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The influence of crustal magnetic fields on the Martian bow shock location: a statistical analysis of MAVEN and Mars Express observations

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Key Points:

- The influence of crustal magnetic fields on the Martian shock is significant based on the first multi-mission study
- The strongest crustal field region has a major influence in a large angular range, when close to noon and when the IMF is stable.
- The crustal field influence varies with season, showing a coupling between crustal fields, the ionosphere and the shock

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Abstract

Previous missions underlined the complex influence of the crustal magnetic fields on the Martian environment, including the plasma boundaries. Their influence on the bow shock is however poorly constrained, with most studies showing North/South differences attributed to the crustal fields, with various conclusions from little to strong variabilities.

We analyze for the first time in detail the influence of crustal fields on the Martian shock location based on a multi-mission analysis (MAVEN and MEX). We introduce the angular distance to the strongest crustal field region in the southern hemisphere that induces the largest influence (but not unique, with a minimum pressure threshold analyzed). Its impact is at large scale ($> 40-60°$ around), is modulated by the local time of the strongest source region (with no influence beyond terminator), and maximizes when the Interplanetary Magnetic field (IMF) is stable during the preceding hours. We introduce a technique, i.e. partial correlations, to provide a coherent picture for both MAVEN/MEX due to existing cross correlations with Extreme UltraViolet (EUV).

A composite parameter is proposed, that represents the combined influence of EUV, magnetosonic mach number (two major drivers) and crustal fields, the latter having an impact of hundreds of km. The influence of crustal fields on the shock appears seasonal and correlated with the Total Electronic Content, revealing a large scale coupling between the crustal fields, the ionosphere and the shock. The crustal field influence on the shock is thus significant and complex, with a coupling to both the ionosphere below and the IMF above.

1 Introduction

The Martian interaction with the solar wind (SW) is unique due to the absence of a global intrinsic dynamo magnetic field but with the presence of remnent crustal magnetic fields (Acuña et al. (2001)). The Mars Global Surveyor (MGS; 1997-2006), Mars Express (MEX; 2004-present) and Mars Atmosphere and Volatile Evolution (MAVEN; 2014-present) missions have revealed major effects of the crustal fields on the Martian induced magnetosphere through various phenomena, such as: plasma precipitation (Brain et al. (2007), Fang et al. (2010), Lillis and Brain (2013)) and induced auroras (Bertaux et al. (2005), Schneider et al. (2018)), density depletions (Mitchell et al. (2001), Hall et

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al. (2016a), Steckiewicz et al. (2017), Flynn et al. (2017)), ion escape (Fang et al. (2010), Ma et al. (2014), Romanelli et al. (2018), Poppe et al. (2021)), cross terminator transport (Xu et al. (2016), Fang et al. (2015)), and magnetic reconnection in the tail region (DiBraccio et al. (2018)).

The interaction between Mars and the solar wind results in several plasma boundaries, such as the bow shock (hereafter BS), the Induced Magnetospheric Boundary (IMB) or Magnetic Pile-Up Boundary (MPB), the Ion Composition Boundary (ICB), the PhotoElectron Boundary (PEB) or the ionopause. These boundaries are highly dynamic and depend on both internal and external drivers. Studying their dynamics is crucial to better understand the response of the Martian environment and thus its evolution with time. The SW dynamic pressure was considered as a major driver for the BS and MPB location (Vignes et al. (2002), Crider (2004)). Edberg et al. (2010) showed that the magnetosonic mach number of the SW also influences significantly the BS. Later, Hall et al. (2016b) analyzed MEX data and showed that the BS location is more sensitive to seasonal variations in the solar extreme ultraviolet (EUV) irradiance than to SW dynamic pressure variations, and Hall et al. (2019) also showed the influence of solar cycle EUV variations. Moreover, Halekas et al. (2017) showed the major influence of the magnetosonic mach number and EUV, as well as a significant influence of SW dynamic pressure but a weak dependance on the geographical longitudes (which would have been expected due to non-uniformly distributed crustal fields).

Among the various drivers of the BS location, the crustal magnetic fields of the planet are among the least understood. Previous studies suggested an influence of the crustal fields, characterized by differences between the north and south locations of BS (e.g. Mazelle et al. (2004)), presumably attributed to the strongest crustal source region located in the southern hemisphere of the planet (centered on $\sim -45°$ IAU latitude and $\sim 180°$ IAU longitude). Such hemispheric differences were also observed for other boundaries (Matsunaga et al. (2017), Garnier et al. (2017)). However, these comparisons showed a weak dependance on the position of the strongest crustal source region, with no clear longitude modulation found. Edberg et al. (2008) proposed wide (i.e. 120°) longitude bins exhibiting large differences in terms of BS location, these differences being found much smaller with MAVEN by Halekas et al. (2017). Gruesbeck et al. (2018) showed that the strongest crustal source region in the southern hemisphere had a different influence on the BS location depending on the dayside vs nightside location of the source region. Fang

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et al. (2017) (hereafter XF17) also suggested a rather global influence of the crustal field on the BS, and that the crustal magnetic pressures over different solar zenith angle zones exert different influences. Recently, Nemec et al. (2020) compared the influence of EUV, SW dynamic pressure and local crustal field intensity on the MAVEN BS crossings, suggesting a non negligible influence of local crustal fields but still much smaller compared to the other two drivers. Overall, the influence of the crustal fields on the BS is still under debate - from little influence (Edberg et al. (2009), Li et al. (2020)) to strong variability, up to above 1000 km altitude differences in the BS location based on North/South asymmetries (Edberg et al. (2008),Gruesbeck et al. (2018)) - or in terms of local (Nemec et al. (2020)) vs more global (Fang et al. (2017)) spatial extent. For these reasons, the main goal of this study is to do the best-to-date characterization of the behaviour of the Martian BS over crustal fields using all available datasets.

In this paper we analyze shock crossing datasets from both the MEX and MAVEN missions. We describe the data in Section 2.1 and our methods in Section 2.2. The results of our study are shown in Section 3, starting with a detailed analysis of the influence of the crustal fields on the Martian shock location in Section 3.1. Then in Section 3.2 we use a partial correlation approach to investigate existing biases vs Extreme UltraViolet fluxes and confirm the significance of the crustal field influence on the shock location. We finally provide a discussion and conclude in Sections 4 and 5.

2 Datasets and methods

2.1 Description of the datasets

We analyze the observations by two missions - MEX and MAVEN - to support the results obtained and avoid biases related to mission specificities.

We first used the list of MEX crossings derived by Hall et al. (2016b), in which an automatic algorithm is used to detect the BS crossings in the measurements from the MEX instrument Analyzer of Space Plasmas and Energetic Atoms (ASPERA-3) Electron Spectrometer (ELS). The ASPERA-3 ELS is an electron spectrometer able to detect electrons in the energy range of 1 eV-20 keV with an energy resolution of around 8% (Barabash et al. (2006)). From January 2004 to May 2015, 12091 BS crossings were identified. Among these, we reduced multiple crossings occurring within a minute into one event, leading to 11,820 crossings in total for the MEX BS.

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Two MAVEN studies dealing specifically with the analysis of the BS boundary - XF17 (who used the list published by Masunaga et al. (2017)) and Gruesbeck et al. (2018) - provided lists of 2934 and 1957 BS crossings over the periods november 2014 to march 2016 and november 2014 to march 2017 respectively. These crossings were identified based on the MAVEN MAG magnetic field data (Connerney et al. (2015)), SWEA electron data (Mitchell et al. (2016)), and SWIA ion data (Halekas et al. (2015)). We removed the crossings that overlapped in time or occurred at the same time within an hour, reducing our MAVEN list to 3837 BS crossings.

The large number of BS crossings of MEX and MAVEN - thanks to their relatively short orbital periods of 6.7 and 4.5 hours respectively - provides a large spatial and temporal coverage for statistical analyses. The coverage in terms of solar EUV flux and SW dynamic pressure, known as significant drivers, is also sufficiently broad (see the dataset descriptions by Hall et al. (2016b) and Masunaga et al. (2017)). However, a noteworthy difference exists between both datasets: MEX covers a whole solar cycle (2004-2015, with the solar maximum in 2014), while the MAVEN dataset corresponds to a shorter period (2014-2017) where the mean EUV level (given by the solar 10.7 cm radio flux) was larger by $\sim 14\%$ at the time of the crossings compared with the MEX dataset. Since the absolute location of the BS may be different between both datasets due to solar activity variability (see Section 3.1), we thus focus on the variability of the BS location rather than on their absolute values.

Moreover, we use a third dataset based on the Mars Global Surveyor (MGS) mission data analysis by Vignes et al. (2002). MGS included a dual fluxgate magnetometer (MAG) and an electron reflectometer (ER) (Acuña et al. (1992)). This third dataset contains 544 BS crossings occuring during the pre-mapping phase of the mission where the orbit was eccentric enough to cross the shock. However, this third dataset is considered with caution, since the number of crossings is limited compared to the MEX and MAVEN datasets. Furthermore, the dataset crossings occurred over a single year (from September 1997 to September 1998, after the solar minimum in 1996) when a relatively narrow range of EUV fluxes (3 times smaller than MAVEN) and solar wind properties were covered.

Finally, we use in Section 4 Total Electronic Content ionospheric data from the MARSIS instrument onboard MEX. TEC retrievals are given from the planetary surface un-

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til MEX altitude, and are obtained when MARSIS operates in the subsurface mode (see more at Sánchez-Cano et al. (2015)). The algorithm for the retrieval is described in Cartacci et al. (2013) and Cartacci et al. (2018). Only data with a signal to noise ratio > 15 dB were used to remove noise and bad quality data.

2.2 Description of the methods

2.2.1 The extrapolated terminator altitude of the shock

We use a one-dimensionnal approach to investigate the variability of the BS location, by considering the so-called extrapolated terminator altitude, defined as follows.

We first rotate (by 4°) the crossing locations into the SW aberrated cylindrical MSO system, to account for the aberration of the solar wind flow direction by the planetary orbital motion. The MSO frame (X,Y,Z) coordinates are defined as follows: X points towards the Sun, Y points approximately opposite to Mars orbital angular velocity and Z completes the right-handed set. We neglect the axis asymmetry of the BS (see Fang et al. (2015)) and assume the shock boundary can be fitted by a conic section described by the following equation:

$$r = \frac{L}{1 + ecos(\theta)} \quad (1)$$

where r is the distance to the focus located at $(X_0, 0, 0)$, L and e are respectively the semi-latus rectum and eccentricity. As performed by previous authors (see e.g. Edberg et al. (2008) or Hall et al. (2016b)), we calculate the extrapolated terminator altitude, defined by the altitude of the conic in the aberrated terminator plane:

$$R_{TD} = \sqrt{L^2 + (e^2 - 1) \cdot X_0^2 + 2 \cdot e \cdot L \cdot X_0} - R_M \quad (2)$$

where R_M is the Martian radius (3390 km). This parameter represents the variability of the BS location, removing the strong solar zenith angle influence by projecting the crossing point toward the aberrated terminator along an assumed conic fit. This simple procedure prevents from doing complex analysis of 3D asymmetries as done by Gruesbeck et al. (2018), but is efficient to focus on a single parameter influence (e.g. the crustal fields). We used the L and e values published by Hall et al. (2016b) for the MEX crossings ($L = 1.82\ R_M$, $e = 1.01$), and the values published by XF17 for MAVEN ($L = 2.303\ R_M$, $e = 0.872$). Note the impact of using various data sets and conic fit parameters is discussed further in Section 3.2.

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Note that we could wonder whether a one-dimensionnal approach, that projects the crossing point along a conic fit, is appropriate to investigate local variabilities of the shock location such as induced by crustal fields. However, first the magnetosonic waves do not propagate radially only, the impact of crustal fields after magnetosonic wave propagation upstream of the planet will thus necessarily influence the shock location in a rather wide region given the distance of the shock. Second, if the influence was very localized at the shock location, this would have been observed earlier, and is in contradiction with the large extent of the influence shown in the following sections, which confirms the ability of the one-dimensionnal approach to study the crustal field influence.

2.2.2 Statistical tools

Beyond the direct analysis of the extrapolated terminator altitude, we use in this paper correlation approaches defined below: linear Pearson correlation coefficients, unpaired t-tests and partial correlations.

First, simple correlation factors are analyzed in Sections 3.1 and 3.2. By default, we consider in the paper Pearson correlation coefficients that inform us about the strength and direction of the linear relationship between two variables, with values ranging from -1 (perfect anti-correlaton) to $+1$ (perfect correlation).

In order to evaluate the significance of the correlation factor which strongly depends on the sample size, we make statistical tests. A t-test evaluates the test statistics associated with the correlation, and compares it with a threshold defined for a given risk. This threshold corresponds to the statistics of the null hypothesis H_0, which is the hypothesis of no significant correlation. The correlation is considered significant if the test statistics t is above the threshold, otherwise the correlation factor is not considered significant with sufficient confidence. The risk value chosen by default for calculating the threshold is 5%, corresponding to a 2 standard deviations (i.e. 95%) tolerance interval for a gaussian probability distribution. Alternatively, two-sided p-values can be calculated to provide the probability that the null hypothesis is true. If the p-value is larger than the risk limit assumed (5% here), there is insufficient confidence that a significant linear relationship exists. On the other hand, if the p-value is smaller than the limit risk considered, the null hypothesis is rejected and the correlation is considered significant.

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In the rest of the paper we will mention that p-values are negligible when they are smaller than 10^{-5} and note them with "(n)".

Unpaired t-tests are also used in Section 3.2. These procedures compare two independent groups to determine if there is a significant difference between them. They assess whether the two groups have significantly different mean values. P-values can also be associated to these tests as for correlation tests.

Beyond these well known methods - linear Pearson correlation coefficients and unpaired t-tests -, we use a partial correlation approach in Section 3.2 to mitigate possible biases due to cross correlations between drivers. The partial correlation approach (Baba et al. (2004); see Appendix A for a detailed description of the method) identifies individual relationships among variables that may be correlated, and calculates the correlation coefficients - and estimates their significance - between two variables after controlling for the influence of other variables. This technique is not a common tool in the literature, but it has been successfully used by several authors in studies such as the solar wind Earth interaction (Kim et al. (2011), Simms et al. (2021)), solar physics (Trottet et al. (2015), Le and Zhang (2017)), surface planetology (Anderson and Bell (2013)) and galaxies and compact objects (Dai et al. (2018), Kang et al. (2018), Yesuf and Ho (2019), Ni et al. (2020)).

For example, if one considers only three variables that are possibly correlated (x, y, z), the partial correlation between x and y, after controlling for z, is calculated as follows: first the linear regression between x and z is performed, and the residuals are given by the difference between the x values and the regression. Subtracting the regression line removes the linear influence of z on x. Residuals are then calculated for y with the same procedure to remove the linear influence of z on y. The partial correlation coefficient between x and y, after controlling for the third variable z, is simply determined by the Pearson correlation coefficient between these two residuals. This technique can be generalized to a larger number of variables.

The relations are assumed linear with this technique ($y = a + \sum_i x_i \cdot b_i$ with a intercept and b_i slopes), but can also correspond to power law relations (of the type $y = a \prod_i x_i^{b_i}$) when linearized with a logarithm. As for direct correlations, the linear assumption is actually a weak assumption and does not need linear relationships between the parameters to remain valid, since the linear assumption keeps true at first order in most

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cases. In order to evaluate the significance of the partial correlation factors, as for zero-order correlations, a t-test can be performed to evaluate the test statistics that shall be larger than the threshold associated to the null hypothesis H_0, and p-values provide the probability that the null hypothesis is true (i.e. that there is no significant partial correlation).

In the rest of the paper, correlations factors and significance test statistics and p-values by default correspond to direct linear correlations, the use of the partial correlations is explicitely specified.

3 Results

3.1 The influence of crustal fields: local vs global influence

Several authors attempted to analyze the influence of the crustal fields on the BS location. The first obvious way is to consider correlations with the geographical longitude, to uncover the influence of the strongest crustal source region located in the southern hemisphere at $\sim [150\ 230]^\circ$ East longitude and in the $\sim [-90\ 0]^\circ$ latitude range (see the crustal field map in Figure 3d). Edberg et al. (2008) used this approach for MEX but could only obtain a rough trimodal behavior with three wide (i.e. 120°) longitude bands with different BS distances attributed to the crustal sources influence. Nevertheless, as cautioned by XF17, the longitudinal position provides only partial but not full information of the orientation of the strongest crustal field region with respect to the impinging solar wind, the latter of which is critical for determining the bow shock formation and location. Overall, most authors essentially attributed the presence of a hemispheric asymmetry to crustal fields (Mazelle et al. (2004); Gruesbeck et al. (2018)). On the other side, Nemec et al. (2020) recently quantified the dependence of the stand-off distance of the Martian BS with respect to local crustal fields, using the local crustal field at 400 km altitude from the Morschhauser et al. (2014) model, to show their influence is non negligible but much smaller than EUV or SW dynamic pressure.

We also performed a direct longitude dependence analysis using the MEX and MAVEN datasets (not shown here), showing no clear dependence except by selecting large longitude bands as performed by Edberg et al. (2008). However, one can refine the analysis by considering only a ($\pm 20^\circ$) latitude band around the strongest crustal source region located around $\sim -45^\circ$ latitude and $\sim 180^\circ$ longitude. This leads to focus on a

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latitude band with a highly variable crustal field intensity around the planet (see Figure 3d where the latitude band limits are superimposed on the crustal field map). The result is shown in Figure 1 for the three datasets (MAVEN, MEX and MGS). A pattern with a "smile" shape is suggested and is roughly consistent among the three missions, with a minimum BS terminator altitude R_{TD} at small/large longitudes (corresponding to weak crustal field regions, see the colorbar) and a maximum value near $\sim 180°$ East longitude where the strongest crustal source region is located. The MEX median profile (and the percentiles area) shows a clear modulation with a minimum in the range 270° to 20° (the two strongest minima of crustal fields being located close to $270-280°$ and around 360/0°). The MAVEN median curve is more flat except a clear peak at $180-225°$ and a low point at 360/0°, but the small dips of MAVEN seem close to crustal field intensity gaps. The MGS median curve is noisy, but overall also consistent with a "smile" shape.

Moreover, taking the terminator altitude vs the cosine of the longitude (translated into the range $-180°$ to $180°$) leads to correlation coefficients of -0.10 and -0.11 for MAVEN and MEX. The correlation is negative since the strongest crustal source region is centered on $cos(longitude) = -1$ while larger cosine values correspond to regions farther from the strongest crustal source region. These correlations may seem small but are still statistically significant given the large number of points, with p-values of about $4 \cdot 10^{-3}/2 \cdot 10^{-8}$ respectively for MAVEN/MEX, i.e far below the 5% commonly considered as an acceptable value. In absolute values, the average BS altitude decreases by 300 km (290/310 km for MAVEN/MEX) from the longitude sector ($135-225°$ East longitude) of the strongest crustal source region to sectors away from it.

The correlation for the MGS dataset is also negative (~ -0.12, with a p-value of 0.04) but is closer to the significance limit due to the lower number of data. Due to the relatively low number of events and smaller significance, we mostly focus on the MEX and MAVEN datasets in the rest of the paper, and only briefly mention the MGS data analysis to discuss the consistence among the mission observations.

We further investigate whether the crustal field influence is global or local. We calculated the correlation between the terminator altitude and either the angular averaged pressure of the crustal magnetic field $B^2/(2\mu_0)$ or the angular averaged crustal magnetic field magnitude. B is the crustal magnetic field magnitude at 400 km altitude from Morschhauser

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et al. (2014) averaged over an area defined by a variable angular range around the sub-spacecraft location of the spacecraft: e.g. 40° range means we average the crustal field pressure or the crustal field intensity over an angular range (based on spherical distance calculations) of 40° around the exact longitude/latitude of the crossing, while 0° means we consider the pressure at the exact longitude/latitude of the crossing (i.e. the local value with no averaging). Such analysis, shown in Figure 2, reveals a positive correlation for both MAVEN/MEX increasing until a maximum for $70-80°$ angular range. The correlation for MAVEN/MEX with the crustal pressure rises from 0.04/0.11 at 0° to 0.18/0.33 at 70−80° angular range (with statistical significant correlations even for 0° angular range and negligible p-value at maximum correlation). Similar peak correlations (even slightly larger for MAVEN) are observed when considering the crustal field intensity instead of the pressure, but the profile becomes more flat with a less pronounced peak. Note that using an even smaller power law index for the crustal field intensity, such as $(B^2/(2\mu_0))^{1/6}$ as used by XF17, also leads to similar results with close peak correlation factor values and an even more flat profile (more and more flat when smaller power law index values of the pressure are considered). The correlation between the terminator altitude of the BS and the crustal fields (either the pressure, or powers law values of it) is always significant, but maximizes for a large angular range considered. Our results suggest a rather global influence (slightly less than hemispheric) of the crustal field pressure on the BS location, in closer agreement with the finding by XF17 rather than the approach considered by Nemec et al. (2020).

We also convolved the crustal field pressure with an angular Gaussian filter (with a variable standard deviation σ defined dynamically) to evaluate the influence of the crustal fields at the sub-spacecraft location compared to farther longitudes/latitudes, leading to similar maximum correlation values for $\sigma > 60°$ (not shown). The need for large angular ranges is expected based on the large distance of the BS boundary, and is in agreement with previous studies showing a rather global influence. Note that the MGS BS dataset also suggests an increasing correlation between the BS distance and the angular range (with a peak at 110° and a maximum correlation factor of 0.4). Any functional forms of the BS location variability with respect to the crustal fields thus need to consider the large-scale effect of the crustal fields rather than a local effect: the small power law index value (0.018) associated with the local crustal field pressure influence on the

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Martian BS location by Nemec et al. (2020) thus inevitably underestimated the crustal field effects due to the limitation of using only local crustal field distributions.

Figure 3 provides another examination of the local vs global influence of the crustal fields on the BS location. It shows the logarithmic value of the occurrence frequency of the MAVEN/MEX BS crossings as a function of the terminator altitude and of the angular distance from the strongest crustal source region (assumed at $\sim -45°$ latitude and $\sim 180°$ East longitude, see Figure 3d)). The angular distance is the angle between the planetary center - spacecraft vector and the planetary center - strongest crustal source region center vector. The occurence frequency is simply the number of shock crossings counted in each cell of the 2 dimensional grid defined by the angular distance and the terminator altitude, then given in % of the total number of crossings. We use the angular distance to consider that the crustal field may influence the plasma environment and thus the BS boundary in any direction, not only along the longitude.

Both MAVEN/MEX results (Figures 3a and 3b) are very similar and reveal a dominant influence of the strongest crustal field region, with the BS altitude decreasing farther from it. The errorbars of the distribution are large probably due to the presence of all other parameters of influence (SW pressure, solar EUV...). The mean altitude is larger in the $0-80/90°$ angular distance range than beyond, which is consistent with the maximum correlation for $70-80°$ angular range as seen in Figure 2. However, a plateau appears in both datasets in a narrower angular range $0-40/60°$ that is consistent with a dominant influence of the strongest crustal field region whose angular extent is of the same order of magnitude (see Figure 3d). On top of the major trend, we notice a slight lift in the BS altitude in the $\sim 110-140°$ angular distance range, which could be attributed to the strong secondary crustal field sources located at such angular distances near the equator (see same panel). The trend in the MAVEN dataset is more prominent than in the MEX dataset, which will be discussed later. Moreover, despite a poorer coverage, the MGS dataset also shows the decrease of the BS distance with angular distance.

One of the challenges of disentangling the crustal field influence is the presence of many other driving factors, including the dynamics of the incident SW and IMF. Indeed, the crustal fields act as pressure enhancements, induce currents that propagate into the Martian plasma environment, through a complex interplay between the incident magnetosheath plasma transport and the magnetic field topology arising from the draping

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of the Interplanetary Magnetic Field (IMF) around the planet and modified by the planetary crustal fields themselves. The whole interaction is driven by the SW plasma and magnetic field, whose orientation varies with time. When the IMF rotates at short timescales, the influence of the crustal fields, that is essentially a geographical influence in the planetary frame with a larger timescale, may be partially masked due to the rotation of the interaction. Several external or internal drivers control the BS location, but the IMF rotation may partially hide the geographical influences such as crustal fields.

Figure 3c shows the same MAVEN map as Figure 3a, but we superimposed mean values during the periods of low and high IMF clock angle variabilities. The IMF clock angle was calculated from the upstream conditions prior to the BS crossings, defined as $tan^{-1}(B_{Z_{IMF}}/B_{Y_{IMF}})$. We use the standard deviation of the clock angle over the two hours before the crossings as a measure of the rotation dynamics of the IMF, and divide the whole MAVEN dataset into one low (i.e. below the median standard deviation value) and one high (i.e. above the median standard deviation value) variability dataset. Panel c shows the mean R_{TD} of the BS for both sub-samples. As expected, the crustal field influence is less visible under high IMF clock angle variability conditions than under the low variability conditions, where the altitude difference is as high as up to 1000 km.

The dynamics of the IMF can actually impact the BS at several levels that should be further analyzed in the future. In particular, a constant IMF or a sudden change of IMF to the same strength and orientation may have different effects on the BS locations. Depending on the conditions considered, the BS shape can be modified, with asymmetries of the global shape appearing, or a sudden compression followed by a recovery phase depending on the mach number and on the dynamic pressure. Previous studies at Earth or Venus also suggested that a rotation of the IMF could have different consequences wether the local conditions lead to perpendicular or parallel shocks with higher perpendicular BS locations in particular in the tail (Wang et al. (2016)). At Venus or Mars authors suggested asymmetries of the BS location depending on the orientation of the $\overrightarrow{E} = -\overrightarrow{V} X \overrightarrow{B}$ electric field that increases the mass loading due to accelerated pickup ions (Alexander et al. (1986), Vignes et al. (2002)).

We performed another correlation analysis between the BS terminator altitude and the crustal fields, by including a maximum threshold on the crustal field intensities (local values at 400 km altitude) considered in the analysis. The results show that no sig-

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nificant correlation between local crustal field intensities and the BS location appears as long as only intensities below a few nT are considered. The correlation then rises when the threshold increases to include stronger and stronger sources. This shows that, even when considering only local crustal fields instead of angular averaged values, a large number of regions around the planet (intensities of few nT are observed in a many regions) can influence the BS location beyond the southern hemisphere strongest crustal source region. Nonetheless, the large size and strong intensity of the crustal fields in this region make it the major crustal field region driver.

Gruesbeck et al. (2018) also showed a significant influence of the local time of the strongest crustal source region on the 3D shape of the BS when it was located on the dayside vs on the nightside. Figure 4 shows how the location of the strongest crustal source region impacts the BS distance using both MAVEN and MEX datasets. Despite large data scattering - with a standard deviation of $\sim 1000\ km$ - due to the combined effects of other driving factors, the average BS R_{TD} altitude is modulated by the MSO longitude (hereafter ϕ_{mso}, equivalent to local time) of the strongest crustal field region: the BS standoff distance peaks when the strongest crustal field region is located at noon. A similar trend may also be seen with the MGS dataset with clear peak at noon longitude. The mean profile suggests a reduced and steady or inexistent influence of the strongest crustal source region when it is located on the nightside.

These results thus suggest a dominant (but not unique) influence of the strongest crustal field region (with a large angular extent consistent with its size) on the BS location. This influence depends on the stability of the IMF orientation that may partially hide the crustal field influence, as well as on the local time of the strongest crustal source region. Regarding the latter, the information corresponding to the increased crustal field pressure by the strongest crustal source region rotation propagate upward at the fast magnetosonic wave velocity, and then probably impact the location of the BS. The information reaches the solar wind flow faster at noon on the dayside than on the nightside due not only to the closer distance, but also to the fact that the magnetosonic waves from the nightside are partially attenuated, and the dayside fast mode magnetosonic wave speed is expected to be larger due to the increased magnetic field in the draping region. Consequently, enhanced crustal fields impact the BS surface, which is significantly reduced when the strongest crustal source region is located far from the noon direction. Figures 3 and 4 show that the crustal field can enhance the extrapolated terminator altitude of

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the Martian BS by several hundreds of km on average. This is in agreement with the large possible range mentioned in the literature, ranging from no or little influence (with e.g. about 100 km influence from MEX observations (Edberg et al. (2009)) or simple dipole based MHD simulations (Li et al. (2020))) to $\sim$ 400 km altitude fluctuation according to XF17, and even above 1000 km influence based on North vs South asymmetries (Edberg et al. (2008),Gruesbeck et al. (2018)).

3.2 Investigating statistical biases

The previous section shows strong evidences regarding the influence of the crustal fields on the distance of the Martian BS, through several spacecraft and several methods providing consistent results: geographical longitude modulation, correlation vs crustal field pressure with a variable angular range, direct plotting of the distance vs the angular distance from the strongest crustal source region, location of the strongest crustal source region with respect to noon. However, differences arise between MAVEN and MEX, with higher absolute BS distances and an apparently stronger influence of the angular distance from the strongest crustal field region for MAVEN than for MEX.

The MAVEN and MEX datasets used in this study cover different periods (respectively 2014-2017 and 2004-2015), corresponding to different EUV conditions. The large MEX dataset provides a wide range of EUV conditions, with a full solar cycle (including the lower and extended ever recorded solar minimum), while the MAVEN dataset corresponds to a period with an active Sun in 2014 and 2015 (where most of our MAVEN crossings occurred) below a declining activity in 2016-2017. The mean EUV level of the MAVEN crossings (given by the solar 10.7 cm radio flux) was thus larger by $\sim$ 14% compared with the MEX dataset. The larger EUV conditions associated to the MAVEN dataset certainly contribute to the larger BS distances observed (by $\sim$ 5%) for MAVEN than for MEX. The EUV fluxes increase indeed the ionospheric scale height and the ionization rate of the Martian atmosphere, which adds mass to the solar wind flow through pickup ions and slows down the solar wind, then creating a larger apparent obstacle that pushes the BS further. The compared magnetosonic mach number conditions, which also have a major influence on the BS location through the Mach cone conditions, may also have induced this absolute difference in the BS altitude between both missions, however these conditions are not known precisely for the pre-MAVEN period.

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A dedicated analysis also reveals a significant bias on the MAVEN dataset due to the EUV conditions during the BS crossings. Figure 5 provides the EUV values and occurrence frequency vs either the angular distance from the strongest crustal source region center or its MSO longitude for both missions. The EUV values were determined for MAVEN from the FISM model (Chamberlin et al. (2007); available for MAVEN but not MEX) for 10−120 nm wavelengths, and for MEX from the solar 10.7 cm radio flux index extrapolated to Mars assuming a $1/r^2_{Mars\,Sun}$ law. Using solar radio flux values for MAVEN leads to almost identical results, since both parameters are strongly correlated (with a correlation factor of 0.98 (n)). However, we choose the FISM model for MAVEN since it is slightly more precise than the radio flux proxy (FISM uses data and a number of proxies including the radio flux proxy, selecting the most appropriate information for each wavelength at each time). Moreover, the absolute values of EUV are of no interest in our case since we only focus on variabilities and correlations.

Figure 5b shows a MEX EUV distribution that is roughly uniform with regards to the angular distance from the strongest crustal source region or to ϕ_{mso}, with also more frequent low EUV fluxes than high fluxes. In contrast, the MAVEN EUV distribution (Figure 5a) reveals the presence of two separate regimes, one low and one high regime (with a difference of almost a factor of 2), corresponding to time periods before (high EUV fluxes) and after (low EUV fluxes) spring 2015. Moreover, the low MAVEN EUV fluxes mainly occurred when the spacecraft was away from the strongest crustal source region, while high EUV fluxes occurred close to the strongest crustal source region. Consequently, the EUV mean profile vs the angular distance to the strongest crustal source region is similar to the MAVEN mean profile of the BS distance (in Figure 3a). The interpretation of the crustal field influence on the BS distance from Figure 3 may thus be biased by the inhomogeneous EUV distribution induced by the evolution of the orbit of the spacecraft while the Sun activity decreased from 2014 to 2017. A similar bias also appears regarding the EUV profile vs ϕ_{mso} (panels c vs d), with a clear peak at noon similar to the peak observed for the MAVEN BS location in Figure 4. Both biases are related to the orbital precession of the MAVEN spacecraft. These biases may then increase artificially the apparent influence of crustal fields in the MAVEN data analysis that appeared stronger than in the MEX case.

These biases may also be seen through the linear Pearson correlation factors, on one side, between the angular distance and the BS extrapolated terminator altitude, and

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on the other side between the angular distance and the main controlling parameters of the BS drivers that are a priori the EUV fluxes and magnetosonic mach number (Halekas et al. (2017)). The MAVEN magnetosonic mach number (Mms) is calculated with the method by Halekas et al. (2017): $Mms = v_{sw}/\sqrt{c_s^2 + v_A^2}$, with v_{sw} SW speed, c_s sound speed, v_A Alfvén speed, with the electron temperature assumed equal to the proton temperature and a polytropic index $\gamma = 5/3$. It cannot be calculated for MEX due to the lack of magnetic field measurements.

The linear correlation coefficients show indeed that the angular distance is more correlated with EUV fluxes for MAVEN (correlation factor -0.34 (n)) than it is with the BS terminator altitude R_{TD} (correlation factor of -0.24 (n)). The same comparison can be done for ϕ_{mso} and its correlation with EUV (correlation factor 0.21 (n)) compared to R_{TD} (correlation factor 0.19 (n)). The situation for MEX is the contrary, thus confirming the absence of bias in the MEX case. We note that the Mms does not introduce a significant bias, with for MAVEN small correlations between the angular distance and the Mms (correlation factor of 0.04 with a large p-value above 1%) compared to the correlation between angular distance and R_{TD}.

As a consequence, a part of the MAVEN observed dependence of the BS distance on the angular distance or the MSO longitude of the strongest crustal source region is probably due to the cross-correlations of these parameters with EUV (see below the partial correlation analysis for a better understanding of the influence of this cross-correlation). These biases may have influenced the results obtained by Gruesbeck et al. (2018) who showed strong hemispheric differences of their 3D modeled BS, either regarding the North/South difference or when the strongest crustal source region was on the dayside vs nightside. More precisely, when focusing around low Solar Zenith Angles (SZAs) in their study, the EUV fluxes were indeed maximum for low SZAs of the spacecraft and in the southern hemisphere, leading to a strong north/south asymmetry ($> 1000\ km$) that was only partially caused by the presence of crustal fields. Moreover, we shall add that using the North vs South asymmetries and attribute them to the crustal field influence (as performed in a number of studies of the Martian interaction) may be significantly biased by the seasonal change of EUV fluxes sweep between the northern and southern hemispheres during the summer and winter solstices. The North vs South asymmetry caused by crustal fields may thus be overestimated or underestimated depending on the seasons due to the significant influence of EUV induced ionization. At high (solar EUV) illumination pe-

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riods of the Martian orbit, one can even observe BS on average further in the northern hemisphere than in the southern hemisphere.

However, these biases impact only the influence of the angular distance and the MSO longitude to the strongest crustal source region in the case of the MAVEN dataset. They impact neither the MEX dataset, nor the analysis of Figure 1 for the MAVEN dataset: there is no correlation between the IAU longitude and the EUV, with a large p-value (35%) when testing for the linear correlation between the cosine of the IAU longitude and the EUV (when selecting only the latitudes around the strongest crustal source region).

In order to confirm that the influence of the angular distance to the strongest crustal source region or of its ϕ_{mso} is not due only to the EUV influence in the MAVEN case, we performed a partial correlation analysis. An approach based on subsets of the whole dataset was tried at first, by separating low vs strong EUV conditions subsets to remove its major influence, but this leads to poor coverage of the crustal fields (in angular distance or crustal field pressure) and can thus not be used to identify the influence of crustal fields.

Table 1 provides the results for a partial correlation analysis of the influence of angular distance and the cosine of ϕ_{mso} on the extrapolated terminator BS altitude (R_{TD}), after controlling the other main parameters of influence. We here consider as controlling parameters the EUV fluxes (for MAVEN/MEX) and magnetosonic mach number (for MAVEN only) which are known major parameters of influence of the BS location.

The partial correlation analysis makes it possible to compare the correlation factors between two variables before and after controlling for the other considered parameters. In the case of MEX, the correlations between R_{TD} and both the angular distance and the longitude of the strongest crustal source region were only slightly reduced after controlling for EUV, while for MAVEN they were reduced by a factor 2 after controlling for EUV and Mms, thus reaching the MEX correlation levels (or close to for the longitude of the strongest crustal source region). This confirms the significant biases for the MAVEN dataset due to the EUV inhomogeneous distribution with respect to angular distance and longitude of the strongest crustal source region center, as well as the absence of bias for MEX. In both cases, the t-test statistics t is well above the t_{H_0} value that corresponds to the null hypothesis for a risk of 5%, corresponding to negligible or small p-values. Note that the significance levels of independent tests cannot be compared

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to each other to discuss the relative importance of variables, each test shall be considered individually.

The multiple linear regression used provides a rough estimate of the relative importance of the drivers included in the regression, by comparing the beta-weights (i.e. magnitudes of the coefficients). These are the slopes associated with each parameter of influence in the regression model, normalized by the ratio of the standard deviations of the BS terminator distance and of each parameter. The beta-weight of angular distance thus appears 3 to 4 times smaller than the EUV beta-weight for both MEX and MAVEN, suggesting a consistent relative influence that is smaller than EUV. Note that for MAVEN $\frac{b^*_{Mms}}{b^*_{ang.dist.}} \sim 4.1$ confirming that EUV and Mms are major drivers of the BS location. The beta-weight of ϕ_{mso} appears 3 to 5 times smaller than the beta-weight of EUV (with a smaller influence for MAVEN). The longitude of the strongest crustal source region center appears, based only on correlation coefficients, less than or as influent as the angular distance to the strongest crustal source region depending on the mission.

Note that a partial correlation analysis confirms that the crustal fields located in the nightside hemisphere have (little or) no influence on the BS location. Partial correlations between the shock location and the local crustal field pressure (after controlling for EUV and mach number when available) for MEX and MAVEN, which are significant on the dayside despite being smaller than correlations with angular averaged crustal field pressures, become non significant (with large p-values close to or larger than 5%) beyond the terminator. Using large scale crustal field parameters (i.e. angular averaged pressure) instead of the local pressure also leads to reduced apparent influence beyond the terminator. However, the correlations still appear significant probably because the large scale parameters integrate to some extent dayside regions as well given the proximity of most of the nightside BS crossings with the terminator region.

The exact values of the statistical results shown above depend on the parameters included in the regression model (number of parameters, various methods to estimate the crustal magnetic field pressure instead of angular distance...), on the chosen model (linear or power law), or on the conic parameters used to derive the R_{TD} altitudes, but the conclusions remain unchanged: the angular distance or crustal magnetic field pressure integrated over an angular range as well as the MSO longitude of the strongest crustal source region are significant drivers of the BS terminator distance - despite a bias in the

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MAVEN case due to the EUV distribution - , and EUV/Mms appear as the major drivers for the BS location.

We have in particular checked the robustness of the results by using different datasets (for example only the Gruesbeck et al. (2018) list or only the XF17 list) and various conic fit parameters (i.e. the parameters by Edberg et al. (2008), Hall et al. (2016b), XF17 for either MAVEN or MEX): except for slightly different absolute altitudes, all results discussed above are unchanged.

The results show that empirical models representing the BS location should include the crustal fields whose influence is thus significant despite being of smaller importance compared to EUV or mach number. A detailed analysis of the best functional form of the shock location combining all the BS location drivers is beyond the scope of this paper, but one can provide a simple empirical proxy that reflects the apparent influence of crustal fields with respect to EUV and mach number based on our study. If one assumes a power law relation for the main drivers (EUV and mach number for MAVEN) and for crustal fields, one can derive power index values of each driver. For example, considering a simple relation such as $R_{TD} = a * K^{1/6} + b$ with a/b free constants and K a composite parameter defined by $K = EUV/(Mms*Ang_{dist}^{1/3})$ (without the Mms parameter for MEX due to the absence of magnetic field) leads to correlation coefficients of 0.65/0.41 (n) for the MAVEN/MEX datasets, which are very strong correlation coefficients given the large amount of data. The 1/3 ratio is approximate but gives an order of magnitude of the relative influence of the EUV/mach/crustal field drivers as given by a classic multivariate regression, or by partial correlation analysis (see e.g. table 1) that provide slope ratios for specific drivers (with a slope ratio $\frac{b^*_{EUV}}{b^*_{Mms}}$ close to 1, and $\frac{b^*_{EUVorMms}}{b^*_{ang.dist.}}$ around 3). Note that using power law or linear forms, or angular averaged crustal field pressure instead of angular distance to the strongest crustal field region, do not change these qualitative results.

This type of composite parameter is representative of the overall behavior of the shock location, but other drivers not studied in this paper shall be studied as well, such as the solar wind dynamic pressure, as well as the IMF intensity and orientation parameters. Moreover, investigating the relative influences in a complex system where numerous possible drivers can influence the BS location and can be cross correlated shall be performed with the use of specific techniques, as investigated in a forthcoming paper.

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Table 1. Partial correlation analysis for the angular distance to and location of the strongest crustal source region

Statistical parameters	**MAVEN**	**MEX**
Direct correlation coefficient R_{TD} vs angular distance (p-value)	-0.24 (n[1])	-0.12 (n)
Controled correlation coefficient R_{TD} vs angular distance (p-value)	-0.12 (n)	-0.11 (n)
Significance ratio t/t_{H_0} for angular distance	3.47	6.10
Relative influence $\frac{b^*_{EUV}}{b^*_{ang.dist.}}$	-3.73	-2.90
Direct correlation coefficient R_{TD} vs cos(ϕ_{mso}[2]) (p-value)	0.19 (n)	0.12 (n)
Controled correlation coefficient R_{TD} vs cos(ϕ_{mso}) (p-value)	0.09 (n)	0.11 (n)
Significance ratio t/t_{H_0} for cos(ϕ_{mso})	2.71	6.19
Relative influence $\frac{b^*_{EUV}}{b^*_{cos(\phi_{mso})}}$	5.22	2.85

[1] "n" refers to negligible p-values ($< 10^{-5}$)

[2] ϕ_{mso} refers to the MSO longitude of the strongest crustal source region center

4 Discussion

Beyond the analysis of the global influence of crustal fields on the BS location, one can also investigate the seasonal variability of this influence. Figure 6 shows the compared seasonal variation of several parameters based on the Mars Express dataset that covered 6 martian years. We chose to focus on the Mars Express dataset that is more reliable than our MAVEN dataset that covers less than one martian year. The figure shows first how the influence of the strongest crustal field region on the MEX BS location varies with the solar longitude. The specific influence of the strongest crustal field region shown in the figure is defined as follows: we consider the crossings in the southern hemisphere latitude band of $\pm 20°$ around the latitude of the strongest crustal field region center assumed at $-45°$, that was used in Section 3.1 to reveal a longitude modulation of the BS location; we then calculate the difference $R_{TD_{close_{mean}}} - R_{TD_{away_{mean}}}$ between the mean R_{TD} altitudes of the BS crossings close ($120-240$ degrees East longitude range, see Figure 3d) vs away ($0-120$ and $240-360$ degrees East longitude) from the main source center located at $\sim 180°$ East longitude.

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Figure 6 shows first that this R_{TD} difference is always positive, which is coherent with the strongest crustal field region pushing the BS further, with up to 400 km altitude difference. The figure also shows that the R_{TD} difference is maximum from about $Ls \sim 150°$ to $Ls \sim 250°$, i.e. from slightly before equinox until perihelion. The R_{TD} difference then shows a minimum around perihelion, at a period where the northern hemisphere is the most illuminated. Most of the crustal field sources are located in the southern hemisphere that is the most illuminated at the periods where the R_{TD} difference is maximum, which suggests a coupling with the ionosphere. The absolute R_{TD} altitude of the BS is expected to vary with the solar longitude due to the direct influence of ionization of the atmosphere, thus increasing the size of the obstacle through e.g. pickup ions and currents. However, one does not expect a priori a seasonal variability inside a given southern hemisphere latitude band between regions close and away from the main crustal field source region, unless a coupling exists between the ionosphere and the crustal fields influence on the BS.

The figure also provides the seasonal variability of the Total Electron Content given by the MEX MARSIS instrument, showing in a similar manner the TEC difference ($TEC_{close_{mean}} - TEC_{away_{mean}}$) between regions close vs away from the strongest crustal field region in the southern latitude band $\pm 20°$ around the center latitude $-45°$. The dataset, already analyzed in detail by Sánchez-Cano et al. (2021), is made of all TEC observations by MARSIS from Martian year 27 until Martian year 32.

One thus observes a strong correlation between the seasonal variability of the BS R_{TD} difference and the seasonal variability of the ionospheric TEC difference. Both profiles exhibit similar trends, with minima and maxima at the same seasons, in accordance with results by Sánchez-Cano et al. (2018). This strong correlation thus suggests that the seasonal variability of the influence of the strongest crustal field region on the BS is associated with the seasonal variability of the ionosphere. This confirms the presence of significant coupling processes between crustal fields and the ionosphere, and consequently with the BS location. The TEC is known to be a good tracer for not only the ionospheric variability, due to solar irradiance that is the major ionization source of the sunlit ionosphere, but also for the thermosphere-ionosphere coupling and possibly for the lower-upper atmosphere coupling. Several studies showed evidence for a coupling between the ionosphere and the crustal fields, resulting in increased ionospheric electron density - by 20% to 50% - and reduced temperature in these regions (González-Galindo et al.

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(2021), Flynn et al. (2017)). The density increase observed above crustal field regions was attributed to stable mechanisms instead of transient phenomena such as solar flares or enhanced particle precipitation. Ions newly formed by photoionization could be inhibited from diffusing out of the regions with strong crustal fields, resulting in higher densities (Duru et al. (2019)) despite the stable ionization efficiencies in these regions (Lillis et al. (2021)). Electrons trapped on closed field lines are indeed protected against loss mechanisms induced by the magnetosheath plasma and solar wind interaction, which leads to larger lifetimes and densities. The crustal fields thus impact the ionosphere characteristics, which then increases the local ionospheric pressure, and may push further the bow shock due to pressure enhancement and due to the inflation of the apparent obstacle to solar wind via magnetosonic waves. For instance, the ionopause is known to be affected by the presence of crustal fields, with fewer ionopause detections over crustal fields since the increased local pressure (thermal + magnetic) makes it difficult for the SW dynamic pressure to penetrate, compress the ionosphere and form the ionopause (Sánchez-Cano et al. (2020)).

The results above show that the coupling between crustal fields and the ionosphere plays a significant role in the influence of crustal fields on the BS location described in the previous sections. However, it remains difficult to conclude wether this coupling is the dominant process that takes place regarding the influence of crustal fields on the BS location, in addition to other processes such as the magnetic pressure enhancement due to crustal fields and the induced draping topology modification. This coupling has probably also a significant influence on the other plasma boundaries such as the Induced Magnetosheric Boundary or the PhotoElectron Boundary which tightly depend on internal drivers. Further work will be performed to better characterize the complex coupling mechanisms that link the crustal fields to the TEC and ionosphere (and thus to the thermosphere) and to the induced magnetosphere up to the BS.

5 Conclusions

The recent studies of the Martian environment, thanks in particular to the MEX and MAVEN missions, underline the strong and complex influence of the crustal magnetic fields on the Martian environment and its interaction with the solar wind. Among them is the influence on the dynamic plasma boundaries that shape this interaction and on the bow shock (BS) in particular. Compared to other drivers of the BS location (e.g.

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SW dynamic pressure, extreme ultraviolet fluxes...), the crustal magnetic fields are poorly understood, with in the literature essentially differences observed between the southern and northern hemispheres attributed to the crustal fields, and an influence that ranges from little or no impact to strong influence depending on the authors and on the methods used. We analyzed in this paper in detail the influence of the crustal fields on the BS location, based on a one-dimensional approach using the extrapolated terminator distance of the shock crossings. This lead to the following results :

- our study provides the first multi-mission detailed analysis of the poorly understood influence of the crustal fields on the Martian BS location, by studying datasets from two different spacecraft (MAVEN and MEX, including $> 15,000$ shock crossings) and using several methods that provide a coherent picture instead of single point of views eventually contradictory as in previous works
- the crustal field sources on the Martian surface induce an influence on the BS location that is maximum when considering crustal field intensities or pressures (or even power law values of it) averaged an angular range of $70-80°$, slightly less than a hemispheric asymmetry
- a number of crustal field source regions can play a role, from few nT intensity at a reference altitude of 400 km
- however, the strongest crustal field region in the southern hemisphere appears as the dominant driver
- we introduce the angular distance to the strongest crustal field region, which better reveals the influence of this region that is shown to extend between at least $40 - 60°$ angular distance (which is consistent with the size of this region) and a full hemisphere
- this influence may also be seen through the modulation of the BS location by a longitude modulation when focusing around southern latitudes (which reveals a stronger modulation than if all latitudes are included as in previous studies)
- the crustal field influence is all the more reduced than the strongest crustal source region is located far from the noon direction, with a strong sinusoidal modulation by the local time of the strongest source region. This modulation is probably due to an increased travel time and attenuation for the magnetosonic wave until the solar wind upstream of the planet, combined with an expected larger Alfven velocity in the dayside draping region where the magnetic field increases

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- our analysis suggests that the crustal fields have no (eventually little) influence beyond the terminator region
- the influence of the strongest crustal field region appears more clearly when the IMF is stable during the preceding hours: the IMF usually rotates at short timescales, while the influence of the crustal fields is essentially a geographical influence in the planetary frame with a much larger timescale, which may partially mask its influence on the distant BS due to the rotation of the solar wind interaction
- we introduce a technique, i.e. partial correlations (Baba et al. (2004)), that allows to quantify the influence of second order importance drivers which may be hidden by the influence of correlated major drivers ; this approach appears necessary to provide a coherent picture when considering several mission datasets (MAVEN and MEX) where cross correlations exist (in particular for MAVEN), and it confirms the significant influence of the crustal fields on the Martian BS location
- we show the existence of a bias in the MAVEN data (but not in the MEX data) that leads to an incorrect estimation of the crustal field influence when authors focus only on north vs south hemispheric asymmetries during the same period of our dataset (2014-2017), since this asymmetry depends significantly on EUV conditions
- the partial correlation approach confirms that EUV and magnetosonic mach number are major drivers of the BS location, while crustal fields are a significant but a second order driver of this boundary, with an induced variability of the order of several hundreds of km
- we provide a composite simple parameter that is representative of the overall behavior of the shock location with respect to EUV, magnetosonic mach number and crustal fields, in a coherent manner for both MAVEN and MEX datasets
- we show the existence of a seasonal variability of the influence of the strongest crustal field region on the BS
- moreover, the seasonal variability of the crustal field influence is strongly correlated to the Total Electronic Content that is a tracer for the ionosphere dynamics and for its coupling with the thermosphere ; our results reveal the existence of a large scale coupling between the crustal fields, the ionosphere and the BS (and probably with other plasma boundaries), presumably due to a density increase fol-

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lowing the trapping of plasma on the closed field lines thus protected against loss mechanisms induced by the solar wind interaction

Our study thus confirms the significant influence of crustal fields on the BS location based on a multi-mission analysis, describes in detail how this influence takes place (planetary longitude modulation, local time of and angular distance to the strongest crustal field region, crustal field pressure minimum threshold), and quantifies it spatial extent as well as its impact in terms of altitude of the BS. It also sheds a new light on the complexity of the influence of crustal fields on the martian environment, with an impact on the BS that is shown to be tightly coupled to both the ionosphere below (and possibly to the thermosphere through the TEC correlation observed) and to the IMF above that can modulate this influence through its rotation. This shows again how the martian environment is a complex fully connected system, where crustal fields make Mars a unique case.

In the future we also plan to investigate the use of artificial intelligence techniques to provide automatic catalogs of plasma boundaries and eventually identify complex non linear relationships between the boundaries location and external/internal drivers. These techniques are mature and proved efficient in space physics to detect plasma phenomena (see e.g. Karimabadi et al. (2009), Nguyen et al. (2019)) or to identify parameters of influence (see e.g. Al-Ghraibah, A. et al. (2015), Benvenuto et al. (2018), Lenouvel et al. (2021)).

Appendix A Partial correlation approach

The partial correlation approach (Baba et al. (2004)) investigates multiple regressions, calculating the correlation coefficients - and estimate their significance - between e.g. two variables y and x_0, after controlling for the influence of other variables x_i. The correlations are assumed linear ($y = a + \sum_i x_i \cdot b_i$ with b_i constant individual slopes and a constant), but can correspond to power law relations of the type $y = a \prod_i x_i^{b_i}$ since the logarithm of the expression linearizes the expression.

For example, if one considers only three variables that are possibly correlated (x, y, z), the partial correlation between x and y, after controlling for z, is calculated as follows: first the linear regression between x and z is performed, and the residuals are given by the difference between the x values and the regression. Subtracting the regression line

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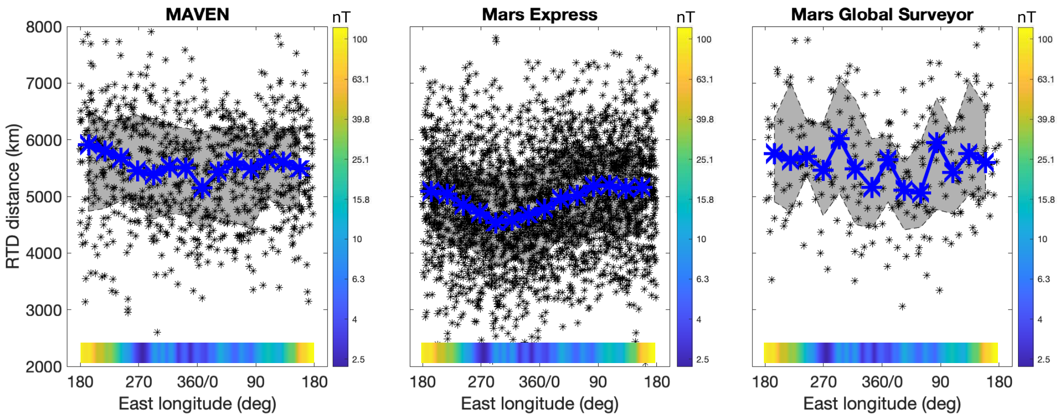

Figure 1. Geographical longitude modulation of the shock terminator altitude for all crossings (points) or the median profile (line), for the shock datasets from MAVEN (left panel), Mars Express (middle panel) and Mars Global Surveyor (right panel). Only crossings that occurred at latitudes inside a $\pm 20°$ latitude band around the strongest crustal source region (assumed centered around $\sim -45°$ latitude and $\sim 180°$ longitude) were considered. The shaded area covers the 20% to 80% percentiles range of shock terminator altitudes. The colorbar shows the longitude modulation of the crustal magnetic field intensity (logarithmic scale, in nT) from the Morschhauser et al. (2014) model at 400 km altitude, averaged over 1° longitude bins in the $\pm 20°$ latitude band.

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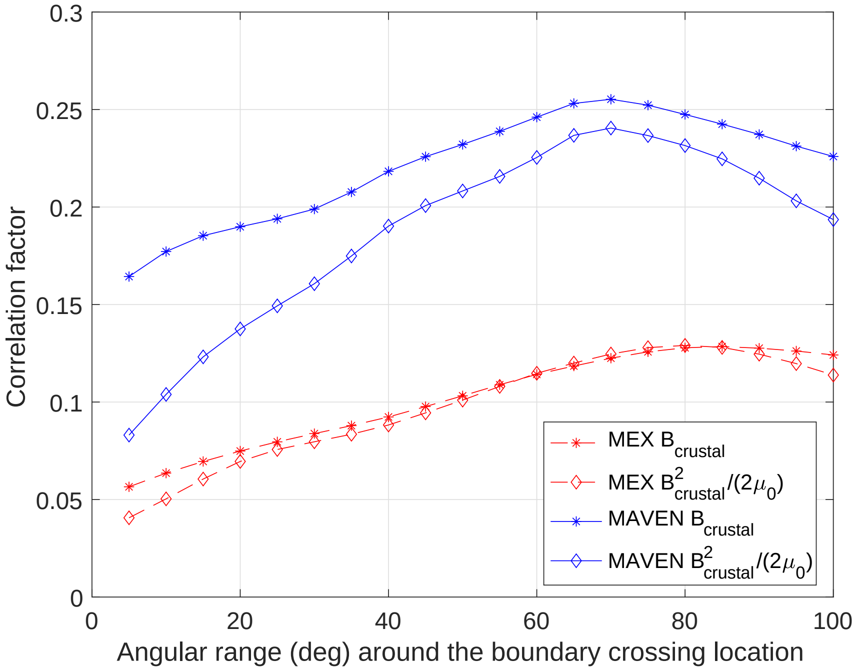

Figure 2. Correlation factor between the R_{TD} terminator altitude of the shock crossings (for MAVEN in blue, for Mars Express in red) and crustal magnetic field pressure or intensity. The crustal field magnetic field intensity or pressure are taken from the Morschhauser et al. (2014) model at 400 km altitude at the sub-spacecraft position (same IAU longitude and latitude) below the crossing, then averaged over an angular range around the sub-spacecraft location. The correlation factor is given as a function this angular range, to reveal whether the crustal field influence on the shock location is local or global.

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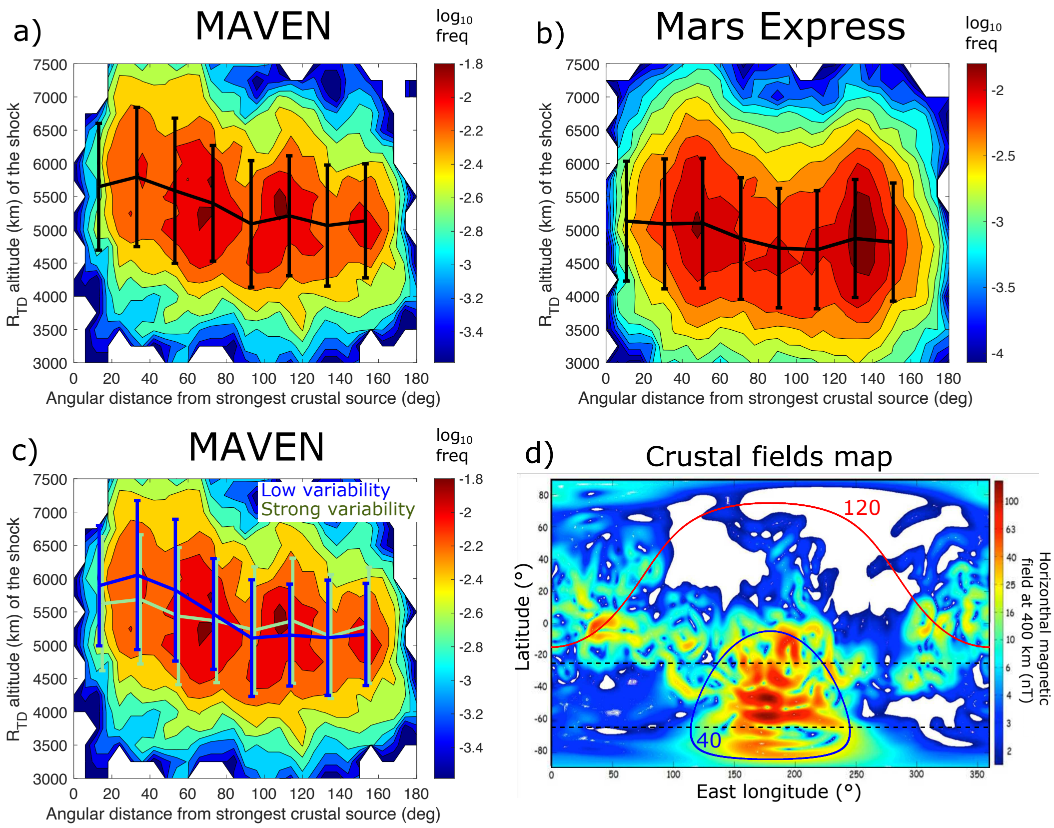

Figure 3. Logarithmic occurrence frequency of the shock crossings distributions for the MAVEN (panel a and c) and Mars Express (panel b) datasets as a function of the terminator altitude and of the angular distance from the strongest crustal source region center (see text for details). The mean and standard deviation are superimposed. Panel c: same distribution as panel a, with means and standard deviations for either low or strong IMF clock angle orientation variabilities preceding the BS crossings. Panel d: geographical map of the horizontal crustal magnetic field at 400 km altitude, with isocontours of the angular distance from the strongest crustal source region (blue line for 40°, red line for 120°) and two isolatitude lines at −25° and −65°.

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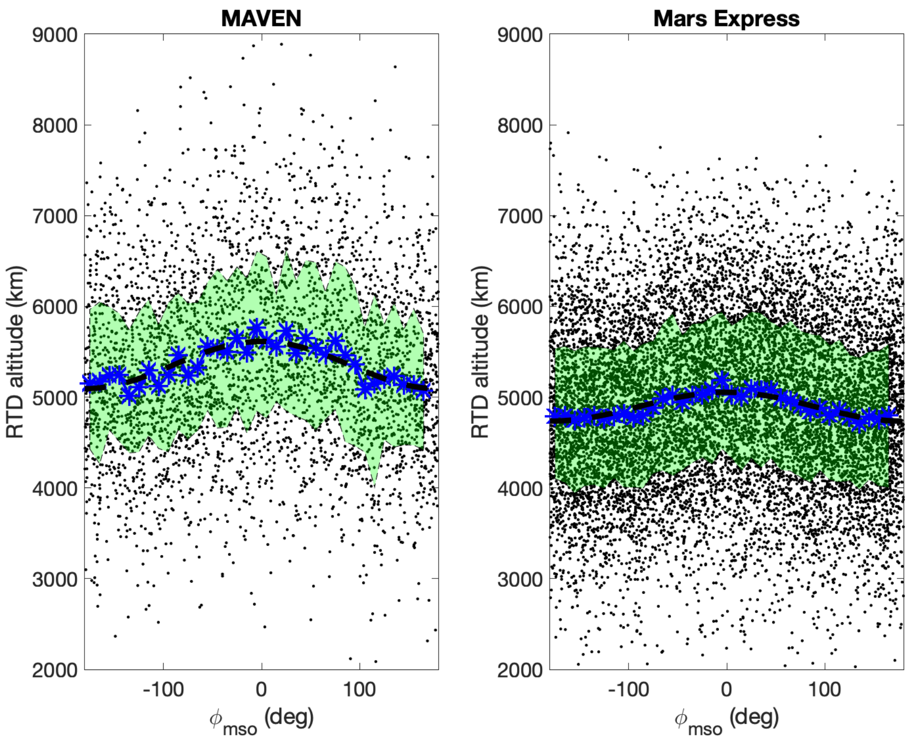

Figure 4. MAVEN (left) and Mars Express (right) shock R_{TD} terminator altitude as a function of ϕ_{mso} the MSO longitude of the strongest crustal source region center: 0° at noon, +90° at dusk −90° at dawn. The mean observed profile (blue stars) is compared with a simple cosine fitting (black dashed line). The shaded area covers the 20% to 80% percentiles range of shock terminator altitudes.

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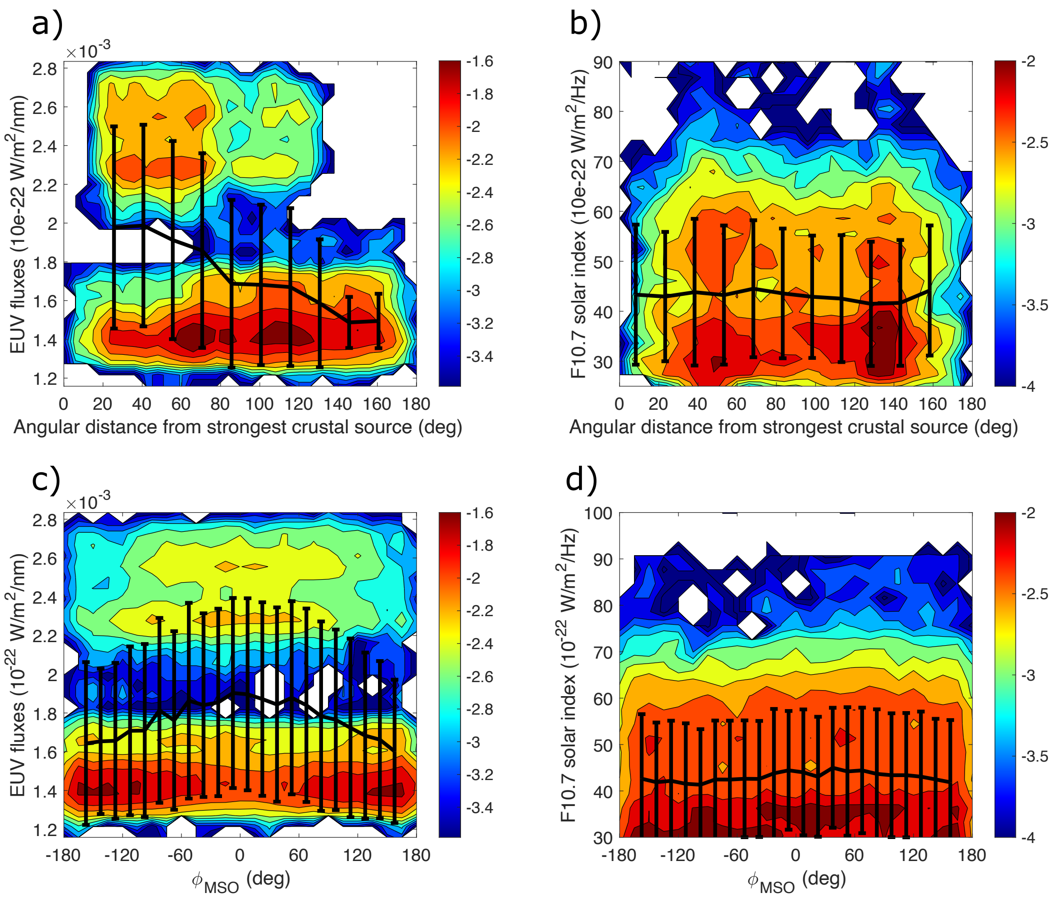

Figure 5. Logarithmic occurrence frequency of the shock crossings distributions for the MAVEN (left panels a and c) and Mars Express (rigth panels b and d) datasets as a function of the extreme ultraviolet fluxes (given by the FISM EUV fluxes for MAVEN and by the solar 10.7 *cm* radio flux index extrapolated to Mars for Mars Express) and of 1) either the angular distance from the strongest crustal source region (upper panels a and b) 2) or ϕ_{mso} the MSO longitude of the strongest crustal source region (lower panels c and d). The mean and standard deviation are superimposed.

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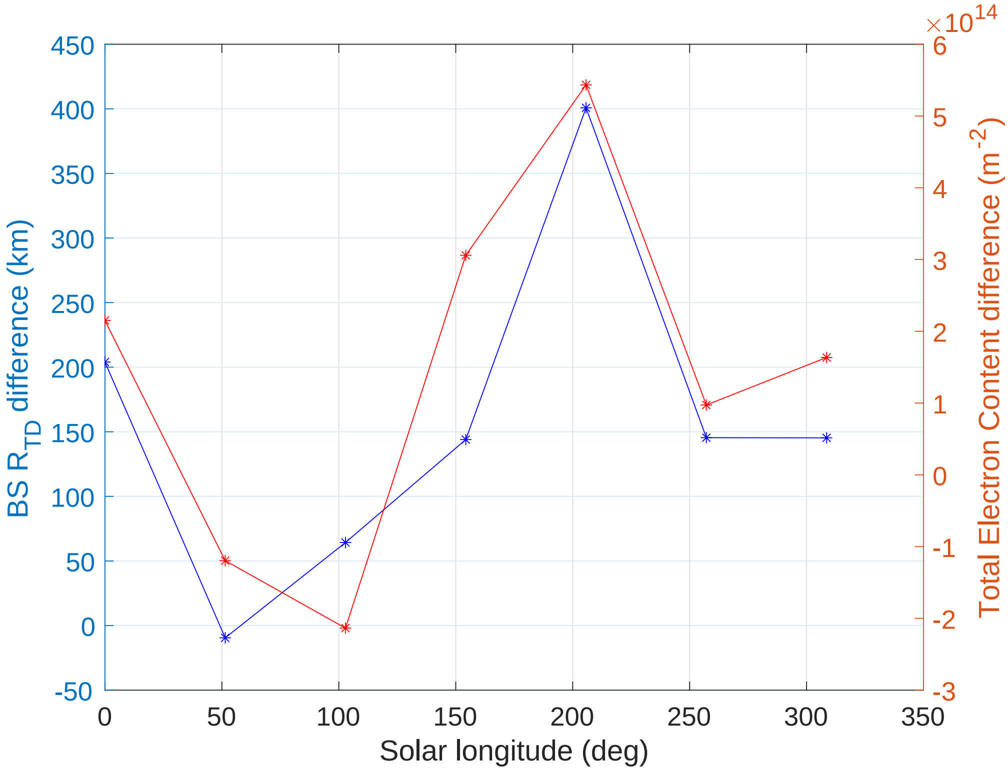

Figure 6. Compared seasonal variation of both the Total Electronic Content (TEC) of Mars ionosphere given by MEX MARSIS data, and of the MEX BS R_{TD} extrapolated terminator altitudes. For both parameters at each season, we show the difference between the value close vs away the strongest crustal field source region (when only focusing on the southern hemisphere $\pm 20°$ latitude band considered in Figure 1 ; see text for more details). The solar longitude (Ls) of Mars is the Mars-Sun angle measured from the Northern Hemisphere spring equinox where $Ls = 0°$ ($Ls = 90°$ corresponds to northern summer solstice, $Ls = 180°$ to northern autumn equinox).

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removes the influence of z on x. Residuals are then calculated for y with same procedure to remove the influence of z on y. The partial correlation coefficient between x and y, after controlling for the third variable z, is simply determined by the Pearson correlation coefficients between the two residuals. This technique can be generalized to a larger number of variables controlled.

The Pearson correlation coefficient between variables x_0 and y controlling for variables x_i ($i > 0$) are calculated recursively. The $i+1$ order partial correlation coefficient is given by:

$$r_{x_0y.x_1...x_ix_{i+1}} = \frac{r_{x_0y.x_1x_2...x_i} - r_{x_0x_{i+1}.x_1x_2...x_i} \cdot r_{yx_{i+1}.x_1x_2...x_i}}{\sqrt{1 - r^2_{x_0x_{i+1}.x_1x_2...x_i}} \cdot \sqrt{1 - r^2_{yx_{i+1}.x_1x_2...x_i}}} \quad \text{(A1)}$$

In order to evaluate the significance of the partial correlation factors with respect to the null hypothesis H_0 (i.e. null correlation), the test statistics $t = \frac{r}{\sqrt{\frac{1-r^2}{n-3}}}$ is calculated. For a risk α (e.g. 5% in our case), the null hypothesis is rejected if $\mid t \mid > t_{H_0}$ where $t_{H_0} = t_{1-\alpha/2}(n-3)$ is the quantile of order $1-\alpha/2$ of the Student law for $(n-3)$ degrees of freedom. Similar to classic correlation coefficients, two-sided p-values can be determined to provide a probability that the null hypothesis is true: i.e. the partial correlation is not significantly different from 0 as soon as the p-value is larger than the risk defined (5%).

Moreover, the quality evaluation of regression models, usually given by the determination coefficient R^2, monotonically increases with the number of variables included in the model. One thus needs to calculate the adjusted determination coefficient R'^2 to compare regression models including more or less variables, with:

$$R'^2 = 1 - \frac{n-1}{n-p-1}(1 - R^2) \quad \text{(A2)}$$

with n number of observations and p number of variables in the regression model, and $R^2 = 1 - SSE/SST$ with SSE the sum of squared error ($SSE = \sum_i (y_{i_{model}} - y_{mean})^2$) and SST the sum of squared total ($SST = \sum_i (y_i - y_{mean})^2$).

Finally, the individual slopes b_i of variables x_i can be transformed into standardized slopes called beta-weights (b_i^*) enabling to compare the relative influence of the variables (to avoid e.g. comparing different units or ranges): $b_i^* = b_i \frac{s_i}{s_y}$ with s_i and s_y the standard deviations of variables x_i and y.

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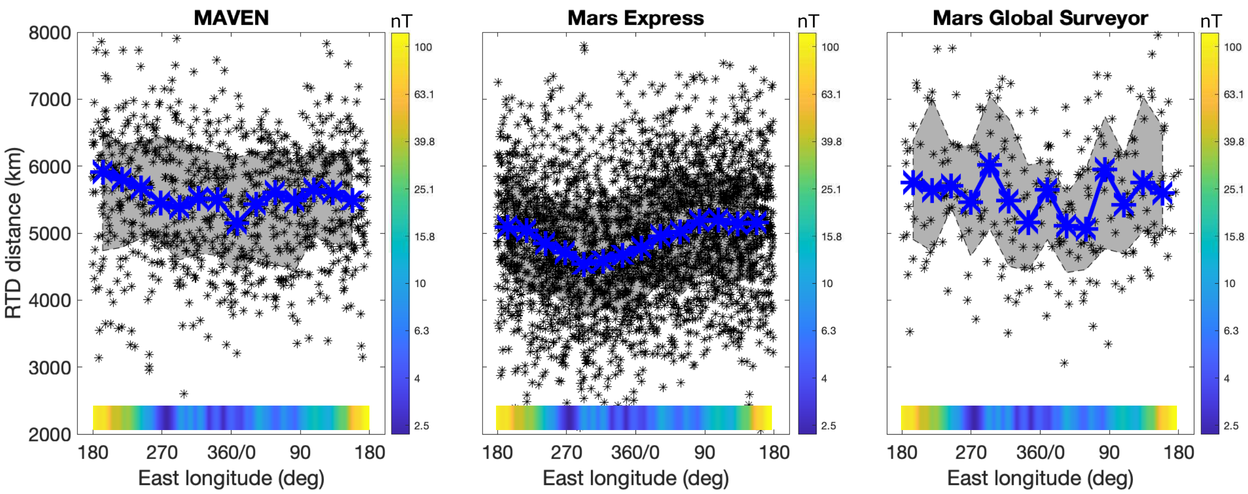

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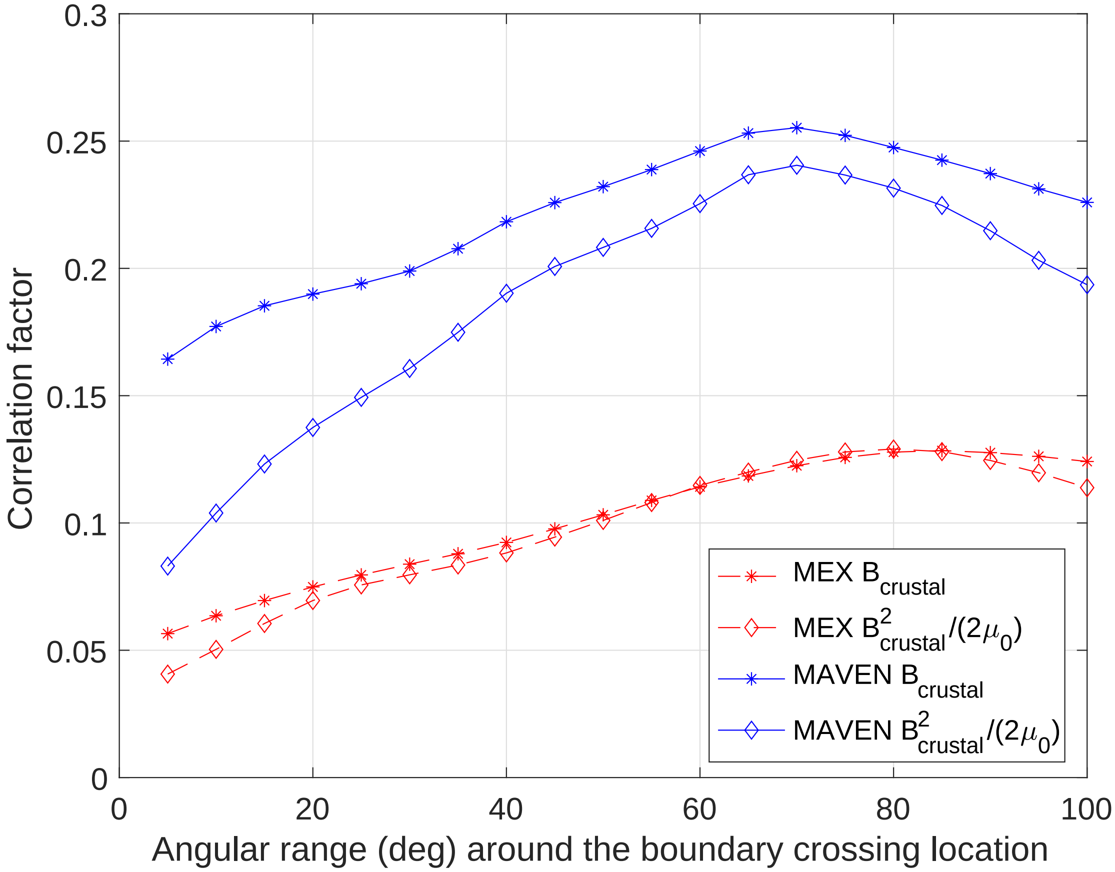

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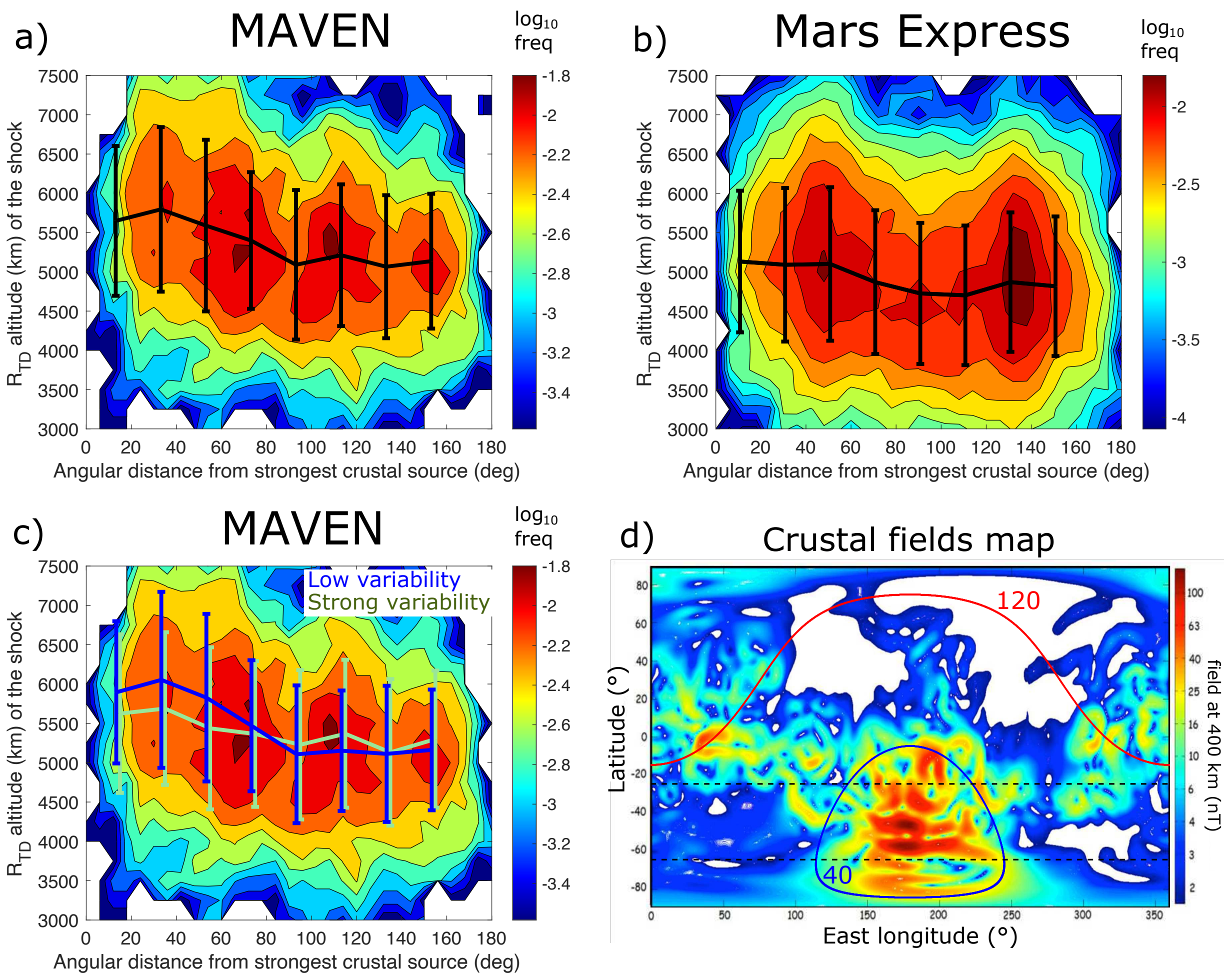

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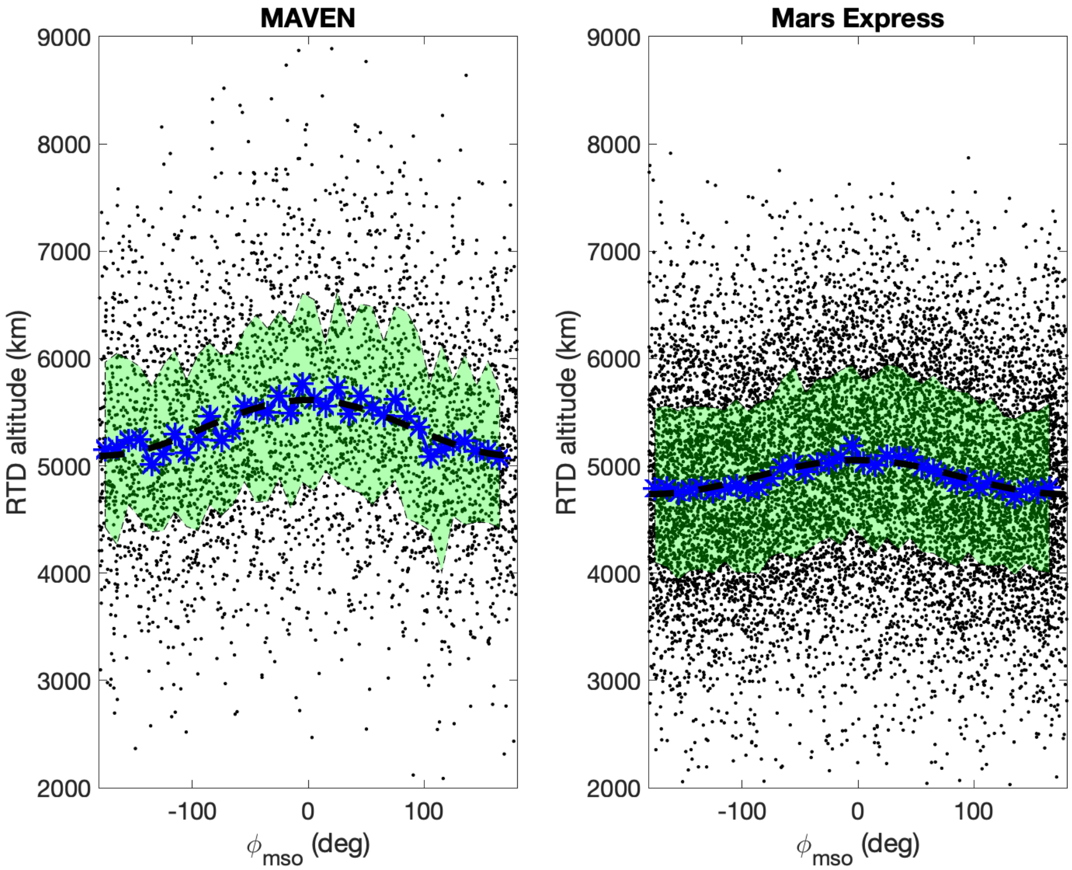

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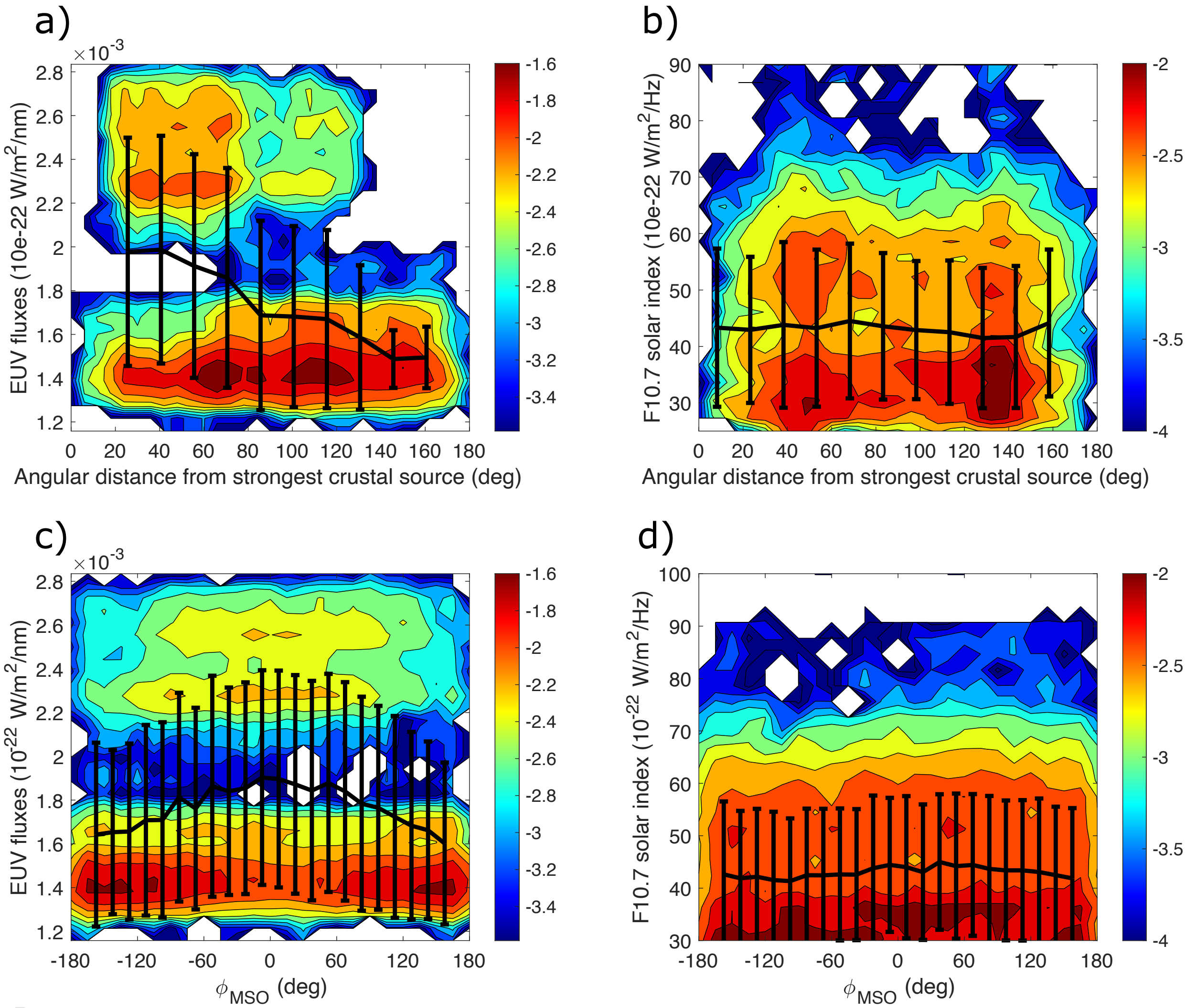

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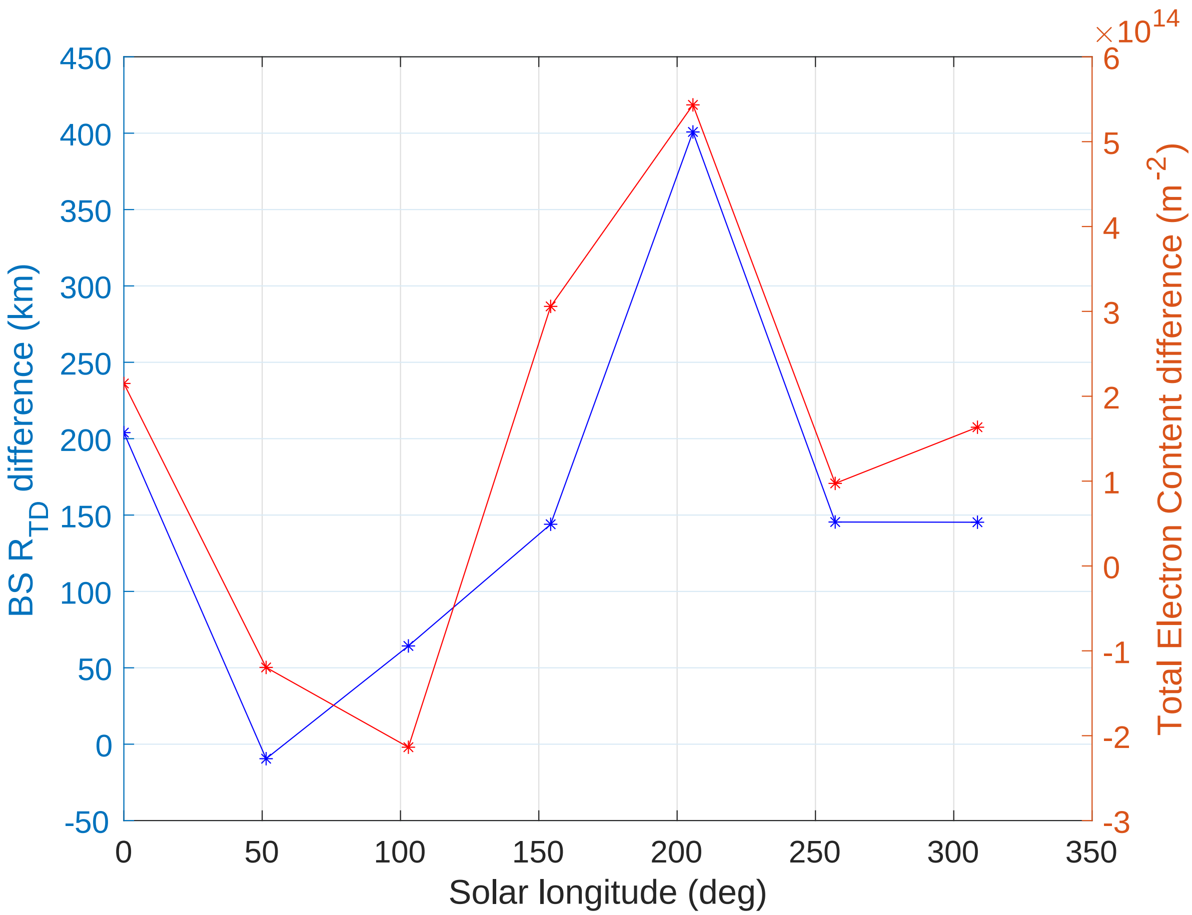

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