Asymmetry of the Mars Ionosphere Boundary Height During a Solar Energetic Particle Event

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ABSTRACT

The Electron Spectrometer (ELS) and the Ion Mass Spectrometer (IMA) from the Analyzer of Space Plasmas and Energetic Atoms (ASPERA-3) experiment on the ESA Mars Express (MEx) spacecraft have been used to study a Solar Energetic Particle event (SEP), associated with a Class X solar flare on January 27, 2012. Arrival of the SEP at Mars about 46 minutes later is observed as an increase in the background of the ASPERA-3 plasma instruments. The background counts were observed to increase sharply, followed by a gradual decrease that lasted for about 4 days. During this time, ELS and IMA also recorded passages across the Martian ionosphere-magnetosphere boundary on the dusk side of the planet, twice during each MEx orbit. The height of the ionospheric boundary was thereby found to have behaved differently in the northern and southern hemispheres. The boundary increased in height in each hemisphere with a time delay as the flare pumped energy into the Mars system. After reaching peak height, the ionospheric boundary returned to its original configuration faster in the northern than in the southern hemisphere. This suggests that the main difference between the northern and southern hemispheres at Mars, namely the presence in the south of crustal magnetic fields, is responsible for the dissipation of the energy input at a slower rate in the southern than in the northern hemisphere.

INTRODUCTION

At 1815:30 UT on 27 January 2012, the Extreme Ultraviolet Imager (EUVI) on the NASA Solar Terrestrial Relations Observatory-A (STEREO-A) detected a solar flare erupting from the Sun at N27°, W71° near the sunspot region 1402. This flare was classified by the Geostationary Operational Environmental Satellite (GOES) solar X-ray sensor (XRS) as class X1.7. Along with this optical flare, solar UV, X-rays, a Solar Energetic Particle event (SEP) and a Coronal Mass Ejection (CME) were released.

Data from the Analyzer of Space Plasmas and Energetic Atoms (ASPERA-3) experiment on the ESA Mars Express (MEx) spacecraft were used to examine the impact of these events at Mars. Frahm *et al.* [2013a] examined ASPERA-3 electron and ion data during the event. They found that there was no penetrating radiation signal in the instruments and no change from normal in the Mars plasma environment between the time of the flare onset and the arrival of the gradual SEP at Mars. During this interval there was direct input from flare UV and X-rays. Using instrument background values as a proxy for the SEP flux, Frahm *et al.* found that the SEP arrived starting about 1855 UT on January 27, 2012 at Mars.

Days after the SEP peak flux, the CME arrived. Frahm *et al.* [2013b] examined the CME at three times when MEx was in the solar wind and magnetosheath of Mars. The measurements were taken from consecutive spacecraft orbits before and after arrival of the CME. By examination of spectra and modeling sector differences with a flowing Maxwellian electron distribution, they found that electron flow in the solar wind occurred during and after the CME arrived at Mars. Detection of this flow corresponded with a reduction in solar wind electron density by about half. In the magnetosheath of Mars, the electron density increased by a factor of 10 during the CME over its value before arrival of the CME.

In this investigation, we examine the effect of the ionosphere/magnetosphere boundary during the encounter of the SEP at Mars. A CME from the 23 January 2012 events encountered Mars a day before the January 27 flare was recorded. The electron magnetosheath flux indicates that Mars may not have totally recovered from the January 23 events before the January 27 events occurred. Boundary results for the bow shock are also presented. The indications of reaction of the bow shock location during the SEP are not as well defined as those for the ionosphere/magnetosphere boundary.

INSTRUMENTATION

The ASPERA-3 experiment on board MEx consists of an electron (ELS), ion (IMA), and two neutral atom (NPI and NPD) instruments [Barabash *et al.*, 2004; 2006]. This study uses data from the electron and ion instruments. The electron instrument is a spherical top hat measuring electrons in the energy range from 1 eV to 20 keV every 4 sec. Measurements are made in 16 sectors (each 22.5° in azimuth) for a total azimuth coverage of 360° and having an elevation of ±2°. The ion instrument contains an elevation analyzer to accept ions within ±45° in 16 polar angle steps (each 5.6° in elevation), a 360° azimuthal top hat (16 azimuthal sectors) to energy analyze ions linearly below 50 eV (through 0 eV) and logrithmically above 50 eV from a maximum energy of 32 keV in a total of 96 energy steps, and an orange-style momentum analyzer for sorting mass less than 40 amu. The IMA instrument measures its full energy-elevation-azimuth-mass matrix in 192 sec.

Background counts within ELS and IMA are mainly caused by penetrating radiation and are energy independent. Background values are generated by a summation of all counts at energies above 10 keV to avoid contamination by the environmental signal. Sector and instrument background count rates are formed at (1) the energy sweep time resolution of the instrument, (2) averaged over 1 minute, (3) averaged over 5 minutes, and (4) averaged over 25 minutes to form products of adequate statistical resolution. Protons above 1 MeV cause penetrating radiation within the ELS and IMA as these protons are able to pass through the aluminum shells of the instruments. This penetrating radiation signal is taken as a proxy of the SEP flux.

SEP AT MARS

ELS and IMA recorded the arrival of the SEP at Mars. The electron and ion energy flux spectrograms from ASPERA-3 are shown in Figure 1 along with instrument backgrounds. Figure 1 begins on the day before the flare (January 26) and continues through completion of CME flux detection (February 3). Spectral data are displayed in time pixels where each contains an average of the data which are represented by that pixel. This procedure emphasizes the locations where the majority of fluxes lie. For the electron spectrogram, fluxes in the Martian magnetosheath dominate the average; whereas, for the ion spectrogram, both the fluxes in the solar wind at high energy and low energy fluxes in the ionosphere dominate the average.

Figure 1 shows a difference in the background count rates from ELS and IMA determined from the SEP penetrating radiation component. The count rates are actually similar when MCP area is taken into account. The differences in total background count are caused by the larger collection area of IMA when compared to ELS.

The IMA telemetry buffers overflow (adjustable) during the peak flux of the SEP, causing the observed telemetry drop outs. In order to maintain continuous measure of the background count rates throughout the SEP bombardment, the electron background count rate was used as the appropriate comparison proxy.

Figure 1 indicates that there was a sharp rise in the background count rates beginning about 1855 UT on 27 January which reached a peak about 100 times above ambient approximately 8 hours later, and then decayed back to ambient over the next 4 days. The background levels have almost returned to their baseline level before arrival of the 27 January CME. The long decay of the SEP signature helps to separate the response of Mars due to the SEP from the response due to the CME.

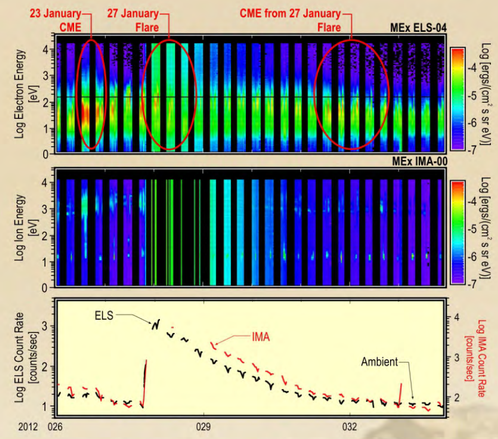

Figure 1. The Martian response to the January 27, 2012 Solar Storm. An 8 day presentation of the electron energy flux spectrogram from ELS-04 is shown on the top panel, the ion energy flux spectrogram from IMA-00 in the center panel, and the background count rates for both instruments are shown in the bottom panel [from Frahm et al., 2013a].

HEIGHT OF THE IONOSPHERE

The ionosphere/magnetosheath boundary is taken as the Induced Magnetospheric Boundary (IMB), i. e., the envelope of the induced Martian magnetosphere [Lundin *et al.*, 2004]. This boundary was observed to change in height during the SEP. Both IMA and ELS data were used to identify the position of the IMB and its locations as a function of time are shown in Figure 2. MEx was almost in the dawn-dusk plane at the time of this event. Positions where the IMB was encountered are marked with symbols and colored lines are drawn between measured values as a visual aid. Boundary locations were determined each time it is encountered, which was normally twice per orbit. Figure 2 covers 7 days, there being about three orbits of MEx per day. Locations of the 23 and 27 January CMEs are indicated at the top of the figure.

Due to the nature of the MEx orbit (periapsis is about 290 km) the IMB is encountered on the planet's dusk side during this period. The center panel of Figure 2 shows that the IMB was first encountered on its inbound trajectory at southern latitudes (green) and then the outbound IMB (red) was observed at northern latitudes. The bottom panel of Figure 2 shows the longitude of encounter for both the inbound and outbound detection of the IMB. The shaded region shows the area where the magnetic anomalies are strongest in the south.

The top panel of Figure 2 shows the heights at which the IMB was encountered. Overlaid in black is the 25 minute ELS background count rate. Gaps between the background segments are caused by the instrument duty cycle. Variations in the background observed over the course of an orbit value are due to differences in penetration depth at the spacecraft as the spacecraft transitions from the solar wind to periapsis at low altitude (290 km) and back into the solar wind.

Measurements made before the arrival of the SEP aid in estimating a base height of the IMB. Frahm *et al.* [2013a] found that the SEP arrived at Mars about 1855 UT on January 27. Figure 2 indicates that the peak background count rate (and SEP flux) occurred roughly about 8 hours later or less. During the time of increasing SEP flux, the height of the IMB in the southern hemisphere began to increase, while in the north, the height remained at about the same level.

After reaching peak flux, the flux of the SEP began to decrease. This decrease was approximately power law in shape and took about 4 days to reach the background baseline count rate. Thus, for 4 days, the SEP pumped energy into the atmosphere of Mars.

About 8 hours after the SEP reached the maximum flux, the IMB height in the northern hemisphere began to increase. About 16 hours after the SEP peak flux was reached, the IMB reached its maximum height in both the north and south, with the IMB in the southern hemisphere reaching a greater height than in the north. The CME arrived at Mars about 1000 UT on January 31, 2012.

After reaching peak height, the IMB in the northern hemisphere sharply decreased and returned quickly to the base height level. However, in the southern hemisphere, there was a gradual reduction in the IMB height, which did not return to the initial height until the CME passes and the SEP ceased adding energy into the Mars atmosphere. It is uncertain if the height of the IMB is affected by the January 27 CME in the southern hemisphere; however, no height signal of the January 27 CME is observed in the northern hemisphere.

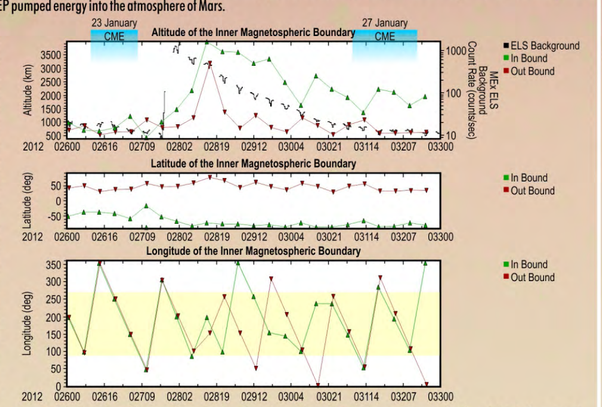

Figure 2. Time Location of the Inner Magnetosphere Boundary. Inbound data is shown in green and outbound data is shown in red, marked against the axis on the left. The height of the IMB overlaid with the ELS background (black) count rate (right axis) are shown in the top panel. The latitude of the IMB is shown in the center panel and the longitude of the IMB is shown in the bottom panel. The shaded region in the bottom panel represents the longitudes at which the southern hemisphere magnetic anomalies are the strongest. CME intervals are shown at the top panel.

HEIGHT OF THE BOW SHOCK

Observations of the bow shock were made on the dawn side of Mars. Figure 3 shows the bow shock measurements in the same format as Figure 2. There are a few times when ASPERA-3 ceased operation before encountering the bow shock. For these times, no boundary location could be determined.

The center panel of Figure 3 also shows that the bow shock was first encountered on its inbound trajectory at southern latitudes (green) and then the outbound bow shock was observed at northern latitudes (red). The bottom panel of Figure 3 shows the longitude of encounter for both the inbound and outbound detection of the bow shock. The shaded region shows the area where the magnetic anomalies are strongest in the south.

The top panel of Figure 3 shows the height at which the bow shock is encountered. Overlaid in black are the ELS background count rate values.

Here it is observed that the height of the bow shock was not as steady and was more variable than the IMB. Before arrival of the SEP, the bow shock could still be responding to the January 23 CME. The response due to the SEP is not easily identifiable in the bow shock; however, there appears to be an organized peak in the boundary about two days after the peak SEP flux.

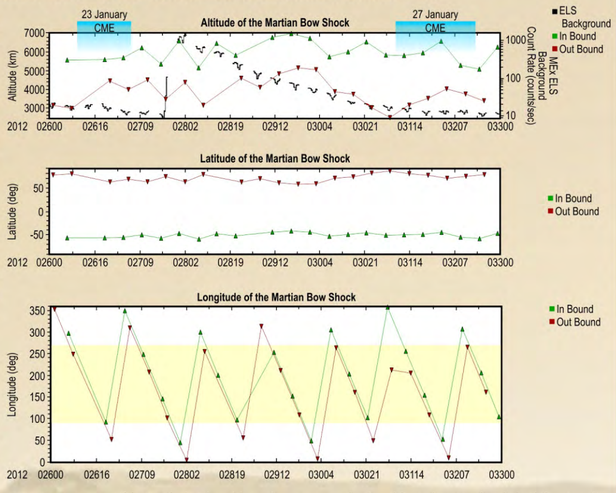

Figure 3. Time Location of the Bow Shock. Inbound data is shown in green and outbound data is shown in red marked with the axis on the left. The height on the bow shock overlaid with the ELS background (black) count rate (right axis) are shown in the top panel. The latitude of the bow shock is shown in the center panel and the longitude of the bow shock is shown in the bottom panel. The southern magnetic anomaly region is shaded in the bottom panel. CME intervals are shown at the top panel.

HEIGHT OF THE BOW SHOCK (cont.)

The CME from the 27 January solar storm encounters Mars just after this signal and also changes the height of the bow shock. This organized peak observed during the SEP (~ 1200 UT between January 29 and 30) may represent inflation of the magnetosheath to account for the increased IMB height, a density increase in the magnetosheath, or ionospheric currents balancing a decreasing solar wind pressure from the vanishing component due to the SEP.

HEIGHT IN NORTHERN AND SOUTHERN HEMISPHERE

Figure 4 shows a composite of the top panels of Figures 2 and 3. Before the arrival of the SEP, the bow shock was located at greater height in the south that in the north. This was maintained throughout the encounter with the SEP. It is observed that the bow shock variability becomes more organized and reaches a peak in both hemispheres between 1 and 2 days after the IMB reaches its peak height. At the peak height of the IMB in the southern hemisphere, the southern IMB was approximately at the same height as the bow shock in the northern hemisphere; however, the exact height of the northern hemisphere bow shock was not determined because ASPERA-3 operation ceased before a measurement of the bow shock was made.

The SEP contains protons of higher energy than are observed in the CME. The SEPs cause heating deeper within the atmosphere where it deposits energy, influencing atmospheric chemistry. Heating occurs from within the atmosphere and the effect travels to greater heights, first effecting the IMB . On the other hand, the CME contains lower energy plasma and causes heating from above, which penetrates down to the atmosphere. The CME influence is first observed at the bow shock.

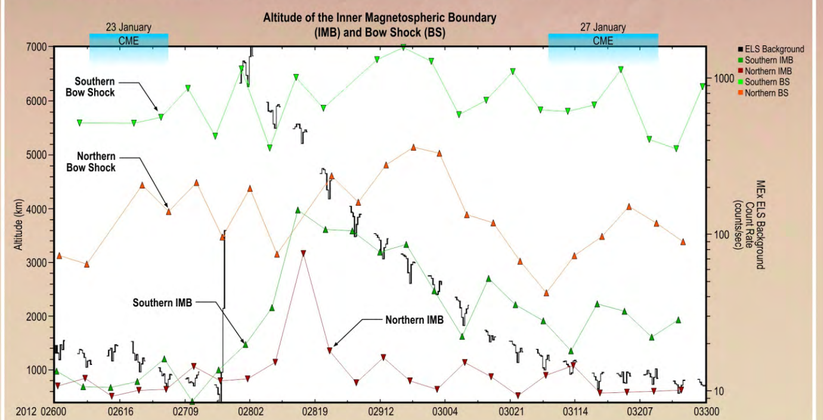

Figure 4. Comparison of the IMB and Bow Shock heights from Northern and Southern Hemispheres During the SEP. The top panels of Figures 2 and 3 are placed on a common height scale. Data from the southern hemisphere is shown in green and northern in red. CME intervals are shown at the top panel.

CONCLUSION

Both ELS and IMA observe the Martian response to the January 27, 2012 solar storm and determine the SEP flux through their background proxies. During the SEP, the height of the ionosphere/magnetosheath increased by factors of 3 to 4, reaching a peak about 16 hours after the SEP flux peak. The time profile of the height in the northern hemisphere showed a sharp rise from and quick decay to the nominal level. In the southern hemisphere, the quick rise was similar; however, there was a gradual reduction in the boundary height which had not returned to its ambient level before CME arrival. This suggests that the main avenue for plasma escape is through the northern hemisphere where there is not sufficient magnetic field to trap and hold on to the extra ionization created in the lower atmosphere by energy dumping by the SEP. The crustal magnetic field in the southern hemisphere is strong enough to trap and hold the ionospheric plasma to a larger extent than in the north.

There is an insufficient signal-to-noise ratio to make an absolute determination of the bow shock height due to the SEP; however, if there is actually a signal caused by the SEP, its height increase occurs 1 to 2 days after the SEP reached peak flux. It was shown that the CME impact influenced the height of the bow shock in the north and south; however, the CME had no effect on the IMB in the north.

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