RESPONSE OF THE MARS IONOSPHERE TO SOLAR FLARES: ANALYSIS OF MGS RADIO OCCULTATION DATA.
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Summary: The increase in soft X-ray irrandiance during solar flares produces increased electron densities in the lower ionosphere of Mars. Although it is known that relative changes in electron density during a flare are greater for lower altitudes and larger flares, this relationship has not been quantified. This has impeded the validation of simulations of the ionospheric effects of solar flares, which are necessary for the development of accurate descriptions of the physical processes that govern ionospheric behavior under the extreme conditions of a solar flare. Here we develop a response function, a mathematical expression for the change in electron density during a solar flare, that meets this need. This response function is based on analysis of 12 Mars Global Surveyor (MGS) radio occultation electron density profiles which have been affected by solar flares. We find that solar zenith angle also affects changes in electron density during a flare, and that the effects of altitude and solar zenith angle can be combined into dependence on an optical depth proxy. We demonstrate that the observed response function can be used to predict ionospheric electron densities during a specified solar flare and to infer the strength of solar flares visible from Mars, but not Earth.

Background: Solar flares can cause very large, very sudden increases in plasma density in the ionosphere of Mars. These enhancements are greatest at low altitudes, primarily encompassing the M1 layer and below. Determining how the ionosphere of Mars functions during solar flares will improve understanding of the important M1 region and will also test under extreme conditions models that are adequate under quiescent conditions. Although it is clear that solar flares increase M1 densities, and that the relative enhancement in ionospheric density increases with decreasing altitude and with increasing flare strength, the ionospheric effects of solar flares have not yet been characterized to the point of predictability. That is, the relative enhancement in ionospheric density as a function of altitude, flare strength, and any other relevant factors has not been surveyed and quantified. Such a survey is necessary to move beyond a series of individual case studies to a general set of quantitative conclusions about how observable ionospheric properties change in response to a solar flare.

Methods: The 5600 MGS radio occultation electron density profiles (1998-2005) are well-suited to studies of the ionospheric effects of solar flares, since they are numerous, are typically acquired at relatively short intervals of two hours, and encompass the peak and declining phase of a solar maximum. We identify 12 profiles that have enhanced electron densities at low altitudes and that occurred shortly after a solar flare (the "flare group"). We also identify 12 profiles that occurred shortly after a solar flare, but do not have enhanced electron densities (the "control group"). Examples are shown in Figure 1, along with GOES X-ray fluxes. The top row shows data from 13 May 2005, one of the clearest examples from the flare group. Electron densities in one profile are obviously enhanced at low altitudes, and this profile was acquired shortly after an M8.0 flare. The middle row shows data from 28 March 2001, one of the least clear examples from the control group. Low altitude electron densities in one profile are slightly enhanced, and this profile was acquired around the time of an M4.3 flare. The bottom row shows data from 6 April 2001, an example from the control group. Electron densities in the profile acquired near an X5.6 flare are not significantly enhanced at low altitudes.

We compare electron densities in the flare-affected profile to electron densities at similar altitudes and solar zenith angles from other profiles acquired on that date. We also compare the integrated solar irradiance at 0.1 to 10 nm at the time of the ionospheric observation to its background level. We find clear trends for increasing relative enhancement in density with decreasing altitude and increasing relative enhancement in irradiance, but also with increasing solar zenith angle. We develop a proxy for optical depth to combine the effects of altitude and solar zenith angle, then describe the changes in electron density as a function of optical depth proxy and flare intensity (Figure 2). This "response function" provides an adequate description of the response of the ionosphere to a solar flare.

Applications: The empirical response function can be used to test numerical models of the ionospheric response to solar flares. It can also be used to predict the ionospheric response to flares that occurred outside the period of MGS observations, such as the X45 flare of 4 November 2003 and to infer the intensity of flares that were visible from Mars, and hence appreciably affected observed densities there, but where not visible from Earth, where most solar observing assets are located.

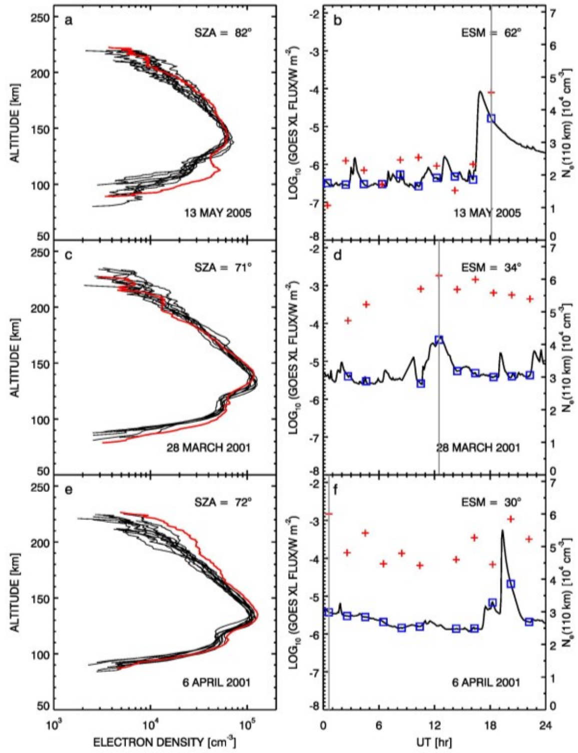

Figure 1. Left column: All electron density profiles measured by MGS on the indicated date. The profile with the greatest electron density at 110 km is highlighted in red. Right column: GOES X-ray solar flux at 0.1-0.8 nm (black curve, left-hand axis). Blue squares at the times at which electron density profiles were measured indicate solar flux. Red crosses at the times at which electron density profiles were measured show the measured electron density at 110 km (right-hand axis). The vertical gray line indicates the time of the profile highlighted in the left column. Solar zenith angle (SZA) and Earth-Sun-Mars angle (ESM) are shown in the left and right columns, respectively.

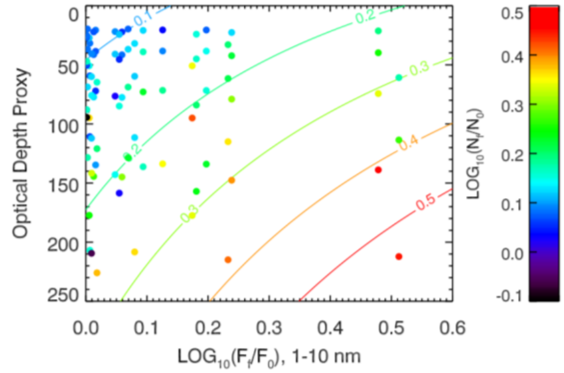

Figure 2. Relative enhancement in observed electron density as a function of optical depth proxy and relative enhancement in solar flux. Data at 95, 100, 105, and 110 km altitude from the flare and control groups are shown as filled circles and contours show the empirical response function fitted to those data.