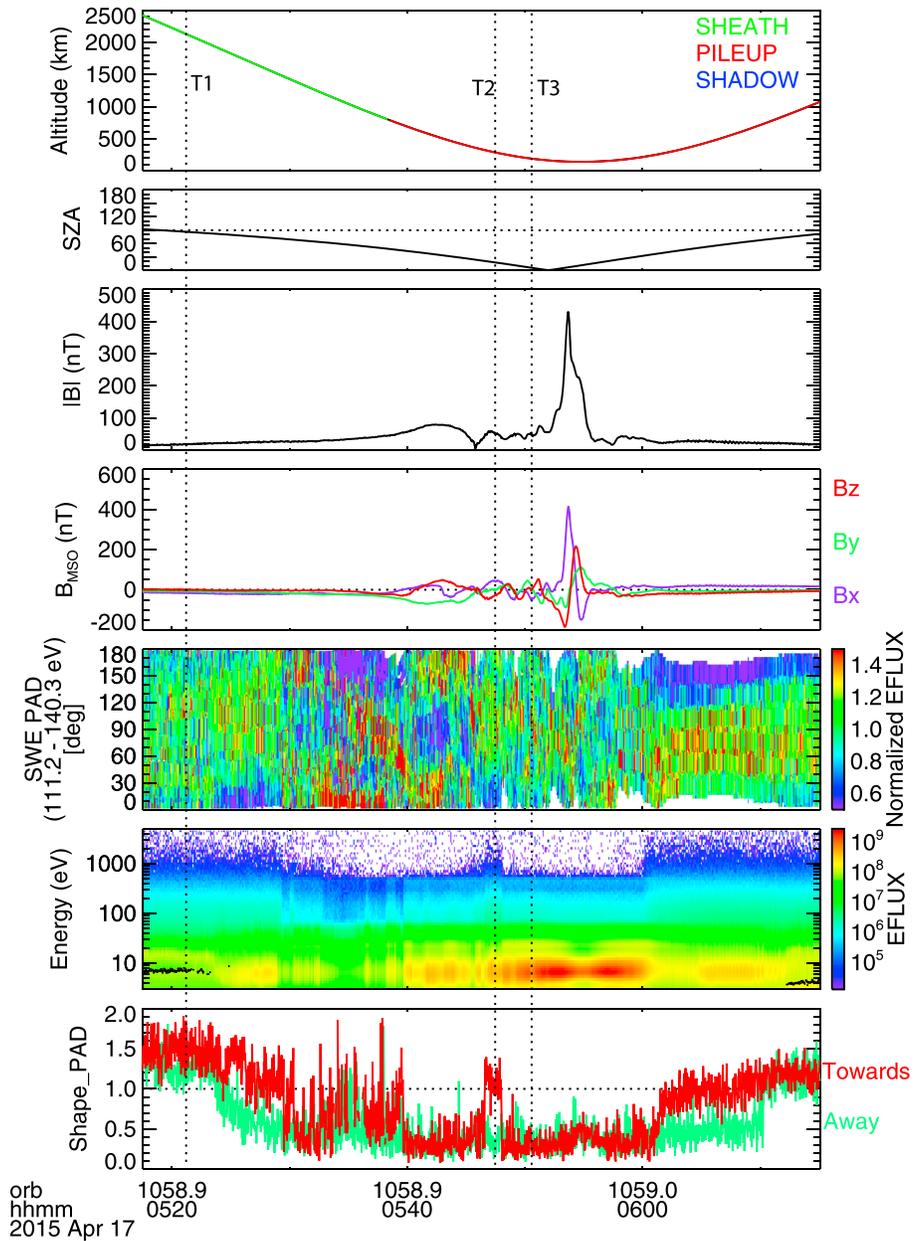
peak near 500 eV produced by ionization of oxygen K-shell electrons by soft X-rays (and subsequent relaxation of the resulting excited ion by the emission of photons and Auger electrons), and (4) a second sharp decrease in electron flux at energies just above the Auger peak due to another drop in solar irradiance. In contrast, these features are absent in the energy spectra of solar wind electrons in all regions of the Mars' plasma environment. Although SWEA cannot resolve the cluster of photoelectron peaks from 22 to 27 eV, the energy resolution is sufficient to readily distinguish between photoelectrons and solar wind electrons.

To infer magnetic topology, the basic idea of this study is to examine what electron population, ionospheric photoelectrons versus solar wind electrons, is measured in the parallel and antiparallel directions. The topology criteria are slightly different for the dayside and nightside hemispheres. In this study, we define the dayside as solar zenith angle (SZA) < 90° and the nightside as SZA > 110° to ensure that the ionosphere near and below the electron exobase is in darkness [cf., *Shane et al.*, 2016]. On the dayside, a closed field (purple lines in Figure 2) is defined as one on which photoelectrons are being measured in both parallel and antiparallel directions. Closed field lines with both ends intersecting the collisional dayside ionosphere fill with photoelectrons and are simultaneously isolated from solar wind electrons. An open field line (orange lines in Figure 2) is identified as having photoelectrons in one direction and solar wind electrons in the other, as one end of the field is attached to the ionosphere and the other to solar wind; the draped field (not shown in Figure 2) is designated when solar wind/sheath electrons are found in both directions, as the field line connects to the solar wind on both ends.

In the darkness of the nightside ionosphere, there is no photoelectron production, so we use a different set of criteria. There are two types of closed field lines on the nightside: (1) one foot point on the dayside and another on the nightside (a cross-terminator closed field line; green lines in Figure 2) and (2) both foot points on the nightside (black lines in Figure 2). In the first case, photoelectrons are produced on the dayside, travel across the terminator along the field line (above the electron exobase), and precipitate into the nightside. Part of the returning flux is magnetically reflected, while the more field-aligned flux suffers collisions with the neutral atmosphere, forming a loss cone. We denote photoelectrons flowing toward the planet as a closed field line. In the second case, there is no photoelectron production at either foot point and no access for solar wind electrons. Superthermal electron fluxes in both directions are ~2 orders of magnitude lower than typical fluxes of either photoelectron or solar wind electron populations. We define this situation as a superthermal electron void.

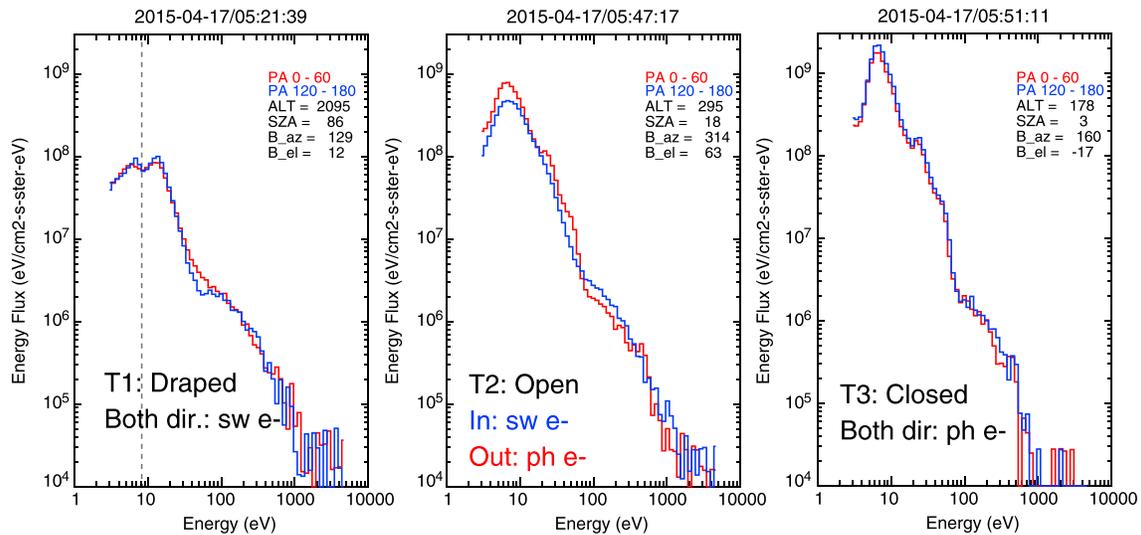
For open field lines, one end is connected to the solar wind while the other intersects the electron exobase on either the dayside (orange lines in Figure 2) or the nightside (blue lines in Figure 2). We identify the first case by observing photoelectrons flowing away from the planet and solar wind electrons flowing toward the planet. We identify the second case as measuring solar wind electrons in both directions, which can arise from solar wind electrons traveling toward the planet and magnetically reflected and/or backscattered electrons traveling in the opposite direction. Thus, one drawback of this particular methodology is that we are unable to differentiate the open field lines attached to the nightside from draped solar wind magnetic fields.

On the dayside, we organize our results into three topological categories: closed, open, and draped (Table 1), which correspond with the definitions used by previous authors. However, on the nightside, because we infer topology based on the presence of ionospheric photoelectrons (which are produced in sunlight), we use the following restricted definitions for these categories. "Closed" refers specifically



**Figure 3.** (top to bottom) Time series of the spacecraft altitude, SZA, magnetic field strength, magnetic field components in the MSO coordinates, the normalized pitch angle distribution of 111–140 eV electrons, the energy spectra, and shape parameters for electrons moving toward (red) and away from (green) the planet, respectively. The blue, green, and red colors in the altitude plot highlight the theoretical region for the optical shadow, magnetosheath, and the pileup region based on fittings of the bow shock and the magnetic pileup boundary [Trotignon *et al.*, 2006]. Three dashed vertical lines mark the time of extracted electron energy spectra in Figure 4. The black dots in the electron energy spectrogram plot indicate the spacecraft potential estimated by SWEA.

to transterminator closed field lines, with one foot point on the dayside and the other on the nightside. “Open” refers specifically to field lines with one foot point on the dayside and the other end connected to the IMF. “Draped” refers to field lines that are connected to the IMF on both ends (the normal definition) but also includes open field lines with one foot point on the nightside and the other connected to the IMF. In the latter case, solar wind electrons are observed in both directions because of backscatter and/or magnetic reflection. “Voids” are a second category of closed field line with both foot points on the nightside.

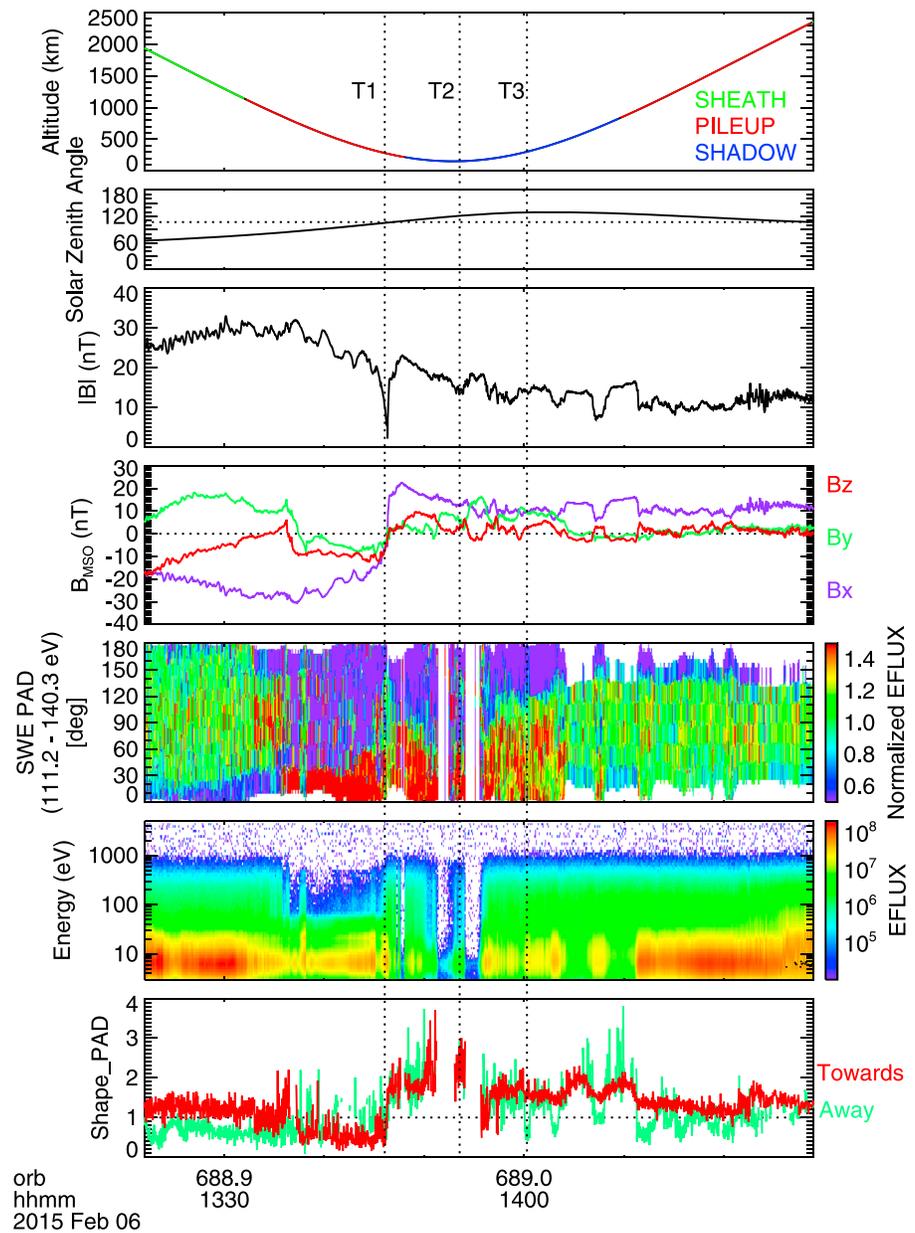


**Figure 4.** Electron energy spectra for the parallel (red) and antiparallel (blue) directions measured by SWEA. The red spectrum is averaged over pitch angles 0–60° and the blue spectrum over pitch angles 120°–180°. The vertical dashed line in the left plot marks the spacecraft potential. The altitude and SZA of the measurement, as well as the azimuthal (in the horizontal plane) and elevation angles (relative to the horizontal plane) of the local magnetic field, are shown in the top right corner. The three plots corresponding to the time marked out by the three dotted vertical lines in Figure 3.

#### 4. Shape Parameter

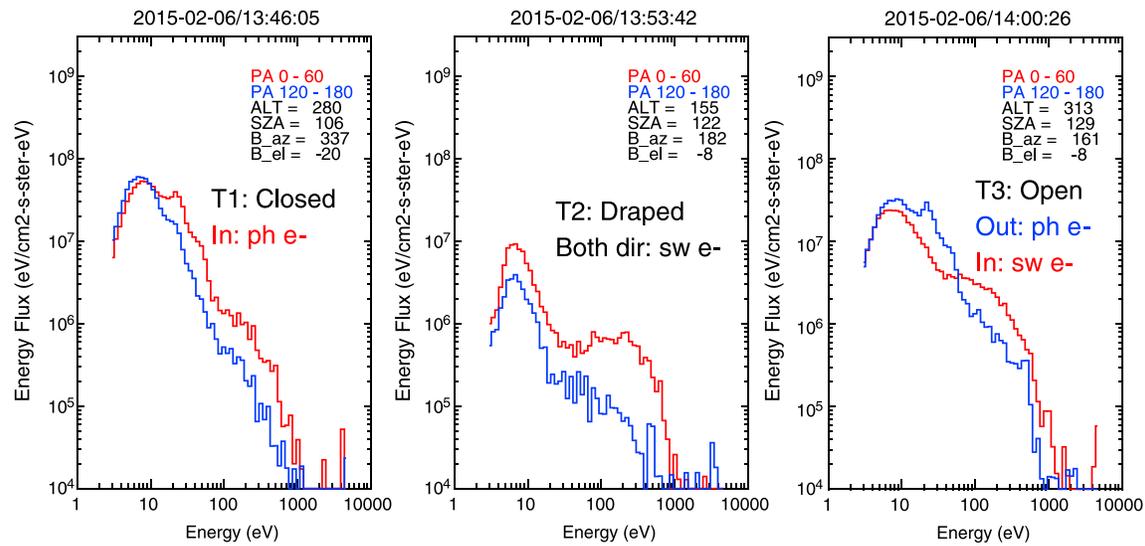
To systematically distinguish ionospheric photoelectrons from solar wind electrons, we have designed a shape parameter to identify the He II peaks and the photoelectron knee in the measured energy spectra. We manually selected 60 photoelectron energy spectra and then calculated the derivative of the electron fluxes with respect to energy log space ( $d(\log F)/d(\log E)$ ) using the three-point Lagrangian interpolation for each spectrum. This differentiation removes overall changes in the electron flux caused by variations in solar irradiance [e.g., Banks and Nagy, 1970; Xu and Liemohn, 2015] and the neutral atmospheric composition [e.g., Xu et al., 2014; Xu et al., 2015c] and also highlights sharp features in the spectral shape of photoelectrons, such as the He II peaks and the photoelectron knee, which are observed in photoelectrons but not the solar wind. We average the 60 derivatives to produce a template with good counting statistics (Figure S1 in the supporting information, black squares). For any measured electron distribution, we can calculate the electron flux derivatives and compare with the template. We define the shape parameter as the sum of the absolute differences between the measured derivative and the template from 20 eV to 80 eV. The more similar the observed derivative is to the template, the smaller the shape parameter and the more likely that the observed distribution contains photoelectrons. Figure S1 shows how a photoelectron observation (red) follows the template and has a small shape parameter, while a solar wind observation (blue) fails to capture the two sharp photoelectron features and has a large shape parameter. Although the shape parameter is a continuous quantity, since both populations can be present in various proportions on a given field line, we find that a value of unity provides a useful separation of distributions dominated by photoelectrons (shape parameter  $<1$ ) and those dominated solar wind electrons (shape parameter  $>1$ ). The shape parameter is calculated separately for the parallel (0°–60° pitch angle) and antiparallel (120°–180° pitch angle) populations. From the local magnetic field direction, we can determine which population is traveling toward the planet and which population is traveling away.

To demonstrate how the shape parameter works, we have selected two orbit examples, for dayside and nightside observations. For the dayside, Figure 3 shows the MAVEN measurements made from 05:17 to 06:15 UT (universal time) on 17 April 2015. The plots from top to bottom are the altitude, solar zenith angle (SZA), magnetic field strength and magnetic field components in MSO coordinates measured by MAG, the normalized 111–140 eV electron pitch angle distribution, and the electron energy spectra measured by SWEA (energy fluxes in units of  $\text{eV cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{eV}^{-1}$ ) and shape parameters for electrons moving toward (red) and away from (green) the planet, respectively. The direction of the electrons relative to the planet is determined based on the local magnetic field measurement. During this time range, the spacecraft moves



**Figure 5.** (top to bottom) Time series of the spacecraft altitude, SZA, magnetic field strength, magnetic field components in the MSO coordinates, the normalized pitch angle distribution of 111–140 eV measured, the energy spectra, and shape parameters for electrons moving toward (red) and away from (green) the planet, respectively. Same format as in Figure 3.

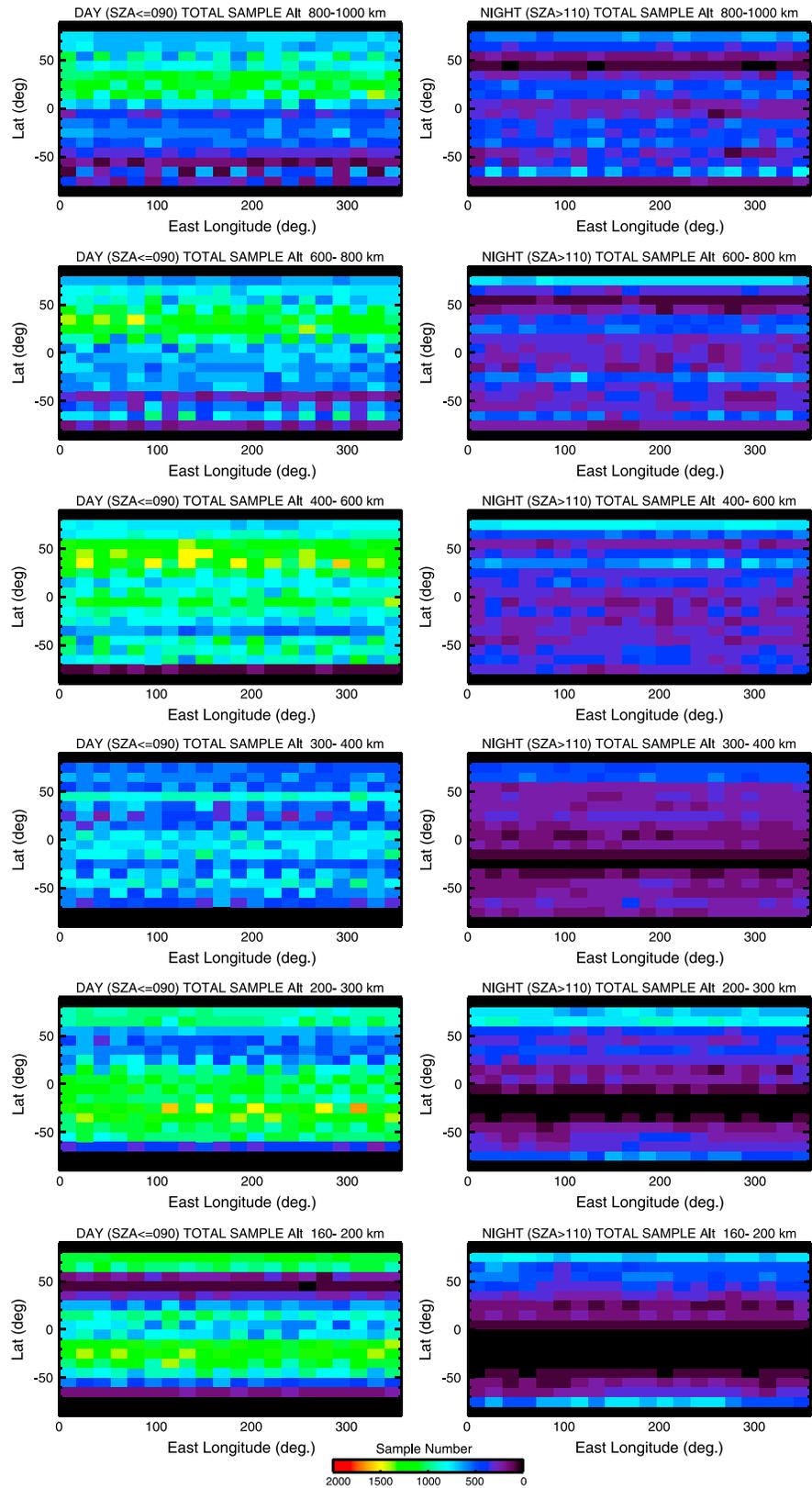
from high altitudes, where the magnetic field is weak, through the periapsis, which is dominated by the crustal fields (~05:40–05:56 UT), and then back to high altitudes. The three bottom plots simultaneously exhibit systematic, correlated changes. From 05:17 to 05:24 UT, the pitch angle distribution (PAD) is nearly isotropic, while the shape parameters for both directions are above 1. The left plot of Figure 4 shows the parallel and antiparallel electron spectra obtained at T1, marked by the first dotted vertical line in Figure 3. The electron spectra in both directions are typical solar wind/sheath electron spectra, with no evidence for photoelectron features. The local minimum at ~8 eV is caused by the spacecraft potential (vertical dashed line), which separates spacecraft photoelectrons at lower energies from ambient electrons at higher energies. From 05:30 to 06:00, the electron energy spectrogram (second plot from the bottom) shows one local maximum from 20 to 30 eV, corresponding to the He II feature of the photoelectrons, and another



**Figure 6.** Electron energy spectra for parallel (red) and antiparallel (blue) directions measured by SWEA. The red spectrum is averaged over pitch angle 0–60° and the blue spectrum over pitch angle 120°–180°. The three plots corresponding to the time marked out by the three dotted vertical lines in Figure 5.

one near 500 eV, indicative of Auger electrons. Meanwhile, the shape parameters for both directions are below 1 (except for a brief interval from 05:46 to 05:48 UT, which will be described below). An example of the electron spectra in this region is shown in the right plot of Figure 4. Several photoelectron spectral features are present in both directions, including the He II peaks, the photoelectron knee, and the sharp drop in electron flux above ~500 eV. There are also time periods during which the shape parameter is  $<1$  for electrons traveling away from the planet and  $>1$  for electrons traveling toward the planet, including 05:24–05:30 UT, 05:46–05:48 UT, and 06:02–06:10 UT. During these time intervals, the pitch angle distribution exhibits a one-sided loss cone, which is classified as an indicator for open field lines [see *Brain et al.*, 2007]. The parallel and antiparallel electron spectra for this case are shown in the middle plot of Figure 4. The local magnetic field has an elevation angle (relative to the horizontal plane) of 63°, pointing away from the planet; therefore, parallel electrons are flowing away from the planet and antiparallel electrons toward the planet. This conversion from pitch angles to the direction relative to the planet is implied below based on the local magnetic elevation angle. The spectrum for electrons traveling away from the planet (0°–60° pitch angle; red) shows typical photoelectron features, and the spectrum for electrons traveling in the opposite direction (120°–180° pitch angle; blue) is typical for the solar wind. Thus, the pitch angle-resolved shape parameter provides a reliable method for determining the source regions of the parallel and antiparallel electron populations, which we use to infer magnetic topology.

For the nightside, an example orbit on 6 February 2015 is shown in Figure 5, in the same format as in Figure 3. The spacecraft was on the nightside ( $SZA > 110^\circ$ ) from 13:47 to 14:28 UT. Three parallel/antiparallel spectral pairs, selected at times marked by the dotted vertical lines in Figure 5, are chosen and shown in Figure 6. For T1, both shape parameters are  $<1$  (Figure 5) and in the left plot of Figure 6. Electrons traveling toward the planet exhibit apparent photoelectron spectral features (Figure 6, left plot, red spectrum), interpreted as photoelectrons precipitating into the nightside on a closed field line that straddles the terminator. The spectra of electrons traveling in the opposite direction (blue) show only faint He II peaks and no clear evidence for a photoelectron knee. This pair of spectra indicates a closed field line with one foot point in the dayside ionosphere and the other foot point in darkness. Photoelectrons produced at the sunlit foot point travel along the field line and precipitate onto the dark foot point. A fraction of the precipitating flux is backscattered, with the photoelectron features washed out mainly by inelastic collisions. This measurement, however, was made near the terminator, and a better example for such a scenario is shown in *Xu et al.* [2016b]. More often than not, the spectrum of backscattered photoelectrons is too washed out to be identified by the shape parameter. Thus, for the nightside, the criterion for a closed field line is only that precipitating electrons have a shape parameter less than 1. For T2, the shape parameters are all  $>1$  and the spectra for both directions (Figure 6, the



**Figure 7.** The total sample number against latitude and longitude. (left column) Dayside ( $SZA < 90^\circ$ ) and (right column) nightside ( $SZA > 110^\circ$ ). (top to bottom) Each row is for the altitude range of 800–1000 km, 600–800 km, 400–600 km, 300–400 km, 200–300 km, and 160–200 km, respectively.

middle plot) are solar wind/sheath-like. There are several time intervals when the shape parameter for electrons traveling away from the planet dips below 1 and remains above 1 for electrons traveling toward the planet. One example marked as T3 is shown in the right plot of Figure 6. The outflowing flux has a photoelectron spectrum (blue), while precipitating flux has a solar wind/sheath-like spectrum (red). To have access both populations, the field line has to have a foot point on the dayside, is pulled back to the nightside (where the measurement is made), and opens to the solar wind (see the yellow lines in Figure 2). Such open field lines have access to the dayside ionosphere and provide a path for ion escape. The last type of topology, superthermal electron voids, is another example of closed field lines, which exists mostly on the nightside. This can be seen in Figure 5, during the time intervals 13:52–13:53 UT and 13:54–13:56 UT, corresponding to extremely low electron fluxes (at or close to the background level at most energies) as well as the absence of shape parameters in both directions. (Our software tags shape parameters for such intervals as undefined.) A reliable method of identifying these regions is to set an energy flux threshold of  $10^5 \text{ eV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ eV}^{-1}$  at an energy of 40 eV. Observed fluxes below this threshold are identified as voids.

The two example orbits have demonstrated that the pitch angle-resolved shape parameter is reliable to infer the magnetic topology. However, a complication is that the shape parameter is a gradually increasing, instead of binary, number to represent changing from photoelectrons to solar wind electrons. The threshold of 1 used in this study is reasonable, but we have tested other thresholds, 0.7, 0.8, 1.2, and 1.4. The overall findings of this study stay the same, but the occurrence rate for each type of topology changes with different thresholds, as expected. In particular, when shape parameter is close to 1, it might be a mixed spectrum of both photoelectrons and solar wind/sheath electrons, for example, having both the He II feature and a less prominent flux drop near the photoelectron knee, or a degraded spectrum like the blue line in the left plot in Figure 6. In addition, when the magnetic elevation angle is small, a small perturbation in the magnetic field can change the field line direction, then the classification of away/toward for the shape parameter, consequently the determination of the topology. This is also why we do not distinguish solar wind electron flowing toward or away from the planet for open field lines on the dayside (see Table 1). These complications are important to take into consideration to analyze case studies. For this statistical study, the simple classifications in Table 1 are sufficient to obtain magnetic topology maps below.

## 5. Maps for Magnetic Topology

Now that we have established the methodology to infer magnetic topology from the pitch angle-resolved shape parameters to determine the magnetic topology, the three-dimensional maps can be created by examining all the available MAVEN data, from 1 December 2014 to 2 May 2016. This study is limited to an altitude range of 160–1000 km to investigate the crustal field control of the Martian magnetic topology. Above 1000 km altitude, the strongest crustal magnetic fields are comparable in strength to the solar wind magnetic field [e.g., *Brain et al.*, 2003]. Below 160 km altitude, collisions become important for superthermal electrons [*Xu et al.*, 2016a], and the pitch angle distribution becomes isotropic, so that our method for inferring topology is no longer valid.

The data are divided into six altitude ranges: 800–1000 km, 600–800 km, 400–600 km, 300–400 km, 200–300 km, and 160–200 km. For each altitude range, the data are further divided into  $18^\circ \times 10^\circ$  geographic longitude-latitude bins. Finally, we divide the data into dayside ( $\text{SZA} < 90^\circ$ ) and nightside ( $\text{SZA} > 110^\circ$ ). Although we present data mapped into geographic longitude and latitude, it is important to note that each bin contains all local times that fall within the SZA range. The total sample number for each bin (Figure 7) is the sum of all cases identified according to Table 1. Because 20% of the sky is outside SWEA's field of view, there is occasionally insufficient pitch angle coverage to calculate the parallel or antiparallel shape parameter. For this reason, 4% of data are excluded on the dayside and 18% on the nightside. The percentage of excluded spectra is higher on the nightside because the magnetic field direction tends to be close to the Mars-Sun line and thus near the edge of SWEA's field of view.

Before calculating the shape parameter, it is necessary to correct the electron data for energy shifts caused by the spacecraft potential ( $\phi_{sc}$ ) shifting the electron energy spectra [*Mitchell et al.*, 2016]. When  $|\phi_{sc}| > 4 \text{ V}$ , the shift is large enough that the shape parameter for an uncorrected photoelectron spectrum can exceed 1. Depending on spacecraft orientation and plasma environment, the spacecraft potential is typically in the

range of  $-20$  to  $+10$  V. We have corrected the data for spacecraft potentials estimated from SWEA measurements, ranging from  $-16$  V to  $-1$  V in the ionosphere and  $> +3$  V throughout the Mars environment. There is no need to correct for potentials from  $-1$  to  $+3$  V; however, some data must be excluded when the potential is more negative than  $-16$  V.

Our current understanding of Mars' magnetic environment (based mostly on MGS observations) is that the southern hemisphere is dominated by crustal fields (to an altitude that depends on crustal field strength), while the north is dominated by draped solar wind magnetic fields [Brain *et al.*, 2003, 2006]. For the first time, the MAVEN orbit allows measurements of magnetic topology over wide ranges of local time, longitude, latitude, and altitude (Figure 7). The altitude ranges from the electron exobase ( $\sim 160$  km) to 400 km is of particular interest, because this region was sparsely mapped by MGS, with most of the measurements in the sunlit northern hemisphere.

### 5.1. Closed Field Lines

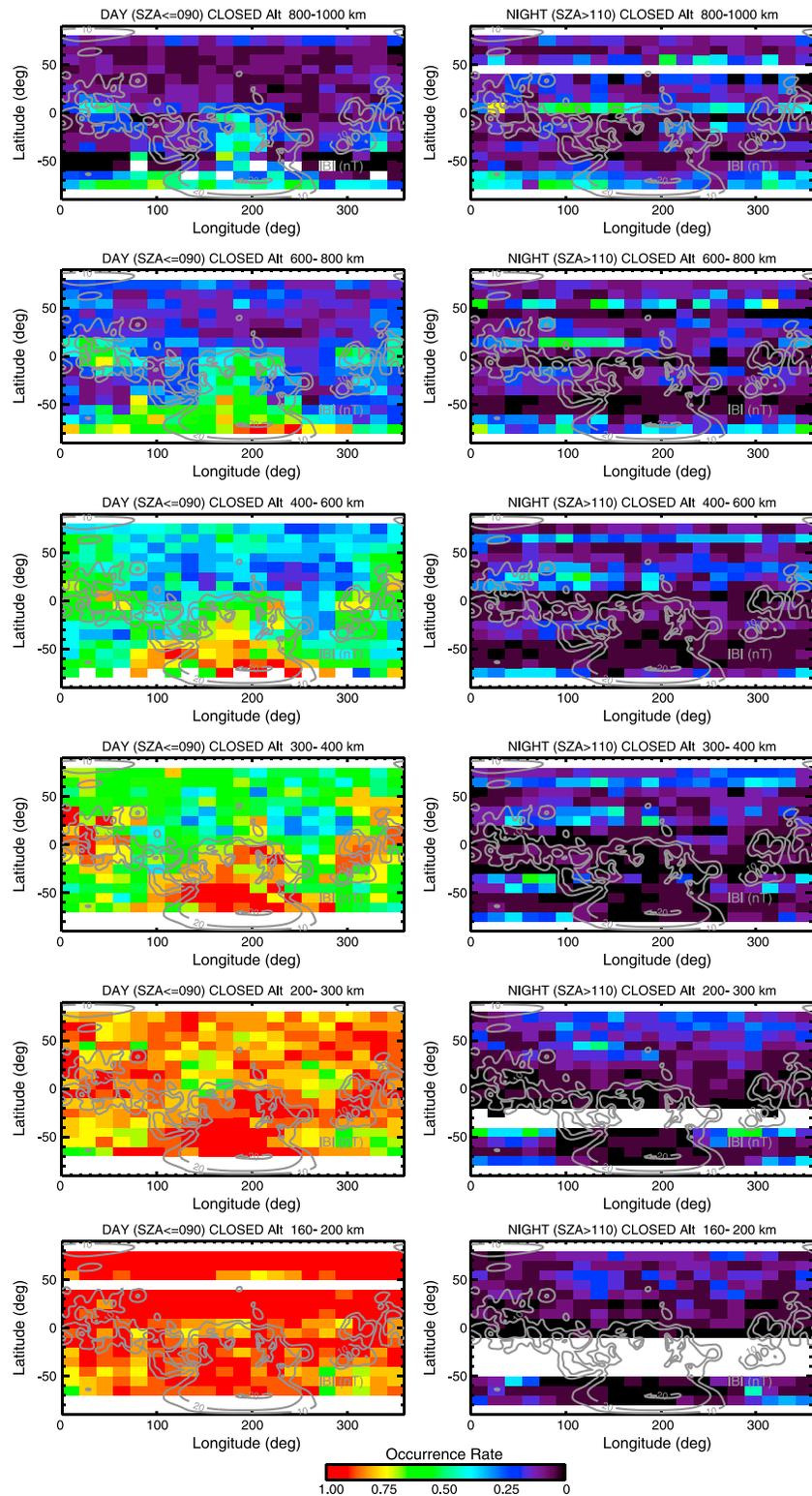
Figure 8 presents the occurrence rate of closed field lines on the dayside (left column) and the nightside (right column). The occurrence rate is the number of spectra satisfying the criteria for this category (Table 1) divided by the total sample number. The rows from top to bottom show the results for altitude ranges of 800–1000 km, 600–800 km, 400–600 km, 300–400 km, 200–300 km, and 160–200 km, respectively. Bins with no value (white) occur when the total sample number is less than 50, which applies to Figures 9–11 as well. The gray contours are the modeled crustal magnetic field magnitude at 400 km [Morschhauser *et al.*, 2014]. On the dayside, the most prominent trend is that the occurrence rate of closed field lines increases with decreasing altitude. This trend occurs over regions where the crustal field is relatively strong, as expected; however, it also occurs in the northern hemisphere, with closed field lines eventually dominating below 300–400 km (occurrence rate  $> 50\%$ ), even over Hellas and Tharsis, the two most weakly magnetized regions of the crust. In the lowest altitude range, magnetic field lines are actually less likely to be closed in some regions of the southern hemisphere, particularly near longitudes of  $20^\circ$  and  $300^\circ$  and poleward of  $40^\circ$ S. Instead, these regions tend to have a fair amount of open field lines (see section 5.2).

For  $SZA > 110^\circ$ , photoelectrons produced in the sunlit ionosphere can travel along closed magnetic field lines above the electron exobase and precipitate onto the nightside atmosphere [Xu *et al.*, 2016b]. The occurrence rate for such a magnetic field configuration is presented in the right column of Figure 8. Overall, the rate is generally below 25% but exceeds 50% in some regions. The occurrence rate drops below 200 km altitude, possibly because of proximity to the electron exobase, where inelastic collisions degrade the photoelectron features. For altitudes above 600 km, the maps are very similar, with regions of relatively high occurrence rates in the northern hemisphere and over the south polar region. Below 600 km, low occurrence rates correspond to the strong crustal fields, suggesting that field lines tend to close more locally in these regions (see section 5.4).

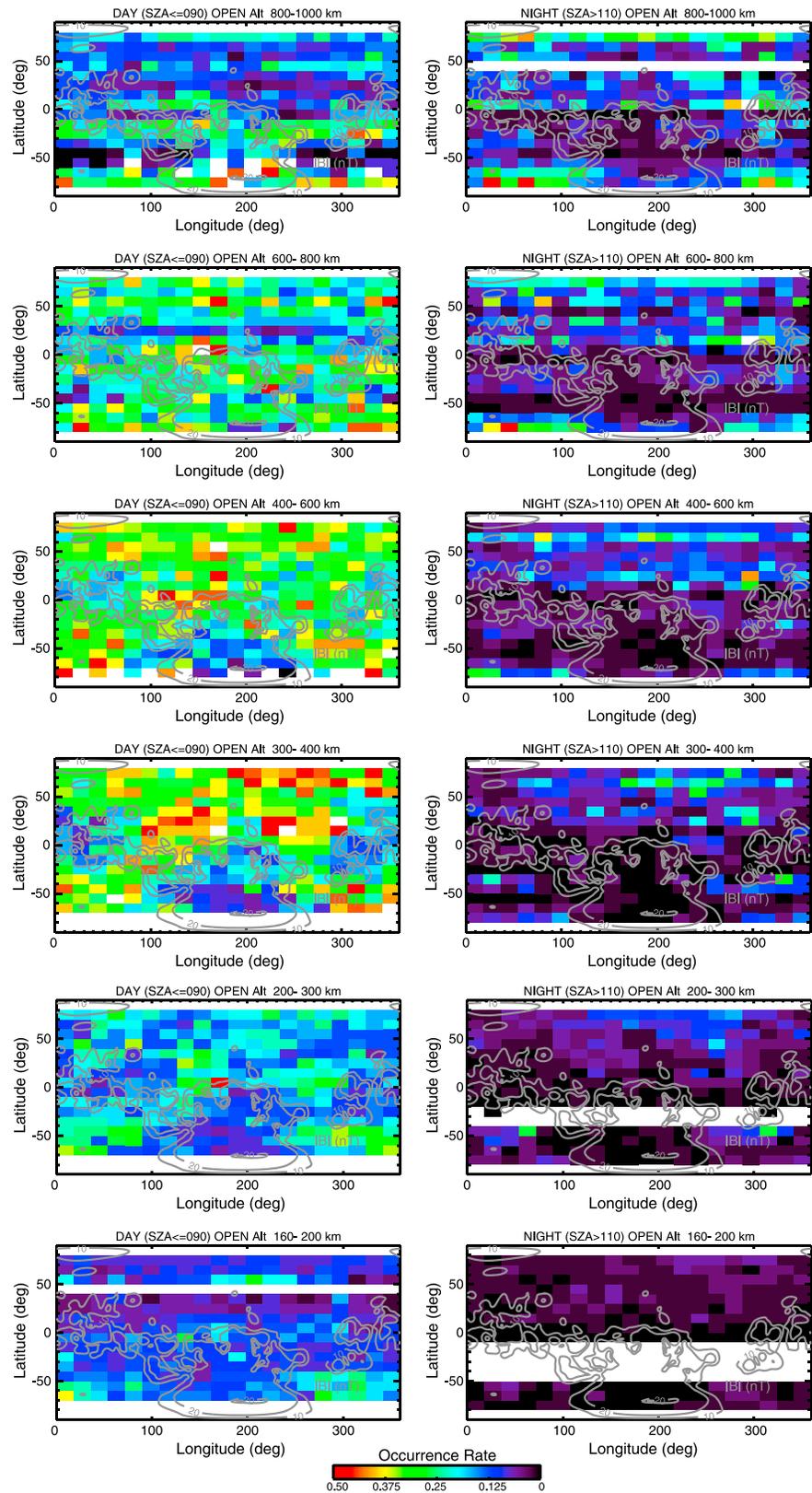
### 5.2. Open Field Lines

Maps for open field lines are shown in Figure 9, with the same format as in Figure 8 but with a more compressed color scale. On the dayside, different trends can be seen over weak and strong crustal magnetic sources. Over weak sources (mostly in the northern hemisphere), the occurrence rate for open field lines is low above 800 km altitude, increases to  $\sim 30$ – $50\%$  in the 300–400 km range, and then falls significantly below 200 km, where closed field lines dominate, as noted above. We will discuss this phenomenon in detail in section 6. Finally, we note that one region of open field lines in the northern hemisphere ( $50^\circ$ – $60^\circ$ N,  $160^\circ$ – $250^\circ$ E) does map down to the 160–200 km altitude range. These open field lines may be associated with crustal sources near Arcadia (Figure 1).

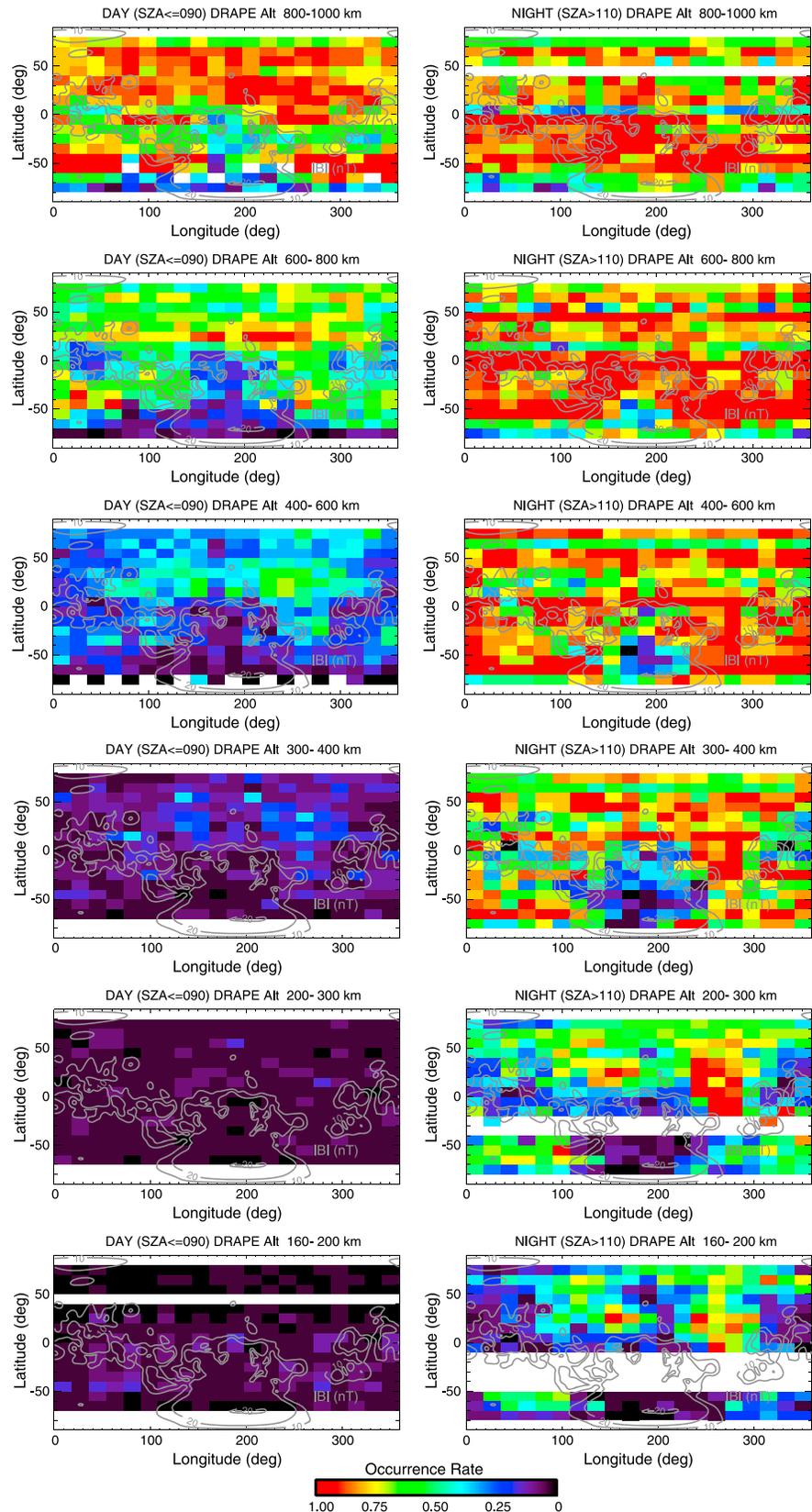
At high altitudes ( $> 800$  km) over strong sources, open field lines cluster over the strong crustal sources and are likely magnetic cusps that span large angular ranges at this high altitude. These cusps are expected to become narrower with decreasing altitudes as they approach the crustal sources; however, our longitude-latitude grid is too coarse to identify this effect. The high occurrence rate of open field lines over the weakly magnetized regions within  $30^\circ$  of both poles, as well as on the nightside (right top plot), is probably due to open field lines originating from crustal sources and extending to high altitudes over the poles as they flare away from the Mars-Sun line. As the altitude decreases from 800 to 400 km, open field lines become less common over strong crustal sources, as closed field lines become predominant. Below 200 km, the occurrence rate of open field lines



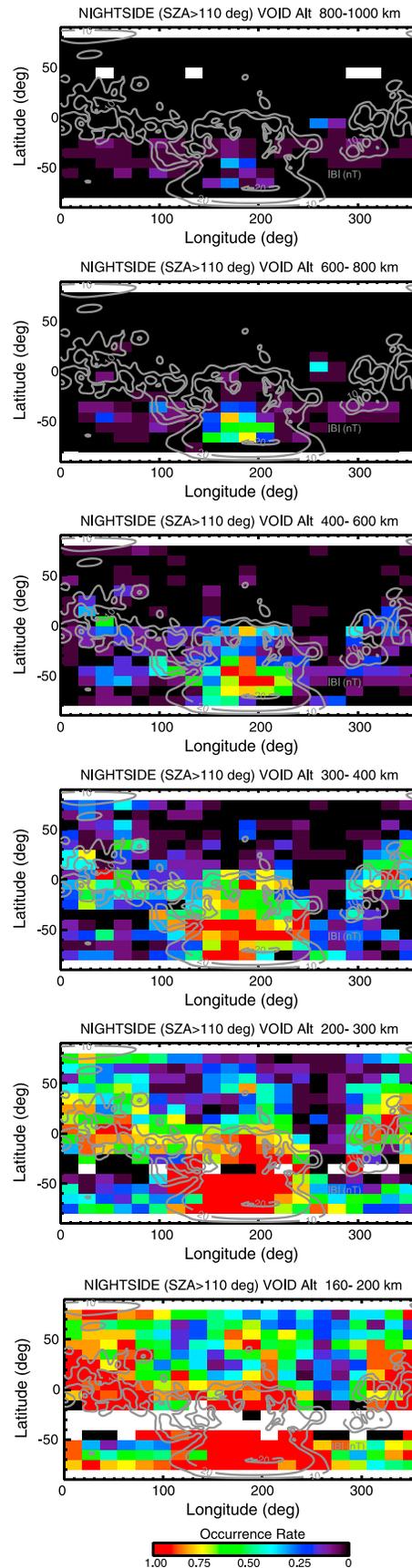
**Figure 8.** The occurrence rate for closed magnetic field lines (color scale) based on pitch angle-resolved shape parameters is mapped in geographic longitude and latitude. (left column) Maps for the dayside ( $SAZ < 90^\circ$ ) and (right column) nightside ( $SAZ > 110^\circ$ ) are shown. Representative field line geometries for the left (right) column are the purple (green) lines in Figure 2. (top to bottom) Altitude ranges for each row are 800–1000 km, 600–800 km, 400–600 km, 300–400 km, 200–300 km, and 160–200 km, respectively. The gray contours are the modeled crustal magnetic field magnitude at 400 km [Morschhauser et al., 2014].



**Figure 9.** The maps of open field lines, the same format as in Figure 8. The color scale is from 0 (black) to 0.5 (red). (left and right columns) The representative field line geometry is illustrated by the orange field lines in Figure 2. The difference is whether it was observed on the dayside or nightside.



**Figure 10.** The maps of draped field lines, the same format as in Figure 8. The color scale is from 0 (black) to 1 (red). (right column) Both the draped IMF and open field lines attached to the nightside atmosphere (green lines in Figure 2).



is low over most of the planet, except for Arcadia in the north, as noted above, and for two regions poleward of 40°S and centered near longitudes of 20° and 300°. The two southern regions of open field lines may map to relatively weak crustal magnetic sources around the periphery of the Hellas and Argyre impact basins (Figure 1).

In the northern hemisphere at solar zenith angles greater than 110°, open field lines with access to the dayside ionosphere are rare below 200 km altitude (Figure 9, bottom right plot). This is not unexpected, since open field lines originating in the dayside ionosphere, which become much more common above 200 km in the northern hemisphere, should flare away from the planet with increasing distance. This picture is confirmed by the first appearance of open field lines on the nightside in the 200–300 km altitude bin, with a generally increasing occurrence rate at higher altitudes. The two regions of open field lines at high southern latitudes (>60°S, 20°–120°E and >60°S, 290°–300°E) are likely associated with strong crustal magnetic sources near the South Pole. Interestingly, even for 800–1000 km in altitude, a region of low occurrence rates is seen and resembles the strong crustal regions (Figure 1), suggesting crustal control. While it might imply fewer open field lines resulting from interaction with IMF on the dayside when the strong southern crustal field located on the nightside, it is more likely that the underlying strong crustal fields on the nightside compel surrounding field lines away, which is an indirect proof of crustal control on the nightside extending beyond 1000 km [Brain et al., 2003].

**Figure 11.** The maps of voids on the nightside (SZA > 110°). The color stands for the occurrence rate. The representative field line geometry is the black lines in Figure 2. (top to bottom) Each plot is for the altitude range of 800–1000 km, 600–800 km, 400–600 km, 300–400 km, 200–300 km, and 160–200 km, respectively. The color scale is from 0 (black) to 1 (red). The gray contours are the modeled crustal magnetic field magnitude at 400 km [Morschhauser et al., 2014].

### 5.3. Draped Field Lines

Figure 10 shows the occurrence rate for the draped IMF on the dayside (the left column) and the nightside (the right column). On the dayside, the occurrence rate increases with altitude, as expected. Below 400 km altitude, the field lines are mostly closed or open, so that few are draped. Beginning at ~400 km, IMF starts to drape over the northern hemisphere, with an occurrence rate of 20%–50% in the 400–600 km range, >50% in the 600–800 km range, and ~100% above 800 km. In the south, strong crustal field regions can be discerned up to 1000 km with low draping occurrence rates and correspondingly high open and closed rates. A relatively high occurrence rate of draped fields is above 800 km in the 40°–60°S latitude range but avoiding the longitudes of the strongest crustal sources from 160° to 250°E. This latitude band includes the Hellas and Argyre basins, which are the most weakly magnetized regions of the southern hemisphere. Thus, it appears that draped IMF occupies a trough between strong crustal fields to the north and south. This is consistent with the analysis of MGS aerobraking magnetometer data [Brain *et al.*, 2003], which indicates that the influence of the strongest crustal fields extends up to ~1000 km altitude on the dayside.

On the nightside, the occurrence rate is mostly higher than on the dayside, because the classification of draped field lines here includes both draped IMF and open field lines with one foot point on the nightside. Since draped field lines are expected to flare away from the Mars-Sun line with distance down the tail, the draped occurrence rate on the nightside is probably dominated by open field lines with foot points in the nightside atmosphere. The low occurrence rates below 800 km over strong crustal sources correspond to the locations of voids (see below).

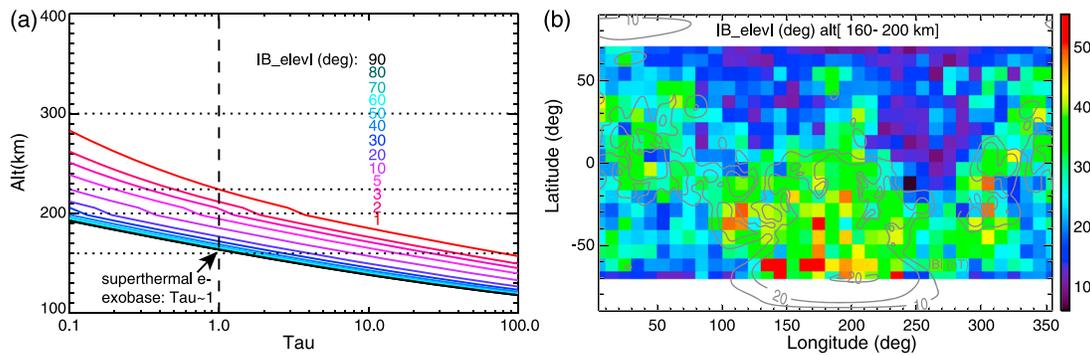
### 5.4. Voids

Superthermal electron voids occur on closed crustal magnetic loops with both foot points in the nightside atmosphere, and any trapped electron population has pitch angle scattered into the loss cone or drifted out of the flux tube (Figure 11), so that the omnidirectional flux falls below our threshold (Table 1). Below 200 km, the void occurrence rate is >50% over most of the nightside and nearly unity over the strongest crustal sources. The six altitude ranges reveal the three-dimensional morphology of the voids, which extend up to ~1000 km over the stronger crustal sources. The longitude-latitude resolution of these maps is insufficient to resolve the narrow crustal magnetic cusps separating closed crustal loops of alternating polarity [Mitchell *et al.*, 2007; Lillis *et al.*, 2008]. These narrow cusps are readily seen in MAVEN time series data (e.g., feature T2 in Figure 4).

The occurrence rate of closed crustal magnetic field lines is generally higher on the dayside (Figure 8, left plots) than on the nightside (Figure 11). One would expect strong crustal fields to be compressed on the dayside by the solar wind interaction, so that closed fields would extend to higher altitudes on the nightside. However, our definition of voids does not include closed crustal field loops with trapped populations; some of which could be identified as draped in Figure 10 (right side).

## 6. Discussion

This study provides the first three-dimensional map of magnetic field topology from the electron exobase to 1000 km altitude. The electron exobase, which defines the lowest altitude at which electron energy-pitch angle distributions can be used to infer magnetic topology, is not at a fixed altitude but instead depends on the atmospheric density profile and the orientation of the magnetic field with respect to vertical. The lowest altitude bin in this study extends down to 160 km, which is the electron exobase altitude based on electron transport calculations along a vertical magnetic field line. When the field line is not vertical, the electron exobase occurs at a higher altitude. Figure 12a shows how the “collisional depth”  $\tau$  [Xu *et al.*, 2016a] varies with magnetic elevation angle or dip angle. The collisional depth  $\tau(h)$ , similar to the optical depth, is defined as the integral of the product of neutral or thermal plasma density and collision cross sections along a field line, from a high altitude where collisions are negligible to a given altitude  $h$ . For this calculation, we include electron-neutral, electron-electron, and electron-ion collisions [see Xu *et al.*, 2016a, equation (2)]. This dimensionless quantity approximates the likelihood that an electron will suffer a collision as it travels from the top of a field line (here is 400 km) to a given altitude or vice versa. The electron exobase is defined to be the altitude where  $\tau = 1$ , i.e., below 185 km for magnetic elevation angles  $>10^\circ$  and ~220 km for elevation angles  $\sim 1^\circ$ . These values are for 20 eV electrons, but Xu *et al.* [2016a] showed that the exobase varies by less than 5 km from 20 to 200 eV.



**Figure 12.** (a) Tau against altitude for different magnetic elevation angles. The vertical dashed line indicates  $\text{Tau} = 1$ , where the superthermal electron exobase is. (b) The average absolute magnetic elevation angle measured by MAVEN MAG at 160–200 km on the dayside. The gray contours are the modeled crustal magnetic field magnitude at 400 km [Morschhauser *et al.*, 2014].

The neutral and plasma density profiles used for this calculation are taken from the simulation results of the Mars thermospheric general circulation model [Bougher *et al.*, 1999, 2000], the same as Xu *et al.* [2016a], run at a solar longitude ( $L_s$ ) of  $90^\circ$  and with an Earth  $F_{10.7}$  of 100 solar flux unit (sfu) ( $\sim 43$  sfu at Mars). We assume that the density profiles are the same as  $\text{SZA} = 0^\circ$  along the path for all the elevation angles, which results in an overestimation for the exobase altitudes in Figure 12a. Figure 12b illustrates the average absolute magnetic elevation angle measured by MAVEN MAG at 160–200 km on the dayside over the same time period as the electron data. For most of the regions, the average elevation angle is greater than  $20^\circ$ , which corresponds to an electron exobase of  $\sim 185$  km. The higher exobase altitude for more horizontal fields can affect the results in the lowest altitude range, especially over the northern weak crustal regions, but our methodology should be robust above 200 km. This is also supported by the fact that the shape parameters pick up significant amount of open field lines for 200–300 km altitude range, which means that it is distinguishable between solar wind electrons and photoelectrons above 200 km.

Based on extensive observations at 400 km altitude by the MGS MAG/ER, the magnetic topology at 02:00 P.M. over the weakest crustal magnetic field regions in the northern hemisphere ( $50^\circ$ – $60^\circ\text{N}$ ) was found to be dominated by draped IMF [Brain *et al.*, 2006]. Our maps show that this is in fact the lowest altitude where draped fields are significant in this region. Closed field lines are found to be dominant below 400 km, even over the weak crustal regions in the northern hemisphere. Although the electron exobase over these weak crustal regions intrudes into the lowest altitude bin, the occurrence rate for closed field lines increases from  $\sim 50\%$  in the 300–400 km altitude bin to  $>75\%$  in the 200–300 km bin, which indicates that closed field lines become increasingly prevalent at low altitudes. Although we have no way of determining field topology below the electron exobase, one possibility is that these closed field lines are of crustal origin. In this case, the closed loops either connect two distant, previously mapped crustal sources (for a possible example, see Xu *et al.* [2016b]) or they are associated with more local, unmapped sources. A second possibility is that an open or draped field line could have a perturbation such that a segment of the line starts below the electron exobase, rises up to the spacecraft altitude, then dips below the electron exobase again. If this is the main explanation, then these perturbations must have a vertical amplitude of approximately hundreds of kilometers, be widespread, and occur much of the time. Note that over the northern weak regions, the elevation angles are small in Figure 12b, which seemingly implies that these field lines are more likely to be draped IMF. However, these can also be large closed field lines connecting distant crustal sources so that they are mostly horizontal over the weak regions. Moreover, over the weak regions, if crustal fields are locally closed, it is likely that we are observing the top of the field lines, which tend to be horizontal as well. We can also use the maps to examine the photoelectron boundary (PEB) [Mitchell *et al.*, 2000]. If we define the PEB as the altitude at which there is a 50% probability of observing closed field lines, then we can find that the PEB is located at 300–400 km in the north and  $\sim 600$  km in the south.

The open field line occurrence rate decreases dramatically from 200–300 km range to 160–200 km range over the north. This could be explained by one or more of the following explanations. First, it could be that the electron exobase over weak crustal sources (more horizontal magnetic fields) intrudes into the lowest

altitude bin enough to bias the probability. Another contributing factor could be that the open field lines converge with decreasing altitude, thus spanning a smaller solid angle and becoming less likely to be observed. The third contributing factor could be that open field lines observed in the northern hemisphere above 200 km intersect the electron exobase at some distant location, most likely near the equator and/or in the south, where strong crustal magnetic sources are present. For such a scenario, open field lines originate from foot points above strong equatorial crustal sources and become more horizontal as they wrap around the planet and extend down the tail. These field lines pass over the northern hemisphere at higher altitudes with a more horizontal orientation. The presence of open field lines, possibly associated with strong crustal sources to the south, beneath the draped IMF would provide an explanation for the asymmetry in the draping direction inferred from MGS observations at 400 km altitude [Brain *et al.*, 2006]. The draping pattern is possibly formed by open field lines draping over the northern hemisphere, resulting from the solar wind interaction with crustal fields at low altitudes. This suggests the presence of topological “layers” over the northern hemisphere: closed field lines below 200 km, open field lines with foot points at lower latitudes that pass over the northern hemisphere or closed field lines connecting distant crustal sources for 200–400 km, and draped IMF above 400 km. This suggests that the influence of crustal fields extends over the entire planet, preventing IMF penetration below ~400 km under the typical upstream conditions.

Consider the occurrence rate of low-altitude (160–200 km) closed field lines over the two most weakly magnetized regions in the northern hemisphere, the Utopia basin and the Tharsis rise. When both foot points are on the nightside (superthermal electron voids), the occurrence rate ranges from 10% to 50%. When both foot points are on the dayside (photoelectrons in both directions), the occurrence rate is close to 100%. One possibility is that collisions with the neutral atmosphere in the lower part of this altitude range are limiting our ability to infer topology because electron motion is dominated by collisions rather than by the magnetic field. On the nightside, voids would be caused by collisions and would occur regardless of the magnetic field topology. On the dayside, the spacecraft would be embedded in the ionospheric production region, and photoelectrons would be incident from all directions.

The observations shown in Figures 5 and 6 provide a test of this possibility. On this date, periapsis occurs in darkness at an altitude of 155 km (T2; Figure 5). At this time, the shape parameter analysis indicates a draped topology (Figure 6, middle); however, an alternative and more likely interpretation is an open field line with one foot point on the night hemisphere. The parallel population (red spectrum) is solar wind electrons precipitating onto the atmosphere, and the antiparallel population (blue spectrum) is backscattered electron flux [e.g., Collinson *et al.*, 2016]. Both spectra show evidence for significant modification by collisions, including a reduced flux at all energies and a change in the spectral shape compared with solar wind spectra measured at higher altitudes (T3; Figure 6). On either side of the precipitation region at T2, the spacecraft passes through superthermal electron voids at nearly the same altitude. Without a precipitating solar wind flux, the electron populations at these locations have more completely thermalized, with only a residual superthermal population peaking near 7 eV. The intermittent occurrence of a precipitating flux indicates that magnetic topology still plays an important role at these altitudes. Thus, we can confidently interpret voids observed above 160 km as topological, which are closed field lines with both foot points on the nightside.

Since the atmospheric-scale height is smaller on the nightside, the electron exobase should occur at a lower altitude than shown in Figure 12a. Significant superthermal electron depletions caused by collisions with the neutral atmosphere occur below the electron exobase. For example, from the middle plot of Figure 6, we see that the electron flux does not reach the threshold of a void (by our definition) even at the periapsis altitude of 155 km. The occurrence rate of nighttime voids over Utopia and Tharsis is significant (10–50%) but much lower than the ~100% occurrence rate of closed field lines during the day. This difference might be because superthermal electron voids represent only a subset of closed field lines on the nightside. There could also be closed field lines with electrons mirroring above the collisional atmosphere, which would likely be categorized as draped field lines in our scheme (solar wind electrons in both directions). Another possibility is that there might in fact be fewer closed field lines over Utopia and Tharsis on the nightside, if it is more likely for these regions to reconnect with the solar wind in the tail than on the dayside. Now consider the two aforementioned possible closed geometries over the weak crustal regions, draped IMF intersecting the collisional atmosphere twice and closed field lines connecting to crustal source. For the first scenario, it might be that fewer draped IMFs connect twice to the dense atmosphere as they move toward nightside, only intersecting once or not at all. For the closed field lines connecting distant crustal source, i.e., the northern hemisphere

layering, crustal fields on the dayside, opened by reconnection, tend to lay over the weak regions, either just as open field lines or closed up with distant crustal sources. In contrast, on the nightside, crustal fields tend to stretch to down tail and reconnect with solar wind fields, no longer “protecting” the weak regions so that it is easier for IMF to penetrate into low altitudes and form open field lines.

On the nightside, the northern hemisphere is found to be mostly draped according to our selection criteria (Table 1). However, as noted above, our criteria for nightside draped fields also include open field lines with one foot point in the nightside atmosphere. MGS observations show that open field lines are common in the northern hemisphere at 02:00 A.M. local time [Mitchell *et al.*, 2007; Lillis *et al.*, 2008]. In contrast, electron voids dominate over strong crustal fields in the southern hemisphere and near the equator at low altitudes. The detailed structure of these void regions [see Mitchell *et al.*, 2005, Figure 2] is unresolved by our longitude-latitude grid. Such closed field lines prevent superthermal electron precipitation, which is the main source of ionization on the nightside, as well as day-to-night transport above the exobase. Where these closed field lines map to the electron exobase, the ionosphere must be dominated by long-lived ions, such as  $\text{NO}^+$ , that can survive during the Martian night [González-Galindo *et al.*, 2013]. In the north, cross-terminator closed field lines (occurrence rate  $< \sim 25\%$ ) can also provide a source of superthermal electrons to the deep nightside [Xu *et al.*, 2016b].

All of the magnetic field topologies inferred in this study are present in MHD simulations (e.g., Figure 2). For example, the low-altitude cross-terminator closed field lines are common in both observations and simulations of the northern hemisphere [see also Xu *et al.*, 2016b]. Also, the absence of draped field lines below 300 km altitude on the dayside is shown in both model predictions and observations (Figure 10, bottom left plot). Thus, this technique can be used to validate simulation results.

Open field lines can intersect the electron exobase on either the dayside or the nightside. Open field lines connected to the dayside ionosphere provide a path for ion outflow and are thus potentially important for ion escape. These lines occur  $< 50\%$  of the time on the dayside and are generally confined to high latitudes on the nightside, with a higher occurrence rate in the northern hemisphere. Open field lines connected to the nightside atmosphere allow precipitation of solar wind electrons and (episodically) solar energetic particle (SEP) electrons, which causes heating, excitation, and ionization, and occasionally observable auroral emissions [e.g., Schneider *et al.*, 2015]. These field lines are common on the nightside [e.g., Mitchell *et al.*, 2005] but are identified as draped in our study (Figure 10, right side), which is based on the shapes of electron energy spectra and not the presence of one-sided loss cones.

## 7. Conclusions and Future Work

MAVEN is the first mission to systematically sample the Mars plasma environment down to altitudes of  $\sim 150$  km over wide ranges of longitude, latitude, local time, and solar zenith angle. We can readily distinguish ionospheric primary photoelectrons from solar wind electrons, and with pitch angle-resolved shape parameters, we deduce the magnetic topology from the electron exobase to 1000 km altitude. For the first time, we are able to determine the topology below 400 km. This study finds that the sunlit hemisphere below 400 km altitude is dominated by closed field lines, even in the northern hemisphere. These maps combined illustrate how the magnetic topology evolves in three dimensions, in particular how one topology connects to another and how crustal control can happen over a large distance. Overall, the results are consistent with many findings from MGS and also qualitatively agree with MHD results. Open field lines attached to the dayside ionosphere can be mapped out by this methodology, which is a key piece to understand ion outflow, and those intersecting the nightside ionosphere allow energetic electron (solar wind electrons and SEP electrons) precipitations, critical to understand the nightside ionosphere dynamics.

This study focuses only on the magnetic topology's dependence on the geographic latitude, longitude, and altitude. One future work would analyze how the topology changes with upstream conditions and the orientation of the crustal magnetic fields with respect to the Mars-Sun line. Our methodology can also be used to analyze the tail magnetic topology as well, especially in the flanks. In addition, the observations qualitatively confirm the predictions of field line types from the multispecies Mars-MHD model. A direct data-model comparison can be performed in the future to further our understanding of the Martian plasma environment from both observational and theoretical points of views.

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