The response of the Mars ionosphere to solar flares: Analysis of MGS radio occultation data

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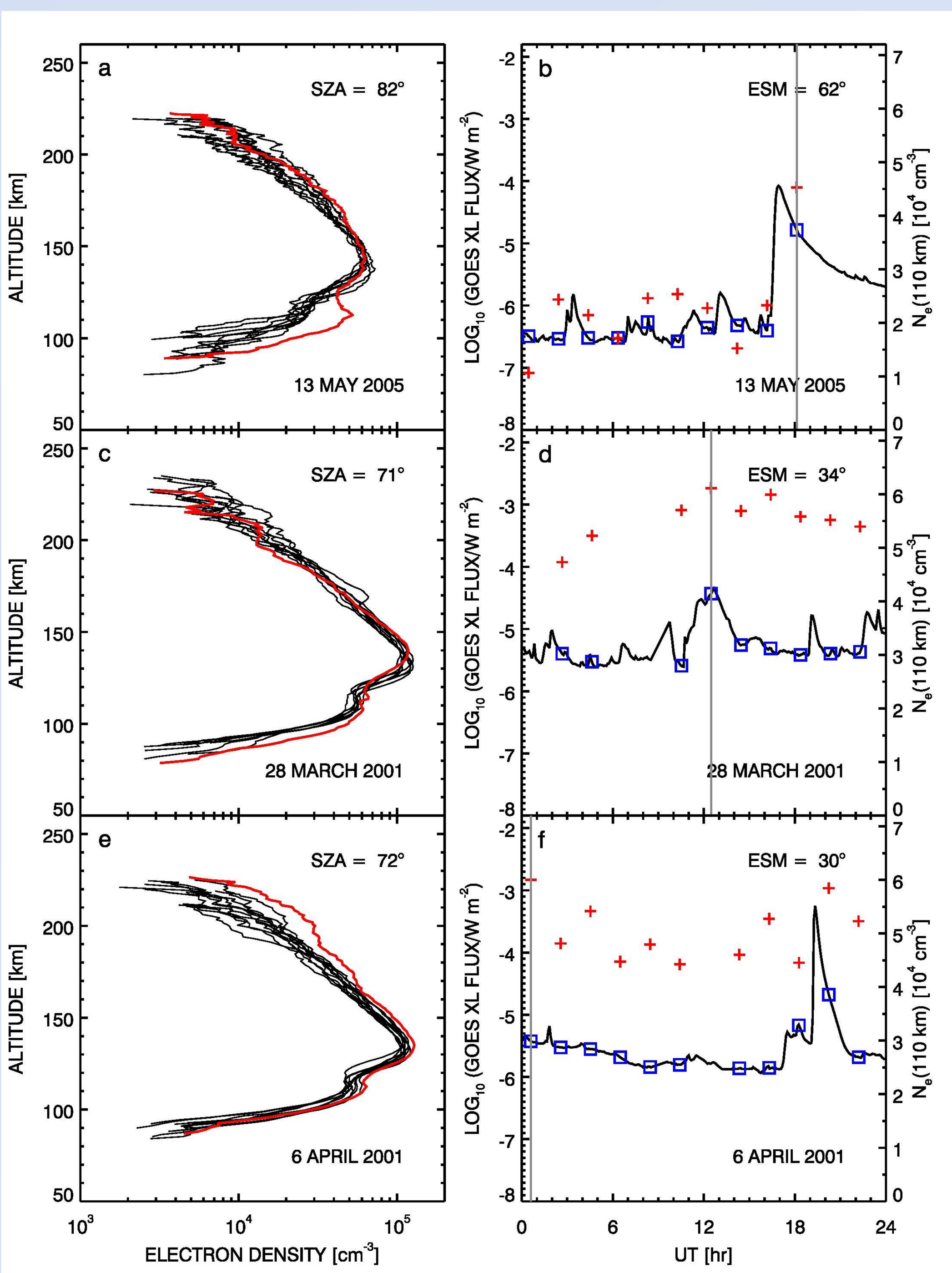
Abstract: During a flare, the increase in solar flux at X-ray and EUV wavelengths causes an enhancement in electron densities in planetary ionospheres. Although it is known that relative changes in electron density during a flare are greater for lower altitudes and larger flares, this relationship has not been quantified. Here we develop a response function, a mathematical expression for the change in electron density during a solar flare, 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. The response function is used to test to a 1D numerical model of the ionospheric response to a solar flare. 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.

MGS radio occultation profiles affected by solar flares

Two sets of Mars Global Surveyor radio occultation profiles are identified: (1) profiles which show low altitude enhancements in electron density due to a solar flare, and (2) profiles which occur during flares but appear unaffected.



Left – All MGS radio occultation profiles measured that date. The profile with the greatest electron density (N_e) at 110 km is highlighted.

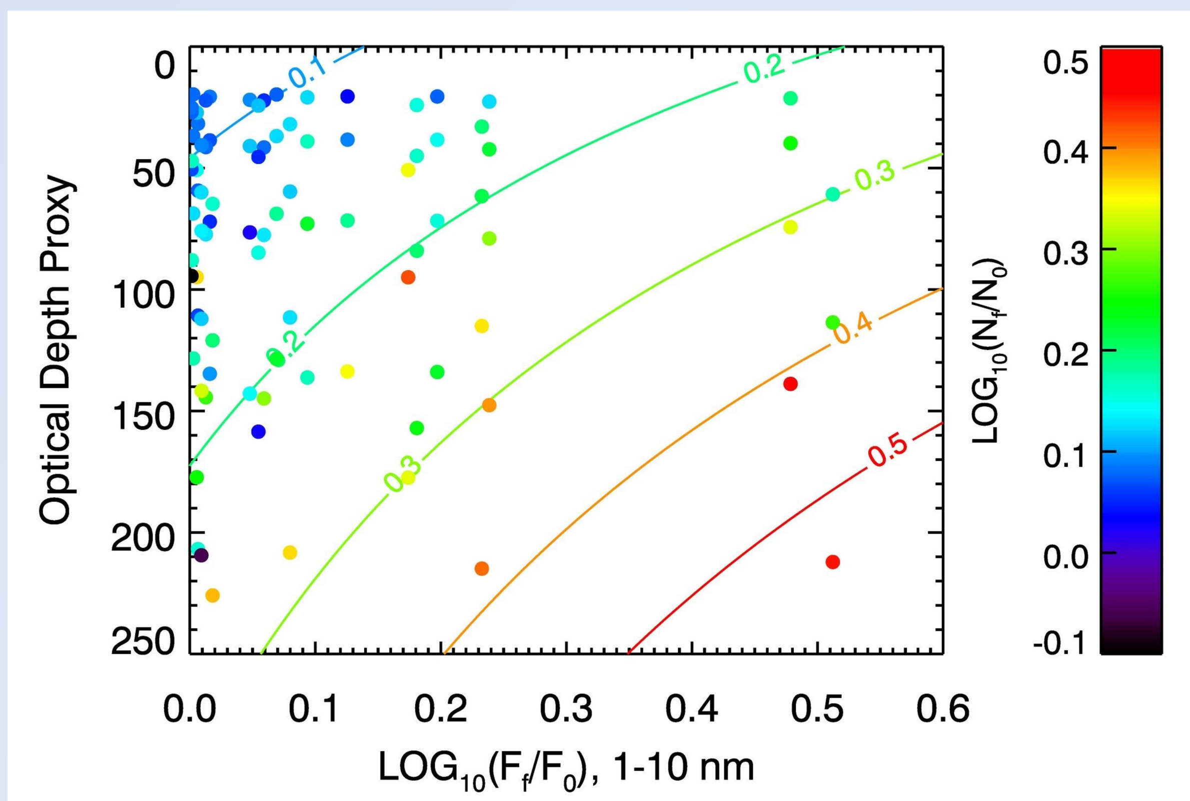
Right – The GOES XL solar flux as a function of time during that date, (solid line), and N_e (110 km) of each profile, at the time the profile was measured, (crosses).

May 13, 2005 and March 28, 2001 – the highlighted profile has the greatest N_e at and below the M1 peak (~110 km), and this profile coincides with a solar flare. These profiles have been **affected by the solar flare**. We include 12 such dates in this analysis.

April 6, 2001 – the profile which coincides with the solar flare does not show a significant increase in N_e above the other profiles below the M1 peak. This profile is **not affected by the solar flare**. We include 13 such dates in this analysis.

Takeaway: An empirical characterization of the response of the Mars ionosphere to solar flares is developed. It can be used to constrain models, and to predict the enhancement in ionospheric electron density or in solar flux during a flare.

Observed Ionospheric Response



$$\log(N_f/N_0) = 0.002\ log(F_f/F_0)\,\tau + 0.261\ log(F_f/F_0) + 0.001\ \tau\ + 0.064$$

A response function characterizes the dependence of the ionospheric response on the increase in solar flux and on atmospheric depth.

Enhancement in electron density, as a function of the **enhancement in solar flux** and an **optical depth proxy**. The optical depth proxy is defined as:

$$\tau = n_0 e^{\frac{z_0 - z}{H}} \sigma_a H \sec\chi$$

where n_0, H, and σ_a are chosen so that τ =1 at the M2 peak, (125 km). This optical depth proxy is designed to function like altitude, but to also account for solar zenith angle.

Four points are chosen from each profile, at 95, 100, 105, and 110 km. The data are fit with a function of the form:

$$\log(N_f/N_0) = A log(F_f/F_0)\,\tau + B log(F_f/F_0) + C\tau\ + D$$

This fit is shown as **colored contours**. This function provides a quantitative characterization of the ionospheric response to solar flares.

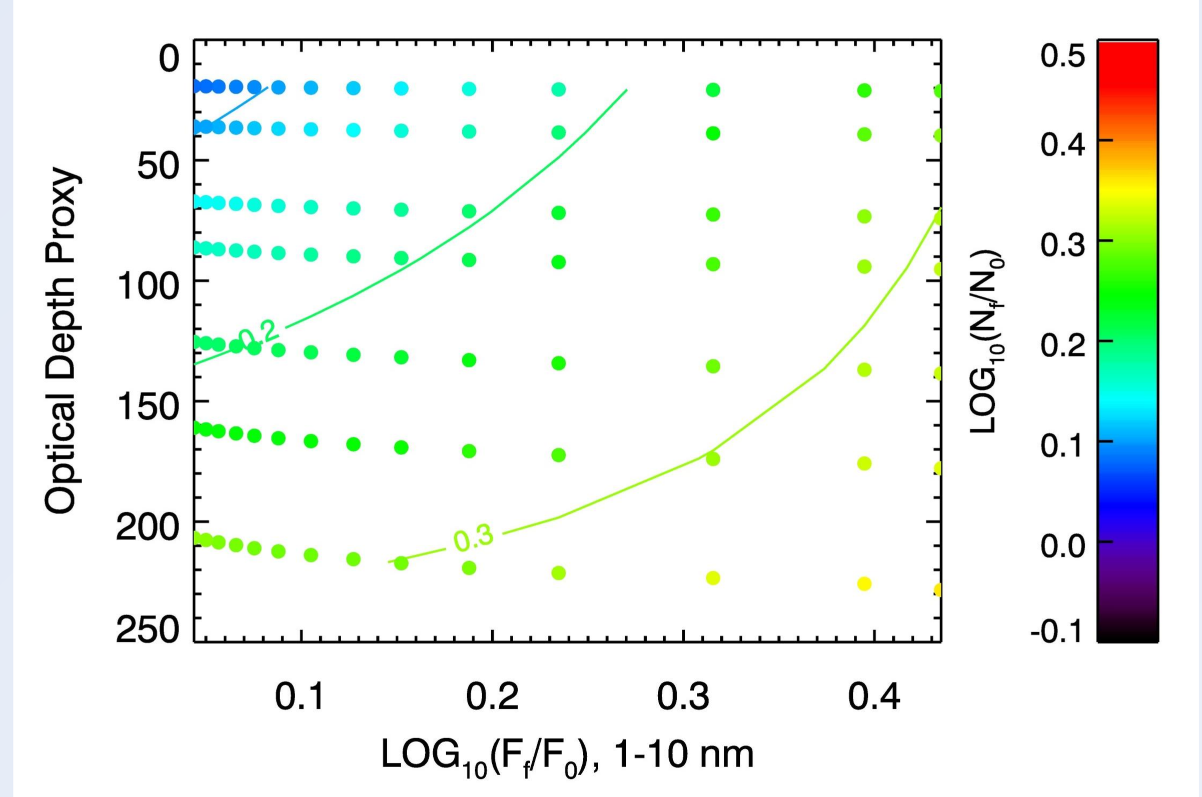
Modeled Ionospheric Response

A model of the ionospheric response to a solar flare shows similar trends as those observed.

The same quantities as above are shown from the results of a **1D photochemical model** of ionospheric electron density during the April 15, 2001 solar flare[1]. A portion of the model results are selected to cover the same optical depths and flux enhancements as the MGS profiles.

The functional fit to the model results is broadly similar to that of the observations. However, the gradient with respect to depth is stronger in the model, relative to the gradient with respect to flux enhancement. Further modeling of individual flare events are required to determine whether this is due to data-model differences, or whether the time evolution of this single event is not representative of the ensemble of events observed.

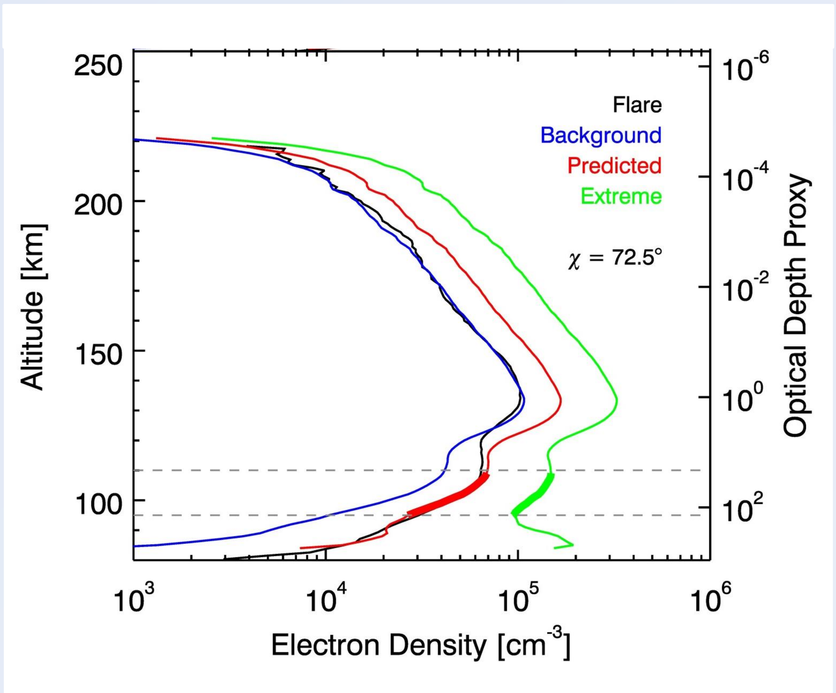
1. Lollo, A., et al. (2012), Numerical Simulations of the ionosphere of Mars during a solar flare, *J. Geophys. Res., 117, A05314, oi:10.1029/2011JA017399.*



$$\log(N_f/N_0) = -0.002\ log(F_f/F_0)\,\tau + 0.568\ log(F_f/F_0) + 0.001\ \tau\ + 0.034$$

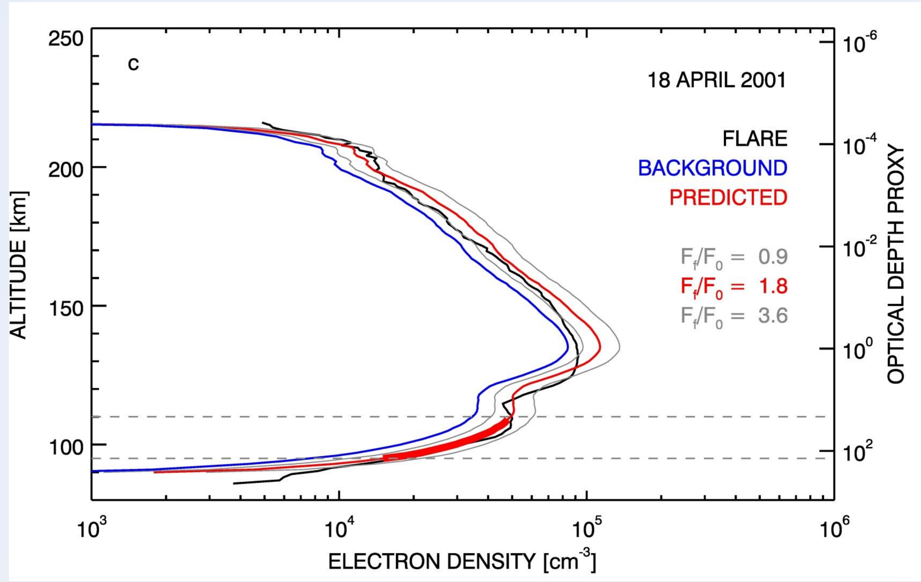
Predicting Ionospheric Response

The simple characteristic function can be used to predict the ionospheric response to a solar flare, or the strength of the flare.



The profile above shows the **predicted enhanced profile (red)** for one flare event, compared with the average of the background profile, (blue), and the observed enhanced profile (black). Dashed gray lines indicate the altitude range for which this fit is applicable. The predicted enhanced profile is in good agreement with the observed flare-affected profile in this region.

The green profile indicates a prediction for a hypothetical extreme case, and is calculated with the flux enhancement during the X45 solar flare of November 4, 2003.



The red profile above is predicted by the response function, given the background profile (blue) and a specified flux enhancement. The predicted profile is a good match to the observed enhanced profile (black), when a flux enhancement of F_f/F_0 = 1.8 is assumed, suggesting that **a flare in which the solar flux with this strength could be responsible for the observed ionospheric response.**