MAVEN Observations Uncover Enhanced Electron Density Variations in Mars' Crustal Magnetic Field Regions

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ABSTRACT:

Solar wind streams strongly influence planetary atmospheres as they propagate through the interplanetary medium. When these high-speed plasma flows reach Mars, the absence of a global dipole magnetic field prevents effective deflection of the solar wind, causing the flow to slow and form a bow shock. This, in turn, produces a compressed region known as the magnetosheath, where ions and electrons accumulate and solar wind density increases sharply. Although Mars lacks an intrinsic global magnetic field, it hosts strong crustal magnetic fields—primarily concentrated in the southern hemisphere between longitudes ~140°–240°—that further shape its plasma environment. These localized magnetic anomalies intensify magnetic field strengths during solar wind disturbances, enhance particle confinement, and lead to elevated electron densities above crustal regions. In this study, we investigate the response of Mars' upper atmosphere to a strong solar wind event by combining in-situ measurements from MAVEN's SWEA, MAG, and LPW instruments with heliospheric plasma simulations from EUHFORIA. This integrated observational–modeling approach enables us to track the solar wind disturbance from its heliospheric origin to its interaction with Mars, quantify variations in solar wind density, and examine magnetic field changes in both crustal and non-crustal areas. Our results reveal clear differences between these regions, demonstrating the crucial role of crustal magnetic fields in modulating the interaction between the solar wind and the Martian ionosphere. Understanding this coupling is essential for constraining atmospheric escape processes and for evaluating the long-term evolution of Mars' atmosphere. More broadly, these results enhance our understanding of solar wind interactions at other weakly magnetized planetary bodies.

1. INTRODUCTION

The outermost layer of the Sun's atmosphere, known as the solar corona, consists of extremely hot plasma composed of ions and electrons, with temperatures surpassing 1,000,000 K. This high-energy plasma continually escapes the Sun's gravity, carrying the solar magnetic field with it in a continuous outflow known as the solar wind. The solar wind travels at several hundred kilometers per second and extends across the entire solar system, influencing the interplanetary environment (Viall & Borovsky, 2020). Direct measurements of the solar wind began in the 1960s (Ness, 1996), and since then, advances in observational instruments, remote sensing techniques, and modeling approaches have greatly enhanced our understanding of its properties and the physical processes that drive it.

The solar wind continuously transports the interplanetary magnetic field (IMF) throughout the solar system. When it encounters Earth, it interacts with the planet's magnetic field and plasma environment, initiating a variety of dynamic phenomena collectively known as space weather. Although Earth is one of the magnetized planets and possesses a strong dipole magnetic field that extends far beyond its surface, offering significant protection from the solar wind (Fowler et al., 2024), this protective region, called the magnetosphere, causes incoming solar wind streams to be diverted and deflected around the planet. Additionally, Earth's ionospheric structure and behavior are strongly influenced by both external and internal magnetic fields (Schunk & Nagy, 2009).

When the solar wind, a high-speed stream of charged particles emitted by the Sun, encounters Mars, it cannot simply flow past the planet as it does around Earth, due to the absence of a strong global magnetic field. Instead, the solar wind is decelerated and diverted upon interacting with Mars' upper atmosphere and the localized magnetic fields generated by its ionosphere and magnetized crust. This interaction results in the formation of a shock wave known as the bow shock. At this boundary, the solar wind is compressed, leading to increased particle density and temperature. The region between the bow shock and the planet, known as the magnetosheath, contains this compressed solar wind plasma (Halekas et al., 2017). Moreover, the interaction of the solar wind with Mars can influence various atmospheric parameters, including dynamic pressure (Mohebbi & Sabri, 2024), solar irradiance levels, and the rate at which ions escape from the atmosphere.

Among the planets in our solar system, Mars possesses a distinctly unique magnetic environment. Unlike Earth, which is protected by a strong, global dipole magnetic field, Mars lacks such a large-scale field (Acuña et al., 1999). Instead, it features localized regions of strong magnetic intensity, known as crustal magnetic fields, which are primarily concentrated in the southern hemisphere, particularly at southern latitudes and longitudes between approximately 140° and 240°. The absence of a global dipole field means Mars is far less shielded from solar irradiation and the solar wind. As a result, the planet's atmosphere is directly exposed to solar wind particles, leading to significant variability in ionospheric properties.

When the solar wind interacts with Mars, parts of its magnetic field can be absorbed into the Martian atmospheric system, generating induced magnetic fields. These interactions result in notable increases in local magnetic field strength, particularly in regions near strong crustal fields, where the effects are amplified. The crustal magnetic anomalies not only enhance magnetic field intensities but also significantly influence ionospheric dynamics. Observations have shown that electron densities are consistently higher in areas above strong crustal magnetic fields (Flynn et al., 2017), suggesting that these regions act as magnetic traps or focal points for charged particles.

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Furthermore, the presence of crustal fields alters the way the solar wind interacts with Mars, modifying the structure of the ionosphere and possibly creating localized mini-magnetospheres (Andrews et al., 2015). These interactions are critical for understanding atmospheric escape processes, space weather effects at Mars, and the long-term evolution of its atmosphere. The complex interplay between solar wind, induced magnetic fields, and crustal anomalies highlights the need for detailed spatial and temporal studies to unravel the intricacies of Martian space physics.

Research on the interaction between the solar wind and Mars' magnetic and atmospheric environment was significantly constrained before the launch of the Mars Atmosphere and Volatile EvolutioN (MAVEN) mission in 2014 (Jakosky et al., 2015). MAVEN marked a turning point in Mars exploration as it was the first mission equipped with a dedicated solar wind monitor to study the planet's upper atmosphere and its response to solar activity. The spacecraft carries eight scientific instruments incorporating nine sensors, enabling a comprehensive analysis of Mars' space environment.

Among these instruments, the Langmuir Probes and Waves (LPW) system plays a critical role by providing high-resolution electron density measurements across a broad altitude range (Andersson et al., 2015). In parallel, the Magnetometer (MAG), consisting of two tri-axial fluxgate sensors mounted on the spacecraft's booms, measures both the interplanetary magnetic field carried by the solar wind and the magnetic fields induced within the Martian ionosphere. Additionally, the Solar Wind Electron Analyzer (SWEA) captures detailed data on the energy and distribution of electrons in the solar wind and ionospheric plasma.

Early results from MAVEN have significantly deepened our understanding of Mars' magnetic and plasma environment. Notably, initial analyses revealed that regions above strong crustal magnetic anomalies exhibit significantly elevated electron densities compared to adjacent areas with weaker magnetic influence (Andrews et al., 2015). These observations confirm that crustal magnetic fields play a critical role in shaping ionospheric structure and solar wind interactions. MAVEN's continuous, in-situ measurements have since enabled numerous discoveries regarding atmospheric escape, ionospheric variability, and the long-term evolution of Mars' atmosphere under solar influence.

Recent studies have highlighted the significant role of magnetic topology in shaping how Martian crustal magnetic fields influence the topside ionosphere's response to variations in upstream solar wind conditions (Fowler et al., 2019). However, the precise mechanisms underlying this interaction remain only partially understood, and many aspects of the solar wind–ionosphere–crustal field coupling are still open questions in planetary space physics.

The primary objective of this study is to investigate how variations in the solar wind influence Mars' crustal magnetic fields and, consequently, modulate electron density in the planet's ionosphere. Understanding this interaction is critical because, in the absence of a global dipole magnetic field, Mars' upper atmosphere is directly exposed to solar wind forcing, with localized crustal magnetic anomalies playing a key role in shaping plasma dynamics. To examine these processes, we utilized the EUHFORIA (EUropean Heliospheric FORecasting Information Asset) space weather modeling tool to simulate the propagation of a strong solar wind disturbance through the inner heliosphere and its subsequent interaction with Mars. We focused on a particularly intense solar wind event that occurred in August 2020, analyzing the temporal and spatial response of the Martian magnetic and ionospheric environment. By combining EUHFORIA simulations with in-situ measurements from MAVEN instruments, we were able to quantify changes in solar wind density, magnetic field strength, and electron density across both crustal and non-crustal regions. Our results demonstrate significant variability in electron density above strong crustal magnetic anomalies, highlighting how localized magnetic topology modulates particle confinement and atmospheric response. These findings provide new insights into the complex coupling between solar wind forcing and Mars' magnetically structured upper atmosphere, contributing to a more comprehensive understanding of atmospheric dynamics, plasma transport, and the long-term evolution of the Martian environment under space weather influence.

2. DATA AND INSTRUMENTATION

2.1 MAVEN (Mars Atmosphere and Volatile EvolutioN)

The Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft is the first mission specifically designed to study the upper atmosphere of Mars, the physical mechanisms driving its present-day behavior, and the ongoing escape of its constituent gases into space (Jakosky et al., 2015). A central, overarching goal of the mission is to quantify the rates and pathways of atmospheric loss and to characterize the physical processes that govern this escape. By determining these present-day rates and linking them to key drivers like solar ultraviolet (UV) radiation and solar wind forcing, MAVEN provides the empirical data needed to extrapolate atmospheric loss backward through geologic time. This is essential for constructing a quantitative history of Mars's climate evolution over the past four billion years, from a potentially warmer, wetter state to its current cold and arid condition.

MAVEN entered its science orbit around Mars in September 2014. Its highly elliptical orbit—with a periapsis as low as ~150 km to sample the dense upper atmosphere and an apoapsis of ~6200 km to measure the pristine solar wind—was uniquely designed to directly connect atmospheric drivers to their effects. The spacecraft's comprehensive suite of eight science instruments can be broadly categorized into three functional groups: particles and fields sensors, remote sensing instruments, and an occultation experiment. This integrated payload allows MAVEN to perform simultaneous, correlated measurements of the solar wind input, the structure of the upper atmosphere and ionosphere, and the resulting escape of planetary ions. The mission's strategy is to characterize the present-day state of the system and its response to solar forcing, enabling the estimation of cumulative loss over Mars's history.

Key instruments used in this study, part of the Particles and Fields Package, include:

Langmuir Probe and Waves (LPW):

The LPW instrument consists of two identical Langmuir probes on deployable booms that measure the in-situ thermal plasma properties of the ionosphere. It provides direct, high-temporal-resolution measurements of electron density (N_e) and electron temperature (T_e). These parameters are fundamental for diagnosing photochemical equilibrium, ion production rates, and plasma transport. The instrument also includes a waves sensor that detects naturally occurring plasma waves (e.g., Langmuir waves, ion acoustic waves), which can indicate wave-particle interactions that may energize ions and contribute to non-thermal escape processes (Andersson et al., 2015).

Magnetometer (MAG):
The MAVEN MAG is a dual, tri-axial fluxgate magnetometer that provides precise vector measurements of the magnetic field from the incoming solar wind through the magnetosheath and into the ionosphere. Its primary roles are to characterize the Interplanetary Magnetic Field (IMF) conditions upstream of Mars and to map the complex magnetic topology within and around the planet. This includes distinguishing between the draped IMF of the induced magnetosphere and the strong, vertical fields of crustal magnetic anomalies. MAG data provide the essential context for interpreting charged particle motions, as they define the gyro-centers and guiding-center drifts of ions and electrons (Connerney et al., 2015).

Solar Wind Electron Analyzer (SWEA):
SWEA is a hemispherical electrostatic analyzer that measures the three-dimensional velocity distribution of electrons in the energy range of ~3 to 4600 eV. It is particularly adept at identifying and characterizing different electron populations, including: Solar wind electrons, which serve as a tracer of the unperturbed solar wind. Shock-energized electrons in the magnetosheath and foreshock. Photoelectrons, produced in the ionosphere by solar EUV radiation, which are diagnostic of atmospheric composition and ionization rates. Auroral electrons, precipitated along crustal magnetic field lines.

By distinguishing these populations, SWEA enables studies of energy deposition into the atmosphere, magnetic connectivity, and plasma boundaries (e.g., identifying the magnetic pileup boundary) (Mitchell et al., 2016). Its measurements are critical for understanding the electron-driven physics of the Martian space environment.

Figure 1. Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft is developed and operated by NASA in 2013. Since entering Martian orbit in 2014, MAVEN has been studying the planet's upper atmosphere, ionosphere, and interactions with the solar wind. Equipped with instruments such as the Solar Wind Electron Analyzer (SWEA), the Langmuir Probe and Waves (LPW) system, and the Magnetometer (MAG), the spacecraft provides in-situ measurements that are critical for understanding Mars' plasma environment and atmospheric escape processes.

2.2 EUHFORIA

EUHFORIA (EUropean Heliospheric FORecasting Information Asset) is a physics-based numerical framework designed to model the ambient and transient solar wind throughout the inner heliosphere. As an operational forecasting tool, it is routinely driven by near-real-time solar observations to provide predictions of solar wind conditions at Earth and other planetary locations (Pomoell & Poedts, 2018).

The architecture of EUHFORIA is modular, consisting of two core components that work in sequence. First, a coronal model reconstructs the global solar magnetic field, typically using a Potential Field Source Surface (PFSS) extrapolation based on synoptic magnetograms. This magnetic topology is then used in an empirical model, such as the Wang-Sheeley-Arge (WSA) relation, to compute the initial plasma parameters—including radial velocity, density, and temperature—at a spherical inner boundary of 0.1 Astronomical Units (AU). These outputs define the steady-state solar wind and serve as the time-varying inner boundary condition for the second component.

The second component is a three-dimensional, time-dependent magnetohydrodynamic (MHD) heliospheric model. This module solves the set of ideal MHD equations to propagate the solar wind plasma and embedded magnetic field from 0.1 AU outward, typically to a distance of 2 AU. It simulates the dynamic evolution of the solar wind, capturing the kinematic interactions between fast and slow streams that form Corotating Interaction Regions (CIRs). Crucially, the model can also inject magnetized plasma structures, such as Coronal Mass Ejections (CMEs), using flux rope models (e.g., the spheromak or flux rope in a cone), allowing it to simulate the propagation, deformation, and interaction of transient disturbances with the ambient wind.

This integrated framework makes EUHFORIA particularly valuable for planetary space weather studies, such as those at Mars. By simulating the solar wind from its coronal source to planetary distances, EUHFORIA provides essential context and causality for in-situ spacecraft measurements. It allows researchers to link specific upstream solar wind structures—like the high-density plasma region of a CIR analyzed in this study—to the subsequent perturbations observed in a planet's induced magnetosphere and ionosphere, thereby offering a predictive capability for the response of unmagnetized or weakly magnetized bodies to solar activity.

3. DISCUSSION AND RESULTS

On August 17th, 2020, a comparatively strong and fast solar wind stream impacted the Martian system, inducing pronounced disturbances in the planet's magnetosphere and ionosphere. To investigate the event's propagation, structure, and subsequent atmospheric interactions, we employed the EUHFORIA (European Heliospheric Forecasting Information Asset) magnetohydrodynamic (MHD) model. This framework simulates the propagation of solar wind plasma and embedded magnetic fields from the Sun through the inner heliosphere out to approximately 2 AU. By using EUHFORIA, we were able to trace the solar wind stream from its coronal origin, track its evolution through interplanetary space, and reconstruct its properties upon arrival at Mars. The simulation provided critical insight into the temporal and spatial profile of the solar wind disturbance and allowed us to determine precisely when its leading edge encountered the Martian system (Figure 2).

Moreover, the model enabled us to examine the sequence of interaction as the solar wind disturbance propagated through and ultimately fully enveloped the Martian environment. This holistic simulation-based perspective provides a comprehensive context for interpreting the in situ observations of magnetic field and electron density variations recorded at Mars.

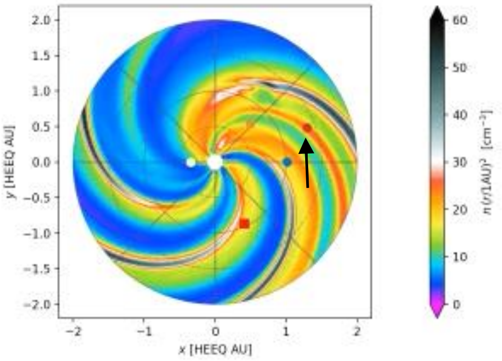

Figure 2. Simulation of the solar wind interaction with Mars on 17 August 2020 using the EUHFORIA space weather modeling tool. The figure shows a relatively strong solar wind stream propagating through the inner heliosphere and impacting Mars. Coordinates are given in the Heliocentric Earth Equatorial (HEEQ) reference frame, with distances displayed in astronomical units (AU). Mars is marked by a red circle and highlighted with a black arrow, while the Sun appears at the center of the plot as a white circle.

Figure 3 presents a comparison between in-situ solar wind electron density measurements from the Mars Atmosphere and Volatile EvolutioN (MAVEN) orbiter's Solar Wind Electron Analyzer (SWEA) and the corresponding solar wind proton density output from the EUHFORIA simulation for August 17, 2020. This date marks the arrival of the simulated high-speed stream at Mars.

Both datasets capture a clear, abrupt enhancement in density, signaling the passage of a large-scale solar wind structure. The observed profile—characterized by a steep gradient—is diagnostic of a pressure front formed by kinematic steepening, where a fast solar wind stream overtakes slower upstream plasma. This interaction compresses the plasma at the interface, leading to localized increases in density, temperature, and magnetic field strength. Such a front can manifest as an interplanetary shock if the velocity difference is supersonic, or as a compressed stream interaction region (SIR).

The close temporal alignment between the simulated and observed density increases validates EUHFORIA's ability to model the propagation and timing of such structures to Mars' orbit. This comparison directly links the in-situ event at Mars to a specific, simulated solar wind disturbance, providing the essential heliospheric context for interpreting the subsequent planetary response.

Near Mars, the effects of an arriving solar wind shock become particularly significant because the incoming disturbance interacts directly with the planet's ionosphere and its highly structured crustal magnetic fields rather than a global dipole magnetosphere. The compressed plasma regions observed in both the SWEA measurements and the EUHFORIA model provide clear evidence of this direct coupling. The agreement between the simulated and observed density enhancements reinforces the interpretation that the elevated particle densities originate from the arrival of a strong solar wind perturbation.

A key consequence of a solar wind shock's arrival is the large-scale motion or oscillation of the Martian bow shock. Recent multi-spacecraft observations have documented these oscillations, with the shock moving over spatial scales of hundreds of kilometers on timescales of minutes even during weakly disturbed solar wind conditions.

These bow shock oscillations signify a dynamic reconfiguration of the entire Martian plasma environment. The shock's motion alters the extent of the magnetosheath, the compression of the magnetic pileup region, and the penetration of energy into the ionosphere. This global adjustment is the context for the localized in-situ measurements of magnetic field and plasma density. The comparison with EUHFORIA is crucial because it establishes that these complex local dynamics are initiated by a specific, large-scale solar wind structure simulated from its coronal origin.

Therefore, combining global heliospheric modeling like EUHFORIA with in-situ measurements is indispensable. The model provides the "upstream" context, identifying the shock and its properties, while the spacecraft data reveal the "downstream" consequences—the resulting deformation of the Martian plasma boundaries and the planet's dynamic response. This integrated approach is essential for characterizing shock-driven disturbances, quantifying atmospheric escape processes, and advancing our understanding of space weather at unmagnetized planets.

The solar wind, carrying the interplanetary magnetic field (IMF), interacts with Mars to form a relatively weak induced magnetosphere because the planet lacks a global dipole magnetic field. During the August 17th solar wind disturbance, this interaction produced significant variations in the local magnetic field environment, as shown in Figure 4. The figure reveals a substantial enhancement in magnetic field strength resulting from the compression and distortion of the induced magnetospheric boundaries by the incoming solar wind. Specifically, the disturbance pushed the magnetic pileup boundary (MPB) and the induced magnetosphere boundary (IMB) sunward, leading to the observed intensification.

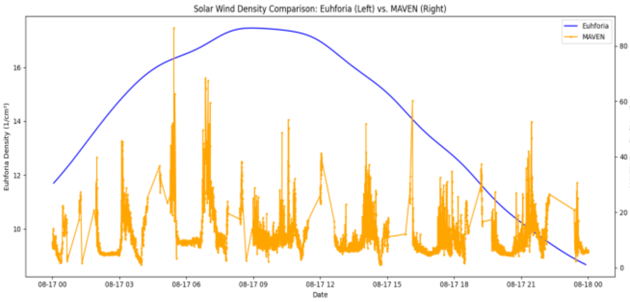

Figure 3. Comparison of solar wind electron density at Mars using observational data from MAVEN SWEA and simulated data from EUHFORIA. The combined profiles provide a clear representation of the variations in solar wind density as the stream interacts with the Martian atmosphere, highlighting the response of the local plasma environment to the incoming solar wind.

These variations are further amplified in regions where Mars' crustal magnetic fields are particularly strong. In such regions, the crustal magnetic anomalies create localized, complex magnetic topologies, ranging from vertical "loop-like" structures to more horizontal "canopy" configurations. These fields act as magnetic traps for charged particles, including electrons and ions. Because these closed or nearly closed magnetic field lines inhibit cross-field transport and direct plasma convection, the confined particles remain within the same magnetic structure rather than freely escaping along open field lines into the magnetosheath or interplanetary space. This trapping effect suppresses atmospheric ion loss processes while simultaneously increasing the local particle population through the accumulation of both solar wind and ionospheric plasma. The mirror force along converging field lines further contributes to this confinement.

As a result, elevated electron densities consistently appear above strong crustal magnetic sources, forming distinct, long-lived plasma enhancements, in contrast to the lower, more uniform densities found in areas dominated by weak or absent crustal fields. The behavior illustrated in Figure 5, therefore, highlights how the combined influence of the solar wind, the induced magnetosphere, and the underlying crustal magnetic topology collectively shapes the spatial distribution of electron density in the Martian ionosphere. This interplay creates a highly heterogeneous plasma environment where local magnetic anomalies act as significant modulators of global atmospheric escape and ionospheric structure.

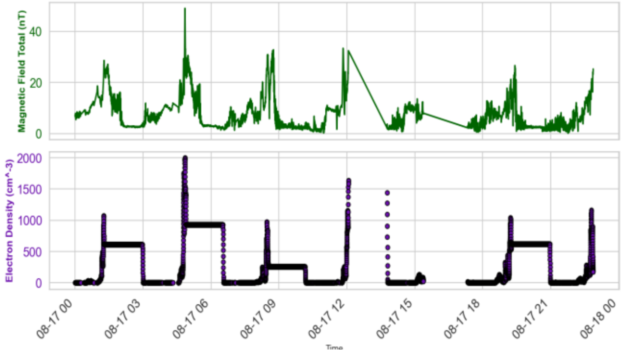

Figure 4. The upper panel presents the magnetic field strength obtained from MAVEN MAG measurements, while the lower panel displays the corresponding electron density. Together, the two panels illustrate how both parameters vary in response to the solar wind interaction.

Although Mars lacks a global dipole magnetic field, it possesses numerous localized crustal magnetic anomalies that create a highly heterogeneous magnetic environment. These crustal fields are remanent magnetism locked in ancient crustal rocks, and they are especially concentrated in the southern highlands, with the strongest and most extensive anomalies located within longitudes approximately 140°–240°. These regions produce localized magnetic loops and can form mini-magnetospheres—distinct, standoff structures that significantly influence the structure and behavior of the overlying Martian ionosphere and atmospheric escape processes.

The influence of these crustal fields is twofold: they act as magnetic traps that confine plasma and as obstacles that divert the shocked solar wind plasma of the magnetosheath. Observations consistently show that areas underlain by strong crustal magnetic fields exhibit elevated ionospheric electron and ion densities relative to the surrounding regions. This pattern is most pronounced over the largest and strongest anomaly clusters in the southern latitudes, where closed magnetic field topologies are more prevalent. These closed loops effectively trap charged particles, inhibiting vertical transport and cross-field diffusion, leading to the accumulation of local photochemical products and, during disturbed conditions, solar wind electrons.

Figure 5 highlights these major crustal magnetic field regions, illustrating the substantial enhancement in magnetic field strength they generate at a reference altitude (e.g., ~400 km). In parallel, the figure compares how the ionospheric electron density responds dynamically during the solar wind interaction event of August 17. Both panels demonstrate that when enhanced solar wind dynamic pressure associated with the shock or stream interface encounters these magnetized areas, the crustal fields become increasingly effective at guiding and confining charged particles. The global compression of the induced magnetosphere amplifies the local crustal fields and further restricts their topology. This interaction compresses magnetic structures and funnels solar wind–driven electrons along converging field lines into closed or quasi-closed magnetic regions, leading to significant increases in trapped particle populations and localized heating.

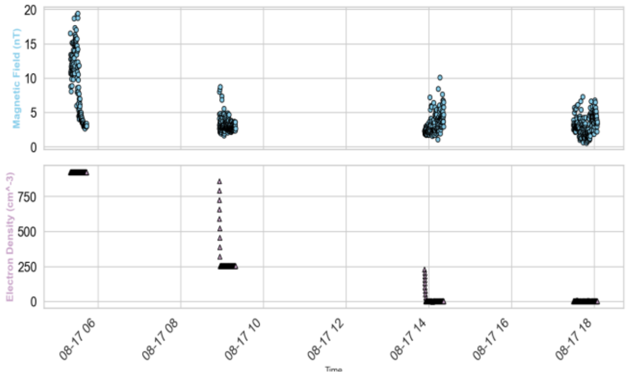

Figure 5. The magnetic field and electron density panels are restricted to strong crustal field regions at southern latitudes and longitudes ~140°–240°. The variations represent the variability of this region to solar wind interactions, and the changes in the magnetic field can highly affect the electron density.

Consequently, electron densities rise dramatically within the strong crustal field zones during the event. This stark contrast with regions of weak or absent crustal fields—where the ionosphere is directly exposed to and eroded by the magnetosheath flow—emphasizes the critical role of magnetic topology in modulating the Martian ionosphere’s spatial structure and its dynamic response to upstream solar wind conditions. This heterogeneity is a defining feature of Mars's space environment and a key control on patterns of atmospheric escape.

The findings presented in this study demonstrate that Mars's plasma environment exhibits a sharp, heterogeneous response to even moderate solar wind disturbances, governed by the planet's unique crustal magnetism. We have shown that localized crustal fields act as decisive modulators, creating mini-magnetospheres that trap plasma and enhance ionospheric densities during compression events, in stark contrast to the more erosive response of unmagnetized regions. This underscores that accurate modeling of atmospheric escape and ionospheric dynamics must account for this fine-scale magnetic topology as a first-order control, not merely a secondary perturbation.

The integrated use of EUHFORIA heliospheric simulations and MAVEN in-situ observations provides a powerful, causal framework that successfully links specific upstream solar wind structures to their downstream effects at Mars. This methodology moves beyond statistical correlation, offering a validated approach for reconstructing and, ultimately, predicting the impact of space weather on the Martian system.

Looking ahead, this study provides a foundation for several critical research avenues essential for advancing a predictive understanding of Martian space weather and its long-term atmospheric effects. The integrated model-observation framework should be extended to a statistical ensemble of solar wind drivers, from frequent stream interaction regions to extreme coronal mass ejections, to systematically quantify ionospheric response functions. This statistical approach will establish how perturbation amplitude, spatial structure, and recovery timescale depend on driver strength, interplanetary magnetic field orientation, and solar cycle phase. Crucially, this analysis must be stratified across different crustal field provinces to isolate the specific role of magnetic topology from other variables like local solar zenith angle or thermospheric conditions. In parallel, targeted high-resolution case studies are needed to probe the underlying microphysics. Specifically, investigations should focus on how specific crustal field geometries (e.g., compact vertical loops versus extended horizontal canopies) couple with the motional electric field of the magnetosheath flow to govern local plasma convection, instabilities, and the opening of closed magnetic loops via magnetic reconnection—processes that directly control ion escape fluxes. The ultimate synthesis of these statistical and mechanistic insights requires their assimilation into next-generation global models, such as 3D hybrid or magnetohydrodynamic simulations with self-consistent, high-resolution crustal field representations. Only through such integrated models can the discrete responses to individual space weather events be accurately scaled to geologic time, transforming our qualitative understanding into a quantitative constraint on how cumulative solar forcing has shaped the atmospheric evolution and present-day habitability of Mars.

4. SUMMARY AND CONCLUSION

Mars's lack of an intrinsic global dipole magnetic field leaves its upper atmosphere directly exposed to the solar wind, resulting in a dynamic plasma environment governed by the interplay between external forcing and internal structure. This study has elucidated a critical facet of this interplay by investigating the ionospheric and magnetic response to a moderate solar wind disturbance on August 17, 2020, with a particular focus on the modulating role of crustal magnetic fields.

By integrating global heliospheric modeling from EUHFORIA with in-situ MAVEN observations, we have established a causal, time-resolved link between a specific upstream solar wind structure, a stream interaction region or weak shock, and its subsequent impact at Mars. The EUHFORIA simulation successfully captured the propagation and timing of the compressed solar wind plasma, while MAVEN data confirmed the resulting compression of the induced magnetosphere and the amplification of magnetic fields, particularly over crustal anomalies.

Our analysis reveals that the ionospheric response is profoundly heterogeneous, governed by the underlying magnetic geology. Regions above strong crustal magnetic fields in the southern hemisphere, acting as localized mini-magnetospheres, exhibited significant enhancements in electron density due to the magnetic trapping of charged particles along closed field lines. In contrast, areas with weak or absent crustal fields showed a more subdued and erosive response typical of a direct solar wind-ionosphere interaction. This spatial dichotomy demonstrates that crustal magnetic topology is not a minor perturbation but a first-order controller of how solar wind energy is partitioned and deposited into the Martian upper atmosphere, directly modulating the spatial patterns of atmospheric escape and ionospheric structure during space weather events.

These findings carry important implications for several key areas:

1) Atmospheric Evolution: The demonstrated efficacy of crustal fields in locally inhibiting ion loss suggests that their spatial distribution has likely influenced global atmospheric escape rates over Martian history. Quantifying this effect requires integrating event-scale responses, like the one studied here, into long-term climate models.
2) Space Weather Forecasting at Mars: The validated EUHFORIA-MAVEN framework provides a methodology for reconstructing and, prospectively, predicting the plasma environment for future robotic and human missions. Understanding these anomalies as protective "shields" or particle "traps" is crucial for mission planning and interpreting sensor data.
3) Comparative Planetology: This work advances the fundamental understanding of solar wind interaction with unmagnetized bodies. The principles observed—where localized crustal fields dominate the global response—may apply to other rocky bodies without global dynamos, such as Mercury in the past, the Moon, and possibly certain exoplanets.

In summary, this study demonstrates that Mars's interaction with the solar wind is fundamentally structured by its crustal magnetism. Moving beyond the paradigm of a uniformly exposed atmosphere to one of a patchwork of shielded and exposed regions is essential for accurately modeling its atmospheric evolution, interpreting its present-day environment, and predicting its space weather.

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