Simulations of the effects of extreme solar flares on technological systems at Mars

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Personnel

- Paul Withers (Boston University, PI)
- Student (Boston University)
- Michael Mendillo (Boston University, collaborator)
- Phil Chamberlin (University of Colorado, collaborator)
- Marina Galand (Imperial College, collaborator)

Summary

- Extreme space weather events modify the ionosphere of Mars, affecting the performance of existing and future navigations/communications systems
- Effects
  - Range error in GPS-like systems
  - D-region absorption reduces signal strength
  - Others? Scintillation?
- Events
  - Nominal conditions
  - Meteors
  - Cosmic rays (plasma at very low altitudes?)
  - Energetic particle events (plasma at low altitudes?)
  - Solar flares

Method

- Obtain vertical profiles of plasma density (data and models)
- Calculate range error, D-region absorption and anything else relevant using that profile
- Examine how effects on nav/comm systems vary with type and intensity of space weather forcing, radio frequency, and other possible factors

GPS-like range errors between lander and orbiter

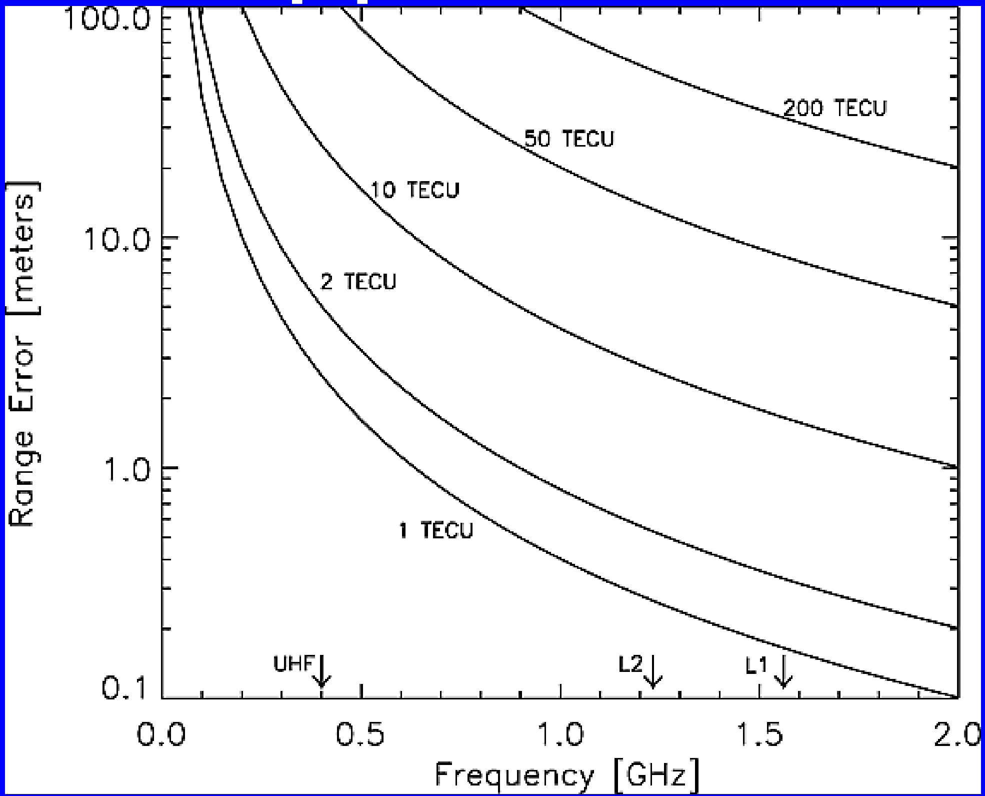
$$\Delta D = 0.403 \ \frac{TEC_{LOS}}{f^2}$$

$$TEC_{LOS} = \int Ne \ ds$$

$$TEC = TEC_{LOS} \cos(OZA)$$

- One-way range error (ΔD in m) depends on line-of-sight total electron content (TEC_{LOS} in 10^{12} cm^{-3}) and frequency (f in GHz)
- TEC_{LOS} depends on zenith angle (OZA) between lander and orbiter
- Plausible frequencies include 40 MHz (aircraft and cordless phones), 400 MHz (UHF, Electra), 1.5 GHz (GPS)

Approximate Range Errors



The main layer of the Mars ionosphere can be crudely approximated as a Chapman layer with scale height of 10 km and subsolar peak electron density (N_m) of 2×10^5 cm^{-3}. Since TEC ~ 4 N_m H for a Chapman layer, subsolar TEC on Mars is ~ 10^{12} cm^{-2} or 1 TECU. A 400 MHz GPS network with a 1 TECU ionosphere and sec(OZA) ~2 will have a range error of ~5 m (Fig 6).

$$\Delta D = 0.403 \frac{TEC}{\cos(OZA) f^2}$$

- How large a value of ΔD is significant?
  - <1 m, 1 m, 100 m?
- Dayside TEC varies by approximately 1 order of magnitude
- 1/cos(OZA) varies by 1 order of magnitude from OZA=0 to OZA=85°
- $1/f^2$ dependence may be more important than ionospheric variations

D region absorption

$$K = \frac{e^2}{2mc\varepsilon_0}\frac{Ne}{\mu}\frac{\nu}{\left(\nu^2+\omega^2\right)}$$

$$\mu^2 = 1 - \frac{Ne\, e^2}{m\varepsilon_0\omega^2}$$

$$\frac{Er}{Et} = \exp\left(-\int K\, dl\right)$$

$$\frac{Er}{Et} = \left(\exp\left(-\int K\, dz\right)\right)^{\sec(OZA)}$$

- E = radio wave amplitude
- l = distance
- K = dE / (E dl)
- ν = e-CO_2 collision frequency, 100x greater than for e-N_2
- Er = received amplitude
- Et = transmitted amplitude
- Let A = Er/Et, the attenuation factor

- Low frequencies are attenuated more than high frequencies

Approximate attenuation

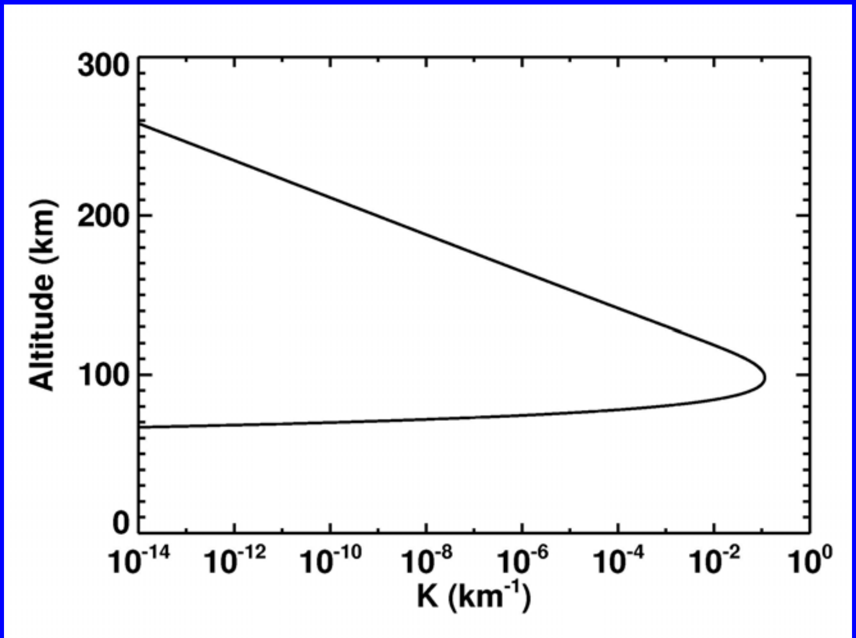


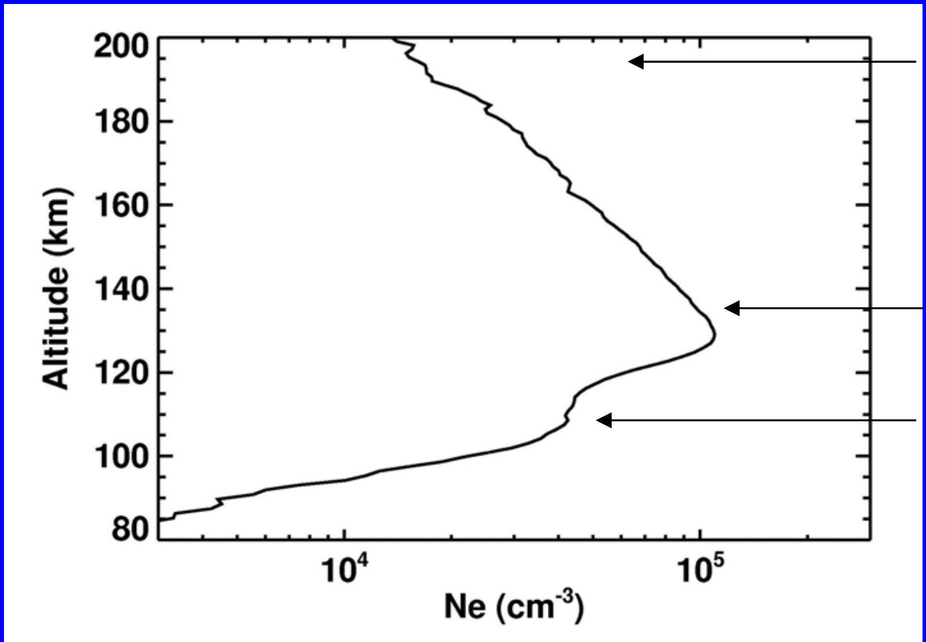
Fig 7. K(z) for f=5 MHz. The electron gyrofrequency is much smaller than the transmitted frequency for f > 1 MHz and B < 100 nT, so martian crustal magnetic fields have no effect on radio wave attenuation (Rishbeth and Garriott, 1969, Eqn 206).

- For nominal ionosphere, A = 0.10 for 5 MHz and 0.98 for 50 MHz
- Ne $\nu/(\nu^2 + \omega^2)$ term, with ν proportional to neutral density, means that plasma at low altitudes is much more "effective" than plasma at high altitudes
- Solar flares, meteors, cosmic rays, solar energetic particles all increase plasma densities at low altitudes

Any other effects?

- Do you know of any other effects that plasma has on radio waves and navigation/communication systems that can be calculated easily given an electron density profile?

Nominal Ionosphere



Topside. Mixture of O^+ and O_2^+ ions, controlled by plasma transport

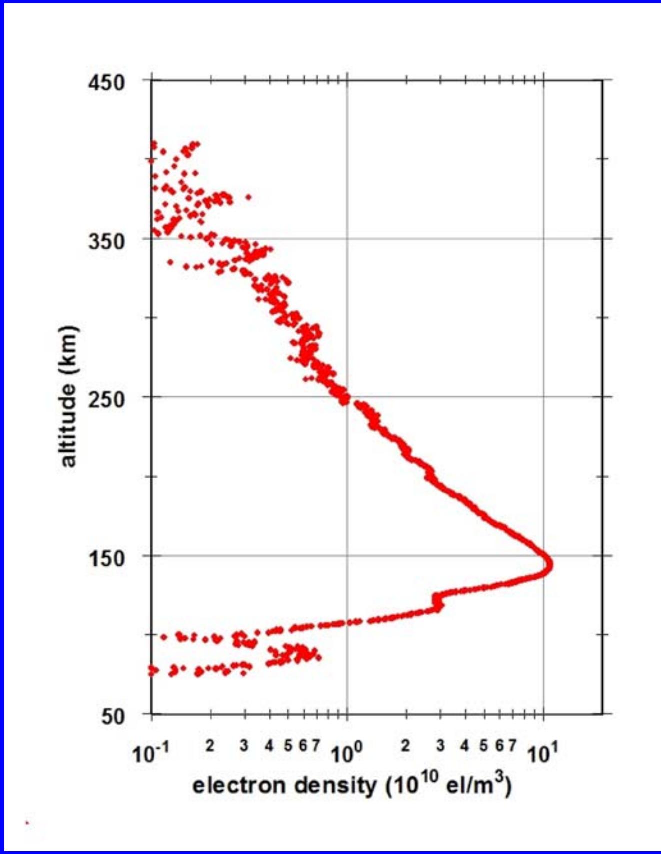
Main layer. O_2^+ ions, controlled by photoionization from 10-100 nm EUV photons.

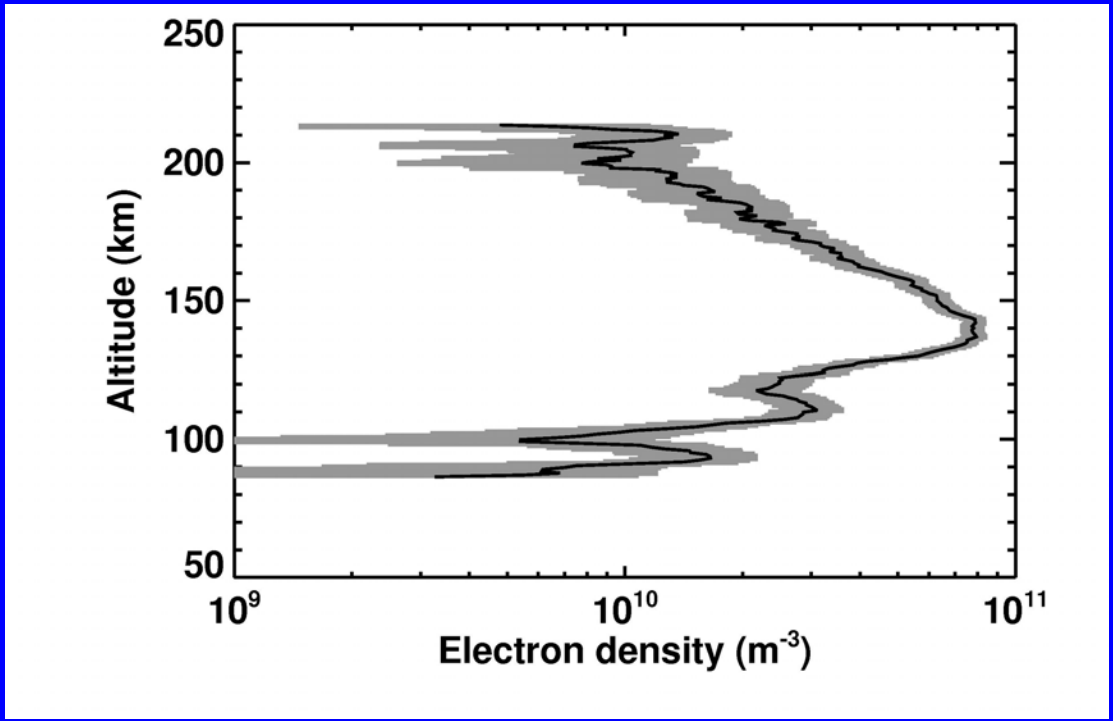
Lower layer. O_2^+ ions, controlled by photoelectron-impact ionization after photoionization by 1-10 nm X-ray photons.

(Typical MGS RS profile)

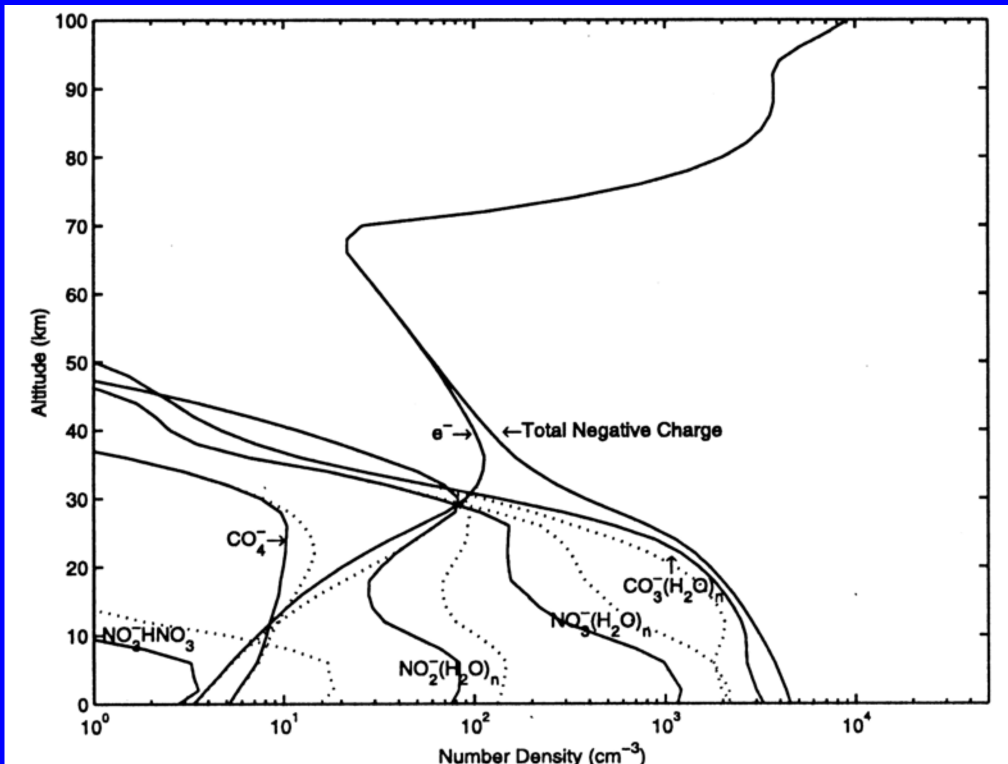
- Essentially varies only with solar zenith angle (SZA) and solar irradiance
- Lots of data available (MGS, MEX)
- Can approximate by simple functions as well, if needed
- Several workers have published set of simulated profiles for standard conditions

Meteors





- Plasma layer at 80-90 km, below normal layers
- Effects on D-region absorption are greater for low z plasma than for high z plasma
- ~150 meteoric layers detected by MGS and MEX; width, height, plasma density vary
- Some model simulations published, but very preliminary



Cosmic rays

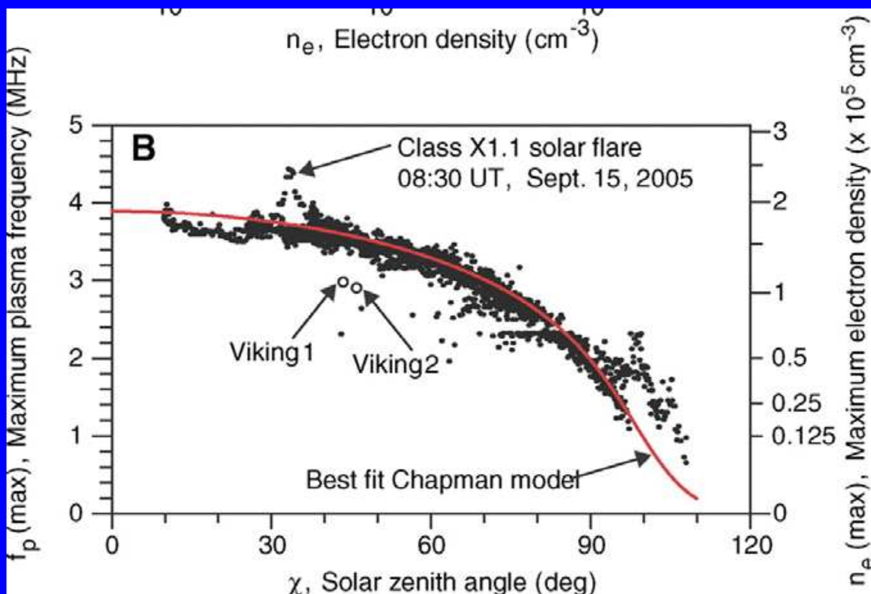
Fig 11. Number densities of electrons and negative ions in the lower Mars ionosphere. Wet case (solid lines) and dry case (dashed lines). From Molina-Cuberos et al. (2002).
No measurements capable of detecting low altitude plasma have been made at Mars. However, the failure of MARSIS to receive radar signals reflected from the Mars surface after major solar energetic particle events suggests that low altitude plasma does exist (Morgan et al., 2006; Espley et al., 2007).

- Cosmic rays are predicted to produce electron densities of 100 cm^{-3} between 30 km and 50 km.
- Calculate attenuation caused by plasma at very low altitudes

Solar energetic particles

- MARSIS topside radar sounder does not detect signal reflected from martian surface for ~1 week after solar energetic particle events
- Protons at 10s of MeV collisionally ionize neutral atmosphere somewhere below 100 km, plasma is long-lived and strongly attenuates radio signals
- Analogous to terrestrial polar cap absorption events (PCAs)
- <u>Predicted Ne(z) profile needed!</u>

Solar Flares (1)



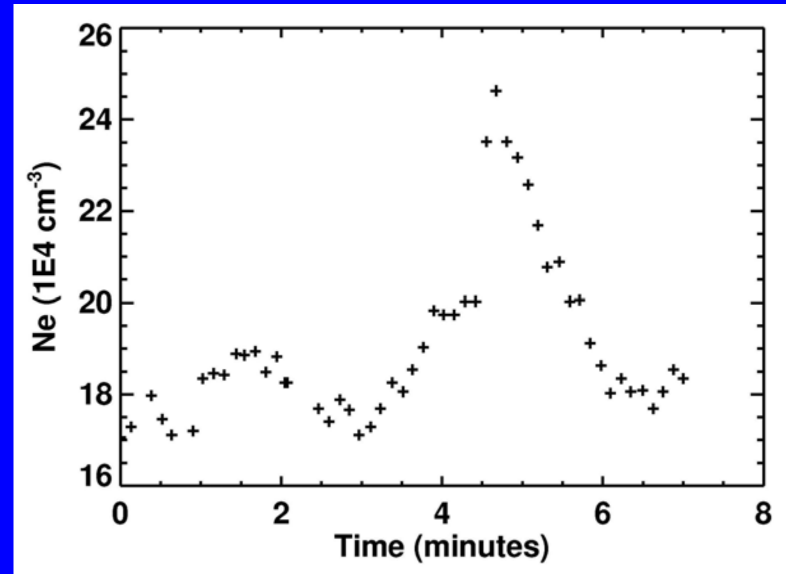
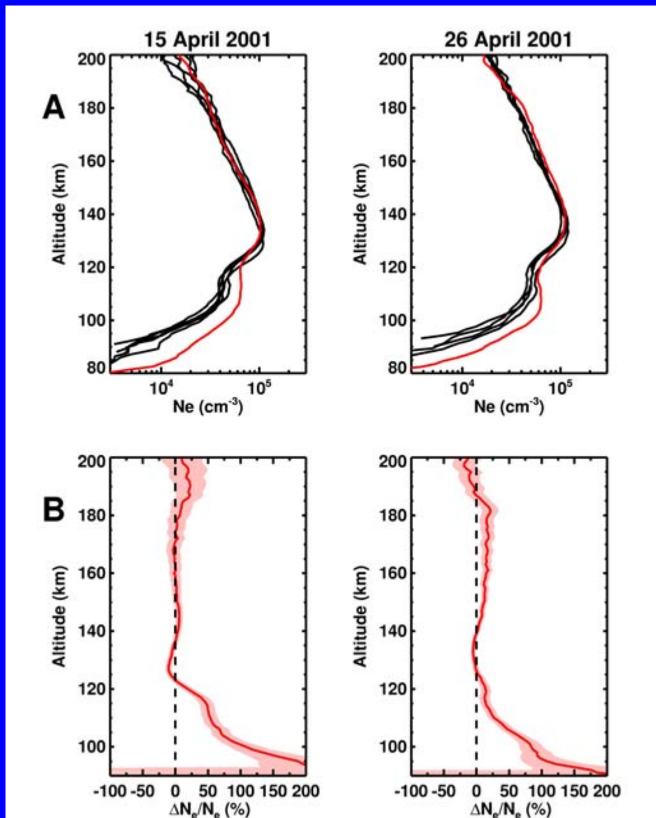


Fig 3. Seven minutes of MARSIS topside radar sounder data at constant solar zenith angle from 15 Sep 2005. Peak Ne increased from 1.8 x 10^5 cm^{-3} to 2.4 x 10^5 cm^{-3} during an X1.1 solar flare (Gurnett et al., 2005; Nielsen et al., 2006).

- Peak plasma densities increases by tens of percent during X-class solar flare
- MARSIS topside radar sounder measures peak plasma density >1/minute, but can't observe below the peak

Solar Flares (2)



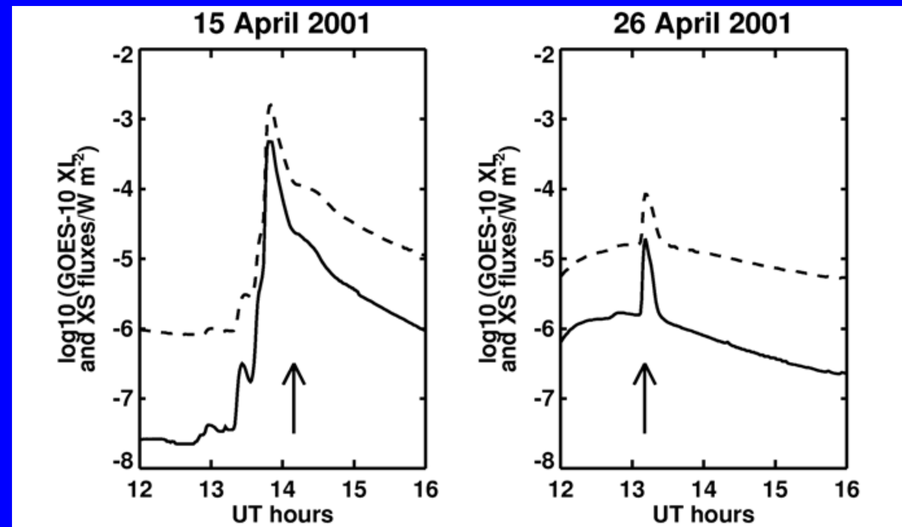
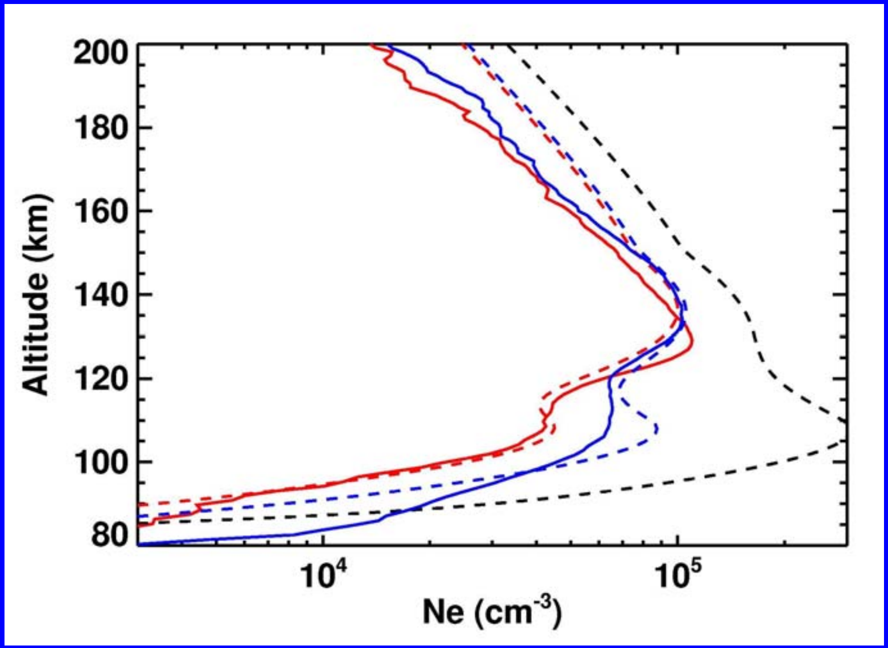


Fig 5. Solar X-ray flux at Earth. GOES XS (solid line, 0.05-0.3 nm) and XL (dashed line, 0.1-0.8 nm) data. Times of MGS Ne(z) are arrowed.

- About 10 MGS Ne(z) profiles show enhancements in bottomside plasma densities consistent with solar flares
- Excellent vertical range and resolution, but measurements made at 2 hour intervals

Solar flare model



Solid lines = MGS profiles
Dashed lines = Simulations with constant solar irradiance

Red = Pre-flare irradiance
Black = Peak irradiance
Blue = Irradiances 20 mins after peak

- 1-D model, transport neglected. Option to use time-varying solar irradiance

- Red simulation (pre-flare irradiance) reproduces the observed profile well
- Blue simulation (20 mins after peak) does not reproduce the observed profile well below 120 km
- What model parameters need improvement or can be adjusted?

Things to vary in model

- Permit time-varying solar irradiance
  - Already implemented with FISM irradiances from collaborator Phil Chamberlin; 0.5-195.5 nm, 1 nm resolution, 1 min cadence
- Adjust secondary ionization parameterization
  - 10 ion-electron pairs formed by electron-impact ionization for every one formed by photoionization at lower layer and below. R = 10
  - Currently using specified R(z), plan to investigate range of possibilities, including wavelength dependence, with advice from collaborator Marina Galand
- Neutral atmosphere, reaction rates, cross-sections
  - Probably relatively minor influence for plausible variations

Simulation plans

- Select some interesting flares, get FISM irradiances
- Run simulations using various parameterizations for R and range of solar zenith angles
- Use simulated vertical profiles to calculate ranging errors and D-region absorption for range of frequencies

Summary of Planned Work

- Acquire many electron density profiles
  - From observations, published figures and any simulations from other members of this focus team (easy)
  - Perform simulations of solar flare effects, adjusting parameters to get reasonable results (hard)
- Calculate values of ΔD and A for each profile and ranges of f, OZA (easy)

Team activities

- If you model how various energetic particle events (solar CMEs, cosmic rays, others) affect the martian ionosphere, then I would like to use your Ne(z) profiles
- Team should chose space weather events to study where MGS Ne(z) profiles show effects of solar flare, if possible
- Other useful collaborations?