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Numerical Simulations of the Ionosphere of Mars During a Solar Flare

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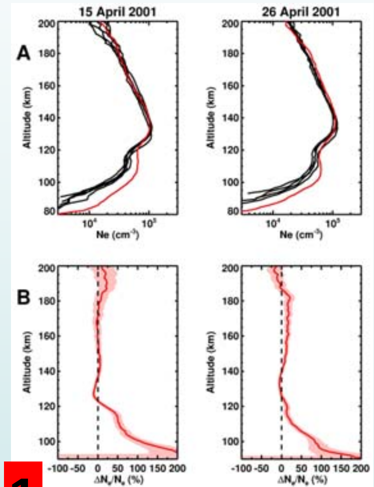
Abstract:

Electron densities in planetary ionospheres increase substantially during solar flares in response to the increased solar irradiance at soft X-ray and extreme ultraviolet wavelengths. Here we modify an existing model of the ionosphere of Mars to incorporate time-dependent solar irradiances and use it to simulate ionospheric conditions during the X14.4 and M7.8 solar flares of 15 and 26 April 2001, respectively. Simulations were validated by comparison to Mars Global Surveyor radio occultation measurements of vertical profiles of ionospheric electron density. Adjustments to the model's representation of the neutral atmosphere were required to adequately reproduce the observations before and during these solar flares. An accurate representation of electron-impact ionization, an important process in the lower ionosphere of Mars, is required in order to adequately simulate the doubling of electron densities that can occur in the lower ionosphere of Mars during a solar flare. We used the W-value representation of electron-impact ionization, in which the number of ion-electron pairs created per photon absorbed equals the ratio of the difference between photon energy and the ionization potential of carbon dioxide to the W-value. A range of possible W-values for Mars have been suggested in the literature and a value of 28 eV led to the best reproduction of flare-affected observations. Simulated enhancements in the electron density are largest and persist the longest in the M1 region. We predict that the peak electron density in the M1 region can exceed that of the M2 region for short periods during intense solar flares.



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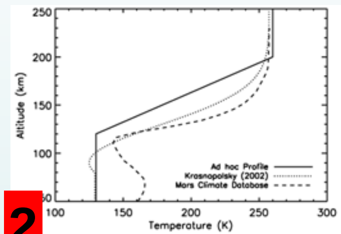

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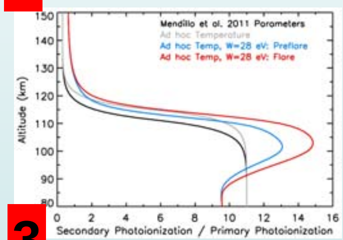

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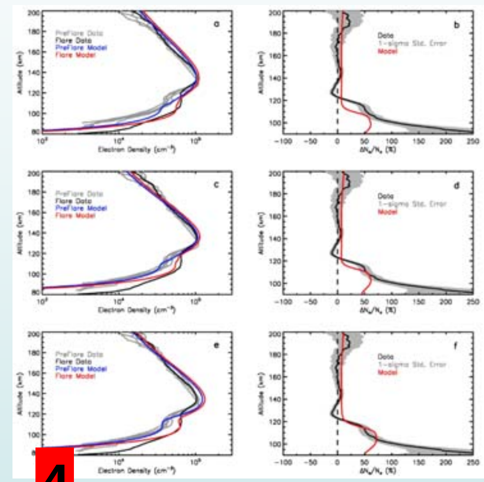

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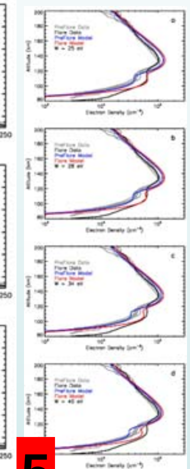

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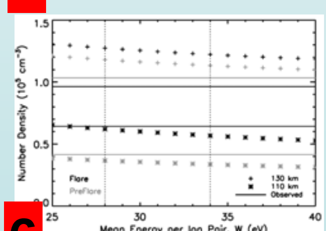

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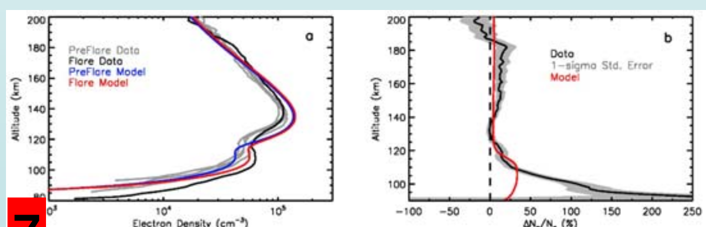

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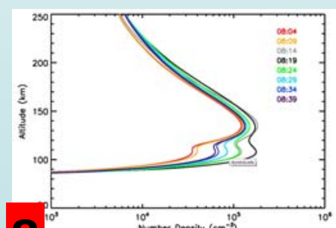

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Results:

Figure 1A shows electron density profiles measured on Mars on 15 April and 26 April 2001. Measurement uncertainty is several thousand e$^-$/cm^3, and so the profiles in red show statistically significant departures at low altitudes due to solar flares. On Apr 15, there were five MGS preflare profiles at 02:28, 06:23, 08:21, 10:19, and 12:17 UT, and none postflare; on Apr 26, preflare profiles at 09:20 and 11:18 UT, and postflare, at 17:11 and 19:09 UT were found. Panel B shows % differences between the flare-affected profiles and the averages of the other profiles on each day. Shadings give the 1-σ error in the relative change in electron density [*Mendillo et al.*, 2006]. Figure 2 shows $T_{neutral}$ for the solar flare model in this work (solid). T_{exo} = 260 K > 200 km, T_{meso} = 130 K @ 120 km. Figure 3 shows the 2^{ndary} ionization parameterized used in this work (blue and red) as the ratio between secondary and primary ionization rates for Apr 15 flare, compared with those used by *Mendillo et al.* [2011] (black and gray). The parameterization adopted in this work assumes a secondary ion-electron pair is produced for every unit *W* of excess energy of the ionizing photon. Here, *W* = 28 eV. Figure 4 shows Apr 15 profiles of simulated and observed electron density (left), and % difference between flare-affected and average background profiles (right). Panels (a) and (b) utilize same model parameters as *Mendillo et al.* [2011]. Panels (c) and (d) show results with an alternate neutral temperature profile. Panels (e) and (f) show the best and final results, which use both the alternate T profile and an alternate 2^{ndary} ionization parameterization, *W* = 28eV. Figure 5 shows Simulated and observed electron density profiles for the Apr 15 flare. Each panel shows results for a different value of *W* used in the secondary ionization parameterization. As *W* is increased, modeled electron density at the peaks decreases. Figure 6 compares simulated (stars) and measured (solid) electron densities of the M1 (110 km) and M2 (130 km) peaks for Apr 15. Simulated electron density at 110 km (M1 peak altitude) and 130 km (M2 peak altitude) for the 15 April flare. Figure 7 shows modeled and observed electron density profiles for the Apr 26 flare, *W* = 28 eV. Figure 8 shows modeled electron density profiles at a few selected times during the 15 April solar flare. The black profile at 08:19, in which the altitude of the peak electron density in the ionosphere is in the M1 layer, rather than the M2.

Modeling:

The model used is an adaptation of the 1-D ionospheric model introduced by *Martinis et al.* [2003] and most recently described by *Mendillo et al.* [2011]. The neutral atmosphere is derived from the Mars Climate Database [*Forget et al.*, 1999; *Lewis et al.*, 1999]. Solar irradiance, is taken from the output of the Solar2000 (v1.24) model [*Tobiska et al.*, 2000; *Tobiska and Bouwer* , 2004], is held constant during a simulation and is attenuated through the atmosphere. Ion-electron pairs are produced by the solar irradiance (primary ionization) in accordance with the relevant ionization cross-sections and neutral number densities. The production of additional ion-electron pairs by electron impact ionization (secondary ionization) is represented by a parameterization of the ratio of secondary to primary ionization. Ion densities evolve due to ion-neutral chemical reactions involving charge exchange, which transfer charge from one species of ion to another without changing the net plasma density. Ion-electron pairs are neutralized by the dissociative recombination of molecular ions. The rates of these loss processes depend on the T_e. Wavelengths shortward of 5 nm dominate the attenuated flux at altitudes below 110 km where the ionospheric response to a solar flare is largest. We expand the two wavelength bins in this region of the spectrum used by *Mendillo et al.*, [2011] into 20 shortest wavelength bins and include suitable cross-sectional information.

Discussion & Conclusion:

The results shown here allow for analysis of flares for which measurements are not available (e.g. Apr 15, postflare). Solar irradiance increases at all wavelengths during the flare, but the largest relative increases occur at the shortest wavelengths (< 5 nm). Similarly, the strongest relative increase in electron density occurs in the M1 region of the ionosphere (100-110 km). The peak irradiance at the shorter wavelengths occurs a few minutes after the longest wavelengths peak, and decays to pre-flare levels more slowly. Likewise, the peak electron density enhancements in the M1 region occur a few minutes after the peak in the M2 region, and persist much longer. Changes in electron density are rapid at flare onset, with values doubling in five minutes or less at all altitudes below 125 km. Electron densities at different altitudes reach their maximum values at different times. Electron densities at the M2 layer (135 km) have nearly returned to their pre-flare values at 08:39, whereas electron densities in the M1 region (108 km) are still significantly elevated. The 08:19 profile of Fig. 8 shows the peak electron density is found in the M1 region, not in the M2 region. This is extremely unusual, as this phenomenon has not been observed or predicted for the dayside ionosphere of Mars.

To conclude, MGS observations of the ionosphere of Mars during solar flares on 15 and 26 April 2001 have been reproduced satisfactorily by our ionospheric model. A key component of the model is the W-value, the energy required to produce one ion-electron pair by electron impact ionization. Our simulations are most consistent with observations for a W-value near 28 eV, as suggested by *Simon Wedlund et al.* [2011], rather than the 34-35 eV value that has extensive heritage from studies of the terrestrial atmosphere. The ionosphere changes rapidly at flare onset, with timescales of a few minutes, but relaxes to its quiescent state more slowly after the flare peak, with timescales of tens of minutes. The low altitude M1 region of the ionosphere is affected much more by flares than is the higher altitude M2 region. We predict that the peak electron density in the M1 region can exceed the peak electron density in the M2 region for short periods during intense solar flares.