Response of Mars' Ionosphere to Different Types of Solar X-Ray Flares: MGS Observations

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Abstract : We studied the observations made by Geostationary Operational Environmental Satellite (GOES) in Earth's orbit and NASA's Mars Global Surveyor (MGS) in Mars' orbit. The responses of Mars ionosphere to different types of solar X-ray flares are presented in this paper. The solar flare effects are observed by GOES in 0.1 – 0.8 nm X-ray flux and by MGS in Electron density of Mars' E-region ionosphere on 15 April 2001, 31 May 2003 and 19 December 2000. The X14.4, M9.3 and C9.5 are the major solar X-ray flares occurred on 15 April 2001, 31 May 2003 and 19 December 2000, respectively during the solar cycle 23. The electron density in E-region ionosphere of Mars enhanced by a factor of 3.0, 2.4 and 1.9 for X14.4, M9.3 and C9.5 flares, respectively. The effect of solar flares on the peak electron density and peak altitude also presented.

Key words **– Solar X-Ray Flares, Mars Ionosphere, Electron Density.**

I. INTRODUCTION

The solar X-ray flares are the sudden explosion of the Sun (*Harvey, 1971*). When the solar flares occur, the solar X-ray flux increases enormously. This increased X-ray flux can disturb the space weather, blackout the function of satellite systems, and influence strongly the ionosphere of planets, harm the astronauts and even harm the life on the Earth. The wavelength 0.1 – 0.8 nm is very sensitive to the solar flares, hence usually the effects of solar flares can be observed by measured the flux coming from the Sun in the wavelength range of 0.1-0.8 nm. Based on the intensity of 0.1-0.8 nm flux, solar flares are classified as X, M, and C – Class flares, with flux range 10^{-4} to 10^{-3}, 10^{-5} to 10^{-4}, and 10^{-6} to 10^{-5} Watts/m^2, respectively (*Veronig et al., 2002*). The X-class flares are more intense than M-class, M-class flares are more intense than C-class. The Geostationary Operational Environmental Satellites (GOES) are serious of satellites launched by the United States' National Oceanic and Atmospheric Administration (NOAA) to measure the solar X-ray flux in the range of 0.1-0.8 nm wavelength (*Machol and Viereck, 2015, Wieman et al., 2014, Ogawa et al., 1998*). GOES 10 observed several solar flares during the solar cycle 23 (the years 1996 - 2008). The major solar flares that GOES observed in different classes were X14.4, M9.3 and C9.5 on 15 April 2001, 31 May 2003 and 19 December 2000.

The Mars ionosphere consisting of two major regions namely E-region and F-region at peak altitudes ~ 110 km and 130 km respectively. The E-region is formed due to the ionization by solar X-ray flux and F-region is formed due to the ionization of solar UV flux. Therefore, the effects of solar flares can be observed in the E-region ionosphere of Mars. The electron density of E-region increases as solar X-ray flux increases. The Radio Science Experiment onboard NASA's Mars Global Surveyor (MGS) dedicated to measure electron density in the ionosphere of Mars between 50 and 300 km altitude (*Mendillo et al. 2006*). It measured more than 5000 electron density profiles of Mars during its lifespan 2000 to 2005.

The analysis of MGS observations is presented in this paper. We studied the electron density profiles measured by MGS on 15 April 2001, 31 May 2003 and 19 December 2000. MGS measured 6, 8, and 10 electron density profile on 15 April 2001, 31 May 2003 and 19 December 2000, respectively (*Fallows et al. 2015, Haider et al. 2016*). Among these profiles, the effects of solar flares deposited in one profile of respective day. The detailed analysis and results are presented in the following sessions.

II. OBSERVATIONS

The GOES 10 launched by US NOAA in 1997. It observed the solar X-ray flux from 1997 to 2009 in two channels in the rage of wavelength 0.05-0.3 nm in one channel and 0.1-0.8 nm in other channel (*Bornmann et al., 1996*). The solar flares response were observed clearly in 0.1-0.8 nm flux because this range of wavelength is sensitive to solar flares. The MGS was launched by NASA's Jet Propulsion Laboratory in 1996 and was active until 2006 (*Mendillo et al. 2006*). Radio Science Experiment was one of five scientific instruments flown one MGS. It was the first experiment on Mars, which observed the full electron density profile between 50 and 300 km. These electron density profiles consist two regions, E- and F-regions. Clear peaks of E- and F- regions are observed by MGS in the electron density profiles.

The effects of major solar flares occurred on 15 April 2001, 31 May 2003 and 19 December 2000 were observed by GOES-10 and RS/MGS. These flares deposited their flux in the E-region ionosphere of Mars and increased the electron density significantly in comparison to other profiles measured on the respective day.

III. RESULTS AND DISSCUSION

Figure 1 shows the universal time (UT) series of solar X-ray flux (0.1-0.8 nm) observed by GOES 10 on 15 April 2001 (1(a)), 31 May 2003 (1(b)), and 19 December 2000 (1(c)). The solar X-ray flux shown in this figure is integrated flux over wavelength rage 0.1 – 0.8 nm. From Figure 1(a)-1(c), the normal averaged value of flux was about 10^{-6} Watts/m^2. In Figure 1(a), the flux started increasing at 13:19 UT and peaked at 13:50 UT. The value of flux at peak time was about 10^{-3} Watts/m^2 that falls under X-class (X14.4) flares. In Figure 1(b), the flux started increasing at 02:13 UT and peaked at 02:24 UT. The value of flux at peak time was about 10^{-4} Watts/m^2 that falls under M-class (M9.3) flares. In Figure 1(c), the flux started increasing at 10:03 UT and peaked at 10:24 UT. The value of flux at peak time was about 10^{-5} Watts/m^2 that falls under C-class (M9.3) flares. The flux enhanced about 1000, 100, and 10 times during X14.4, M9.3, and C9.5 flares compare to normal flux value. GOES 10 observed these major solar flare event.

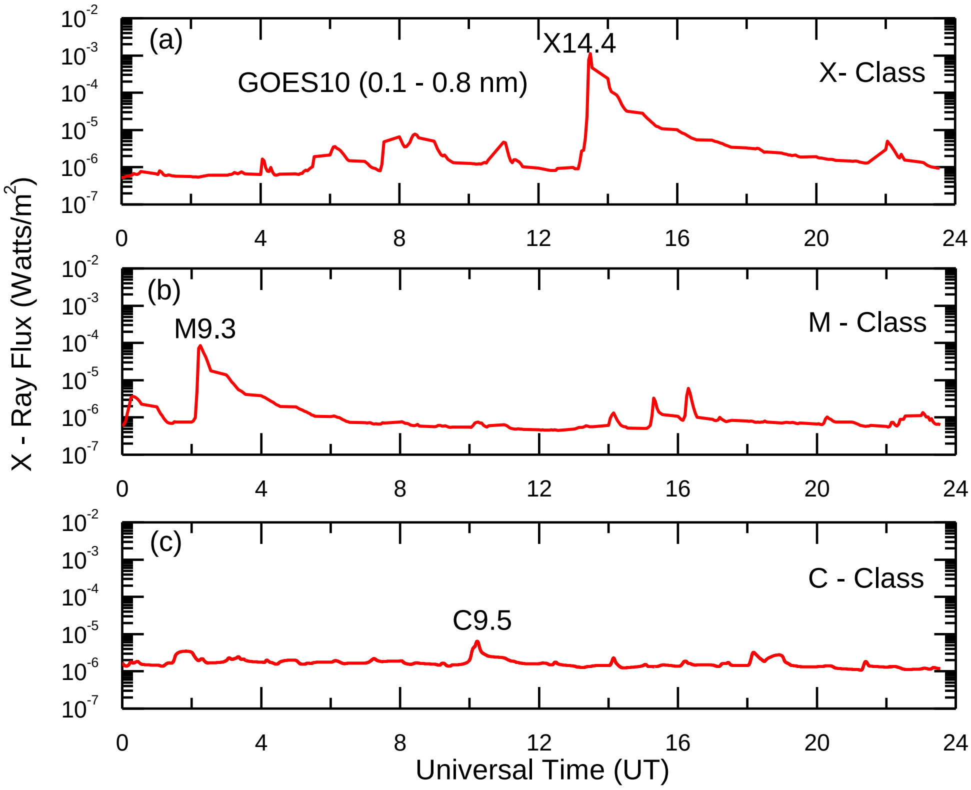

Figure 1: Time series of Solar 0.1-0.8 nm X-ray flux observed by GOES 10 on (a) 15 April 2001, (b) 31 May 2003, and (c) 19 December 2000.

Figure 2 shows the electron density profiles observed by Radio Science experiment onboard MGS on 15 April 2001. Figure 2(a) shows six electron density profiles measured by MGS on 15 April 2001 at different UT. To understand the effect of solar flare, we averaged the five non-flare profiles and compared with flare profile in Figure 2(b), where black colored curve is averaged non-flare profiles and red colored curve is flare profile. From Figure 2(a), clear E- and F-region peaks can be noticed in almost all profiles at ~110 km and ~135 km, respectively. The electron density is enhanced significantly in the E-region of profile measured at 14:14 UT (red colored curve). It can be noticed from Figure 2(b) that the non-flare vale of peak E-region electron density is about 4×10^4 cm^{-3} and the flare value of E-region electron density is about 7×10^4 cm^{-3}. The electron density increased by a factor of 3.0 during X14.4 solar flare.

Figure 3 shows the electron density profiles observed by MGS on 31 May 2003. Figure 3(a) shows eight electron density profiles measured by MGS on 31 May 2003 at different UT. The comparison of averaged the seven non-flare profiles with flare profile shown in Figure 3(b), where black colored curve is averaged non-flare profiles and red colored curve is flare profile. The electron density is enhanced significantly in the E-region of profile measured at 02:40 UT (red colored curve). It can be noticed from Figure 3(b) that the non-flare vale of peak E-region electron density is about 4×10^4 cm^{-3} and the flare value of E-region electron density is about 6×10^4 cm^{-3}. The electron density increased by a factor of 2.4 during M9.3 solar flare.

Figure 4 shows the electron density profiles observed by MGS on 19 December 2000. Figure 3(a) shows ten electron density profiles measured by MGS on 19 December 2000 at different UT. The comparison of averaged the seven non-flare profiles with flare profile shown in Figure 4(b), where black colored curve is averaged non-flare profiles and red colored curve is flare profile. The electron density is enhanced significantly in the E-region of profile measured at 10:30 UT (red colored curve). It can be noticed from Figure 4(b) that the non-flare vale of peak E-region electron density is about 4×10^4 cm^{-3} and the flare value of E-region electron density is about 4.5×10^4 cm^{-3}. The electron density increased by a factor of 1.9 during C9.5 solar flare.

From Figures 1 to 4, we can notice that the solar flares showed their effect in the E-region ionosphere of Mars with 30 minutes of their occurrence at the Sun. The below table gives the details of flares and their occurrence at the Sun and their effects at Mars.

Table 1: Details of solar flares

Date	**Flare Class**	**GOES Flare Peak Time**	**MGS Flare Profile Time**
15 April 2001	X14.4	13:50 UT	14:14 UT
31 May 2003	M9.3	02:24 UT	02:40 UT
19 December 2000	C9.5	10:24 UT	10:30 UT

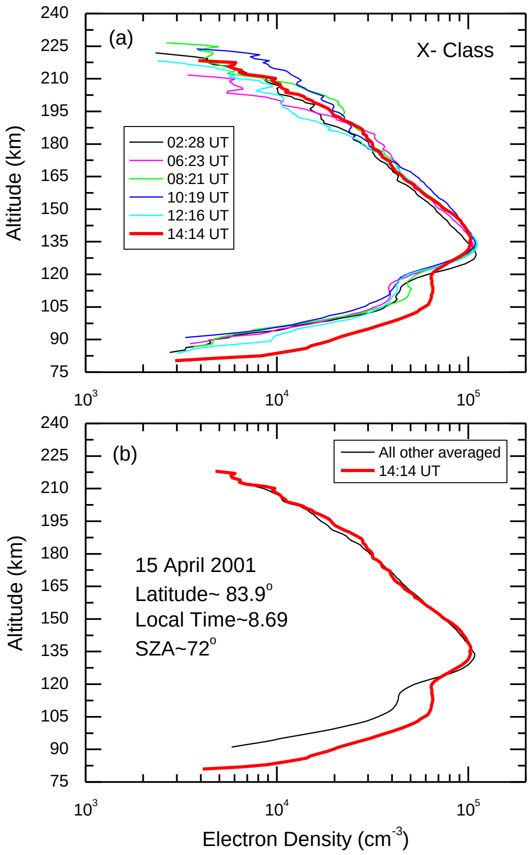

Figure 2: Electron density profiles measured by MGS on 15 April 2001: (a) all electron density profiles at different UT, (b) comparison of non-flare averaged profiles with flare profile. The geometry of measurements are mentioned in below panel. The flare affected profile shown with red color.

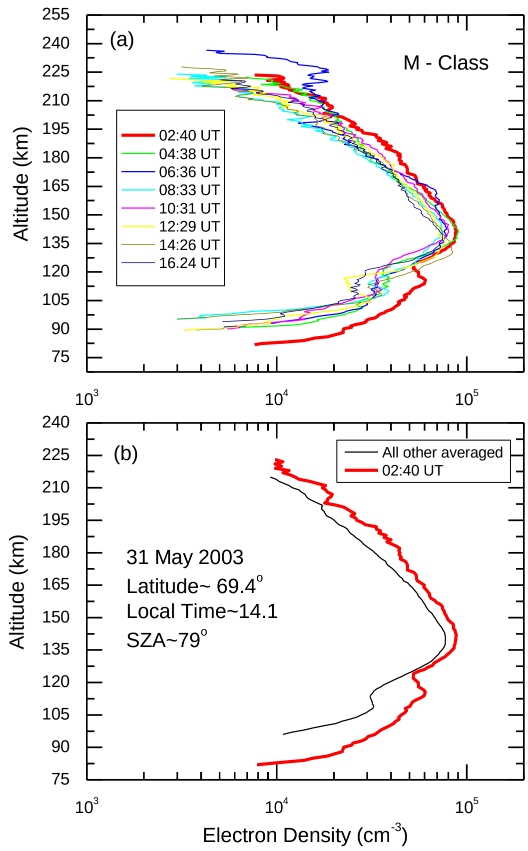

Figure 3: Electron density profiles measured by MGS on 31 May 2003: (a) all electron density profiles at different UT, (b) comparison of non-flare averaged profiles with flare profile. The geometry of measurements are mentioned in below panel. The flare affected profile shown with red color.

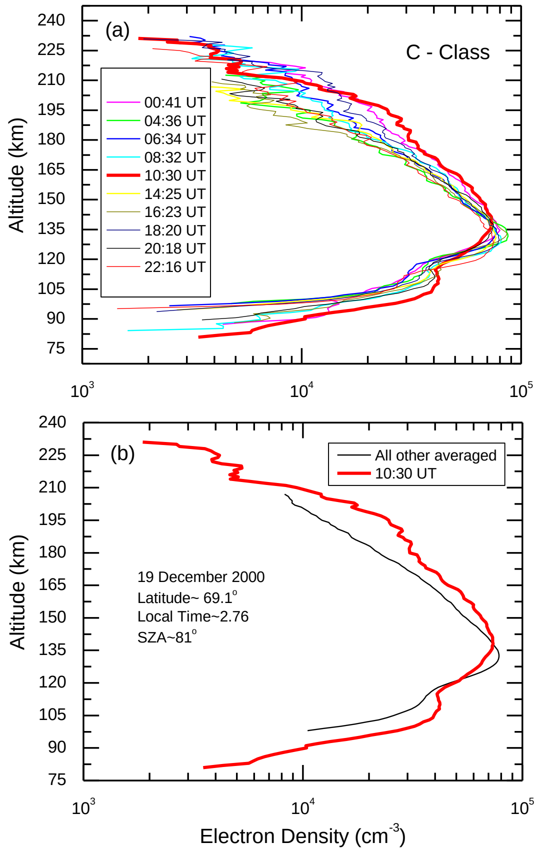

Figure 4: Electron density profiles measured by MGS on 19 December 2000: (a) all electron density profiles at different UT, (b) comparison of non-flare averaged profiles with flare profile. The geometry of measurements are mentioned in below panel. The flare affected profile shown with red color.

IV. CONCLUSION

Three major solar flares X14.4, M9.3 and C9.5 of X, M, and C class are observed on 15 April 2001, 31 May 2003 and 19 December 2000 by GOES 10, respectively. Their responses in the E-region ionosphere of Mars were measured by MGS. We found that the MGS observed the effects of these solar flares in E-region ionosphere of Mars within 30 minutes after the occurrence of flares at the Sun. It has been found that the E-region electron density increased by a factor of 3.0, 2.4, 1.9 for X14.4, M9.3, and C9.5 flares on 15 April 2001, 31 May 2003, and 19 December 2000, respectively.

V. ACKNOWLEDGMENT

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