The search for weak crustal magnetic fields on Mars using solar energetic electrons observed by the SEP instrument on-board the MAVEN spacecraft

Ishita Malik, Shaosui Xu, Ali Rahmati, David L. Mitchell
Research Sponsor: David L. Mitchell

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ABSTRACT

The purpose of this study is to understand the connectivity of magnetic field lines to the surface of Mars in areas of "weak" crustal magnetism, where the existence of magnetization cannot yet be determined, but nonetheless has implications on Mars's evolution. More specifically, the goal is to search for closed magnetic field lines that are connected to the Martian surface on both ends in weakly magnetized regions. Closed field lines can be identified by observing the absence of solar energetic particles electrons (SEP e^-). These high-energy particles of solar origin infiltrate the magnetosphere of Mars as they travel along magnetized solar wind during coronal mass ejections (CMEs) or solar events. In this study, data collected during a solar event in May 2015 by the MAVEN (Mars Atmosphere and Volatile EvolutioN) spacecraft orbiting Mars was used to examine the electron fluxes of SEPs near the closest point in its orbit or in proximity of MAVEN's periapsis. A numerical threshold was established through statistical analysis to identify regions where the flux of SEP electrons is significantly lower than its surrounding environment, implying a lack of high-energy electrons and therefore an SEP electron void. These features are indications of closed magnetic field lines, which are field lines solely connected to the planet, thus most likely representative of planetary origin. Based on the results of this study, it has been ascertained that regions exhibiting a reduction in the population of SEP electrons to approximately 10% to 20% in comparison to the ambient SEP electron population correspond to areas characterized by enclosed magnetic field lines, thereby denoting these regions as sources of crustal magnetism. By examining and evaluating the magnetic topology, this study offers valuable insights into the complex interplay between the incoming solar wind and its influence on the evolution of the Martian crust.

Introduction

Crustal magnetism is the magnetic field that originates solely from the crust of the planet, in other words, when planetary crust is exclusively the source of magnetism in a particular region. The rocks of these regions acquire intense magnetism after cooling below a critical magnetization temperature known as the Curie temperature. The motivation for this paper arises from the very complex crustal magnetic field patterns on the surface of Mars, first observed by the Mars Global Surveyor (MGS) spacecraft. The presence of these fields affirms that Mars must have had an active core dynamo that caused the magnetization of crustal rock; but ceased to continue operations early in its evolution. MGS findings revealed an intensely magnetized crust in the southern hemisphere of Mars and areas of very weak magnetization in the northern lowlands.[1] Currently, Mars lacks an active dynamo, the mechanism responsible for generating planetary magnetic fields. However, the Martian crust exhibits strong crustal magnetic remanence due to its richness in iron and other magnetic minerals with 'hard' remanence properties, meaning that once crustal rocks are magnetized, magnetization is sustained over billions of years. Furthermore, it was also discovered that the oldest terrain of the planet had the strongest magnetic fields associated with it.[3] In such regions, with a strong crustal magnetic presence, magnetic field lines are connected to the surface of Mars on both ends and form localized closed loop crustal fields which create 'miniature' magnetospheres., Mars' crustal magnetization was found to be approximately ten magnitudes greater in comparison to earth.4This finding sparked a widespread effort to study the strong crustal fields of the southern highlands of Mars, with little attention given to the weaker magnetic regions of the north.[1]

The search for magnetic signatures in the weakly magnetized crust of northern plains could help put constraints on the magnetic history in the north as well as contribute to the current understanding of the forces that have influenced and shaped planetary conditions on Mars.[8] Figure 1 is a visual representation of the complexity and the extremity of Mars' crustal magnetic field. The interest of this study lies in the gray regions of Figure 1, which include the Utopia Planitia, Olympus Mons in the northern lowlands and the Hellas and Argyre Basins in the southern highlands. Since the martian crustal field is weak and patchy in nature with strong remnant fields present across its surface appearing in patterns at various locations and intensities, the magnetic topology of Mars can provide useful insights into Mars' complex magnetic field behavior and its interactions with the solar wind.[9]

Magnetic topology describes the connectivity of magnetic field lines in relation to the planet's surface and the surrounding space environment, which includes the magnetized solar wind.[9] It can largely be classified into three categories: open field lines, draped field lines,

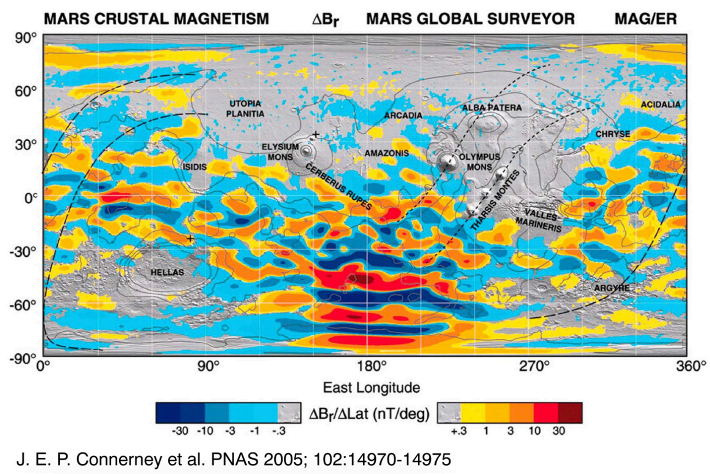

Figure 1: Crustal magnetic field strength mapped by MGS.[8] Derivative of the radial component of the magnetic field with respect to latitude observed at an altitude of 400 km by Mars Global Surveyor. This derivative effectively filters out large-scale induced fields arising from the Mars-solar wind interaction in order to maximize sensitivity to crustal sources. The color scale ranges from -30[nT/deg] (dark blue) to 30[nT/deg] (deep red). The gray regions represent magnetic strength data that are below the detection threshold of the measuring instruments.

and closed field lines, which are visually presented in Figure 2.[10]Closed field lines (red lines) are closed loops with both footpoints connected to the surface of the planet and are thus most likely planetary. For this study, closed magnetic field lines are used as indicators of magnetized crust. Draped field lines (blue lines) are solar magnetic field lines that drape around the planet. When the draped solar magnetic field interacts with a planetary closed field (via a process called magnetic reconnection), an open field line (green line), connected to Mars on one end and solar wind on the other end, can be generated (Figure 2).

Methodology

This research uses statistical analysis of measurements recorded by the SEP/SWEA instrumentations onboard the MAVEN spacecraft to determine the typical SEP electron flux depletion level as the spacecraft passes through the ionosphere within a few hundred km of the surface, which is then used to search for SEP electron voids and infer sources of crustal magnetism. This quantifiable method of determining closed topology is particularly effective for regions of weak magnetism since the detection of faint crustal sources becomes challenging in the presence of powerful external magnetic field lines that are being carried by the solar wind.

MAVEN, selected by NASA, was launched in November 2013 and entered its orbit around Mars after a 10-month flight in September 2014. The elliptical orbit of the spacecraft ranges from altitudes of ~6000 km at apoapsis (the furthest point of the spacecraft from the surface) to ~120 km at periapsis (the closest point of the spacecraft to the surface).12The primary goal of the MAVEN mission is to explore the upper atmosphere of Mars, its interaction with the solar wind, and the role that has played in the loss of the martian atmosphere to space. MAVEN contains six instruments that characterize the solar wind and the ionosphere of the planet. For the purposes of this paper, the instruments of interest currently operating onboard MAVEN are the Solar Energetic Particle (SEP) instrument and the Solar Wind Electron Analyzer (SWEA) instrument. The SEP instrument consists of two sensors, each with forward and rear facing field of views (FOVs) aggregating to four looking directions that are decked on the corners of the MAVEN spacecraft. This sophisticated apparatus has been carefully engineered to measure the energy levels, as well as directionality, of charged particles such as electrons and protons that are emitted from the Sun during solar flares or coronal mass ejections.[13]The SEP instrument is critical for the MAVEN mission, granting scientists the ability to analyze interactions between solar winds and the Martian

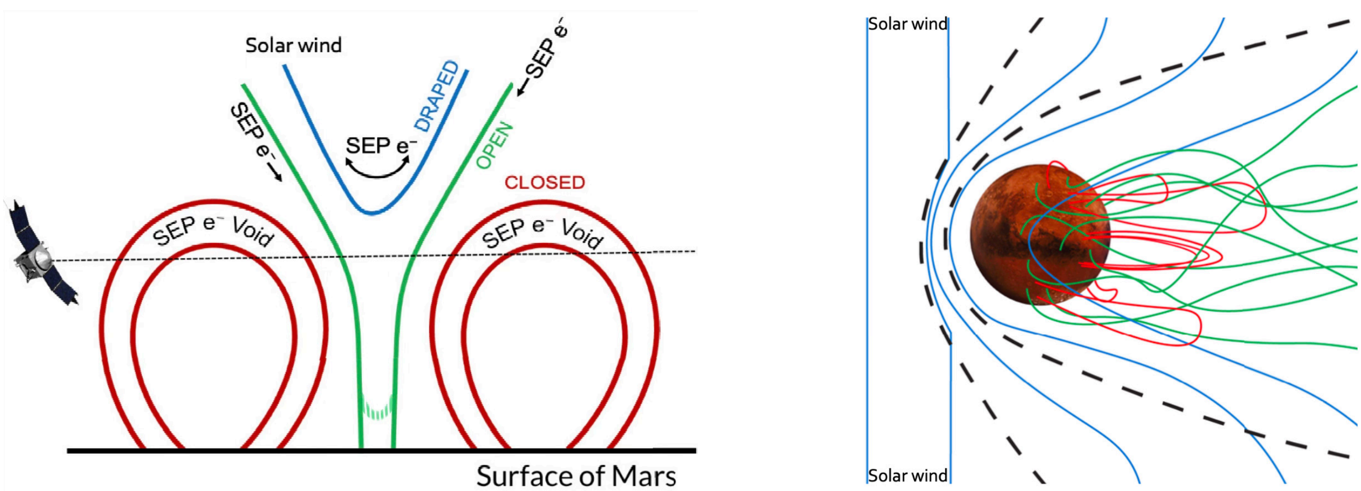

Figure 2: SEP electrons and topology schematic. Fig 2a. (left) A schematic display of the relationship between solar energetic particles and the magnetic topology of Mars. red is for the closed field lines identified using SEP electron voids. These lines represent Mars' crustal fields and are connected to the surface of mars on both ends; green is for open field lines, or deeply draped field lines observed below the exobase. Open field lines are connected to the surface on one end and to the solar wind; and blue for draped field lines, or field lines only connected to the solar wind. For open and draped field lines, solar energetic electrons are observed (incoming from the solar wind). However, for closed topology void of solar energetic electrons is observed. Fig 2b. (right) A 3D representation of closed (red), open (green), and draped (blue) field lines in presence of an external magnetic field and Mars' crustal field.

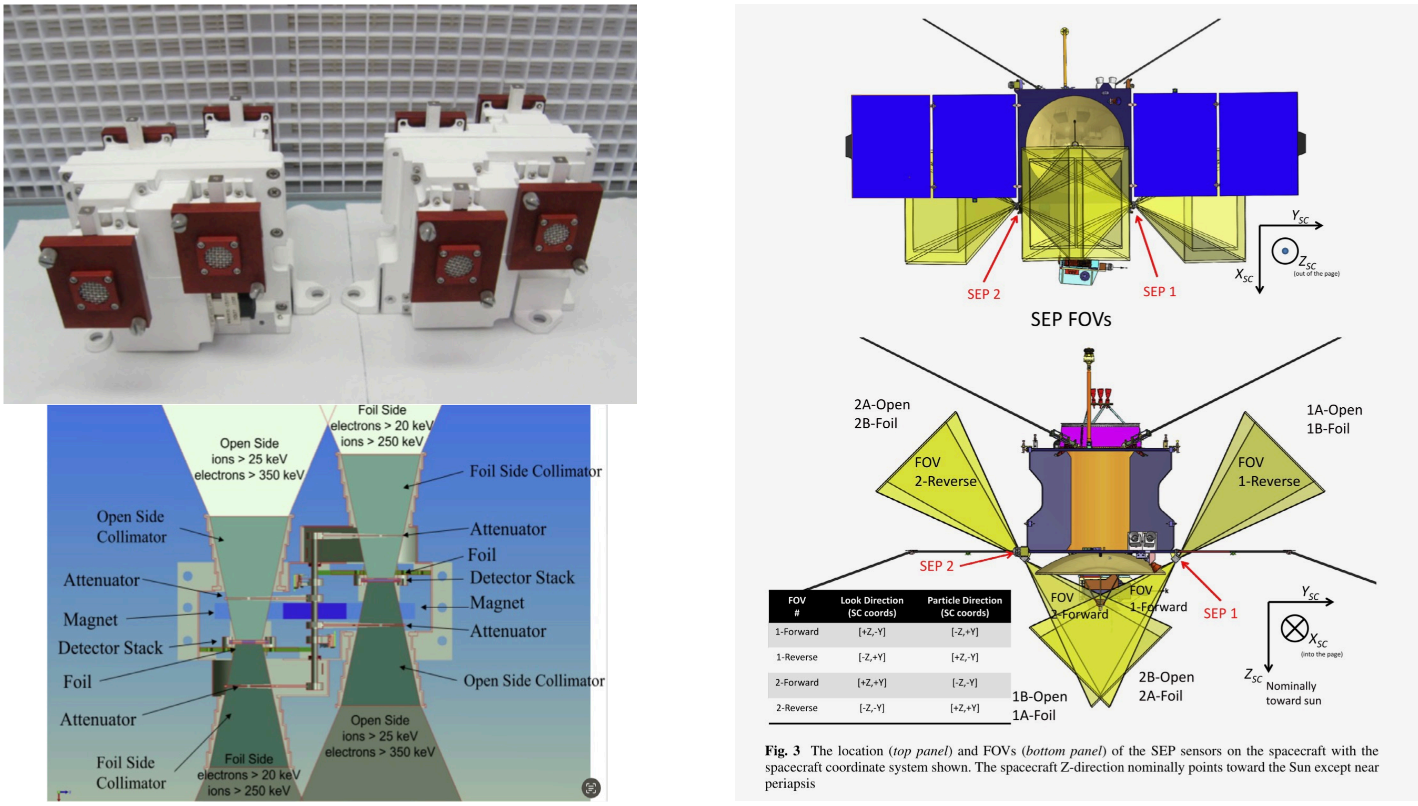

Figure 3: SEP instrument, its optical elements, the location of SEP sensors on MAVEN and their 4 FOVs.[13] Fig 3a. (top left) - the two SEP sensors on board the MAVEN spacecraft. These instruments are identical in design and functionality. Fig 3b. (bottom left) - Top-down view of the SEP sensors optics layout. Fig 3c. (top right) - illustration of the location of the two SEP sensors on the MAVEN spacecraft; (bottom right) - field of views of the SEP sensors, often referred to as the four SEP looking directions.

atmosphere using precipitation SEPs. The SEP instrument enables us to measure the energy spectrum, angular distributions, and densities of high-energy particles, ranging from 30keV to 1MeV for electrons and 30keV to 12MeV for ions.[13] Figure 3 includes images of the actual SEP sensors and an overview of its optical elements.[13]

Furthermore, The Solar Wind Electron Analyzer (SWEA) instrument provides context regarding the magnetic topology of the martian magnetosphere at the given spacecraft location for a more complete analysis of the SEP measurements. SWEA also measures the energy spectrum, and angular distributions, but for a lower energy range (3eV to 5keV) of electrons of both solar wind origin and planetary origin compared to the SEP instrument.12It is important to emphasize that this project primarily focuses on comparing closed topologies identified using SEP and SWEA data to ascertain sources of weak crustal magnetism.

Previous research studies have established reliable techniques using the SWEA measurements to infer magnetic topology at Mars. Hence, it is plausible to question the reasons behind investigating closed magnetic topology using SEP data. The key distinction between these instruments lies in the electron energies they record: electrons observed by the SEP sensors, ranging from 30 to 50 keV, possess energies two to three orders of magnitude greater than those used by SWEA in topological studies, which range from 20 to 200 eV. Magnetic topology can be inferred using either of the two instruments as long as the electrons measured remain magnetized. Electrons observed by SWEA become demagnetized at ~170 km due to collisions with neutral atmospheric particles present in the Martian atmosphere.[14] This means that the motion of electrons within this energy range is no longer

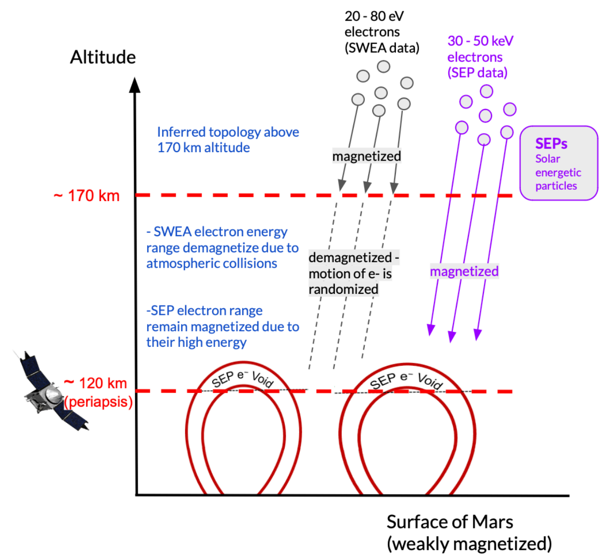

Figure 4: Comparison of SEP/SWEA data Magnetic connectivity has already been inferred using SWEA data for electrons ranging from 20eV to 80 eV. Electrons within this energy range demagnetize past 170 km altitudes due to atmospheric collisions. The data coming in from the SEP instrument records a much higher energy range for both the electrons and the ions. Due to the high energy of SEPs, electrons remain bound to the magnetic field lines up until MAVENs periapsis at ~120km. Thus, SEP electron flux measurements can infer magnetic topology for weak magnetic regions with higher accuracy than SWEA data.

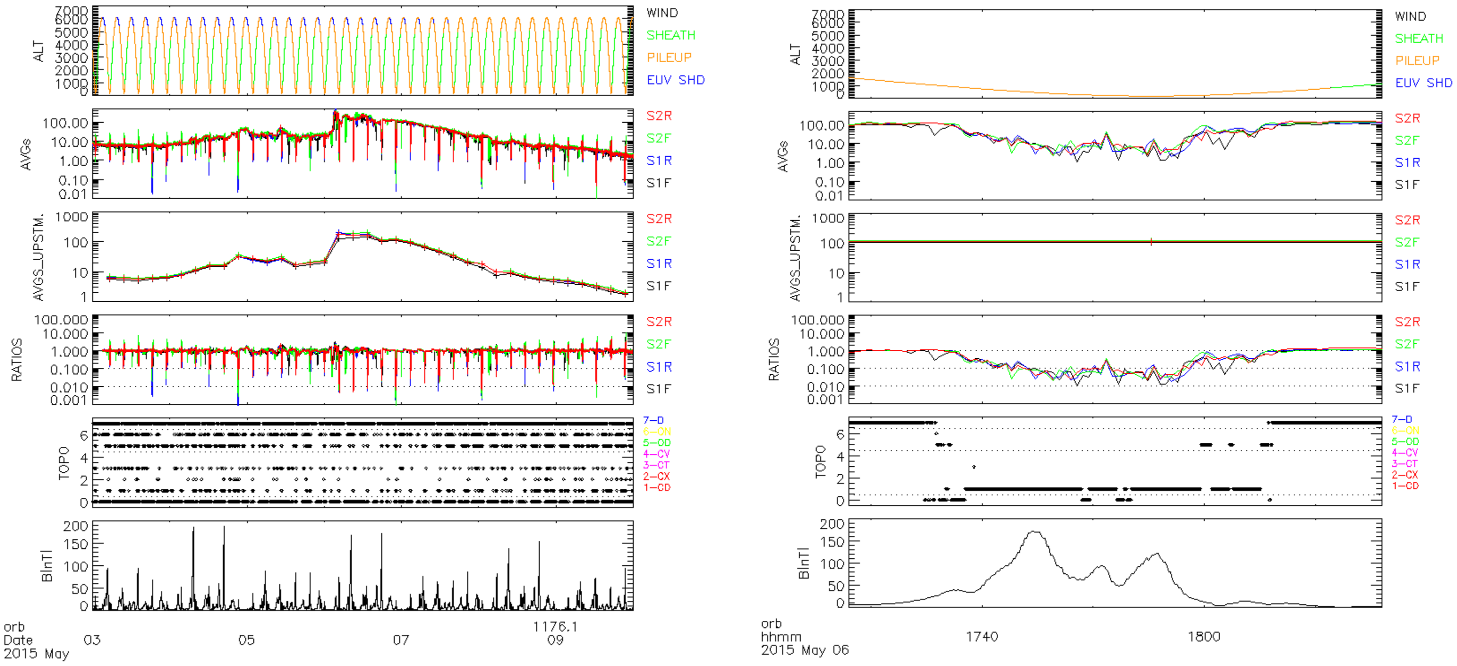

Figure 5. May 2015 solar event and close up of 1 orbit with heavy solar activity. Fig 5a. (left) Data example from the SEP/SWEA instruments ranging from 05/03/2015 - 05/10/15, which is a period of heavy solar activity. The first panel shows the location of the MAVEN spacecraft altitude for reference. The four look directions of the two SEP sensors are distinguished based on color for panels 2-4 and are labeled on the graph. The second panel displays the average electron flux, with an energy range of 30-50 keV. The third panel displays the average flux of 'upstream' electrons, or electron flux for an altitude greater than 1000 km. The upstream average was computed for each orbit. The fourth panel is the computed ratios of avg(30-50keV) to upstream average. The fifth panel refers to SWEA data and tells us the topology at the location of the MAVEN spacecraft. The final panel displays the magnitude of Mars' crustal magnetic field at ~ 400 km altitude. Fig 5b. (right) Zoomed in at periapsis on May 6th 2015, from ~5:30 pm till ~6:30pm during heavy SEP precipitation to observe all the features carefully.

bound to their carrier magnetic field lines. Due to this randomization, SWEA electrons below the altitude of 170 km cannot be used to infer topology.[14] The closed topology loops in the northern lowlands and regions of weak magnetism do not extend to high altitudes due to their low magnetic strength, making them primarily present in proximity to the Martian surface.[10] While magnetic field connectivity recorded by SWEA at an altitude below 170 km from the surface could be of planetary origin, it may also be due to an effect of magnetic field lines carried by the solar wind. This uncertainty motivates the observation of higher energy electrons that would remain magnetized for much lower altitudes and be more precise in inferring magnetic topology below 170 km. SEP sensors record and measure particles with a higher energy range enabling identification of regions with magnetic connectivity below an altitude of 170 km, which can be then characterized as crustal magnetic regions. Therefore, SEP electrons that remain magnetized for lower altitudes are more effective at reading topology for weaker crustal magnetic fields.

During periods of intense solar activity, SEPs traveling on the field lines of the incoming solar wind populate the martian atmosphere and interact with its ionosphere. By examining the electron flux of SEPs along the MAVEN trajectory, it is possible to detect areas with a significantly lower abundance of electrons than expected. This indicates the existence of an electron void and enables traceability of magnetic topology at lower altitudes. To determine electron voids for this study, a numerical threshold was computed for the expected electron flux depletion levels, and SEP measurements with a lower depletion level than the defined threshold are considered as SEP electron voids. These regions, exhibiting considerable reductions in high-energy electron fluxes directly correspond to the closed topology of Mars and are identified as sources of crustal magnetism.

The approach to establish a numerical threshold delineating the existence of Solar Energetic Particle (SEP) electron voids initiates with the computation of the average ratio of the local (surrounding) to upstream (originating from solar wind) SEP electron flux across closed topologies for previously ascertained moderate or strong crustal fields. This process was instigated for a phase of pronounced solar activity, from May 3rd, 2015 to May 10th, 2015. To determine the ratio of the local to upstream flux, an initial average calculation for the electron flux confined within an energy range of 30keV to 50keV was executed for all timestamps of the solar event (Figure 5a, panel 2). An equivalent average computation was performed for the incoming upstream SEP electron flux and the value was assigned to all timestamps of a given orbit, i.e. there was only one value for an upstream electron flux average per orbit (Figure 5a, panel 3). For the purpose of this study, upstream was defined as the electron flux recorded when the spacecraft exceeded an altitude of 1000 kilometers. This constraint ensured that the SEP flux measurements used to calculate the average upstream electron flux were a true reflection of the SEPs that were being carried by the incoming solar wind and precipitating the Martian magnetosphere. As a result, there were two electron flux averages, one for the local SEP electron flux and one for the

upstream SEP electron flux per orbit. From these values, a ratio of local to upstream SEP electron flux was determined (Figure 5a, panel 4). These calculations were repeated for all four FOVs of the SEP instrument and graphed over the duration of the solar event (figure 5a). Subsequently, the SEP electron flux ratio distributions across moderate/strong closed fields (previously identified by the SWEA data) were presented using a histogram and analyzed statistically (figure 6). Medians of these distributions were determined for each of the four FOVs. The culminating value, a computation of the median of the ratio distribution, is defined as the numerical threshold for an SEP electron void. In essence, we define the typical SEP electron flux depletion level (the threshold) over unambiguous closed topologies through a statistical analysis. This threshold is then employed to probe for SEP electron voids, thus inferring closed topologies across all regions of Mars, including those with weak magnetization. By detecting such voids we gain an insight into how these fields affect particle motion

Results

behavior within the Martian magnetosphere.

This detailed methodology was utilized to define solar energetic particle (SEP) electron voids across all four fields of view (FOVs) of the two SEP sensors. This threshold was specifically determined for a solar event spanning from May 3rd, 2015 to May 10th, 2015. Figures 5a and 5b serve as examples of typical data captured by the SEP/SWEA instruments during a solar event characterized by precipitating SEPs that have traveled along solar wind magnetic field lines prior to reaching Mars. Figure 5a presents relevant data from both instruments throughout the entire solar event, while Figure 5b focuses on a single periapsis of the MAVEN spacecraft's orbit during a period of intense precipitating SEPs on May 6th, approximately from 5:30 pm to 6:30 pm. The initial panel of both figures provides the relative position of the spacecraft with respect to the Martian surface.

In Figure 5a, the second panel depicts the local average flux, which begins on May 3rd

with low electron flux values, averaging around 10 keV cm-2s-1sr-1 keV-1, across all four FOVs of the SEP instrument. This low flux level indicates a relatively quiet solar period. Subsequently, an increase in SEP flux is observed on May 6th in both the second and third panels, signifying the arrival of Interplanetary Coronal Mass Ejections (ICMEs) on Mars. The SEP sensors record high counts of SEPs being carried by the solar wind on this date, evident by the upsurge of the average upstream flux displayed in the third panel. A gradual decay in SEP flux is observed as the ICMEs traverse the Martian magnetosphere, eventually returning the SEP electron flux values to conditions resembling a quiet solar period, as indicated by an average of 10 keV cm-2s-1sr-1 keV-1in the second panel. The fourth panel presents the ratio of the local electron flux to the upstream electron flux. Details for the computations in the second, third, and fourth panels of figure 5 can be found in the preceding section.

The primary identification of an SEP electron void occurs when there is a sharp decline in the flux of high-energy electrons compared to the surrounding plasma environment. These dips are detected as the spacecraft passes through closed magnetic loops while approaching periapsis, which will be discussed later. Panel 5 presents supporting data from the SWEA instrument, revealing the magnetic topology at the spacecraft's location at an altitude of approximately 250 km. In the fifth panel, denoted as "TOPO," closed magnetic topology is depicted through marked labels ranging from 1 to 4. This provides information on topology analyzed using data from SWEA and reaffirms sources of crustal magnetism identified using SEP electron voids. Lastly, the final panel in the figure presents data from the crustal field model and provides information about the crustal magnetic field strength of Mars measured in nanotesla (nT) at an altitude of approximately 400 km as the spacecraft moves along its orbit.16 Higher values observed for the field strength in the vicinity of MAVEN's periapsis are indicative of regions of crustal magnetism.

Figure 5b replicates all the panels of Figure 5a but focuses specifically on a periapsis of one MAVEN orbit during the evening of May 6th. The zoomed-in view allows for a more detailed observation of the average electron flux depletion levels across all four FOVs. In the second panel, occurring roughly from 5:40 pm to 6:10 pm, a 30-minute period as MAVEN is in close proximity to the Martian surface. In the fourth panel, the ratio of local to upstream flux averages around 0.1 for all FOVs, indicating that the SEP electron flux depletion level is approximately 10% of the surrounding environment. This suggests that an SEP electron void is recorded when the ratio of local SEP electron flux to incoming upstream SEP electron flux drops below 10% of the surrounding plasma environment, signifying closed topology. The SWEA data in the fifth panel confirms this observation, with flux dips from the fourth panel aligning with closed topology markings (1-CD). This indicates that MAVEN is passing through regions of crustal magnetism or magnetic field lines connected to Mars on both ends. However, Figure 5b displays the key results and its elements for only one orbit of a week-long solar event and is therefore only an exemplary case for this study. Hence, it is vital to consider data accumulated for all orbits of the solar event and for all 4 FOVs of the SEP sensors in order to gain a more complete interpretation of the features and trends observed in Figure 5.

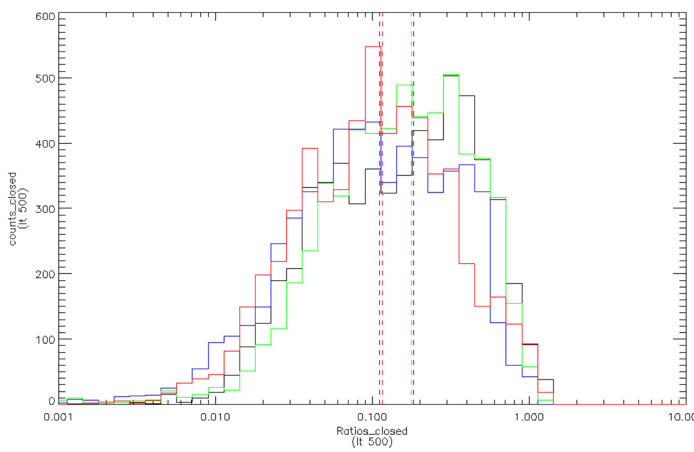

Figure 6: Results: Threshold to define SEP electron voids for each field of view. The given histogram is a graphical representation of the results discussed. These are the ratio distribution for closed crustal fields, given by the SWEA data over moderate to strong crustal magnetic fields. The median of the SEP electron flux ratio distribution is defined as the SEP electron void threshold for that direction.
Black: SEP1F, Blue: SEP1R,
Green: SEP2F, Red: SEP2R

A statistical analysis was performed to account for the data of the entire period discussed and to provide numerical limits that define an SEP electron void for all FOVs considered. These voids, which represent magnetospheric features, are identified by utilizing the medians of the electron flux ratio distribution over closed topology regions identified by SWEA below an altitude of approximately 500 km. This altitude range is fundamental to the study as crustal magnetospheres for weakly magnetized areas are typically found below this limit. The outcomes of this analysis are visually depicted in Figure 6, which presents a histogram displaying local to upstream flux ratio distribution over SWEA identified closed fields plotted on a logarithmic x-axis. This graphical representation of the combined SEP/SWEA data facilitates the estimation of medians and provides an approximation of the location of these SEP electron voids as these features are recorded whenever the ratio of the local to upstream flux of the 4 FOVs drop below it's computed median values.

The peaks of the histogram for each FOV can be estimated to be the medians that define the limit for an SEP electron void to be around 0.1 to 0.2. This is representative of the most common flux depletion levels observed across all FOVs. For each FOV, namely SEP1F (black), SEP1R (blue), SEP2F (green), and SEP2R (red); numerical limits are individually calculated and marked using vertical dashed lines at 0.18, 0.11, 0.18, and 0.12, respectively. These results reveal that both forward-facing SEP sensors have values very close to each other and the same holds true for the reverse-facing SEP sensors. Further investigation is needed to explain these similarities, i.e. the correlation between the sensor's FOV and the median used to define a SEP electron void. When converted to percentages, these median values indicate that the threshold for classifying a SEP electron void corresponds to around 10% to 20% of the surrounding SEP electron population. Therefore, whenever the ratio of local to upstream electron flux falls below the established threshold, it is indicative of a region exhibiting closed topology. These findings convey that regions of closed topology loops and occurrence of SEP electron voids are both present due to magnetized crust, highlighting the significance of understanding incoming SEPs behavior, its interaction with the Martian magnetosphere, and its role in inferring the magnetic topology of Mars.

Discussion

Identification and characterization of SEP electron voids provide insights into the presence of closed magnetic fields over weakly magnetized regions on Mars. The results reveal that the threshold for categorizing an SEP electron void corresponds to a dip in the recorded ratio of local to upstream electron flux by approximately 10% to 20% of the surrounding SEP electron population. In other words, a drop in the ratio of local to upstream electron flux below this threshold indicates the presence of a region characterized by closed topology. In the third and fifth panel of Figure 5, it is evident that flux depletions observed by the SEP sensors as the spacecraft travels through its periapsis directly coincide with closed topology identified by the SWEA instrument. This validates that the methodology used in this study to infer magnetic topology is robust and can therefore be effective in locating sources of weak crustal fields on Mars.

Understanding the motivation and implications of this study is crucial for ongoing research on the evolution of Mars. Weakly magnetized regions on the Martian surface are of interest due to previous mission findings that raise questions about the formation of the current state of the planet. These regions consists of impact basins such as Hellas and Argyre, which exhibit very weak magnetic fields compared to the surrounding terrain due to thermal and shock demagnetization caused by asteroid impacts.[4] Further relevant findings include discovery of Quasi-Circular Depressions (QCDs), which are features observed in high-resolution topography datasets and are indicators of buried impact craters beneath a thin, recently formed crustal layer.[5] The presence of QCDs implies that the crust associated with the northern lowlands of Mars might be much older than what the surface appearance suggests.[5] Another puzzling magnetic arrangement is observed in the southern highlands in form of magnetic stripes centered near 180° longitude and displaying coherence over thousands of kilometers on the surface.[2] Southern highlands with heavy crater density are associated with being the older terrain of the planet compared to the northern lowlands with low crater density. The separation between the two hemispheres and their contrasting geographical features is bound by the crustal dichotomy.[6] These discoveries need further examination to answer questions about the processes that lead to the formation of these sites with such complex magnetic patterns.

Advancements have been made in investigating the Martian crustal dichotomy, such as studying magnetic signatures of impact basins, utilizing QCDs to explore deeper buried layers, and analyzing crater density to infer chronological information about the planet's surface. However, the origin of the crustal dichotomy still remains a mysterious yet fundamental aspect of studying the history of the Martian crust and the causes that have led to its current state. Identifying and examining crustal fields in weakly magnetized regions can be challenging during periods of Coronal Mass Ejections, as these weak fields can get overwhelmed and shadowed by the strong magnetic fields that are carried by the solar wind. Magnetic fields at Mars have been mainly measured hundreds of kilometers above the surface so far, which provides a limited understanding of crustal magnetism on Mars. In contrast, it is largely unknown whether regions with low measured magnetic fields are magnetized at the surface or not, and if so, then to what degree .[6]This is one of the primary questions this study aims to answer.

Furthermore, it is critical to think about future projects that can deepen our understanding of the martian crust and that are derived from the results of this study. A new method for quantitatively identifying crustal magnetic fields for regions of only a few nT of field strength has been established. The findings of this study reveal notable similarities between the values of the forward-facing SEP sensors and likewise for the reverse-facing SEP sensors. This outcome raises questions regarding the correlation between the sensor's field of view (FOV) and the median employed to define an SEP electron void. Further investigation is required to elucidate the reasons behind these similarities and understand the potential relationship between the FOV of the sensors and the threshold used for identifying SEP electron voids. Moreover, this study pertains to the magnetic topology inference on Mars's surface during a specific solar event that occurred in early May 2015. To generalize the results to the entire duration of MAVEN's orbit, further investigations are warranted which encompass the examination of other solar events that transpired within the MAVEN mission timeframe. Same methodology discussed earlier shall be employed to probe out locations of SEP electron voids on the surface of Mars and therefore precisely identify regions of weak crustal magnetic sources.

In conclusion, this study has showcased the efficacy of utilizing SEP electron flux measurements to infer magnetic field line connectivity in regions of weak crustal magnetism. Moving forward, the application of MAVEN/SEP orbital observations, coupled with the methodology outlined in this study, holds great potential for advancing our comprehension of the intricacies within Mars' magnetosphere and exploring the mysteries of the crustal dichotomy. This includes delving deeper into the presence of localized closed loop crustal fields that give rise to "miniature" magnetospheres, as well as investigating the interactions between Mars' ionosphere and the incoming solar wind. The findings of this study provide a catalyst for future explorations delving into the dynamics of Mars' magnetic environment, the interplay between the incoming solar wind and the Martian magnetosphere, and their profound influence on the evolutionary processes governing the planet's crust.

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