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# JGR Space Physics

## RESEARCH ARTICLE

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### Key Points:

- The energization of electrons crossing the Martian bow shock can be described in terms of a quasi-static localized potential drop
- The energy difference of electrons entering the Martian bow shock at opposite locations on the same flux tube is much less than expected
- A global, distributed potential within the sheath could resolve the unexpected trends reported in this work

### Supporting Information:

Supporting Information may be found in the online version of this article.

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## Observations of Energized Electrons in the Martian Magnetosheath

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**Abstract** This observational study demonstrates that the magnitude and location of energization of electrons in the Martian magnetosheath is more complex than previous studies suggest. Electrons in Mars's magnetosheath originate in the solar wind and are accelerated by an electric field when they cross the bow shock. Assuming that this acceleration is localized solely to the shock, the field-aligned electron distributions in the sheath are expected to be highly asymmetric. However, such an asymmetry is not observed in this study. Based on the analysis here, it is suggested that an additional parallel acceleration takes place downstream of the Martian bow shock. This additional acceleration suppresses the expected asymmetry of the electron distribution. Consequently, along a flux tube in the magnetosheath that is tied on both ends to the bow shock the difference in energization between parallel and anti-parallel electrons is less than about 20 eV. Where this energization difference is expected to be maximal, we find the energization difference to be at most  $\lesssim 25\%$  of the predicted value.

**Plain Language Summary** As the supersonic solar wind plasma encounters an obstacle, it is first slowed down to subsonic speeds and then diverted around the object. At the shock wave ahead of a planet, called the planet's "bow shock," individual electrons are accelerated by an electric field within the shock. These energized electrons move quickly along the local magnetic field from one side of the bow shock to the other. Downstream of the bow shock, the two electron populations moving in opposite directions along the magnetic field line should then have crossed the bow shock at the two locations where the field line meets the shock. Since the amount of energy gained by electrons is in general different at the two crossing locations, the two streaming electron populations observed downstream of the bow shock are expected to be energized by different amounts. On the contrary, this study identifies that away from the shock the two populations appear to have been energized very similarly. This may imply an additional acceleration downstream of the bow shock is required. This paper suggests two viable mechanisms that could explain the observations.

## 1. Introduction

When the solar wind encounters an obstacle, the bulk flow is decelerated at the bow shock to become subsonic. The bulk flow is then decelerated further and diverted behind the bow shock so that the magnetic field lines—which are approximately frozen in to the fluid—"drape" around the obstacle. This effect is observed at comets (Koenders et al., 2016) and downstream of planetary bow shocks such as at Earth (Spreiter et al., 1966) and Mars (Nagy et al., 2004; C. Mazelle et al., 2004).

The bow shock is the location where the solar wind goes from supersonic to subsonic. As the solar wind slows down, that is, the bulk speed decreases, individual electrons are accelerated to higher energies by the cross-shock potential. The degree of electron energization is dependent on position at the shock surface: the electron kinetic temperature at the subsolar point in the sheath may reach  $\sim 100$  eV, while the energization is much less pronounced at the flanks of the shock. This may be compared to the ambient solar wind electron temperature  $\sim 10$  eV at Mars.

Earth studies of collisionless shocks (such as bow shocks) are applicable to Mars since the physics of shocks is universal. In a planetary bow shock, electrons are energized in a very thin region perhaps 1–10 km wide (Montgomery et al., 1970; Stasiewicz & Eliasson, 2020a). The observed electron distributions have

a “flat-top” shape (Montgomery et al., 1970), which may arise from stochastic heating (Stasiewicz & Eliasson, 2020b). A kinetic model was developed in Mitchell and Schwartz (2014) to predict the form of this relatively isotropic feature in Earth’s magnetosheath, by propagating electrons along field lines that employed Rankine-Hugoniot jump conditions, described in Kivelson and Russell (1995). The distributions are not perfectly isotropic however, as noted for example, in Mitchell et al. (2012). Indeed, the perpendicular and parallel cuts of the distribution may have different profiles at low energies, that is, one cut may be a flat-top while the other is not (L. B. Wilson et al., 2019). Comparison of the field-parallel and perpendicular temperatures has been used to suggest that anisotropic heating might also take place (Feldman, Anderson, Bame, Gosling, et al., 1983). The electron energization is widely believed to be caused by an ambipolar potential (Lefebvre et al., 2007; Scudder et al., 1986), which owes to the strong electron pressure gradient across the shock. Other explanations of electron energization at shocks, such as via turbulent dissipation (Galeev, 1976; Sagdeev, 1966) and energization by waves (Stasiewicz & Eliasson, 2020b) have been developed. Recent work has shown that different portions of the electron distribution may evolve differing manners across a collisionless shock, suggesting multiple processes may be at work (L. B. Wilson et al., 2020).

The region inside the bow shock, known as the sheath, is where the shocked solar wind diverts around the object and further deceleration of the advecting flux tubes takes place. At the lowest altitudes in the sheath, a transition region separates the external decelerating solar wind ions from an internal region where plasma processes are controlled by the planetary plasma environment. The transition from the sheath to the planetary plasma occurs over a region identifiable by multiple observational signatures. In this transition region, one can find for example the “magnetic pileup boundary” or “MPB” (Acuna et al., 1998), Ion Composition Boundary (e.g., Halekas et al., 2019), and Induced Magnetospheric Boundary (Lundin et al., 2004). The exact location of the boundary is not crucial for the outcome of this paper, so we will adopt the empirical position of the MPB reported in Vignes et al. (2000) to locate this transition region.

In the Martian sheath near the transition region that includes the MPB, the sheath electron distributions were found to be “eroded” (Crider et al., 2000); that is, the phase space density of energetic electrons (at a given energy  $\sim 100$  eV) sharply decreased over this region, by up to 2 orders of magnitude as compared to higher altitudes in the sheath. In that study, the erosion was explained by the presence of the neutral Martian corona, which reaches well into the Martian sheath. It was suggested that sheath electrons collide with the neutral gas, and the resulting process of electron impact ionization (a process that has also been reported independently in the Martian foreshock, e.g., C. X. Mazelle et al., 2018) causes the electrons to lose energy. This suggestion was critiqued in Schwartz et al. (2019), where it was argued that sheath electrons spend too little time at the highest neutral densities for this process to be of importance. Therefore, a collisionless kinetic model was developed describing electrons flowing along a solar wind magnetic flux tube as it drapes around Mars. The model accounted for the non-uniformity of the flux tube deceleration, and also distinguished between electrons that pass through the system and those that are temporarily trapped inside the bow shock. The different electron histories were evaluated, which resulted in eroded distributions that compared favorably with electron distributions observed by the MAVEN (Mars Atmosphere and Volatile Evolution) spacecraft. We may infer from this recent work that to a first approximation electrons evolve collisionlessly in the Martian sheath.

Such collisionless evolution of electrons has been investigated in the context of Earth’s magnetosheath, in Mitchell et al. (2012) and Mitchell and Schwartz (2013, 2014). These studies emphasized the non-locality of electron kinetics in the sheath. By non-locality we mean the following: Since guiding centers of moving electrons are expected to propagate along the magnetic field lines (which in turn advect with the bulk flow), and moreover because the electrons are transported collisionlessly at speeds much greater than the bulk flow speed, the distribution function  $f(\mathbf{v})$  observed at a given point in the sheath will in general be a convolution of electrons that crossed the bow shock at different locations. This communication between distant bow shock locations was termed “electron cross talk.”

In Mitchell et al. (2012), using Cluster and THEMIS B data it was shown that the electron distributions in Earth’s magnetosheath can exhibit appreciable field-parallel anisotropy. The authors argued that this asymmetry arises because field-parallel and anti-parallel electrons cross the shock at two different locations along the field line, with different cross-shock potentials. In Mitchell and Schwartz (2014), a theoretical model was developed that traced the trajectories of particles across Earth’s bow shock in order to predict

their distribution in the sheath. This model predicted anisotropic sheath distributions due to cross-talk. It should be noted that this asymmetry was predicted even though the isotropic source (solar wind) distribution applied in the model ignored the intrinsic asymmetry that can arise from the presence of a solar wind strahl distribution. Because the magnetic fields at Mars are similarly draped and thread the local bow shock, we may expect cross talk to generate Martian field-parallel electron distributions with this same systematic anisotropy.

This study investigates if the sheath electrons at Mars carry information from the bow shock via “cross talk.” The mission and the data set from MAVEN’s SWEA electrostatic analyzer is first presented in Section 3. A statistical study of the energization of the electrons in the sheath is presented in Section 4. This study will show the asymmetry of the electron distribution that may be caused by cross talk to be smaller than expected. Processes that could cause these more symmetric electron distributions are suggested in Section 5. The study is summarized in Section 6. A detailed presentation of the distribution mapping (used to infer the energization) and error evaluation are provided in the supporting information to this study.

## 2. Theory

In a collisionless plasma, the evolution of the distribution function  $f(\mathbf{v}, \mathbf{x}, t)$  obeys *Liouville’s theorem*. That is, the total derivative  $df/dt$  is identically zero in the absence of sources and sinks in phase space (Evans & Morriss, 2014). If the electric and magnetic fields are known along a particle path, one can perform a “Liouville mapping” (Schwartz et al., 1998) to predict how the distribution will vary with position along the path. Conversely, if the particle distributions and magnetic fields at various points along an expected particle path are measured, the electric field along the path can be estimated. Since the variation of magnetic field strength does not influence the pitch angles of particles whose velocities are exactly field-aligned, the field-aligned cuts of the electron distribution are only influenced by the electric field. For particles with a significant perpendicular velocity component, the magnetic field gradients should also be considered when performing a Liouville mapping. This methodology is commonly applied assuming the conservation of magnetic moment, steady-state fields and particle distributions, and the absence of collisions, as in for example, Lefebvre et al. (2007).

In the process of Liouville mapping, one must take care to distinguish between the “passing” and “reflected” populations. Both electric fields and magnetic field gradients can reflect particles, which may lead the distributions to develop a loss cone. The term “loss cone” usually refers to particles of certain pitch angles but also there are also regions in energy which are excluded. Therefore, when implementing Liouville mapping only the part of the distributions that can be observed at the two locations should be considered; only the portions outside the excluded in pitch angles and energies should be evaluated.

The sheath is populated by energized solar wind electrons. When they cross the bow shock, these electrons receive a net acceleration that can be attributed to the frame-invariant ambipolar component of the cross-shock electric field. The size of the potential depends primarily on the solar wind conditions and the angle of the solar wind flow vector relative to the shock normal. The low-energy region of the electron distribution typically exhibits a “flat top” ( $f = \text{const.}$ ) shape in Mars’s magnetosheath (Crider et al., 2000); electron distributions in Earth’s magnetosheath exhibit a similar feature (Feldman, Anderson, Bame, Gary, et al., 1983). The energy at which the flat-top “breaks” may be used to roughly estimate the degree of energization.

Due to their high speeds the electrons will approximately follow trajectories along the instantaneous draped magnetic field. A kinetic theory of electrons in the Martian magnetosheath was developed in Schwartz et al. (2019); we note that in that study the cone angle  $\theta_c$  of magnetic field was assumed to be exactly  $90^\circ$ . The cone angle is defined here as follows:

$$\theta_c \equiv \cos^{-1}(\mathbf{B} \cdot \mathbf{v}_{sw} / B v_{sw}), \quad (1)$$

where  $\mathbf{B}$  is the upstream magnetic field and  $\mathbf{v}_{sw}$  is the solar wind velocity. Note from the definition 1, we have  $0^\circ < \theta_c < 180^\circ$ ; the range  $\theta_c < 90^\circ$  corresponds with an anti-sunward pointing upstream field. Assuming a cylindrically symmetric bow shock, when the cone angle is not exactly  $90^\circ$ , the sheath electrons on the same field line originating from two different ends will in general have experienced different cross-shock potentials (see supplementary document for details).

In this study the observed field-parallel anisotropy of the electron distribution function will be parametrized by the quantity  $\Delta\Phi$ :

$$\Delta\Phi = \Phi_{\parallel} - \Phi_{\perp}. \quad (2)$$

In Equation 2 the quantities  $\Phi_{\parallel}$  and  $\Phi_{\perp}$  respectively denote the apparent constant energization of the parallel and anti-parallel propagating electron populations. As described above, if the electron energization occurs solely at the bow shock, we should expect the difference  $\Delta\Phi$  to be non-zero in general. This motivates the present study, where we will investigate statistically if electrons in the sheath retain information of where they crossed the bow shock.

### 3. MAVEN SWEA Electrostatic Analyzer

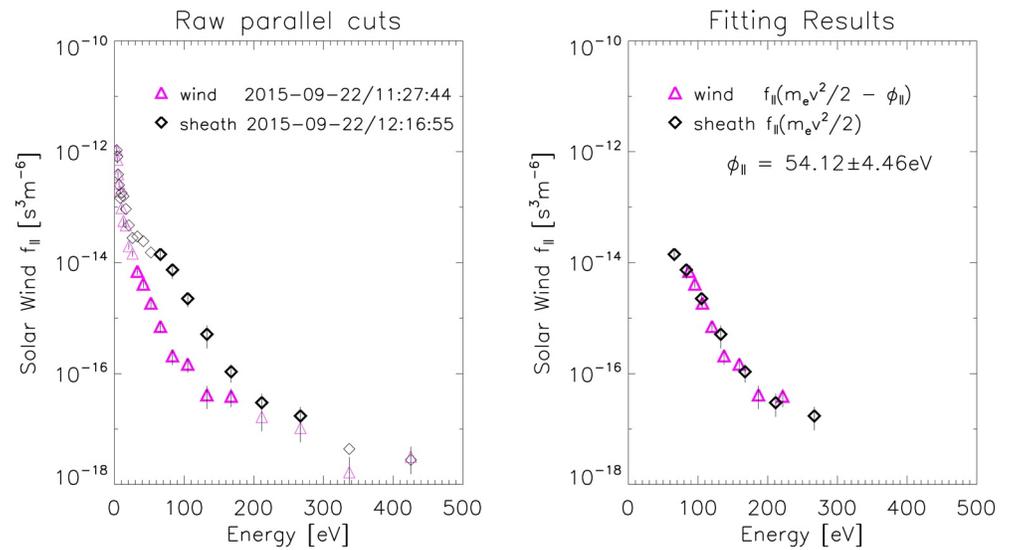
The MAVEN mission's primary focus is to study the Martian atmosphere (Jakosky et al., 2015). As a result, the satellite includes a comprehensive suite of instruments capable of providing high-quality measurements of the space plasma environment near Mars. In this paper, we will focus on measurements of the electron velocity distribution provided by MAVEN's Solar Wind Electron Analyzer (SWEA) instrument (Mitchell et al., 2016). The SWEA instrument has an energy resolution  $\Delta\mathcal{E} / \mathcal{E}$  (FWHM) = 17%, providing 79% coverage of the sky at  $\sim 7^{\circ} \times 22.5^{\circ}$  angular resolution. Magnetic field observations are made by the MAG magnetometer (Connerney et al., 2015). The moment information from the Solar Wind Ion Analyzer (SWIA) onboard MAVEN (Halekas et al., 2015) is used to get the solar wind speed.

In this study, we will consider pitch angle distributions (PADs) computed onboard the MAVEN satellite. These “survey” PADs were regularly sampled by the SWEA instrument, with a time cadence of  $\sim 2$  s with 32 distinct energy steps 3eV–4.6 keV. These energies are given in the spacecraft frame, which for the fast-moving ( $\gtrsim 30$  eV) electrons considered here is nearly identical to the Mars rest frame—the frame assumed in our calculations, see supplementary document for details. At each energy, SWEA uses an automated algorithm to choose 16 different angular positions in phase space (azimuth + elevation pairs) that were sampled by the detector during the accumulation period; these angular positions are so chosen as to lie roughly on a great circle that intersects the local instantaneous magnetic field direction determined by the MAG instrument. The pitch angle is calculated onboard, by comparison with the contemporaneously measured magnetic field provided by MAG. For the present study, most of the time at least one sector was within  $\sim 15^{\circ}$  of the magnetic field.

The data considered here cover the time range January 1, 2015 to May 15, 2019. The MAVEN spacecraft orbits Mars in an inclined ellipse with a nominal periapsis altitude targeting a pressure corridor at 150–180 km and an apoapsis altitude of 6,220 km (Jakosky et al., 2015), resulting in an orbit period of 4.5 h. The subsolar point of the bow shock is located approximately at 2,200 km, well within MAVEN's orbit. However, over the Martian year the apoapsis moves from being in front of the planet in the solar wind to deep into the tail of the planet. Consequently, there are time periods where MAVEN never crosses the bow shock into the solar wind. For this study only orbits where the satellite reaches well into the solar wind are included.

### 4. Observations

To estimate the energization of the sheath electrons, the electron distributions in the sheath are compared to distributions in the solar wind via Liouville mapping. The simplest approach is to only use the field-aligned (or anti-aligned) portion of the particle distributions to conduct the mapping, yielding the quantities  $\Phi_{\parallel}$  and  $\Phi_{\perp}$  (which appear, e.g., in Equation 2). For this purpose, the single most field-aligned (or anti-aligned) “cut” of any given distribution is selected, with the additional criterion that the orientation of each cut must point within  $30^{\circ}$  of the local magnetic field line. At low energies photoelectrons can dominate the spectrum, motivating the application of an energy cutoff at 30 eV. The maximum acceleration is expected to be  $< 500$  eV, which is selected to be the upper energy range for the comparison. Above that energy range, count rates of the instrument are often too low for our purposes and errors can result in an incorrect determination of the energization. So, only energy bins in the 30–500 eV energy range and only energy bins which register  $\geq 5$  counts are included in the comparison. Examples of two electron distributions, one from the sheath and a reference spectrum from the solar wind, are presented in Figure 1a. These distributions are from September



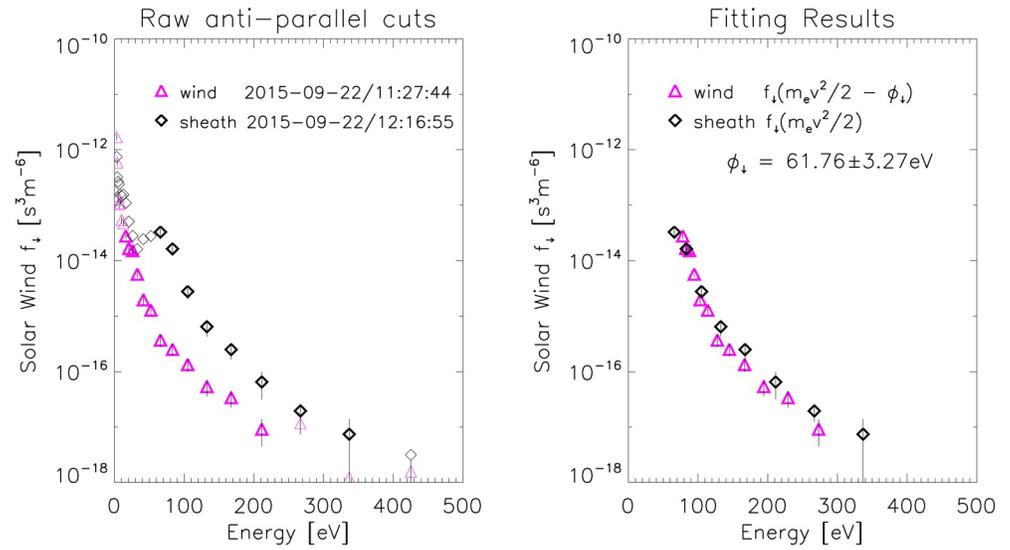
**Figure 1.** An example of the parallel cuts in the solar wind and sheath, showing the results of the Liouville mapping procedure. Left: Field-parallel cuts  $f_{||}$  of the electron distribution, plotted at an example time in the sheath (black diamonds) and a nearby time in the solar wind (purple triangles) on September 22, 2015. The symbols in bold represent the data that satisfy our selection criteria; these data are used to interpolate the two spectra and calculate their energy difference  $\Delta\Phi_{||}$  (see supplementary document for details). Right: The raw magnetosheath spectrum is again plotted (black diamonds, bold), as well as the same solar wind distribution shifted by the fitted energization  $\Phi_{||} = 54 \pm 4$  eV (purple triangles, bold). We observe that when the solar wind spectrum is shifted by this energy  $\Phi_{||}$ , it successfully lines up with the magnetosheath spectrum. Here only the data that satisfied the selection criteria were retained in the plot; that is, data with sufficient count rates in the energy range 30–500 eV.

22, 2015—the sheath distribution is measured at the nominal time 12 h 16 m 55 s and the solar wind reference distribution is averaged over a 10-min period centered on 11 h 27 m 44 s. Vertical error bars are shown in the figure based on the counting statistics of the detector.

The solar wind reference distribution, an example of which is presented in Figures 1a is derived in the same way for each orbit as follows. A time period where the MAVEN spacecraft is located in the solar wind is first identified based on the empirical bow shock position (Vignes et al., 2000). Then a 10-min interval is selected, which is centered on the time in the orbit where the satellite is radially farthest from the empirical bow shock position. The SWEA energy spectra are then averaged over this 10-min interval to derive one solar wind reference spectrum. For each orbit, all other electron distributions will be compared to this reference spectrum.

Note that the electrons measured in the sheath by MAVEN will not generally be found on a flux tube that connects to the position where the solar wind reference spectrum is sampled. It is here assumed that the reference spectrum approximates the source distribution of electrons entering the sheath during a given orbit.

To evaluate whether the field-parallel sheath electrons can be viewed as the solar wind population accelerated by a parallel electric field, a Liouville mapping is performed. To this end the reference spectrum is shifted by a constant energy to best match each electron distribution of the orbit, yielding the energization ( $\Phi_{||}$  or  $\Phi_{\perp}$ ). For the mapping to be valid, only distributions moving in the same direction with the respect to the magnetic field are compared (i.e., with the same orientation in the solar wind and sheath). However, since the orbital period is long the solar wind magnetic field orientation might change between the times of the sheath and solar wind measurements; say, if the planet encounters a new flux tube in the interim. This fact is accounted for by identifying the orientation of the electron strahl population (if it is significant enough to be identified), which is either aligned or anti-aligned with the magnetic field. The strahl component is required to maintain the same orientation with respect to the field across both the sheath and solar wind in order for the Liouville mapping to be performed—this accounts for some of the natural variability of the interplanetary conditions.



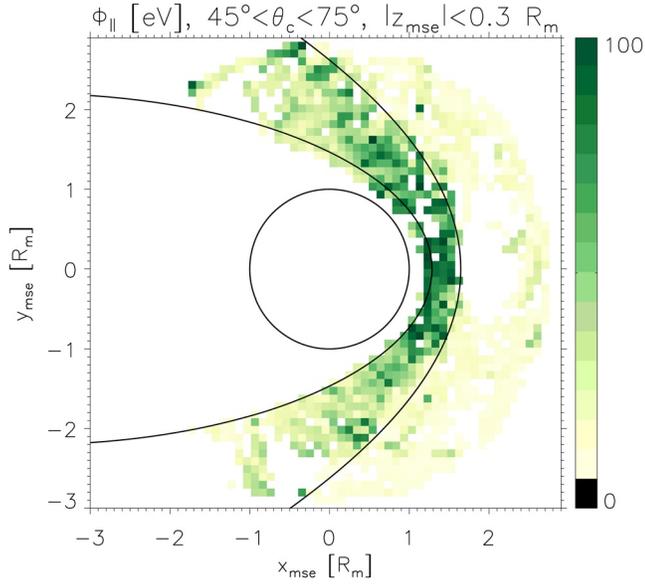
**Figure 2.** An example of the antiparallel cuts in the solar wind and sheath, analogous to Figure 1. An energization  $\Phi_{\perp} = 62 \pm 3$  eV is calculated by the fitting procedure. In the right panel, we observe that when the solar wind spectrum is shifted by this energy  $\Phi_{\perp}$ , it successfully lines up with the magnetosheath spectrum.

The Liouville mapping is implemented as a least squares fit, that calculates the energy the solar wind spectrum would need to be shifted by in order to match the sheath spectrum. This energy is denoted as either  $\Phi_{\parallel}$  or  $\Phi_{\perp}$ , respectively, dependent on whether the fit is conducted between two field-parallel or anti-parallel energy spectra. The results of such a fit for a field-parallel energy spectrum can be seen in Figure 1b. In the example, the derived  $\Phi_{\parallel}$  is  $4 \pm 4$  eV. The Liouville mapping process involves comparing the energies of two spectra at common values of the phase space density; this comparison is made possible by linearly interpolating the discretely sampled data between the solar wind and sheath spectra. The fitting is done by weighting each energy bin appropriately by the count rate. The solar wind distribution effectively maps to the sheath distribution at energies  $\geq \Phi_{\parallel}$ , suggesting the sheath electrons originated from the solar wind. The details of the fitting and the calculation of uncertainties are provided in the supplementary material.

Figure 2 shows the same fitting procedure applied to the anti-parallel electrons. These have entered the sheath through the shock at the opposite end of the field line, where the shock potential may be different. The fitting procedure yields  $\Phi_{\perp} = 62 \pm 3$  eV, similar to the measurement of  $\Phi_{\parallel}$  at the same time.

The energy spectra are not corrected for the spacecraft potential  $\phi_{sc}$  that arises from spacecraft charging, and this omission introduces systematic error in the estimates of  $\Phi_{\parallel}$  and  $\Phi_{\perp}$  of the order  $\lesssim 10$  eV. However, it is unnecessary to correct for this error for the present study, which is concerned with  $\Delta\Phi$  (Equation 2). To illustrate, let us assume that the spacecraft potential is known at the measurement times of a magnetosheath spectrum and also of the solar wind reference spectrum, and write these potentials as  $\phi_{sc,m}$  and  $\phi_{sc,w}$  respectively. The measured electron energy spectra will have been shifted by such amounts, so that the uncorrected quantities  $\Phi_{\parallel}$ ,  $\Phi_{\perp}$  would be strictly speaking inaccurate. To correct for the spacecraft charging effect, the quantity  $\Phi_{\parallel}$  would need to be adjusted by an amount  $\Delta\phi_{sc} \equiv (\phi_{sc,m} - \phi_{sc,w})$ . For example, we could calculate the corrected quantity  $\Phi_{\parallel}^*$ , from the formula  $\Phi_{\parallel}^* \equiv (\Phi_{\parallel} - \Delta\phi_{sc})$ . Similarly, the corrected quantity  $\Phi_{\perp}^*$  would be calculated as  $\Phi_{\perp}^* \equiv (\Phi_{\perp} - \Delta\phi_{sc})$ . However, this correction is not of great importance for the present work, as we are interested primarily in measuring the difference  $\Delta\Phi = (\Phi_{\parallel}^* - \Phi_{\perp}^*)$  which is just the same as  $(\Phi_{\parallel} - \Phi_{\perp})$ , see Equation 2. That is, the spacecraft potential correction cancels out with the subtraction so it is not necessary to correct for it.

The energization is calculated via Liouville mapping in this manner for every electron distribution in the >4-year data set, enabling the statistical study of  $\Phi_{\parallel}$  and  $\Phi_{\perp}$ . The statistical average of the observed parallel energization  $\Phi_{\parallel}$  is shown in Figure 3, revealing the spatial structure of the electron energization. As expected  $\Phi_{\parallel}$  is nearly zero in the solar wind and increases dramatically near the bow shock location. Near



**Figure 3.** Statistical map of the parallel energization  $\Phi_{\parallel}$  averaged across the > 4-year data set. The data are shown in the Mars Solar Electric (MSE) frame, averaged over times when the spacecraft position satisfied  $|z_{\text{mse}}| < 0.3R_m$ , where  $R_m$  is the Martian radius. This plot only includes times when the solar wind magnetic field was directed antisunward, with a cone angle  $50^\circ < \theta_c < 70^\circ$ , as evaluated at the nominal time associated with the solar wind reference spectrum. Overlaid on the plot is the empirical location of the bow shock and MPB (Vignes et al., 2000).

the subsolar point at the bow shock the average  $\Phi_{\parallel}$  is calculated to be  $\sim 100$  eV on average. Note that this empirical value is the basis for the model of the bow shock developed in the supporting document, wherein the cross shock potential is assumed to be 100 eV at the subsolar point.

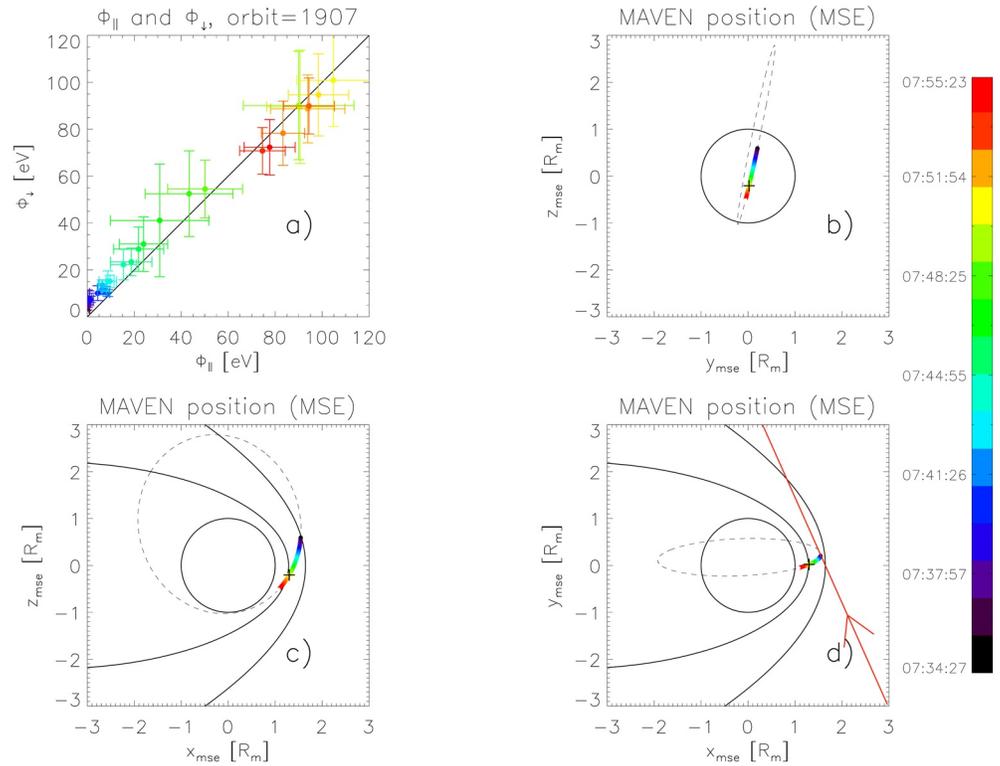
We remind the reader that electron distributions in the sheath may be expected to be asymmetric if the particle acceleration occurs solely due to the cross-shock electric field. The field-aligned and anti-aligned electron distributions would then show different amounts of energization, that is, one expects  $\Phi_{\parallel} \neq \Phi_{\perp}$ . Assuming that the cross-shock potential is roughly cylindrically symmetric about the  $x_{\text{mse}}$  axis, one expects that the difference  $(\Phi_{\parallel} - \Phi_{\perp})$  would be most suppressed for cone angles  $\theta^\circ \approx 90^\circ$ . Likewise, the effect would be most stark when the solar wind flow yields the smallest cone angles. From the Parker spiral model one may quickly estimate a typical cone angle of  $\theta_c \approx 60^\circ$  at Mars. Under these conditions one expects a maximum difference in energization  $\Delta\Phi \approx 60$  eV at a location behind the bow shock just offset from the subsolar point (see supporting information for details).

To illustrate the variation of the electron energy near the bow shock under typical conditions, a study of a single orbit is now presented. Orbit 1907 on September 22, 2015 was selected because the orbital geometry and IMF B angle conditions are such that maximum  $\Delta\Phi$  may be expected to be large (i.e., on the order of the expected  $\sim 60$  eV mentioned above). During the interval, the (10-min avg.) solar wind magnetic field had the value  $\mathbf{B} = (-0.93, 2.06, 0.34)$  nT in MSO cartesian coordinates. This corresponds with a cone angle  $\theta_c \approx 66^\circ$ , which is within 10% to the typical Parker spiral value. This magnetic field is used to calculate the spacecraft vector position in the MSE frame ( $\mathbf{x}_{\text{mse}}$ ). The spacecraft's traversal of the

sheath takes place over a range of positions satisfying  $|z_{\text{mse}}| \lesssim 0.5R_m$  ( $R_m$  denotes the Martian radius), appropriate for this study since the simple bow shock model assumes  $z_{\text{mse}} \approx 0$  (see supporting information). Likewise, the spacecraft crosses the shock the near the subsolar point, which is of interest because this is where the strongest signal  $\Delta\Phi$  is expected according to the model. Although the exact location of the maximum  $\Delta\Phi$  depends on the solar wind cone angle, this expectation may be roughly explained by the fact that in our model the cross-shock potential (which sets  $\Phi_{\parallel}$ ) peaks at the sub-solar point. This is where the incident ram energy along the vector normal to the bow shock is maximal.

The results of the fits from MAVEN's 1907th orbit on September 22, 2015 are presented in Figure 4a. The  $\sim 30$ -min time interval during which the spacecraft crossed into the sheath is divided into 30 subintervals of  $\sim 1$ -min duration, and averages of  $\Phi_{\parallel}$  and  $\Phi_{\perp}$  within those subintervals are plotted. The central time within each subinterval is displayed by the color. The standard deviation of the  $\Phi_{\parallel}$  and  $\Phi_{\perp}$  data within each subinterval (the scatter) is displayed as error bars. Recall the quantities  $\Phi_{\parallel}$  and  $\Phi_{\perp}$  represent the derived net energization that the two electron populations (moving along and against the field) have each experienced. The spacecraft location for the selected orbit is presented in Figures 4b–d with the same color coding.

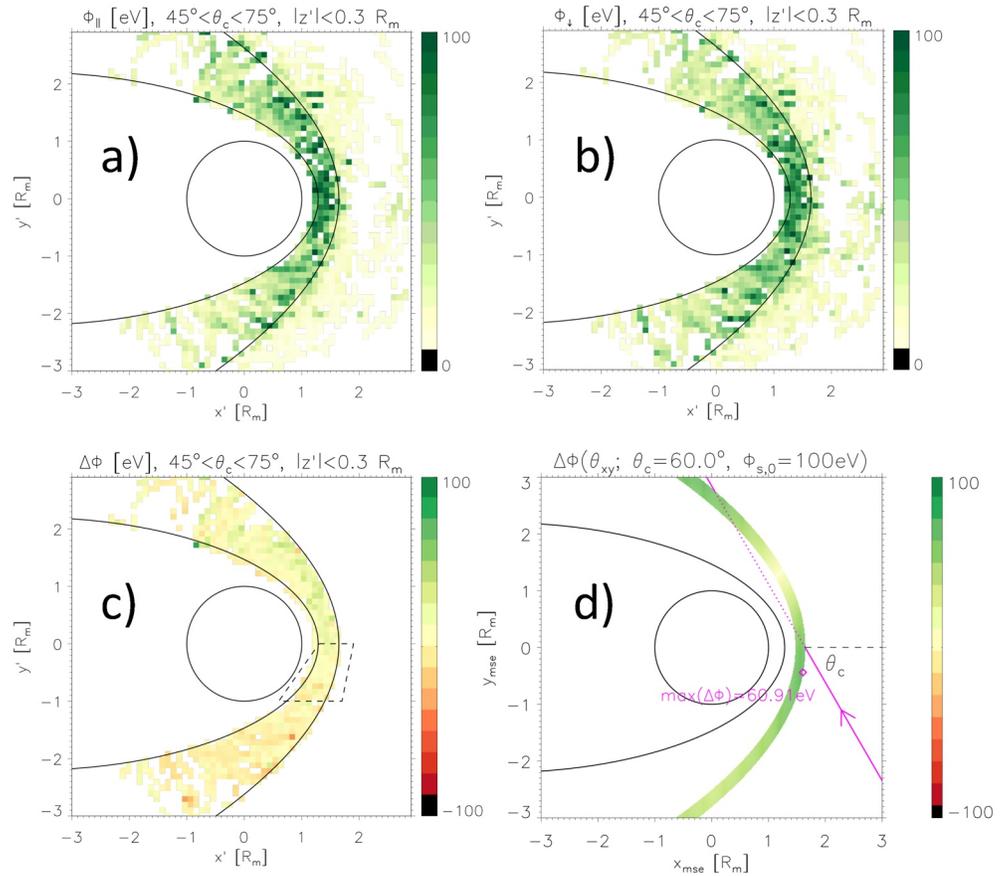
As discussed above, for the conditions of the selected orbit one may expect  $\Delta\Phi \sim 60$  eV just downstream of the bow shock. But,  $\Phi_{\parallel}$  and  $\Phi_{\perp}$  for this orbit lie along the unity line (solid line) in Figure 4a, suggesting that the magnitudes of the energizations are actually quite similar. The time where the spacecraft crosses the bow shock (07 h 49 m 20 s) has been identified by manually looking at the data and is marked by the “+” sign in Figures 4b–4d. Note that this shock crossing is detected at a lower altitude than that of the average bow shock (Vignes et al., 2000), indicating that the shock happened to be relatively compressed during this orbit. The largest  $\Delta\Phi$  should be observed just behind the bow shock, near the subsolar point. But no such systematic difference is observed, as the points in Figure 4a adhere to the unity line throughout the time interval. The scatter in the data is slightly larger at the bow shock (where  $\Phi_{\parallel}, \Phi_{\perp} \sim 100$  eV). Although there seems to be a slight bias  $\Phi_{\parallel} > \Phi_{\perp}$  at this time, the magnitude of  $\Delta\Phi$  is only  $\sim 10$  eV (i.e.,  $\ll 60$  eV). This figure therefore suggests that electrons in the sheath cannot have been accelerated at the bow shock alone.



**Figure 4.** (a) A plot of  $\Phi_{\parallel}$  versus  $\Phi_{\perp}$  in the nominal sheath region. Data are from September 22, 2015, during MAVEN's 1907th orbit; in the interval the spacecraft crossed into the sheath near the subsolar point, at  $z_{\text{mse}} \sim 0$ . Generally, it is observed  $\Phi_{\parallel} \approx \Phi_{\perp}$ . Although some small bias  $\Delta\Phi \lesssim 10$  eV may be observed at the shock crossing, this signal is much less than that predicted by the model (see text for details). (b) Spacecraft position in the  $y_{\text{mse}} - z_{\text{mse}}$  plane. (c) Spacecraft position in the  $x_{\text{mse}} - z_{\text{mse}}$  plane. (d) Spacecraft position in the  $x_{\text{mse}} - y_{\text{mse}}$  plane. As the magnetic field in MSE coordinates falls exactly in this plane, a line showing the solar wind magnetic field orientation during the interval ( $\theta_c = 66^\circ$ ) is shown for reference. In all plots (a)–(d), the time of day is shown by the color. The Martian surface, MPB, and bow shock boundary are shown as solid lines where applicable in plots (b)–(d), and MAVEN's orbital trajectory is shown as a dashed line. MAVEN, Mars Atmosphere and Volatile Evolution; MPB, magnetic pileup boundary; MSE, Mars Solar Electric.

To see if the observed trend  $\Phi_{\parallel} \approx \Phi_{\perp}$  holds generally for other orbits, a statistical evaluation of the two energies  $\Phi_{\parallel}$ ,  $\Phi_{\perp}$  and their difference  $\Delta\Phi$  is presented in Figure 5a–5c. Again only times for which the cone angle satisfied  $50^\circ < \theta_c < 70^\circ$  are considered in the averages. The individual  $\Phi_{\parallel}$  and  $\Phi_{\perp}$  values that go into the averages are calculated as already described in this section (following the same selection criteria). The >4 years of data are aggregated by calculating the spatial averages of these quantities in a dynamic coordinate system.

The dynamical coordinate system is developed as follows. For each orbit, the location of the bow shock is identified from among times where the derived quantity  $\bar{\Phi} \equiv (\Phi_{\parallel} + \Phi_{\perp}) / 2$  is in the 99th percentile for that orbit. This simple criterion is used because the electrons are known to be strongly energized at the shock; however, the reader should note that this methodology does not account for the presence of foreshock transients, (e.g., Liu et al., 2017). From among these times, the shock crossing is designated as the location where the spacecraft altitude is maximal. Once the location of the bow shock has been specified, this information is used to estimate the local scale of the bow shock relative to the nominal shock size (Vignes et al., 2000). The spacecraft's position in MSE coordinates is normalized by the local shock size (evaluated each orbit) before conducting the spatial averages presented in Figures 5a–5c. These normalized MSE positions are denoted by the vector components  $x'$ ,  $y'$ , and  $z'$ . Normalizing in this way minimizes the effects of natural variance of the system. For instance, the signature of the electron energization near the shock is less blurred out by the time-varying size of the shock, and the sheath and solar wind populations are well-separated before averaging.



**Figure 5.** The electron energization in the Martian magnetosheath, in the  $z' = z_{\text{mse}} = 0$  plane under typical conditions ( $\theta_c = 60^\circ$ ). (a) Average parallel energization,  $\Phi_{\parallel}$ , plotted in the shock-normalized MSE frame. Before averaging the data, we normalize distances to the inferred scale of the shock (see text). We further restrict ourselves to data satisfying  $|z'| < 0.3R_m$ , and only consider data when the solar wind cone angle fell within the range  $50^\circ < \theta_c < 70^\circ$ . (b) Same as (a), but here we plot the average anti-parallel energization  $\Phi_{\perp}$ . (c) Same as (a), but here we plot the energization difference  $\Delta\Phi = \Phi_{\parallel} - \Phi_{\perp}$ . Only data measured within the magnetosheath are included, to highlight the variation in this region. (d) The predicted  $\Delta\Phi$ , that arises from a model in which the electron energization occurs solely at the bow shock. The model assumes  $\theta_c = 60^\circ$  (the typical cone angle observed at Mars) and  $z' = 0$ , so it may be compared with (c). A magnetic field line with cone angle  $\theta_c = 60^\circ$  is shown for reference, but note that in the sheath region (dashed lines) the field is expected to be curved, not straight. Note the dissimilarity between the  $\Delta\Phi$  signature in (c) and (d)—see text.

The presented statistical maps should only include data with similar cone angle  $\theta_c$ , so as to not mix electrons originating from different locations along the bow shock. The typical  $\theta_c$  at Mars is about  $60^\circ$ , as predicted by the Parker spiral model. For Figure 5 we therefore only include data where the cone angle at the nominal time of the solar wind reference spectrum's measurement satisfied  $50^\circ < \theta_c < 70^\circ$ . Analogous, nearly identical plots (not shown) may be produced for the cases when the magnetic field had the same orientation with opposite polarity ( $\theta_c = 120^\circ$ ). We chose to treat supplementary angles (e.g.,  $\theta_c = 60^\circ$  and  $\theta_c = 120^\circ$ ) as separate cases because planetary magnetospheres can sometimes exhibit dawn-dusk asymmetry. Such asymmetries have been reported, for example, in the plasma parameters observed in Earth's magnetosheath (Walsh et al., 2012) and in simulations of the configuration of Mars's magnetotail and magnetosheath (Liemohn et al., 2017).

In the averages presented in Figure 5, only data from the regions nominally occupied by the solar wind and sheath are included (Vignes et al., 2000). Also, only data where the spacecraft position satisfied  $|z_{\text{mse}}| < 0.3R_m$  are included. This reflects the fact that the parallel asymmetry, if it exists, should be most stark in the plane  $z_{\text{mse}} = 0$ . The (unscaled) surface of Mars and the empirical boundary locations of the bow shock and the transition region where the MPB is located are presented by the black lines in the figure. Also, a drawing of

the magnetic field with  $\theta_c = 60^\circ$  illustrates how the magnetic field encounters the system; this is shown as a dashed line in the sheath region because the draped field is actually curved there. It is quite obvious that the statistical result of Figures 5a–5b is similar to Figure 4—that is,  $\Phi_{\parallel}$  and  $\Phi_{\perp}$  are similar in magnitude and the largest  $\Phi$  are seen close to the subsolar point.

Because of the selected range of cone angles,  $50^\circ < \theta_c < 70^\circ$ , the energization of the electron distributions may be expected to be asymmetric. That is, we may expect  $\Phi_{\parallel} \neq \Phi_{\perp}$ , and some difference between Figures 5a and 5b should be observed. Therefore,  $\Delta\Phi$  is first calculated for each individual point before deriving the average, which is presented in Figure 5c. The difference is close to zero throughout the sheath, which is an unexpected result in this study. Near the bow shock there is a slight trend in the  $\Delta\Phi$  data, with  $\Delta\Phi \gtrsim 0$  in the region  $y_{\text{mse}} > 0$  and  $\Delta\Phi \lesssim 0$  in the region  $y_{\text{mse}} < 0$ . This systematic signal is strongest at the flanks, with a maximum strength of 10–20 eV. The region where the maximum  $\Delta\Phi$  may be expected is outlined by a dashed trapezoid—although the model predicts  $\Delta\Phi \sim 60$  eV in this region (see next paragraph), the actual signal varies within the range  $-21 \text{ eV} < \Delta\Phi < 16 \text{ eV}$ . In other words, the observed  $\Delta\Phi$  is only about  $\lesssim 25\%$  of the predicted value in the region where the signal is expected to be strongest.

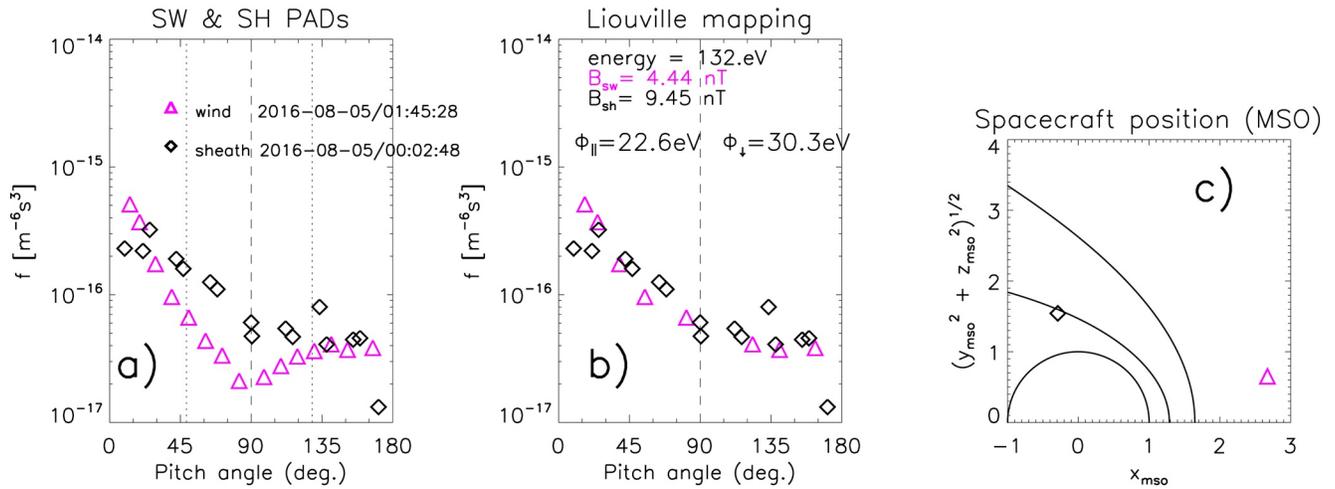
For comparison, Figure 5d shows a model prediction of  $\Delta\Phi$  just downstream of the bow shock in the region  $z_{\text{mse}} = 0$ , assuming a cone angle of  $60^\circ$  and a peak cross-shock potential of 100 eV at the subsolar point (see supporting information for details). For such conditions the expected  $\Delta\Phi$  is estimated to be 61 eV, as calculated from the difference in cross-shock potentials at two ends of a flux tube. In the model,  $\Delta\Phi = 0$  near where the downstream magnetic field is tangent to the shock surface  $\mathbf{B} \cdot \hat{\mathbf{n}} = 0$ .

The predicted signal Figure 5d differs from the observed signal Figure 5c in a number of important respects. Note that the model predicts  $\Delta\Phi \geq 0$  throughout the sheath, whereas the actual signal skews negative in the region  $y_{\text{mse}} < 0$ , as mentioned above. Also the observed  $\Delta\Phi$  is very close to zero near the subsolar point, whereas this is where the model predicts  $\Delta\Phi \approx 60$  eV. In fact, the observations show no systematic signal of strength  $\sim 60$  eV anywhere in the sheath, and in the statistical map the maximum and average values of  $|\Delta\Phi|$  observed are about 20 and 8 eV respectively.

We have assumed so far that the electrons in the sheath have evolved collisionlessly, and moreover that the magnetic moment is a conserved quantity. If other processes such as collisions and nonlinear wave acceleration are present in the flux tube, the modification of the distributions will be clearly observable in the particles with large pitch angles. Therefore, an investigation is made to see if the angular distributions of sheath electrons can be described as solar wind electron distributions that have been exposed to a quasi-static electric field (ignoring nonlinear effects). In investigating electrons with large pitch angles, magnetic field gradients must also be considered. This investigation is based on Liouville mapping; first the field-aligned distribution is used to identify the energization (parametrized by  $\Phi_{\parallel}$ ,  $\Phi_{\perp}$ ) due to the electric field and then conservation of magnetic moment is applied to calculate the mapped angular distribution. Note that in the presence of a spatially varying magnetic field, the pitch angles of particles will change in order to conserve the magnetic moment.

Two pitch angle distributions, one from the solar wind and another from the sheath, are presented in Figure 6a. The data are from August 5, 2016 where the sheath was measured at 00 h 02 m 48 s and the solar wind reference spectrum is derived from a 10-min window centered at 01 h 45 m 28 s. The sheath distribution was measured by SWEA at energy 132 eV. The solar wind pitch angle distribution displayed in Figure 6a is taken from the solar wind reference as usual, but interpolated to the appropriate energy. That is, the field-aligned part ( $\theta < 90^\circ$ ) of the solar wind distribution is interpolated to the energy  $\mathcal{E}_{\parallel}$ , so that the total energy of the electrons (after they migrate from the solar wind to the sheath location) would match the sheath distribution; that is,  $\mathcal{E}_{\parallel} + \Phi_{\parallel} = 132$  eV. An analogous interpolation process, using  $\Phi_{\perp}$ , is used to construct the rest of the distribution (where  $\theta > 90^\circ$ ). In this way, a solar wind pitch angle distribution is constructed that may be mapped to the sheath distribution.

The results of the Liouville mapping are presented in Figure 6b. In this panel the solar wind distribution from panel 6(a) has been mapped to new pitch angles—as the distribution would appear once the electrons had migrated to the selected location in the sheath. The change in pitch angle  $\theta$  can be predicted by accounting for the gain in parallel energy ( $\Phi_{\parallel}$  and  $\Phi_{\perp}$ , derived as shown in Figure 1) and the conservation of magnetic moment. That is, given an electron's initial velocity components  $v_{\parallel,1}$ ,  $v_{\perp,1}$ , the ratio of the magnetic



**Figure 6.** Liouville mapping of pitch angle distributions for a particular case study, chosen because the solar wind distribution exhibited a prominent strahl population during the orbit. (a) Sheath pitch angle distribution measured at 132 eV, and a solar wind pitch angle distribution interpolated at energies ~102–110 eV (appropriate for Liouville mapping in pitch angle, see text). (b) Results of the Liouville mapping. The sheath distribution is shown again as in panel (a), to be compared with the Liouville mapped solar wind distribution. The curves line up well, indicating a successful mapping. (c) Position of the spacecraft at the time of measurement, respectively for the solar wind (triangle) and sheath (diamond) distributions. The average position of the bow shock and MPB Vignes et al. (2000) are shown for reference.

fields in sheath and solar wind  $B_{sw}/B_{sh}$ , and the gain in energy  $\Phi_{\parallel}$  (or  $\Phi_{\perp}$ ), the final velocity of a particle can be computed. The relevant equations for computing the final (sheath) velocity components are described in section 1.1 of the supplementary document.

For the purposes of the pitch angle mapping, the magnetic field values in the solar wind and sheath locations were measured as  $B_{sw} = 4.6$  nT and  $B_{sh} = 9.5$  nT. The parallel and anti-parallel energization of the solar wind electrons were  $\Phi_{\parallel} = 22.6$  eV and  $\Phi_{\perp} = 30.3$  eV, respectively. The position of the MAVEN spacecraft at the two locations, in MSO coordinates, is shown in Figure 6c.

For this example, no mapping is conducted at pitch angles  $|\theta - 90^\circ| \lesssim 40^\circ$  because the ratio of magnetic fields dictates that any such particles from the solar wind would have been reflected (the mirror condition) before they reached the location of the sheath observation. The pitch angles corresponding to the mirror condition, for the particular magnetic fields used in the mapping, are shown as vertical lines in Figure 6a. Note that these boundaries are only valid if a strong magnetic field doesn't exist between the sheath and solar wind locations—such a field would change the domains in phase space of the “passing” and “reflected” populations.

Figure 6b demonstrates that there is reasonable agreement between the solar wind reference distribution and the Liouville-mapped sheath distribution. If pitch angle scattering or perpendicular wave heating were acting on electrons considered here (e.g., at energies above the flat-top regime), these effects would distort the sheath distribution and likely cause the Liouville mapping to fail. The importance of these two processes is small, as can be seen from the significant asymmetry of the distribution, where the phase space density of the field-parallel beam ( $\theta = 0^\circ$ ) is about an order of magnitude greater than that of the anti-parallel electrons. This inferred lack of pitch-angle scattering provides a key to understanding the similarity between  $\Phi_{\parallel}$  and  $\Phi_{\perp}$  as presented in Figure 5.

## 5. Discussion

In this study, we have operated under the assumption that the Martian magnetosheath is a collisionless medium. We have further assumed that 1) the electrons observed in the sheath are sourced from the solar wind and are only energized by a parallel (or anti-parallel) electrostatic field that increases the particle energy by an amount  $\Phi_{\parallel}$  (or  $\Phi_{\perp}$ ), and 2) the solar wind and sheath do not vary dramatically on timescales  $\Delta t \sim 1$  h, allowing distributions measured at two points in the MAVEN orbit to be compared. This simple framework is

sufficient to explain the field-aligned sheath distributions (e.g., Figure 1), and accounting for the magnetic field can also explain the pitch angle distributions (Figure 6). Therefore, any process of collisions or plasma wave acceleration must have only a minor effect on the sheath electron distributions.

This study shows that the electron energization is more symmetric than expected from the electron “cross talk” picture, as demonstrated by Figures 4 and 5. This suggests that the model of local shock energization, quantified explicitly in the supplementary document, does not fully describe the electron distributions. Some additional acceleration must be introduced to explain the relative symmetry of the energization experienced by the sheath electrons. This leads us to consider two different explanations for why the observed  $\Delta\Phi$  is not more significant, detailed below.

### 5.1. Scalar Potential $\phi(\mathbf{x})$

One explanation for the observation  $\Delta\Phi \sim 0$  may be that the electrons are not exclusively accelerated at the shock front as we originally assumed. Rather, the particles may also respond to parallel electric fields as they traverse the magnetosheath. We stress that rapid energization would still occur as the electrons cross the bow shock, but the electrons would also be gradually accelerated by the presumed electric field in the sheath.

In this interpretation, the observation  $\Delta\Phi \approx 0$  suggests that the energizing electric field is itself the gradient of some scalar potential  $\phi(\mathbf{x})$  in the shock and magnetosheath. That is, the energization of an electron depends on its position rather than its trajectory. In this view, we may drop the subscripts  $\parallel, \downarrow$  and express the energization  $\Phi$  as a sole function of the position  $\mathbf{x}$ :

$$\Phi(\mathbf{x}) = |q_e| \phi(\mathbf{x}). \quad (3)$$

Note that  $q_e < 0$  is the electron charge in Equation 3—empirically, electrons gain kinetic energy as they cross into the sheath, so  $\phi \geq 0$ . Such a picture may neatly account for the lack of electron anisotropy that would otherwise be expected from cross-talk.

To explain the electrostatic potential, we will invoke the presence of an ambipolar electric field  $\mathbf{E}_A$ . Such fields are found in the presence of electron temperature and density gradients, and such gradients may be seen in the quasi-steady sheath. Indeed, the cross-shock energization  $\Phi_s$  (see supplementary material) is widely attributed to the ambipolar field established in the Martian bow shock, where these gradients are most pronounced. A weaker ambipolar field in the sheath region could still have a significant effect on the electron energy, as the total distance traveled by an electron through the sheath is much greater than the cross-shock distance.

Let us investigate the effect of  $\mathbf{E}_A$  on the electron energization in the Martian frame, by considering the following formula for the electric field, which follows from retaining the leading terms of the generalized Ohm's Law:

$$\mathbf{E}(\mathbf{x}) = \mathbf{E}_C(\mathbf{x}) + \mathbf{E}_H(\mathbf{x}) + \mathbf{E}_A(\mathbf{x}). \quad (4)$$

In Equation 4, the convective ( $\mathbf{E}_C$ ) and Hall ( $\mathbf{E}_H$ ) and ambipolar ( $\mathbf{E}_A$ ) contributions to the electric field are given by the standard expressions:

$$\mathbf{E}_C \equiv -\mathbf{v}_b \times \mathbf{B}, \quad (5)$$

$$\mathbf{E}_H \equiv \frac{1}{n_e |q_e|} \mathbf{J} \times \mathbf{B}, \quad (6)$$

$$\mathbf{E}_A \equiv \frac{1}{n_e q_e} \nabla P_e. \quad (7)$$

In Equations 5 and 6,  $\mathbf{v}_b$  is the bulk flow velocity,  $n_e$  is the electron density,  $P_e = n_e T_e$  is the electron pressure (assuming isotropic electrons with kinetic temperature  $T_e$ ), and  $\mathbf{J}$  is the current density. Assuming

**Table 1**  
Typical Plasma Parameters in the Sheath and the Velocity of Components ( $v_{\parallel}$ ,  $v_{\perp}$ ) of a Representative  $\sim 300$  eV Particle as May be Observed by MAVEN's SWEA Instrument

$n_e$	$10^7 \text{ m}^{-3}$
$ v_{\parallel} $	$10^7 \text{ m/sec}$
$v_{\perp}$	$2 \times 10^6 \text{ m/sec}$
$ v_b $	$10^5 \text{ m/sec}$
$ E_c $	$10^{-3} \text{ V/m}$
$ E_H $	$10^{-4} \text{ V/m}$
$ E_A $	$10^{-5} \text{ V/m}$
$ E $	$10^{-3} \text{ V/m}$
$ J $	$10^{-8} \text{ A m}^{-2}$
$ B $	$10^{-8} \text{ T}$
$ (B \times \nabla B)/B^2 $	$10^{-6} \text{ m}^{-1}$
$ R $	$4 \times 10^6 \text{ m}$

Note. These values are used to estimate the magnitude of the perpendicular drifts in Sections 5.1, and may be applied to reduce Equation 13 to the form 14 by neglecting small terms.

typical values in the sheath  $|v_b| \sim 10^5 \text{ m/sec}$  and  $|B| \sim 10^{-8} \text{ T}$ , we find  $|E_c| \sim 10^{-3} \text{ V/m}$ . In the environment of Mars's magnetosheath with plasma parameters  $\sim 10^{-8} \text{ T}$  and electron density  $n_e \sim 10^7 \text{ m}^{-3}$ , the current density  $J$  has to have a magnitude of  $\sim 10^{-8} \text{ A/m}^2$  (Ramstad et al., 2020); this leads to an estimate  $|E_H| \sim 10^{-4} \text{ V/m}$ . The ambipolar field is about 1/100 the typical convective field: assuming  $T_e$  varies by about 100 eV over the magnetosheath scale ( $\sim 10^7 \text{ m}$ ), we estimate  $|E_A| \sim 10^{-5} \text{ V/m}$ . Although it provides the smallest contribution to the total electric field (Equation 4), we note that the ambipolar field may alone account for the observed electron energization  $\Phi \sim 100 \text{ eV}$  when integrated across the magnetosheath scale. Indeed, to a first approximation the convective and Hall terms in Equation 4 may be ignored for the purpose of understanding electron energization—as will be shown shortly.

Let us consider the trajectory of an electron that moves through the electric field (4) with guiding center velocity  $\mathbf{v}_{gc}$ :

$$\mathbf{v}_{gc} = v_{\parallel} \hat{\mathbf{b}} + (\mathbf{v}_E + \mathbf{v}_R + \mathbf{v}_{\nabla B}), \quad (8)$$

where  $v_{\parallel}$  is the velocity component along the magnetic field direction,  $\hat{\mathbf{b}} \equiv \mathbf{B} / B$ . The remaining terms represent the field-perpendicular drifts; that is,  $\mathbf{v}_E$ ,  $\mathbf{v}_R$ , and  $\mathbf{v}_{\nabla B}$  denote the  $\mathbf{E} \times \mathbf{B}$ , curvature, and grad-B drifts respectively:

$$\mathbf{v}_E = \frac{\mathbf{E} \times \mathbf{B}}{B^2}, \quad (9)$$

$$\mathbf{v}_R = \frac{m_e v_{\parallel}^2}{q_e B} \frac{\mathbf{R} \times \mathbf{B}}{R^2 B}, \quad (10)$$

$$\mathbf{v}_{\nabla B} = \frac{m_e v_{\perp}^2}{2q_e B} \frac{\mathbf{B} \times \nabla B}{B^2}. \quad (11)$$

In the equations above we introduce the electron mass  $m_e$ , the radius of curvature of a field line  $\mathbf{R}$ , and the parallel and perpendicular velocity components of a particle  $v_{\parallel}$ ,  $v_{\perp}$ . Let us estimate the drifts (Equations 9–11) for a representative  $\sim 300$  eV particle with pitch angle  $\theta \sim 10^\circ$ , i.e., with velocity components  $v_{\parallel} = 10^7 \text{ m/sec}$  and  $v_{\perp} = 2 \times 10^6 \text{ m/sec}$ . Assuming typical values of plasma parameters found in the magnetosheath (Table 1), we estimate the perpendicular drift speeds to be  $|v_E| \sim 10^5 \text{ m/sec}$ ,  $|v_R| \sim 10^4 \text{ m/sec}$ ,  $|v_{\nabla B}| \sim 10^3 \text{ m/sec}$ .

In an infinitesimal time  $\Delta t$ , the work  $\Delta W$  done on the particle by the electric field is given by:

$$\Delta W = \Delta t q_e (\mathbf{v}_{gc} \cdot \mathbf{E}), \quad (12)$$

which from substitution of Equations 4 and 8 evaluates to the expression:

$$\Delta W = \Delta t q_e \left\{ v_{\parallel} \hat{\mathbf{b}} \cdot \mathbf{E}_A + [\mathbf{v}_R + \mathbf{v}_{\nabla B}] \cdot \mathbf{E} \right\} \quad (13)$$

As may be estimated from the representative sheath parameters (Table 1), the dominant term of Equation 13 is the work done by the ambipolar electric field  $\mathbf{E}_A$ . Noting  $v_{\parallel} \hat{\mathbf{b}} \sim \mathbf{v}_{gc}$ , we may approximate:

$$\Delta W \approx \Delta t q_e (\mathbf{v}_{gc} \cdot \mathbf{E}_A). \quad (14)$$

Comparison of Equations 12–14 reveals that electrons primarily “see” the ambipolar component of the electric field,  $\mathbf{E}_A$ . The systematic energization comes from the parallel component of the ambipolar field  $E_{a,\parallel}$ . As expressed previously, the observation  $\Delta \Phi \sim 0$  then requires some explanation for how electrons moving

oppositely along the same field line may be energized by the same amount. If we assume that the ambipolar electric field can be expressed as the gradient of a potential, that is,

$$\mathbf{E}_A(\mathbf{x}) = -\nabla\phi, \quad (15)$$

then we need look no further—we have identified a potential field  $\phi(\mathbf{x})$  capable of energizing the electrons isotropically, in the manner of Equation 3.

The assumed form 15 is not at all far-fetched. Taking the curl of Equation 7, we note the ambipolar electric field will be a potential field ( $\nabla \times \mathbf{E}_A = \mathbf{0}$ ) if and only if:

$$\nabla n \times \nabla T_e = 0. \quad (16)$$

This condition (Equation 16) is quite reasonable, as observations show the variation of  $n$  and  $T_e$  to be correlated—both quantities exhibit local maxima in the sheath near the  $x_{\text{mse}}$ -axis, and the contours of these quantities will be roughly symmetric about this axis. We note that if the electron temperature is a function of the density, i.e., if  $T_e = T_e(n)$ , then the condition (16) will be trivially satisfied. As a special case,  $\mathbf{E}_A$  will be a potential field if the electrons obey a polytropic equation of state (in which case  $T_e(n)$  is a power law). This idea has some precedent, as polytropic models have been applied in Earth's magnetosheath, and the polytropic index has been measured in that system for both ions and electrons (Hau et al., 1993; Pang et al., 2016). The condition (16) also has the appealing property of preserving the frozen-in flux condition (assumed to apply in this study) even for a non-ideal electric field of the form 4—see (e.g., Scudder et al., 2015).

As mentioned in Section 4, a small systematic correlation between  $y_{\text{mse}}$  and  $\Delta\Phi$  can be observed in Figure 5, so that  $|\Delta\Phi|$  can be as large as 10–20 eV on the flanks. This trend might be accounted for if the ambipolar field is not exactly potential. Alternatively, it may owe to the drifting of electrons through the strong ( $|E_{cl}| \sim 10^{-3}$  V/m) convective field (Equation 13, rightmost term). As estimated above, in the  $z_{\text{mse}} = 0$  plane the curvature ( $\mathbf{v}_R$ ) drift may amount to velocities  $10^4$  m/sec oriented in the  $+z_{\text{mse}}$  direction, that is, opposite the convective electric field. We estimate these drifts would cause typical electrons to gain about  $\sim 10$  eV during their entire ( $\sim 1$  s) traversal of the sheath. This effect may be responsible for the slight systematic correlation between  $y_{\text{mse}}$  and  $\Delta\Phi$  observed in Figure 5. The mechanism may be roughly imagined as follows: Particles with  $v_{\parallel} > 0$  at a given location in the region  $y_{\text{mse}} > 0$  will have spent more time traveling along the field line than particles at the same location with  $v_{\parallel} < 0$  (which have crossed the bow shock more recently). So, the parallel-propagating electrons will generally have gained more energy via drifting than the anti-parallel electrons in the region  $y_{\text{mse}} > 0$ , that is,  $\Delta\Phi > 0$ . Similar reasoning may be applied to argue  $\Delta\Phi$  should be slightly negative in the region  $y_{\text{mse}} < 0$ . We note that the energy gained via the curvature drift is velocity-dependent because of the quadratic dependence of  $\mathbf{v}_R$  on  $v_{\parallel}$  (Equation 9). This could lead to minor departures from our approximation that all electrons moving with a particular orientation with respect to the magnetic field will gain a constant amount of energy. For example, this may explain the slight discrepancies seen at high energies between the two spectra plotted in the right panel of Figure 2. Detailed investigation of the curvature and gradient drifts, which could contribute a small but non-zero  $\Delta\Phi$ , is left to future research.

## 5.2. Current Feedback

In another scenario, the observation  $\Delta\Phi \sim 0$  might be explained by applying a more self-consistent model of the shock potential. That is, our model of the cross-shock potential  $\Phi_s$  (see supporting document) may not represent a true steady-state, despite being empirically based. Notably, if electrons are energized by different amounts at the two points where the field line meets the shock front, the expected asymmetry of the distribution functions may form a field-parallel current. These currents may lead to a local build-up of charge, and the resulting electric fields would suppress the currents themselves and alter the imposed form of the electric field. Analysis of electron motion in such a self-consistent field might better agree with the observations of  $\Delta\Phi$  presented here.

In order to model the cross-shock potential  $\Phi_s$  and our assumed boundary conditions for  $f(\mathbf{v})$  more realistically, an approach similar to that of Mitchell and Schwartz (2014) may be required. In that study, which was concerned with Earth's magnetosheath, the electrons were assumed to be energized entirely by a cross-

shock potential  $\Delta\Phi^H$ . In this kinetic model, the magnitude of  $\Delta\Phi^H$  was set throughout the shock to a value that would 1) suppress the parallel current  $J_{\parallel}$  and 2) also satisfy the density predicted by the one-fluid Rankine-Hugoniot relations. Determining whether such a study could reproduce the observed energization and isotropy of the Martian magnetosheath is beyond the scope of this paper. However, we do note that the distributions reported in Mitchell and Schwartz (2014) were not highly asymmetric, which is qualitatively consistent with the observations reported here.

Along these lines, we note a promising result from Mitchell and Schwartz (2014): The authors found that the cross-shock potential at Earth on the flanks should not asymptote to zero at infinity, but rather to some constant value. Such a profile at Mars would flatten the potential variation along the shock front, so that the two ends of a given field line would tend to be at more similar potentials (leading to smaller  $|\Delta\Phi|$ ). However, we also note that in their study of Earth's bow shock the authors found that the magnetosheath should settle into an isothermal state; the significant spatial temperature observed in Mars's magnetosheath does not agree with this picture.

## 6. Summary

In this paper we analyzed the energization of electrons in the Martian magnetosheath. The  $>30$  eV electrons considered in this study move quickly enough to traverse the magnetosheath in about 1 s, so that during this time the field line along which an electron moves is essentially fixed. Due to the different cross-shock potentials at the two locations where the field line intersects the shock (under typical solar wind conditions), we may expect to see a significant difference (as much as  $\sim 60$  eV) between the derived quantities  $\Phi_{\parallel}$  and  $\Phi_{\perp}$ . The absence of such a signature, as demonstrated for a single orbit (Figure 4) and in a statistical average of the  $z_{\text{mse}} = 0$  plane (Figure 5), indicates that our basic model of the Martian bow shock needs to be reconsidered.

We presented two possible resolutions for the discrepancy between our model and the observations of  $\Delta\Phi$ . In one case, we suggested that an ambipolar, (nearly) potential electric field distributed throughout the magnetosheath region could plausibly explain the observation  $\Delta\Phi \sim 0$ . In another case, we considered that our predictions for  $\Delta\Phi$  would change (and possibly agree better with the observations) if a more self-consistent model for the cross-shock potential  $\Phi_{\perp}$  were applied. Further investigation of these two explanations is beyond the scope of the present paper, which is observational in its focus. But in any case, we may conclude that diffusive effects such as collisions and wave-particle interactions have a negligible effect on the electron distributions through most of the magnetosheath. This is based on the effectiveness of the Liouville mapping technique.

The study was motivated by the simple collisionless model of the sheath developed in Schwartz et al. (2019), which sought to explain the so-called "erosion" of the electron flux observed in the inner magnetosheath. This study suggests that additional acceleration inside the sheath is taking place, obscuring the observational signature that would otherwise be seen if electrons were solely energized at the shock. We are not concerned with the electron flux erosion here. However, we note that if a significant electrostatic field is present in the magnetosheath (as suggested above), incorporating this field's effect may improve the Schwartz et al. (2019) model. Not incorporated into this study is the interaction of electrons with neutral hydrogen in the Martian foreshock (C. X. Mazelle et al., 2018).

The significant energization of electrons observed at a planetary bow shock is not unique to the Martian system. We speculate that techniques similar to those employed here may be applicable to magnetosheaths at Venus and Earth, for instance. No two systems are identical, however, and we foresee that the conditions at other planets may contradict some assumptions applied here. For instance, at Earth one cannot assume that electrons flow along essentially fixed field lines due to the larger shock scale (Mitchell et al., 2012). Though such details may complicate the observational analysis, it is nonetheless clear that Liouville mapping can be an effective technique for probing the electric field structure in planetary shocks and magnetosheaths elsewhere in the solar system.

## Data Availability Statement

The solar wind speed, magnetic field, and MAVEN ephemeris were obtained from the MAVEN “key parameter” summary data available from the CDAWeb database at <https://cdaweb.gsfc.nasa.gov/index.html/>. The SWEA pitch angle distributions are available online via the MAVEN Science Data Center at <https://lasp.colorado.edu/maven/sdc/public/>.

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