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Mars Express and Venus Express multi-point observations of geoeffective solar flare events in December 2006

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Abstract

In December 2006, a single active region produced a series of proton solar flares, with X-ray class up to the X9.0 level, starting on 5 December 2006 at 10:35 UT. A feature of this X9.0 flare is that associated MeV particles were observed at Venus and Mars by Venus Express (VEX) and Mars Express (MEX), which were ~80° and ~125° east of the flare site, respectively, in addition to the Earth, which was ~79° west of the flare site. On December 5, 2006, the plasma instruments ASPERA-3 and ASPERA-4 on board MEX and VEX detected a large enhancement in their respective background count levels. This is a typical signature of solar energetic particle (SEP) events, i.e., intensive MeV particle fluxes. The timings of these enhancements were consistent with the estimated field-aligned travel time of particles associated with the X9.0 flare that followed the Parker spiral to reach Venus and Mars. Coronal mass ejection (CME)

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signatures that might be related to the proton flare were twice identified at Venus within <43 and <67 h after the flare. Although these CMEs did not necessarily originate from the X9.0 flare on December 5, 2006, they most likely originated from the same active region because these characteristics are very similar to flare-associated CMEs observed on the Earth. These observations indicate that CME and flare activities on the invisible side of the Sun may affect terrestrial space weather as a result of traveling more than 90° in both azimuthal directions in the heliosphere. We would also like to emphasize that during the SEP activity, MEX data indicate an approximately one-order of magnitude enhancement in the heavy ion outflow flux from the Martian atmosphere. This is the first observation of the increase of escaping ion flux from Martian atmosphere during an intensive SEP event. This suggests that the solar EUV flux levels significantly affect the atmospheric loss from unmagnetized planets.

Keywords: Solar flare; Space weather; Ion escape; Mars; Venus; SEP

1. Introduction

Solar flares are violent eruptions seen in the solar atmosphere. Especially strong events, called X-class flares, influence the Earth and human activities. They are associated with the generation of high-energy particles, which can potentially cause satellite malfunctions, and with the ejection of hot plasma clouds called coronal mass ejections (CMEs) giving rise to magnetic storms. Severe magnetic storms can cause energization of radiation belt particles. Further, strong aurora activities can be triggered, which stimulates increased charging and strong currents in the terrestrial ionosphere, potentially causing problems with regard to telecommunications and, in the worst case, black-outs of the power grids. While large solar flare events have been investigated over several decades (e.g. Reames et al., 1999; Woods et al., 2003; Tsurutani et al., 2005; Thuillier et al., 2005), it is worthwhile to report on the characteristics of recent large solar flare events.

Geoeffective X-class flares typically occur several times per year. It is known that large flare events occur more frequently around the time of solar maximum than at solar minimum. One of the most famous series of X-class flares occurred from October 28, 2003. This sequence is called the 'Halloween event', and has been investigated by many researchers. For example, Tsurutani et al. (2005) investigated the response of the terrestrial ionosphere to EUV flux by using global positioning system (GPS) data. They found that the total electron content at the subsolar ionosphere increased by 30% above the background. Similar work using an EUV sensor on TIMED satellite and an energetic particle sensor aboard FAST during another X-class flare event (April 21, 2002) was carried out by Woods et al. (2003).

The Halloween event affected not only the Earth but also Mars. Mars was around the opposition of the Earth at that time. Using Mars Global Surveyor data, several investigations were conducted. Crider et al. (2005) reported that the high-pressure solar wind compressed the Martian plasma environment. They pointed out that such a compression allows solar wind to access the lower atmosphere, which theoretically results in an increase in mass loss from the Martian atmosphere. Espley et al. (2005) found powerful coherent oscillations even in the Martian nightside during the passage of a CME. They concluded that these oscillations implied an ambient increase in ions of planetary origin.

As seen using a heliospheric wide view of solar flares and of certain associated phenomena, field-aligned MeV particle streams originating from events associated with solar energetic particles (SEPs) and CMEs are known to spread widely in the heliospheric azimuthal direction as they travel outward from the Sun (e.g. Reames (1999) and references therein). Large CMEs starting at the solar limb sometimes reach the terrestrial magnetosphere and SEPs may travel over a yet wider angle in the heliosphere. The largest CMEs and SEPs can extend more than 90° in azimuth between the solar corona and the Earth, and therefore some of the magnetospheric disturbances and proton events at the Earth can originate from CMEs/flares that take place on the back (invisible side) of the Sun. This possibility potentially demands attention for space-weather forecasting. Hence, it is important to know how far the largest CMEs and SEPs can expand in the azimuthal direction.

In December 2006, when a large active region produced a series of CMEs and proton-related solar flares close to the time of solar minimum phase of Solar Cycle 23, we could simultaneously achieve three-point plasma observations—one aboard the European Space Agency's (ESA) Mars Express (MEX) mission, one aboard ESA's Venus Express (VEX) mission, and the third aboard satellites near Earth (SOHO and GOES). MEX and VEX carry plasma sensors capable of detecting *in situ* CMEs (directly) and SEPs (indirectly).

A unique feature of the present investigation is that we can detect effects of this SEP event on atmospheric escape at three Earth-type planets simultaneously, which is important for making comparable planetary studies. For example, the ion escape from the terrestrial ionosphere is known to drastically increase in both its flux and characteristic energy during periods of high solar wind dynamic pressure (e.g. Cully et al., 2003).

While physical mechanisms of the ion outflow from unmagnetized planets such as Mars are thought to be quite different from those at the Earth due to the lack of a large magnetosphere, an SEP/CME event is thought to induce ion escape from unmagnetized planets (e.g. Lammer et al., 2003; Modolo et al., 2005; Ma and Nagy, 2007). One possible mechanism is the extra-charging of the ionosphere.

An enhanced flux of MeV ions that reach the lower atmosphere causes extra ionization of the exospheric particles there. Part of this extra-ionized population is expected to escape through ordinary escape processes. Another mechanism is that the plasma boundary (magnetic pileup boundary or ion induced boundary) is lowered by high dynamic pressure or high magnetic pressure, so as to weaken the shielding effect of ionospheric and atmospheric particles (Crider et al., 2005; Kaneda et al., in press). In order to investigate the characteristics of the escape flux and its associated mechanisms, it is important to compare the ionospheric response to the same CME/SEP event at different planets.

In December 2006, VEX (at Venus) and MEX (at Mars) were located at about $\pm 160^\circ$ away from the Earth in opposite directions in the ecliptic plane viewing from the Sun (see Fig. 1). Furthermore, both Venus and Mars were on the same magnetic field line of the ideal Parker spiral. The solar minimum conditions militate against the likelihood that CMEs and SEPs originating in two or more different active regions which would cause ambiguity in the measurements. During this ideal opportunity to pinpoint azimuthal propagation, SEP signatures associated with the large proton flare (X9.0) of 10:35 UT on December 5 were observed at Venus, the Earth, and Mars. Venus and Mars were located at 80° and 125° east of the flare site, and the Earth was located at 79° west of the flare site. The arrival times of the SEPs strongly indicated that the proton streams detected at the different planets originated from the X9.0 flare of December 5, 2006. In this paper, we report on the SEP observations made aboard VEX and MEX, and discuss influences exerted on the plasma environments of unmagnetized planets.

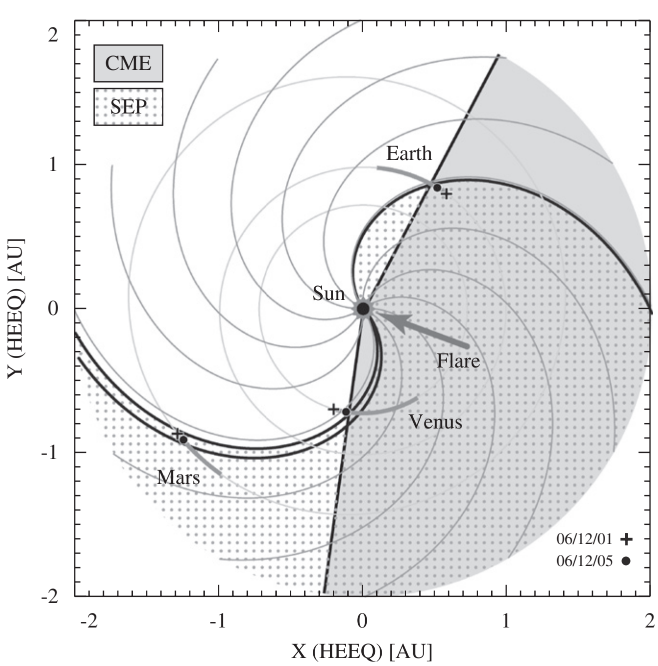

Fig. 1. The locations of Venus, the Earth and Mars relative to the Sun in December 2006. The location of the flare of December 5 is indicated by an arrow. The solid curves are the magnetic field lines of the ideal Parker spiral. Shadowed and hatched areas indicate the regime deduced to be affected by CMEs and SPEs originating in active region 930 (see text for details). These areas are deduced from available data at Earth, Venus and Mars; therefore, the affected areas are expected to be wider than those shown in the figure.

2. Instrument

The hot plasma was measured by the Analysers of Space Plasma and ENergetic Atoms (ASPERA) experiments on board MEX (ASPERA-3) and VEX (ASPERA-4), respectively. The ASPERA-3 and ASPERA-4 instruments are almost identical: hot ions (10 eV to 30 keV) are observed by the Ion Mass Analyser (IMA), and hot electrons (up to 20 keV) are measured by the ELectron Spectrometer (ELS). IMA covers $\pi \times 2\pi$ 3-D directions and ELS covers 2π 2-D directions. Detailed descriptions of ASPERA-3 and -4 are contained in Barabash et al. (2006).

Although the ASPERA experiment is not designed to detect energetic protons, both IMA and ELS are capable of detecting high-dose radiation (X-ray, gamma-ray, or MeV ions) through recording the high level of uniform background counts produced because particle radiation can penetrate through the aluminum wall of the instrument and impact on the microchannel plate (MCP). This is a well-known phenomenon in the Earth's radiation belt where such penetration can give rise to satellite malfunctions. Because of this radiation, the enhancement of background levels in ASPERA caused by high-dose radiation which is independent of both the energy steps of the instrument and the ambient plasma domain—such as the solar wind, the magnetosheath, the induced magnetosphere boundary (or magnetic pileup boundary) (Lundin et al., 2004), the photoelectron boundary (Mitchell et al., 2000) and so on.

The orbital period for VEX is ~24 h, and ASPERA-4 was operated only close to Venus. In December 2006, the observations were conducted over about 4 h (from ~05:30 to ~09:30 UT) in each orbit. This means that ~20 h data gaps existed between the observations of ASPERA-4. The orbital period for MEX was ~6 h, and the ASPERA-3 operations were limited to ~3 h close to Mars. There were ~3 h data gaps between the observations.

3. Observations: December 5, 2006 flare

A large solar flare, X9.0, occurred at the east limb (S07, E79) of the Sun as seen from the Earth at 10:35 UT on December 5, 2006 in the active region NOAA 0930. It was accompanied by a halo-type CME. This was the only X-class flare on December 5, 2006. Other X-class flares in the same region were the X6.5 flare on December 6, 2006, the X3.4/4B flare on December 13, 2006, and the X1.5 flare on December 14, 2006 (McKenna-Lawlor et al., 2007). A proton event at the Earth was observed to start at 15:55 UT on December 6, 2006, and it reached maximum at 19:30 UT on December 7, 2006, as recorded aboard GOES satellites (http://www.sec.noaa.gov/ftpdir/indices/SPE.txt).

Venus and Mars were respectively at about 80° and 125° east, while the Earth is west (W79°) relative to the flare site (see Fig. 1).

3.1. SEP events at Venus and Mars

Figs. 2 and 3 show, respectively, ion energy–time spectrograms and time series of ELS background level obtained by ASPERA-4 on board VEX and by ASPERA-3 on board MEX over a 10-day period (December 2–12, 2006). In both figures, (a) the integrated ion counts from IMA and (b) the total count rates of the highest 15 energy steps of ELS are displayed (because this energy range is normally free from real data, we can consider the total count rate in this energy range to provide a proxy for the background level). In Fig. 2, the uniform background level drastically increased during the data gap between December 5, 09:30 UT, and December 6, 05:30 UT. This high-background level continued until December 9 with peak enhancement on the morning of December 7. The same type of high-background level is seen in Fig. 3a (MEX/IMA) and in Fig. 3b (MEX/ELS) between December 5 near noon and December 8.

The background levels of both ASPERA-4 and ASPERA-3 were uniform in all energies (Figs. 2a and 3a) and in all $\pi \times 2\pi$ directions (not shown here). The uniformity of the background, its long duration (3 days), and good correspondence between the measurements at Venus and Mars suggest that the background enhancement was caused by SEPs because solar X-ray or gamma-ray bursts do not normally last for 3 days. Although we cannot identify the exact starting time of the background level increase because of the data gap, the most likely source was the X9.0 flare on December 5, 2006, perhaps supplemented by the X6.5 flare on December 6, 2006, which occurred in the same active region. We have no other possible candidate source region including on the back side of the Sun as seen from the Earth during this period thanks to the pertaining solar minimum conditions.

If this scenario is correct, the SEPs traveled from the flare site westward 79° to the Earth and eastward 80° to Venus and 125° to Mars (Fig. 1). Scaling to 1 AU, a large proton flare which takes place on the invisible side of the Sun as seen from the Earth could cause a severe SEP event at the Earth that could potentially give rise to a satellite malfunction.

From the travel times of the SEPs, we can in principle estimate the energy of the high-energy doses. Since there is too long a data gap in the case of VEX, we used only MEX data in making this estimation. The high background started before 14:00 UT on December 5, 2006, which means that the high-energy flux arrived at Mars in less than 3.5 h ($\sim 1.3 \times 10^4$ s). Assuming the flying distance to be along a straight Sun–Mars line (2.3×10^8 km), the velocity should then have been more than 2.3×10^8 km/1.3×10^4 s$\sim 1.8 \times 10^4$ km/s (1.7 MeV for protons). Since the high-energy particles concerned were positively charged, they would have traveled along the Parker spiral magnetic

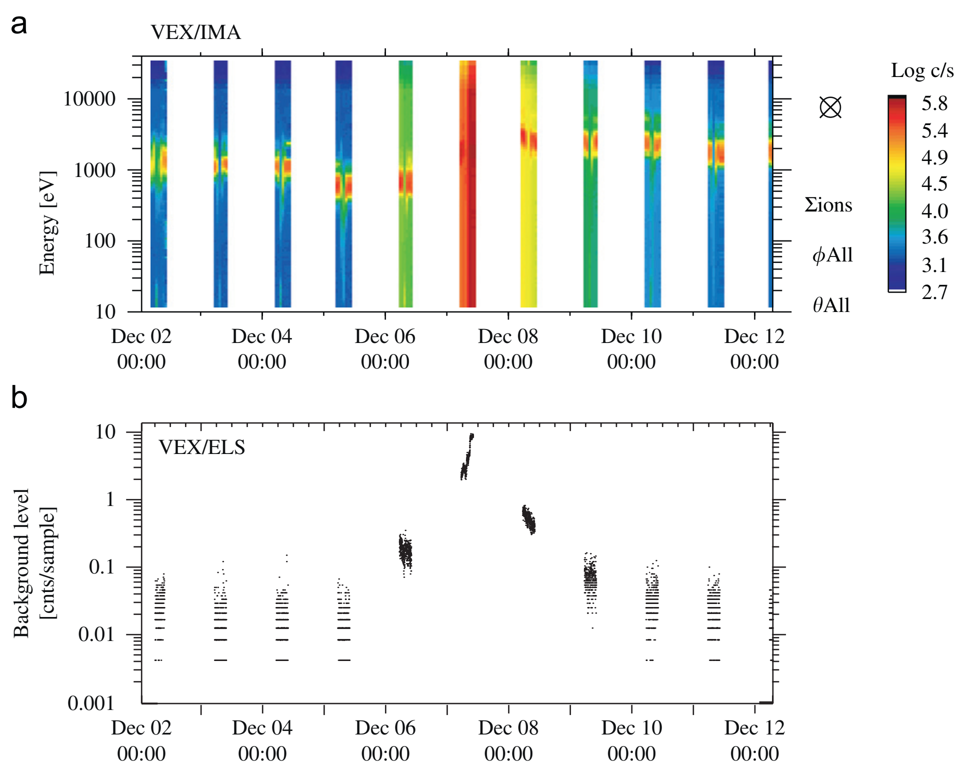

Fig. 2. (a) The observed energy–time spectrogram from ASPERA-4/IMA and (b) a total count rate in the highest 15 energy steps of ASPERA-4/ELS (a proxy for background level) on board VEX between December 2 and 12, 2006.

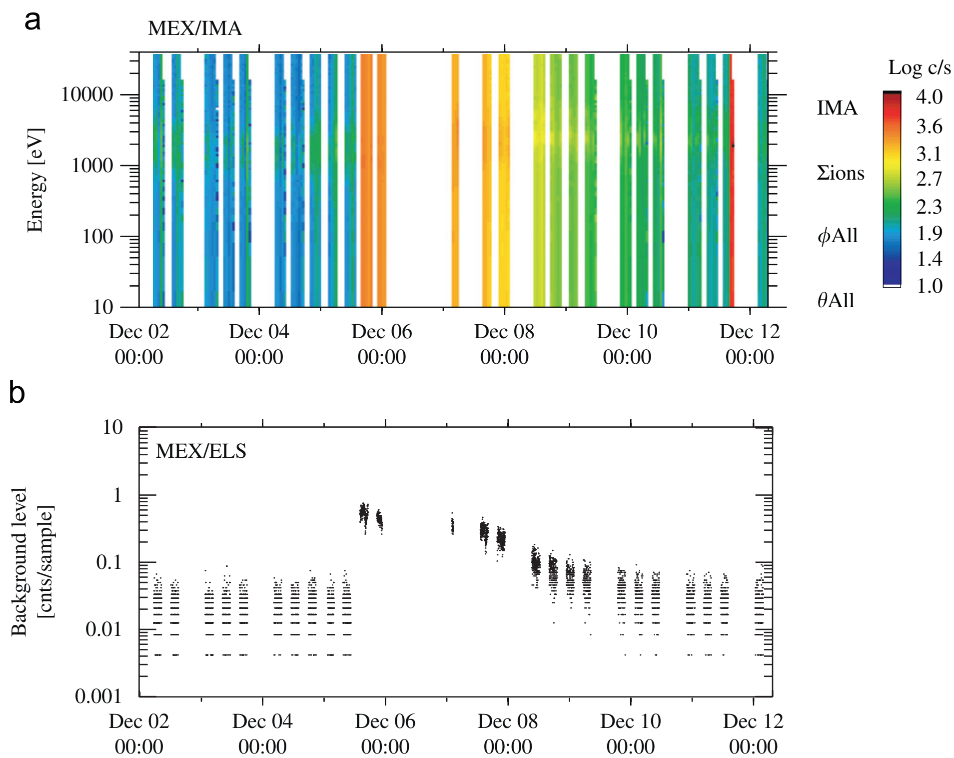

Fig. 3. (a) The energy–time spectrogram obtained from ASPERA-3/IMA and (b) a total count rate in the highest 15 energy steps of ASPERA-3/ELS (a proxy for background level) on board Mars Express between December 2 and 12, 2006.

field lines, thereby causing the trajectory to be longer. The energy should therefore correspondingly be higher.

We can compare our observations with previous investigations of this kind of wide-spreading, solar flare-related SEP events. Fig. 3.4 in Reames et al. (1999) depicts the typical longitude dependence of high-energy particle flux. Generally, when an observer located east of a flare site (location of Mars in this observation), SEPs increased quickly, and decreased monotonically. This signature can be seen in Fig. 3b. The rise time of high-energy particle flux we observed at Mars was very quick (<3.5 h). On the other hand, when an observer is located west of a flare site (the Earth in this observation), the increase in the SEPs is gradual, and extends monotonically over several days before starting to decrease. The observation at Earth (W79°) agrees well with this picture (see bottom panel of Fig. 1 by GOES 11 and Fig. 2 by SOHO EPHIN in McKenna-Lawlor et al. (2007)). It took about 3 days to reach peak proton flux at the Earth. At Venus, the signature was rather similar to the Earth. It took 2 days to reach the highest flux even though it was located in the eastern longitude (E80°). This is probably because the associated CME had a large extent in longitude covering Venus and the Earth, but it did not arrive at Mars (as discussed in Section 3.3).

3.2. *Heavy ion escape from Mars*

Fig. 4 shows the *in situ* observations of heavy ion fluxes around Mars recorded by ASPERA-3 before the SEP event on December 3 (top panel) and during the SEP event on December 7 (middle panel). The bottom panel shows the solar wind proton flux observed on December 7. In these plots, background levels, which were estimated from energy channels where no physical counts were expected, have been subtracted. During the SEP event, heavy ion counts can be clearly seen in the keV energy range (up to $\sim$3 keV). The count rate of the heavy ions exceeded 2000 counts per sample, which is approximately one order of magnitude higher than the pre-flare observations of December 3 (up to $\sim$100–200 counts/sample). Note that the count rate observed on December 3, 2006, is of the same order as the nominal escaping heavy ion count rate between April and December 2004 reported by Carlsson et al. (2006). The particle energy is also extremely high ($\sim$3 keV) compared with the typical energy of several hundred eV observed on December 3, 2006, as well as the nominal energy reported by Carlsson et al. (2006). Such an energization and enhancement of heavy ion flux during SEPs and CMEs has been reported to occur at Venus (Luhmann et al., 2007) and at the Earth (for example, Cully et al., 2003), even though in the latter case the generation mechanisms for escaping flux are completely different owing to the presence of a large magnetosphere. We, in particular, would like to emphasize that this is a first report of enhanced escape flux (both flux and energy) during an SEP event at Mars.

The SEP-related observation of enhanced escaping flux may explain, from the perspective of solar activity, a discrepancy between the Phobos-2 and MEX observations

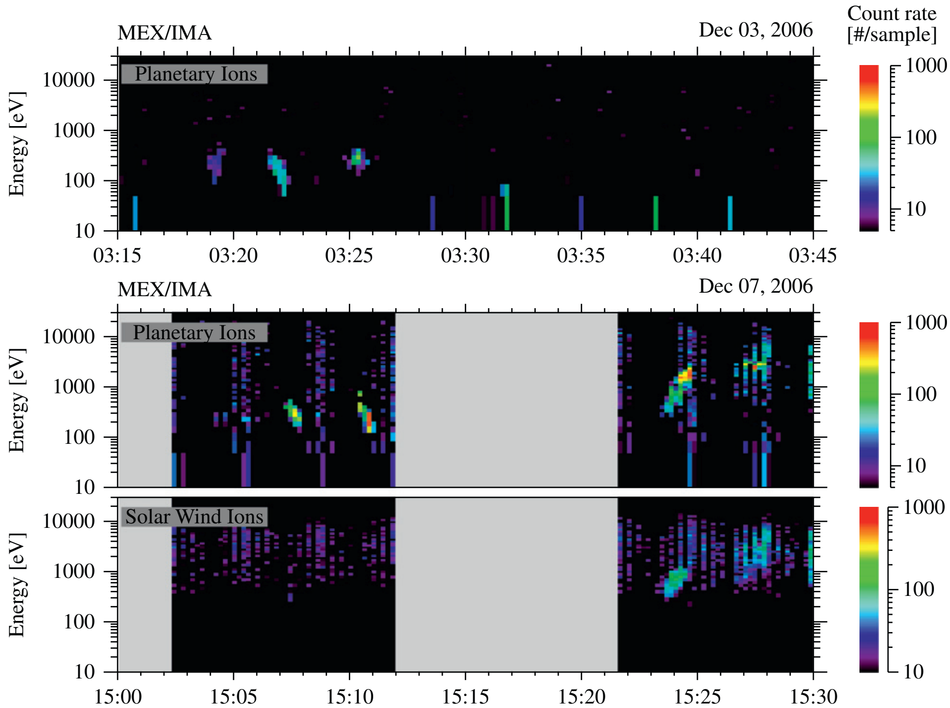

Fig. 4. Energy–time spectra of escaping ions inside the induced magnetosphere boundary recorded by MEX/IMA before the solar flare happened (on December 3, 2006, top panel) and during the SEP event (on December 7, 2006, middle panel). The energy–time spectrum for solar wind protons on December 7, 2006, is shown in the bottom panel. Background counts have been subtracted. Due to high background counts, onboard memory overflowed and data have been lost between 14:56–15:02 UT and 15:12–15:22 UT.

such that the ASPERA-3 experiment displays a much lower level of ion outflow from Mars than was recorded aboard Phobos-2 in early 1989 (Lundin et al., 1989; Barabash et al., 2007). During the latter solar maximum period in 1989, the solar EUV flux can be expected to have been higher. Thus, assuming that SEPs produce a similar effect to that caused by EUV flux, i.e., extra ionization in the Martian ionosphere, the December 2006 event can be taken as a proxy for observations made under solar maximum conditions. The level of EUV flux is one of the most important parameters influencing the flux of escaping ions, and can potentially account for the difference in outflow observed at solar maximum (Phobos-2) and at solar minimum (MEX).

Recently, several numerical models have estimated the ion outflow flux and its dependence on solar activity. Modolo et al. (2005) discussed the EUV dependence of the escaping flux of heavy ions at Mars using their hybrid model. Their calculations show that the O^+ ion outflow is four to five times higher during solar maximum (high EUV flux) than at solar minimum (low EUV flux). Another simulation, using a 3-D MHD model, was made by Ma and Nagy (2007). Their conclusion was that the total escape rate of heavy ions is two to three times larger under a high EUV flux condition than under a low EUV condition. They also mentioned that under an extremely high solar wind condition, the escape flux could be increased by two orders of magnitude. While our ASPERA-3 observations do not cover the complete energy range (we can only detect heavy ions with energies higher than ~100 eV), we can conclude that our observation (an increase of one order in flux) is qualitatively consistent with the numerical simulations.

Further careful analysis of the present event, as well as future observations and analyses of similar events, should be continued in this regard. In addition, it will be important to conduct statistical studies of the escaping flux under various solar EUV conditions at Mars and Venus. Such measurements are essential for estimating the loss rate of the atmospheres of Mars and Venus, which influences, in turn, the atmospheric evolution of these planets in a geological time scale (Lammer et al., 2003; Chassefière and Leblanc, 2004).

3.3. CMEs at Venus and Mars

Since VEX/ASPERA-4 was operated only 4 h each day (at around 05:30–09:30 UT) during this period, we cannot detect the moment of CMEs' arrival, although we can monitor daily changes in the solar wind. On December 5 and 6, 2006, the solar wind velocity was about 350 km/s (700 eV protons). This increased to about 550 km/s (1.7 keV protons) on December 7, 2006, and to about 750 km/s (3 keV protons) on December 8, 2006.

Similar changes in the solar wind velocity were observed at the Earth, starting from a level of about 300 km/s on December 5, 2006. Data from the Mass Time-Of-Flight (MTOF) sensor on SOHO (not shown here) indicate that both the solar wind velocity and density gradually increased on two occasions—first from 320 km/s and 5 cm^{-3} at 17:00 UT to 400 km/s and 7 cm^{-3} at 21:00 UT, December 5, 2006 (reaching 10 cm^{-3} at 20:00 UT). Then, from 470 km/s and 7 cm^{-3} at 08:00 UT to 560 km/s and 7 cm^{-3} at 18:00 UT on December 6, 2006 (attaining 10 cm^{-3} at 10:00–14:00 UT). Both increases likely belong to CMEs. The solar wind velocity increased to 700 km/s but with reduced density on December 7, 2006. A third CME arrived at 4 UT on December 8, 2006, at which time the solar wind density jumped by nearly a factor of 3, with a slight accompanying increase in velocity.

The timing of the increase in the solar wind speed agreed quite well both at Venus and at Earth, which were separated by nearly 160° in heliospheric longitude. The second CME (velocity increase at the Earth on the afternoon of December 6) most likely corresponded to the increased solar wind velocity on December 7 at Venus (it is recalled that data are taken at Venus only once a day between 05:30 and 09:30 UT). The third CME (enhancement at the Earth on the morning of December 8) most likely corresponded to the increased solar wind velocity on December 8 at Venus. These timings and velocities are consistent with the timings of the X9.0 flare (and accompanying CME release) of December 5 and the following X6 flare on December 6. The solar minimum condition singles out the source location of the CMEs identified at both Venus and the Earth as the same active region that produced the X9.0 flare, even if this flare itself was not directly linked to the genesis of the observed CME. The location of Venus at only 0.72 AU from the Sun indicates that CMEs, as well as SEPs, may each expand more than 90° in azimuth at 1 AU.

At Mars, it is difficult to investigate the solar wind velocity around the time of flare eruption because there were no meaningful data between December 5, 20:40, and December 7, 13:30, due to limitations in the operation. However, an increase in the energies of solar wind proton and alpha particles was identified between December 7, 13:30 UT (~1.4 keV for protons and ~3 keV/q for alpha particles) and December 8, 09:30 UT (~2.4 keV for protons and ~5 keV/q for alpha particles). This high-energy solar wind (>2 keV) lasted until December 11. After December 12, the solar wind energy decreased to ~1.4 keV.

These signatures were compared with the HAF v.2 solar wind model (for description see Dryer et al., 2004). The heliospheric-wide model does not show any strong CMEs toward Mars between December 7 and 8. Then, this change in energy is interpreted to be independent of the solar flare events. On the other hand, the HAF v.2 solar wind model indicated that a co-rotational interaction region (CIR) passed at Martian orbit on December 11–12 (not shown here). Therefore, the decrease of the energy from December 11 to 12 can be interpreted as an entry to different solar wind sector. It is noted that the HAF v.2 model was successfully used (McKenna-Lawlor et al., 2005) to predict (ex post facto) shock arrivals at Mars recorded by the SLED instrument aboard Phobos-2 during multiple orbits of Mars in March 1989. Also, for the present series of flares in December 2006, the predicted shock arrival time on December 19–20, 2006, coincides with a signature of ion heating recorded by ASPERA-3/IMA, which can be interpreted as the successful prediction of the interplanetary shock passage (McKenna-Lawlor et al., 2007).

4. Concluding remarks

In December 2006, an active region (NOAA 0930) produced four proton flares close to the time of solar minimum. An X9.0 flare in the sequence occurred at the eastern limb (S07E79) of the Sun at 10:35 UT on December 5, 2006. Within 1 day, both VEX/ASPERA-4 and MEX/ASPERA-3 recorded enhancements in their uniform background levels, which constitute signatures of flare-related SEP radiation. The source of these SEP particles is interpreted to have been the X9.0 flare, because no other region on the Sun (including the invisible side from the Earth) produced an X-class flare on December 5, 2006, close to the time of solar minimum. It is inferred that SEP particles must have traveled from the flare site westward 79° to the Earth and eastward 80° to Venus and 125° to Mars (shadowed area in Fig. 1). The time series of the high energetic particle fluxes at these three different planets are consistent with characteristic view of the fluxes caused by typical solar flare as reviewed in Reames et al. (1999).

Signatures of CMEs originating in NOAA 0930 were identified at both Venus and the Earth, i.e., 160° apart in heliospheric longitude. It is notable that, at both planets, we can see correlated multiple increases of the solar wind proton energy. This correlation indicates that the CMEs hit both Earth and Venus, separated by 160° from each other. On the other hand, at Mars, we did not see clear CME signatures.

The region influenced by the CMEs is also schematically depicted in Fig. 1. The location of Venus at only 0.72 AU from the Sun indicates that CMEs, as well as SEPs, may expand more than 90° in longitude at 1 AU. Thus, the heliosphere-wide multi-point observation of solar flares and related phenomena suggests that an active region on the invisible side as seen from the Earth could produce geoeffective flares and CMEs. This potentially has a significant bearing on space weather forecasts.

Another important consequence of the analysis of SEP events is the insight they potentially provide into the process of planetary atmospheric evolution. During the SEP event of December 5, 2006, the heavy ion escaping flux was enhanced by approximately one order of magnitude. This event provides the first observation of a sporadic enhancement in the flux of escaping energized heavy ions from Mars under extreme solar conditions.

During the next solar maximum period, it is anticipated that there will be several plasma instruments distributed widely in the heliosphere (in addition to Earth-orbiting spacecraft, Cassini, MEX, VEX, Messenger, New Horizon, STEREO, etc., are expected to monitor the interactions between planetary environment and the solar wind). This will provide a good opportunity to conduct further stereo observations during energetic solar flare events and, thereby, to investigate the 2-D structure of CMEs. This will not only increase our knowledge of the physics of solar flares and the response of various planets to these events, but it will also enable us to investigate the historical impact of the solar wind and solar flares on a geological time scale at various planets.

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References

Barabash, S., et al., 2006. The analyzer of space plasmas and energetic atoms (ASPERA-3) for the Mars Express mission. Space Sci. Rev. 126, 113.

Barabash, S., et al., 2007. Martian atmospheric erosion rate. Science 315, 501.

Carlsson, L., et al., 2006. Mass composition of the escaping plasma at Mars. Icarus 182 (2), 320.

Chassefière, E., Leblanc, F., 2004. Mars atmospheric escape and evolution; interaction with the solar wind. Planet Space Sci. 52, 1039.

Crider, D.H., Espley, J., Brain, D.A., Mitchell, D.L., Connerney, J.E.P., Acuna, M.H., 2005. Mars Global Surveyor observations of the Halloween 2003 solar superstom's encounter with Mars. J. Geophys. Res. 110, A09S21.

Cully, C.M., Donovan, E.F., Yau, A.W., Arkos, G.G., 2003. Akebono/suprathermal mass spectrometer observations of low energy ion outflow: dependence on magnetic activity and solar wind conditions. J. Geophys. Res. 108 (A2), 1093.

Dryer, M., et al., 2004. Real-time predictions of interplanetary shock arrivals at L1 during the "Halloween 2003" epoch. Space Weather 2, S09001.

Espley, J.R., Cloutier, P.A., Crider, D.H., Brain, D.A., Acuna, M.H., 2005. Low-frequency plasma oscillations at Mars during the October 2003 solar storm. J. Geophys. Res. 110, A09S33.

Kaneda, K., Terada, N., Machida, S., 2007. Time variation of nonthermal escape of oxygen from Mars after solar wind dynamic pressure enhancement. Geophys. Res. Lett., 34, L20201, doi:10.1029/2007GL030576.

Lammer, H., Lichtenegger, H.I.M., Kolb, C., Ribas, I., Guinan, E.F., Abart, R., Bauer, S.J., 2003. Loss of water from Mars: implications for the oxidation of the soil. Icarus 165, 9.

Luhmann, J.G., Kasprzak, W.T., Russell, C.T., 2007. Space weather at Venus and its potential consequences for atmosphere evolution. J. Geophys. Res. 112, E04S10.

Lundin, L., et al., 1989. First measurements of the ionospheric plasma escape from Mars. Nature 341, 609.

Lundin, L., et al., 2004. Solar wind-induced atmospheric erosion at Mars: first results from ASPERA-3 on Mars Express. Science 305, 1933.

Ma, Y.J., Nagy, A.F., 2007. Ion escape fluxes from Mars. Geophys. Res. Lett. 34, L08201.

McKenna-Lawlor, S., et al., 2005. Particle radiation in the close Martian environment. J. Geophys. Res. 110, A03102.

McKenna-Lawlor, S.M.P., et al., 2007. Predicting interplanetary shock arrivals at Earth, Mars, Venus, and Mercury: a real-time modeling experiment following the X-class-flares of 5–14 December 2006. J. Geophys. Res., in press.

Mitchell, D.L., Lin, R.P., Reme, H., Crider, D.H., Cloutier, P.A., Connerney, J.E.P., Acuna, M.H., Ness, N.F., 2000. Oxygen Auger electrons observed in Mars' ionosphere. Geophys. Res. Lett. 27, 1871–1874.

Modolo, R., Chanteur, G.M., Dubinin, E., Matthews, A.P., 2005. Influence of the solar EUV flux on the Martian plasma environment. Ann. Geophys. 23, 433–444.

Reames, D.V., 1999. Particle acceleration at the Sun and in the heliosphere. Space Sci. Rev. 90, 413.

Thuillier, G., Perrin, J.-M., Lathuillere, C., Herse, M., Fuller-Rowell, T., Codrescu, M., Huppert, F., Fehrenbach, M., 2005. Dynamics in the polar thermosphere after the coronal mass ejection of 28 October 2003 observed with the EPIS interferometer at Svalbard. J. Geophys. Res. 110, A09S37.

Tsurutani, B.T., Judge, D.L., Guarnieri, F.L., Gangopadhyay, P., Jones, A.R., Nuttall, J., Zombon, G.A., Didkovsky, L., Mannucci, A.J., Iijima, B., Meier, R.R., Immel, T.J., Woods, T.N., Prasad, S., Floyd, L., Huba, J., Solomon, S.C., Straus, P., Viereck, R., 2005. The October 28, 2003 extreme EUV solar flare and resultant extreme ionospheric effects: comparison to other Halloween events and the Bastille Day event. Geophys. Res. Lett. 32, L03S09.

Woods, T.N., Bailey, S.M., Peterson, W.K., Solomon, S.C., Warren, H.P., Eparvier, F.G., Garcia, H., Carlson, C.W., McFadden, J.P., 2003. Solar extreme ultraviolet variability of the X-class flare on 21 April 2002 and the terrestrial photoelectron response. Space Weather 1, 1001.