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 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.

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 in solar flux during a flare.

Observed Ionospheric Response

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:

\[ \tau = n_0e^{\frac{2\pi r}{\sigma_a H \sec \chi}} \]

where \( n_0 \), \( H \), and \( \sigma_a \) are chosen so that \( \tau = 1 \) at the striated 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:

\[ \log(N_e/N_0) = A \log(F/F_0) \tau + B \log(F/F_0) + C \tau + D \]

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

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. 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 is 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.

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.