Ionospheric effects of solar flares at Mars

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1From an analysis of electron density profiles recorded aboard Mars Global Surveyor, we report observations of some new and aeronomically important solar flare effects in the ionosphere of Mars. We find that all flares result in the formation of a well defined E layer peak, not always seen on other days. Further, while majority of flares result in elevated electron densities in the E region alone, some flares affect both the E and F1 layers. These altitude related effects can provide vital information on the relative enhancement of photon fluxes in the various wavelength bands during solar flares. By using the unit optical depth values at Mars from Fox (2004) and the XUV irradiance model of Meier et al. (2002) for the Bastille Day solar flare, we infer that the well defined E peaks could result from enhancement of photon fluxes in the 10–13 nm spectral band. The extension of effect to the F1 layer is due to hardening of the 26–91 nm spectral band, as supported by Solar EUV Monitor measurements on Solar Heliospheric Observatory. Citation: Mahajan, K. K., N. K. Lodhi, and S. Singh (2009), Ionospheric effects of solar flares at Mars, Geophys. Res. Lett., 36, L15207, doi:10.1029/2009GL039454.

2Large eruptions of photon radiation on the sun, called solar flares, can cause sudden changes in the plasma environment of a planet. Effects of these eruptions in the earth’s ionospheric plasma have been studied by several workers and most of the earlier works have been described by Mitra [1974] and by Davies [1990]. Some of the more recent works on this topic are those of Thomson et al. [2004], dealing with effects in the D region and those of Meier et al. [2002], Tsurutani et al. [2005], Liu et al. [2006] and Liu et al. [2007], dealing with effects in the ionospheric F region and the Topside. On the other hand, there have been only three studies dealing with the effects of solar flares in the ionosphere of other planets, first by Kar et al. [1986], second by Mendillo et al. [2006] and the third by Haider et al. [2009]. Kar et al. reported enhanced electron and ion densities in the Topside (160 to 200 km) ionosphere of Venus during three low intensity (optical class1) solar flares by analyzing ionospheric measurements aboard Pioneer Venus Orbiter [Colin, 1980]. Similarly, Mendillo et al. [2006] observed elevated electron densities in the E region (90 to 120 km) of Mars ionosphere during two intense solar flares, while Haider et al noted enhancement of E region electron content during a violent solar event. In both of these works electron density profiles measured by the Radio Science (RS) experiment aboard Mars Global Surveyor (MGS), were used.

3Several solar flares occurred during the lifetime (24 Dec. 1998 to 09 June 2005) of RS - MGS experiment and we found that quite a few electron density profiles, in addition to the two reported by Mendillo et al. [2006] and the one reported by Haider et al. [2009], were recorded during some of these flares. While the events examined by Mendillo et al and Haider et al exhibited the flare effect as elevated electron densities in the altitude region 90 to 120 km alone (i.e., Mars E region), our analysis based on all the flare affected profiles has shown that there are other vital altitude-related effects in the Martian ionosphere. These effects can lead to important information about the solar irradiance during flares, since solar photons create most of the ionization at the altitude of unit optical depth and in a planetary ionosphere this altitude varies with the wavelength of the ionizing radiation. In this paper we report these altitude related solar flare effects in the ionosphere of Mars.

2. Data and Sources

4In our study we have made use of two sets of data, namely (1) electron density profiles observed by the Radio Science experiment on the Mars Global Surveyor (MGS), and (2) EUV and XUV photon fluxes measured by the Solar EUV Monitor (SEM) experiment on the Solar Heliospheric Observatory (SOHO). The Radio Science experiment on the Mars Global Surveyor measured 5600 electron density profiles in the Martian ionosphere between 24 December, 1998 and 09 June, 2005 on 695 different days and this experiment has been described by Hinson et al. [1999]. Each electron density profile showed a well defined peak at about 135 km for the primary layer (called the F1 layer). The secondary layer (known as the E layer) often appeared as a shoulder below the main peak between 105 to 120 km. Several profiles were recorded on any one day at the same solar zenith angle (SZA), the same local time and about the same latitude but at different longitudes. There was an interval of about 2 hours (that is the orbital period of MGS) between each profile and thus as many as 12 profiles were recorded on some days, though the average number was 8. All these profiles were essentially restricted to high latitudes and corresponded to near terminator conditions with SZA varying between 71° and 89°. We retrieved the MGS-RS profiles from the NASA Planetary Data system website: ftp://pds-geosciences.wustl.edu/mgs-m-rss-sdp-v1, courtesy of Dr. D. Hinson. These profiles have been used by several groups to study some important aspects of Mars ionosphere. A brief summary of these works has recently been presented by Fox and Yeager [2006] and Mahajan et al. [2007].

5The SEM - SOHO experiment has been described by Judge et al. [1998]. SEM measures EUV flux integrated in
The wavelength band 26 to 34 nm and the XUV flux integrated in the wavelength band 0.1 to 50 nm. These are the wavelengths which are indeed responsible for the creation of a planetary ionosphere [e.g., Bauer, 1973]. The SEM-SOHO fluxes have been used in several studies dealing with the earth’s ionosphere, especially for solar flare effects [e.g., Meier et al., 2002; Tsurutani et al., 2005; Liu et al., 2007]. In our analysis, we used the 15-second averaged SEM/SOHO fluxes taken from the website: ftp://pds-geosciences.wustl.edu/dep/space-science/semdata.html, courtesy of Dr. D.L. Judge and Dr. H.S. Ogawa.

3. Response of Mars Ionosphere to Solar Flares

As stated before, several solar flares occurred during the lifetime of RS-MGS experiment. We first identified these flares by surveying the daily plots of 15 s - averaged XUV fluxes measured by SEM/SOHO on days for which MGS-RS electron density profiles were available and then examined all the profiles which were recorded on each of these flare days. Despite the fact that the MGS data had a time resolution of about two hours, and that flares occur occasionally, our search rewarded us with quite a few profiles which were recorded during some of these XUV flares. Not surprisingly, we found that all flares, which were visible both at Earth and at Mars, affected the Martian ionosphere. The altitude region which exhibited these effects however, varied from one flare to the other as will be clear from the following examples.

Figure 1 shows the time series of 15 s - averaged EUV and XUV fluxes as observed on Earth during three of the solar flares identified by us from the SOHO/SEM data. These fluxes continued to be above normal for more than 1.5 hours during all these three flares. The time scale on the X-axis has been adjusted by 4.5 minutes to compensate for the extra time taken by solar photons to reach Mars. These photon fluxes will reduce approximately to 43% of these values after reaching Mars. The vertical dashed line on X-axis for each day indicates the time at which electron density profile was recorded during the XUV flare. To examine the effect of these solar flares, all the profiles recorded on each flare day are plotted in Figure 2 (left). Lines with filled circles indicate the flare-time electron densities while the thin-full lines exhibit profiles recorded at other times on the respective day. Universal times, local times, solar zenith angles and latitudes for these profiles are also shown. It can be immediately noted that electron densities were enhanced nearly at all altitudes during these three flares, thereby indicating that all regions of the Martian ionosphere including the E (90 to 120 km), F1 (120 to 140 km) and Topside (140 km and above) were

Figure 1. Time series of solar EUV, XUV photon fluxes for 24 Nov., 2000, 29 May, 2003 and 31 May, 2003 as measured by SEM-SOHO. The dashed vertical line in each panel indicates the time when electron density profile was recorded by MGS during the flare. The time scale on X-axis has been adjusted to compensate for the extra 4.5 minutes required for the solar photons to arrive at Mars. The fluxes at Mars will be about 43% of these fluxes measured at Earth.

Figure 2. (left) Electron density profiles observed by the MGS on each of the three flare days. Profile recorded during solar flare, on each of these days, is drawn with filled circles. Elevated electron densities through out the Martian ionosphere can be noted for all the three flare-time profiles. (right) Flare-time profile is also compared with the average of non-flare profiles for the respective day (along with one standard deviation). Well formed E peaks can be noted in all the flare-time profiles. These peaks are not always seen in the non-flare profiles.
affected. These effects can be better appreciated by looking at Figure 2 (right) where the flare affected profiles are compared with the average of the non-flare profiles for the respective day. Further, in addition to the elevated electron densities, we note another feature in the flare affected profiles. This is the formation of a well defined E peak. This peak is not always seen in the other non-flare profiles, as can be observed from Figure 2.

[8] Relevant information about these flares (along with a few other flares to be discussed subsequently in the text) is given in Table 1, which contains: (1) Date, (2) Heliocentric coordinates of active region – taken from NOAA’s Space Environment Center, (3) Earth-Sun-Mars Angle, with Earth leading in all cases, (4) Class, X-ray as well as optical and (5) Ionospheric region affected. It may be noted that the flare of 24 Nov. 2000 occurred when Earth-Sun-Mars angle was rather high (=102.6). However, the heliocentric longitude of the active region was 14°W, so the flare was visible at Mars, as well. Further, the electron density profile was recorded when the XUV flux was quite high and was nearly coincident in time with the maximum phase of the flare, as can be noted from Figure 1. Consequently, for this particular event, the flare effect was quite prominent at all the altitudes. As in Figure 2, electron densities observed during flares are shown by filled circles, while the non-flare time profiles for the respective day are shown by thin-full lines. It can again be observed that each of the flare-time profile exhibits a well formed E peak at about 115 km, not always seen in the non-flare profiles. Further, whole of the E region, covering the altitude range 90 to 120 km, shows elevated electron densities, as also observed by Mendillo et al. [2006] in the two events (i.e., 15 April, 2001 and 26 April, 2001) examined by them. The data for 15 April, 2001 is also shown in Figure 3. The EUV and XUV fluxes for each of these flare days are shown in Figure 3 (right). The vertical dashed line on the X-axis for each day indicates the time at which the electron density profile was recorded during the XUV flare. It may be noted that all the flare-time profiles were recorded during the decay phase, and the XUV and the EUV fluxes for all these profiles were well above the preflare values. It is perhaps necessary to mention that EUV and XUV fluxes measured by SEM/SOHO have sometimes been corrupted due to the impinging of energetic particles upon the SEM detectors [Tsurutani et al., 2005].

Table 1. Solar Flares and Martian Ionosphere

<table>
<thead>
<tr>
<th>S.N.</th>
<th>Date</th>
<th>Active Region</th>
<th>E-S-M Angle</th>
<th>Class/ Importance</th>
<th>Region Affected</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24 Nov. 2000</td>
<td>N21W14</td>
<td>102.6</td>
<td>X18/2N</td>
<td>E, F1</td>
</tr>
<tr>
<td>2</td>
<td>02 April 2001</td>
<td>N16W62</td>
<td>32.9</td>
<td>X11/1F</td>
<td>E</td>
</tr>
<tr>
<td>3</td>
<td>10 April 2001</td>
<td>S23W09</td>
<td>28.2</td>
<td>X2/3B</td>
<td>E</td>
</tr>
<tr>
<td>4</td>
<td>15 April 2001</td>
<td>S20W85</td>
<td>25.6</td>
<td>X14/2B</td>
<td>E</td>
</tr>
<tr>
<td>5</td>
<td>29 May 2003</td>
<td>S06W37</td>
<td>31.2</td>
<td>X12/2B</td>
<td>E, F1</td>
</tr>
<tr>
<td>6</td>
<td>31 May 2003</td>
<td>S07W65</td>
<td>30.4</td>
<td>M9/2B</td>
<td>E, F1</td>
</tr>
<tr>
<td>7</td>
<td>13 May 2005</td>
<td>N12E11</td>
<td>62.5</td>
<td>M8/2B</td>
<td>E</td>
</tr>
</tbody>
</table>

[10] The EUV and XUV fluxes for the flare affected profiles of 29 May, 2003 and 31 May, 2003 were not as large as those for the flare affected profile of 24 Nov. 2000. In fact the XUV fluxes were barely around 10% and 25% respectively above the normal values at the time when the flare time profiles of 29 May, 2003 and 31 May, 2003 were recorded. The absence of strong fluxes, perhaps, did not result in any significant increase in the electron density in the small altitude range from 120 to 130 km on these two days. This region is the base of the Martian F1 layer and is formed by solar X-rays and EUV photons.

[11] We found that in majority of cases, solar flares affected only the E region of the Martian ionosphere. Figure 3 shows four such cases and Table 1 contains relevant information about these flares. Figure 3 (left) exhibits electron density profiles observed on these four days. As in Figure 2, electron densities observed during flares are shown by filled circles, while the non-flare time profiles for the respective day are shown by thin-full lines. It can again be observed that each of the flare-time profile exhibits a well formed E peak at about 115 km, not always seen in the non-flare profiles. Further, whole of the E region, covering the altitude range 90 to 120 km, shows elevated electron densities, as also observed by Mendillo et al. [2006] in the two events (i.e., 15 April, 2001 and 26 April, 2001) examined by them. The data for 15 April, 2001 is also shown in Figure 3. The EUV and XUV fluxes for each of these flare days are shown in Figure 3 (right). The vertical dashed line on the X-axis for each day indicates the time at which the electron density profile was recorded during the XUV flare. It may be noted that all the flare-time profiles were recorded during the decay phase, and the XUV and the EUV fluxes for all these profiles were well above the preflare values. It is perhaps necessary to mention that EUV and XUV fluxes measured by SEM/SOHO have sometimes been corrupted due to the impinging of energetic particles upon the SEM detectors [Tsurutani et al., 2005].

![Figure 3](image-url)
This phenomenon can be noted in the EUV and XUV plots of 15 April, 2001, in Figure 3.

[12] The day time E and F1 layers of the Martian ionosphere are expected to be in photochemical equilibrium [Bauer, 1973], given by the equation \( Q = \alpha N^2 \), where \( Q \) is the electron (ion) production rate, \( \alpha \) the dissociative recombination coefficient of the dominant ion \( O_3 \) and \( N \) the electron (ion) density. Since \( Q \) is directly proportional to the solar ionizing flux \( = F \), then the flare-time increase in electron density should be related to the flare-time increase in the ionizing flux, \( F \). We have examined this relationship in Figure 4 by plotting \( F/F_0 \) against \((N_t/N_0)^2\) at 115 and 135 km (the respective altitudes of E and F1 peaks). The subscripts \( f \) and \( 0 \) stand respectively for the flare time and preflare values. Although the sample is small, yet one sees a positive correlation between the flare time increase in electron density and the ionizing flux in the relevant spectral band. It is also seen, that small increases in the integrated fluxes, result in large changes in electron density at the E and F1 peaks. This feature can only be explained if photon fluxes at some specific wavelengths (like He 304) get relatively more enhanced than at the rest of the wavelengths.

4. Discussion

[13] A unique feature noted in the flare affected profiles was the formation of a well defined E region peak. This peak can show up either due to the formation of a minimum between the E and F1 peaks or due to the creation of relatively more ionization at the altitude of E peak [see also Fox, 2004]. Since most of the energy of the solar photons is deposited at the altitude where the optical depth is unity, the wavelengths responsible for the ionization at the E peak can be inferred from a knowledge of unit optical depth. Fox [2004] has calculated the altitude ranges as a function of wavelength for unit optical depth at Mars with her standard 60° SZA model. She found that for the altitude ranges 105–110 km, 110–115 km and 115–120 km, these spectral ranges would be 5.5 to 7.5 nm, 7.5 to 10.0 nm and 10.0 to 13.0 nm respectively. These altitude ranges are expected to be somewhat lower for higher solar zenith angles (say for example, 110–115 km for 10.0 to 13.0 nm). The flare-affected profiles were observed at SZA between 71° and 78°. Thus if photon flux for wavelengths longer than 10.0 nm gets relatively less enhanced during solar flares, a minimum in electron density can be formed above 110 km thereby creating an E peak. Alternately, a well defined E peak may be formed, if the photon flux in the wavelength range 10.0 to 13.0 nm gets relatively more enhanced during a solar flare.

[14] Meier et al. [2002], by analyzing the effects of Bastille Day flare of July 14, 2000 on the dayglow and ionosphere data at Earth, generated a solar irradiance model with a spectral resolution of 1 nm. In this model the irradiance during this flare increased from a factor of 1.5 at 10.0 nm to a factor of about 10 at 14.0 nm. Since the major enhancement in the solar ionizing flux during the Bastille Day flare according, to Meier et al’s model was in the spectral range 10.0 to 13.0 nm, it seems to us that the formation of a well defined Martian E peak could be due to production of relatively more ionization at altitudes between 110 and 115 km. However, this argument is only valid if Meier et al’s model is uniformly applicable to all the flares.

[15] The second important effect observed by us is the presence of elevated electron densities nearly at all altitudes in the Martian ionosphere, covering the E, F1 and Topside, during some flares. While the ionosphere E region at Mars is created by soft X-ray, in the wavelength band 2 to 15 nm, the F1 and Topside are formed due to ionization by wavelengths in the band 26 to 91 nm [Bauer, 1973]. The EUV fluxes in the wavelength band 26 to 34 nm have indeed shown values, somewhat above the non-flare values when the flare-time profiles were recorded and thus are responsible for the effect in F1 layer and Topside. It has been observed that during solar flares fluxes in some wavelengths get relatively more enhanced than at others and Meier et al’s model indeed shows that.

5. Conclusions

[16] An analysis of electron density profiles measured at Mars during solar flares shows three major effects; (1) formation of well defined E peaks, not always seen on other days (2) elevated electron densities in the E region alone in majority of the flares and (3) elevated electron densities both in the E and F1 regions during some flares. By using the unit optical depth values at Mars from Fox [2004] and the XUV irradiance model of Meier et al. [2002] for the Bastille Day solar flare, we infer that the well defined E peaks could result from enhancement of photon fluxes in the 10–13 nm spectral band. The extension of effect to the F1 layer is due to hardening of the 26–91 nm spectral band, as supported by SEM - SOHO measurements.

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References


