

Mars Express observations of the stretch effect of mini-magnetospheres formed by crustal fields on the Martian bow shock location

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Key Points:

- Mars Express observations show that strong crustal fields can lift bow shocks into higher altitudes on both the Martian dayside and nightside.
- The tailward shifting of the enlarged shocks from the strong crustal field location confirms the stretching effect of mini-magnetospheres.
- Due to the dawnside bias of shock crossings, the average sizes of Mars Express observed shocks are larger on the west side of strong crustal field.

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Abstract: The strong crustal magnetic fields significantly alter the structure of the Martian space environment, including all plasma boundaries. The stretches of mini-magnetospheres formed by crustal fields from the location of the Martian bow shocks were first found from the Mars Atmosphere and Volatile Evolution (MAVEN) observations. The present study aims to test whether this effect is also present in the shocks observed by Mars Express (MEX). We find that the bow shocks above the crustal field regions are enlarged, resulting in a north–south asymmetry and a longitude dependence in the shock size. The longitude dependence is more pronounced for near-subsolar shocks, and more dispersed for near-terminator shocks. The enlarged shocks are also observed to have shifted tailward from the longitudes of the strongest crustal fields. Due to a dawnside bias in MEX shock crossings, the enlarged shocks generally display a westward shift from the strongest crustal field region. These results confirm that stretches of the mini-magnetosphere are also present in the MEX shock observations.

Keywords: Mars; bow shock; crustal fields

1. Introduction

A bow shock, the outermost boundary of planetary space environment, can be formed when a supersonic solar wind encounters a planetary charged obstacle. The shape of the bow shock depends on the Mach number of the solar wind, and the obstacle's shape (Hida, 1953; Kellogg, 1962; Spreiter et al., 1966). For example, Earth's intrinsic dipolar magnetic field interacts with the solar wind, forming a dipolar magnetosphere and a bow shock of a shape that varies with the dipolar magnetopause or the solar wind dynamic pressures (Sibeck et al., 1990). By contrast, Venus lacks an evident intrinsic magnetic field. Its ionosphere directly interacts with the solar wind, forming an induced magnetosphere and a bow shock of a shape that varies with the ionopause or the extreme ultraviolet (EUV) flux (Russell et al., 1988; Wang M et al.,

2024). Mars has a hybrid magnetic structure, consisting of intrinsic crustal fields (Acuña et al., 1999) and induced magnetic fields (Xu SS et al., 2017, 2019, 2020; DiBraccio et al., 2018). Like the Venusian bow shock, the Martian bow shock terminator distance increases linearly with the EUV flux (Hall et al., 2016, 2019). However, the influence of crustal fields on the bow shock location is rather complicated. It is worth mentioning that, besides the EUV and crustal fields, Martian bow shock locations are also determined by Mach number, solar wind pressure, interplanetary magnetic field (IMF) intensity and direction (Garnier et al., 2022), and both the bow shock and the magnetic pileup boundary beneath it are three-dimensional (Wang M et al., 2020, 2022).

The strong crustal fields can alter the structure of the ionosphere (Mitchell et al., 2001; Brecht and Ledvina, 2014; Andrews et al., 2015; Matta et al., 2015; Dubinin et al., 2020), influence particle escape (Lundin et al., 2011; Ramstad et al., 2016; Dubinin et al., 2020; Weber et al., 2021), and lift the magnetic pile-up boundary (MPB) (Crider et al., 2002; Edberg et al., 2008, 2009).

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A significant north–south asymmetry is observed in the Martian bow shock location, i.e., the bow shock in the southern hemisphere is higher, which is attributed to the strongest crustal magnetic fields being located in the southern hemisphere (Crider et al., 2002; Mazelle et al., 2004; Edberg et al., 2008; Fang XH et al., 2017; Gruesbeck et al., 2018; Garnier et al., 2022; Guo MD et al., 2025). However, as was found by Edberg et al. (2008) from Mars Express (MEX) observations, the bow shocks in the southern hemisphere over weak or non-crustal field regions are also higher than those in the northern hemisphere. Fang XH et al. (2017) demonstrated that the crustal fields have a global impact on the bow shock location by combining simulations and observations. Based on a multi-mission analysis of MEX and Mars Atmosphere and Volatile Evolution (MAVEN) observations, Garnier et al. (2022) found that the bow shocks within an angular range of maximum 70° – 80° over the crustal fields are uplifted. More recently, based on a large dataset of MAVEN bow shock crossings, Guo MD et al. (2025) found that the enlarged shocks in the dawn and dusk sides shifted westward and eastward, respectively, by about 45° from the strongest crustal field region, and pointed out that this is due to the tailward stretches of the mini-magnetospheres formed by the crustal fields.

This study aims to test whether the stretch influence of the mini-magnetospheres on the Martian bow shock still exists in the shock observations by MEX. Section 2 introduces the dataset and methodology. Section 3 presents the main results, which include the latitude and longitude dependences of bow shock size and longitude shift due to the tailward stretch of the mini-magnetospheres. Section 4 is the discussion and conclusion.

2. Data and Methods

This study analyzes the 13,585 MEX bow shock crossings (blue dots in Figure 1a) provided by Hall et al. (2019) in the Mars–Sun–Orbital (MSO) coordinate system, in which the X-axis points

from Mars center to the Sun, the Y-axis points in the direction opposite to Mars' orbital motion, and the Z-axis completes the right-handed coordinate system (Figure 1a). There are two main differences between the shock crossings of MEX and MAVEN. First, MEX has a better orbital coverage of the nightside bow shock. Second, the MEX orbits have a strong bias in the dawn–dusk (Y) direction. As shown in Figure 1b, most of the MEX orbits (red curves) distribute at high altitudes on the dawnside ($Y < 0$) and low altitudes on the duskside ($Y > 0$), which means that MEX crosses more bow shocks (blue dots in Figure 1b) at the dawnside (9477 shock crossings) than duskside (4108 shock crossings). This dawnside bias of shock crossings will notably alter the location of the shocks lifted by mini-magnetospheres formed by crustal fields. Detailed discussions of this can be found in Section 3.3.

To compare the size of the bow shock crossings observed at different solar zenith angles (SZAs), it is necessary to normalize them into the same SZA. The first step is to establish a general bow shock model by fitting the locations of the shock crossings (x, y, z) to a conic curve:

$r = L/(1 + \varepsilon \cos \theta)$, where $r = \sqrt{(x - x_0)^2 + y^2 + z^2}$, $\theta = \cos^{-1}(x - x_0)/r$. Then, the eccentricity (ε), focus point (x_0), and semilatus rectum (L) of the conic curve can represent the shape, position, and size of bow shocks, respectively. Since the crossings in $X < -1.5 R_M$ (R_M is Martian Radius) exhibit an uneven distribution, as seen from Figure 1a, only the crossings in $X > -1.5 R_M$ are used for fitting. The resulting parameters and their corresponding uncertainties by standard variances are: $\varepsilon^{\text{model}} = 0.9863 \pm 0.0085 R_M$, $L^{\text{model}} = 1.8004 \pm 0.0267 R_M$, $x_0^{\text{model}} = 0.8043 \pm 0.0262 R_M$ (The red curve in Figure 1), which is very close to the results of Hall et al. (2019).

The second step is to normalize the shock crossings into the terminator plane by assuming that all shock shapes ($\varepsilon = \varepsilon^{\text{model}}$) and positions ($x_0 = x_0^{\text{model}}$) remain unchanged, but the shock sizes (L) remain variable. Then, the normalized shock sizes are represented by the distances between the bow shocks and the Mars

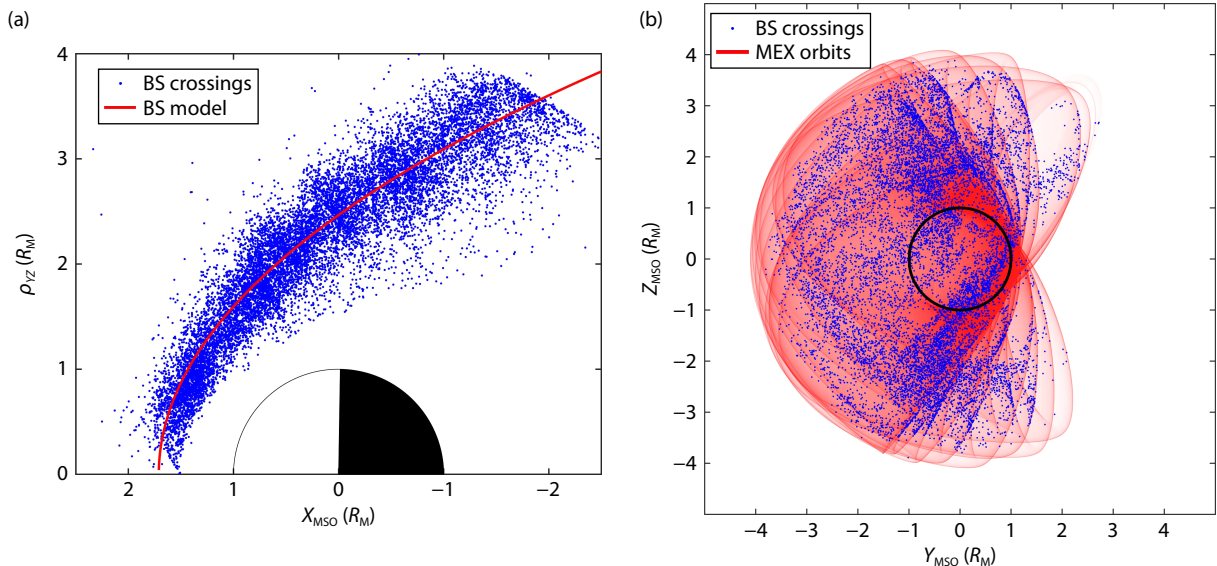


Figure 1. The location of the Martian bow shock crossings by MEX and the distribution of the MEX orbits. (a) shows the locations of the Martian bow shock crossings (blue dots) and the shock location model (red curve) on $X\rho_{YZ}$ plane, where $\rho_{YZ} = \sqrt{Y^2 + Z^2}$ is the distance from the Mars–Sun line. (b) shows the distributions of the MEX orbits (red curves) and shock crossings (blue dots) projected on the YZ plane.

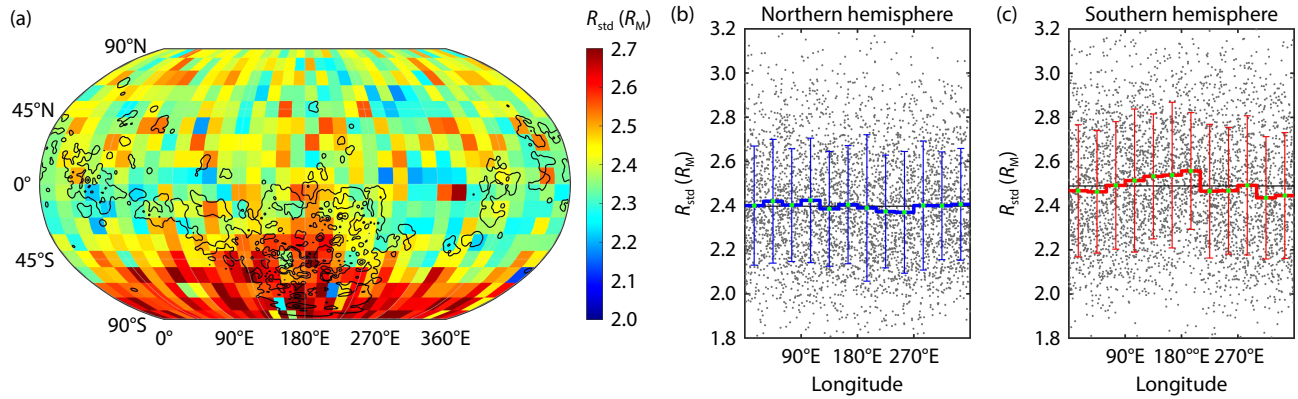


Figure 2. The crustal field dependence of the Martian bow shock size. (a) is the average bow shock size projected on the Mars global geologic map. The colors represent the average R_{std} in the longitude–latitude bins of $10^\circ \times 10^\circ$. The black curves are the crustal magnetic field contour map at the Martian surface (Morschhauser et al., 2014). (b) and (c) are the longitude dependences of the bow shock sizes in the northern and southern hemispheres, respectively. The grey dots represent the observed shock crossings, and the horizontal black lines represent the hemispheric average values. The green dots and horizontal blue (b) and red (c) lines represent the averages, and the vertical blue (b) and red (c) lines represent the standard deviations in the longitude bins of 30° .

center at the terminator plane (R_{std}), which can be calculated as $R_{\text{std}} = \sqrt{(L + \varepsilon x_0)^2 - x_0^2}$, $L = \sqrt{(x - x_0)^2 + y^2 + z^2 + \varepsilon(x - x_0)}$. The large variation in the Martian bow shock crossings (blue dots) relative to the average model (red curve) in Figure 1a are likely due to the multiple control factors of Martian bow shock location (Garnier et al., 2022), and the bow shock is in fact unsymmetric along the X axis (Wang M et al., 2020). The large standard deviations in calculating the average shock sizes relative to crustal field longitudes and latitudes (Figures 2–4) also indicate that besides the crustal field, there are other factors influencing the location of Martian bow shocks.

3. Results

3.1 The North–South Asymmetry

Figure 2a is the average shock terminator distances R_{std} in bins of $10^\circ \times 10^\circ$ (Longitude $\times$ Latitude) in Mars geologic coordinates. An evident north–south asymmetry is present in the Martian bow shock size. The average shock size in the southern hemisphere ($2.49 R_M$) is $\sim 3.7\%$ higher than that in the northern hemisphere ($2.40 R_M$), which is on the same order of magnitude as previous studies (Edberg et al., 2008; Hall et al., 2016; Fang XH et al., 2017; Gruesbeck et al., 2018; Guo MD et al., 2025). Figures 2b and 2c present the longitude dependences of shock sizes in the northern and southern hemispheres, respectively. The northern bow shocks are also slightly enlarged over the weak crustal field regions (30°E – 120°E , 150°E – 180°E , 270°E – 360°E) (Figure 2b). In contrast, the southern bow shock reaches its highest altitude ($2.56 R_M$) above the strongest crustal fields (150°E – 210°E) (Figure 2c), indicating a strong correlation between the enlarged bow shocks and the strength of crustal fields. Moreover, in the west of the strongest crustal field region near the equator (longitude $< 180^\circ\text{E}$, $30^\circ\text{S} < \text{latitude} < 60^\circ\text{S}$), the average R_{std} is $2.50 R_M$, indicating that most of the bow shocks there are enlarged by the nearby crustal fields. By contrast, in the east (longitude $> 180^\circ\text{E}$, $30^\circ\text{S} < \text{latitude} < 60^\circ\text{S}$), the average R_{std} is $2.44 R_M$, indicating that the shocks there are not significantly affected by the nearby crustal fields. This effect is attributable to the orbital bias of MEX, on which we elaborate in the following analysis of the enlarged bow shock shift.

orate in the following analysis of the enlarged bow shock shift.

3.2 The Longitude Dependence of the Martian Bow Shock

Figure 3(a–c) present the average shock terminator distances R_{std} for near subsolar ($\text{SZA} < 45^\circ$), near terminator ($45^\circ < \text{SZA} < 90^\circ$) and nightside ($\text{SZA} > 90^\circ$) shocks, respectively. As shown in Figure 3a, the near subsolar bow shocks are only enlarged above regions with strong crustal fields. The longitudinal dependence (Figure 3b) also confirms that the largest bow shocks ($2.51 R_M$) appear above the strongest crustal field region ($\sim 180^\circ\text{E}$). As illustrated in Figure 3g, for the near subsolar shocks, only the shocks (blue dashed curve) above the mini-magnetospheres (blue area) formed by crustal fields are lifted, which indicates that the mini-magnetospheres are confined within a small area. In contrast, the near terminator (Figure 3c) and nightside (Figure 3e) shocks over south polar (latitude $> 60^\circ\text{S}$) are enlarged in all ranges of longitude, including directly over the non-crustal field regions. This is why the longitudinal dependence of the shock sizes becomes dispersed relative to the crustal field longitudes (Figures 3d and 3f). As illustrated in Figure 3h, all longitude shocks (red dashed curve) are lifted, which indicates that the mini-magnetosphere (dark red area) can protrude poleward (light red areas) far enough that all south pole bow shocks (red dashed curve) are affected. These results agree very well with the dayside shocks observed by MAVEN (Guo MD et al., 2025). Moreover, MEX orbits have better coverage of the nightside shocks (Figure 1a) than MAVEN, thus MEX can provide information of the nightside shocks' response to the crustal fields. As seen from Figures 3e and 3f, the nightside shocks are enlarged throughout the southern polar region (Figure 3e), and the locations of enlarged shocks are shifted westward from the strongest crustal field longitudes (Figure 3f), just like the near terminator shocks (Figures 3c and 3d). Therefore, the stretched mini-magnetospheres (Figure 3h) can also effect the nightside shock locations.

3.3 The Shift of the Bow Shock

Figures 4a and 4b present the average shock terminator distances

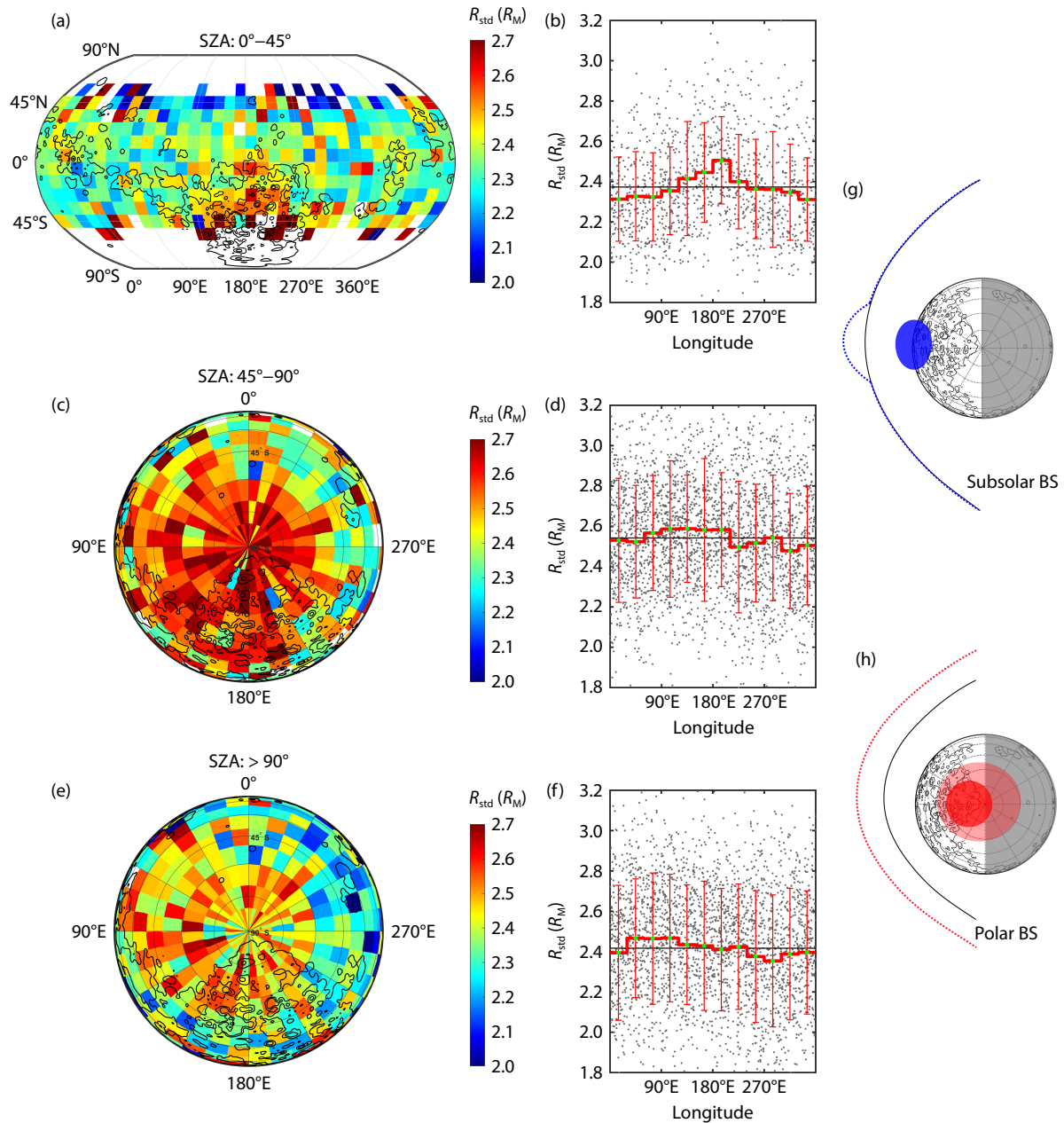


Figure 3. The crustal field dependence on the sizes of the Martian bow shock near subsolar ($SZA < 45^\circ$), near the terminator ($45^\circ < SZA < 90^\circ$) and nightside ($SZA > 90^\circ$). (a) are the same as Figure 2a, but for the bow shocks near the subsolar; (c) and (e) are the same as (a), but viewed from above the south pole for the bow shock near the terminator and nightside. (b), (c) and (f) are the same as Figure 2c, but for the southern bow shocks near subsolar, near the terminator, and nightside. Panels (g) and (h) show the influence of the mini-magnetospheres on the near subsolar and south-polar shocks, viewed from above the south pole. The color (blue and red) dashed curves and black curves represent the bow shock locations with and without the crustal field influence. The dark blue and red areas represent the mini-magnetospheres formed by the crustal fields, and the light red area represents the mini-magnetospheres protruding into the magnetosheath and stretching tailward.

R_{std} for dawnside and duskside shocks, respectively. The dawnside shocks (Figure 4a) over non-crustal field regions are also enlarged in the west of the strongest crustal field region (longitude $< 180^\circ\text{E}$). By contrast, the duskside shocks (Figure 4d) over non-crustal field regions are enlarged in the east of the strongest crustal field region (longitude $> 180^\circ\text{E}$). The longitudes of the enlarged bow shocks extend from 0°E to 180°E on the dawnside (Figure 4b), and from 180°E to 300°E on the duskside (Figure 4e). In other words, the longitudes of the bow shocks enlarged by

crustal fields shift westward on the dawnside, and eastward on the duskside. These results indicate that, as illustrated in Figures 4c and 4f, the mini-magnetospheres (dark blue area) formed by the crustal fields stretch tailward (light blue area), driven by the tailward dynamic pressure of the magnetosheath flow, causing the dawnside and duskside bow shocks (blue dashed line) to respond differently to the crustal fields. Although there are only limited shock crossings on the duskside, the general trends of MEX observations agree very well with the results of MAVEN (Guo

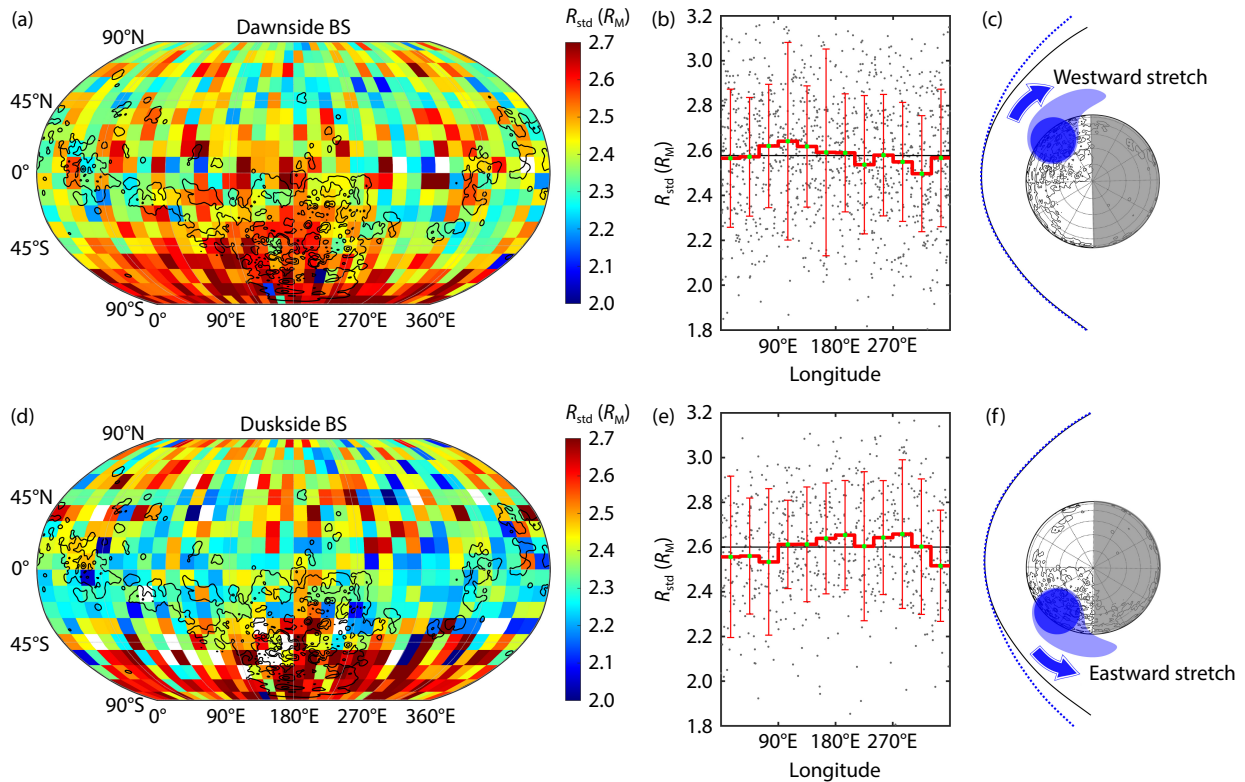


Figure 4. The crustal field dependence on the sizes of the Martian bow shock on the dawnside and duskside. (a) and (d), same as Figure 2a, but for the dawnside (a) and duskside bow shocks (d). (b) and (e), same as Figure 2c, but for the dawnside (b) and duskside (e) southern bow shocks. Planes (c) and (f) illustrate the influence of the tailward stretch of the mini-magnetospheres formed by crustal fields on the bow shock, viewed from above the south pole. The dark and light blue areas represent the original and stretched mini-magnetospheres formed by the crustal fields. The blue arrows represent the direction of stretching due to the magnetosheath flows. The blue dashed curves and black curves represent the bow shock locations with and without the crustal fields.

MD et al., 2025). Considering the tailward shift of the mini-magnetospheres, and the fact that MEX crosses more shocks in the duskside, it makes sense that the overall average shock sizes in MEX observations are enlarged in the west of the strongest crustal field region (Figure 2a).

4. Conclusions and Discussion

Guo MD et al. (2025) found that the stretch of the mini-magnetospheres formed by the crustal fields can be detected from Martian bow shock location, based on the MAVEN observations. The present study aims to test whether the same phenomenon can be detected by the MEX observations. The results show that the stretch effect of the mini-magnetospheres on the bow shock location is also present in the MEX observations. The main findings can be summarized as follows:

- (1) The overall bow shock observed by MEX is enlarged in the west of the strongest crustal field, due to the tailward stretch and the dawnside bias in MEX shock crossings.
- (2) The average shock sizes above the crustal field regions are enlarged. The north–south asymmetry in the Martian bow shock location observed by MEX is $\sim 0.09 R_M$, which generally agrees with the MAVEN observations ($\sim 0.10 R_M$).
- (3) The near subsolar shocks are only enlarged directly above the crustal field regions, whereas the near terminator and nightside

shocks are enlarged over the whole range of longitudes over the south polar region. It is consistent with the conclusions from the MAVEN observations that the mini-magnetospheres are confined to a small area near the subsolar region but protrude poleward deep into the magnetosheath near terminator and nightside.

- (4) The locations of the enlarged bow shocks shift westward on the dawnside and eastward on the duskside. It is consistent with the conclusions from the MAVEN observations that the mini-magnetospheres formed by crustal fields undergo a tailward stretch by the magnetosheath flows.

- (5) The MEX orbits provide good coverage of the nightside bow shocks, allowing us to analyze the nightside shock response to crustal fields. The results show that the stretch of the mini-magnetospheres formed by crustal fields can also affect the nightside shock locations.

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Open Research

The MEX shock list used in this study is provided in Hall et al. (2019) with DOI: 10.1029/2018JA026404.

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