# Observations of the Effects of Solar Flares on Earth and Mars

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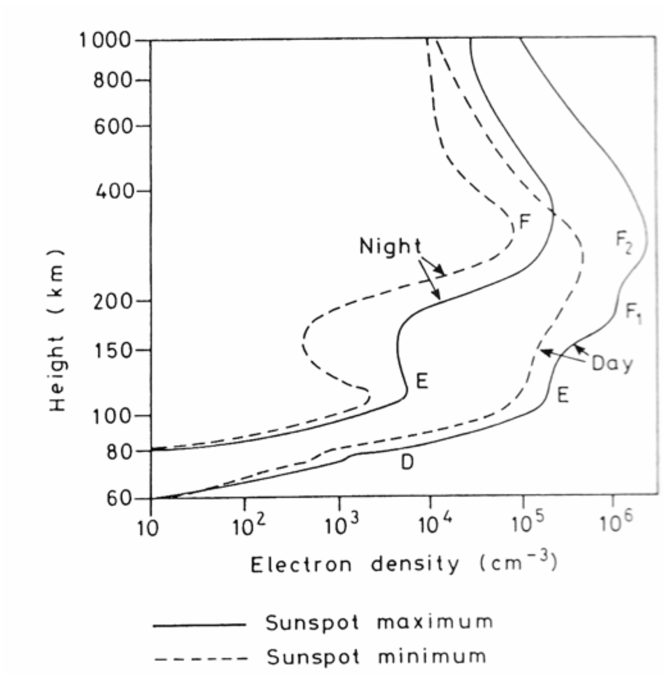
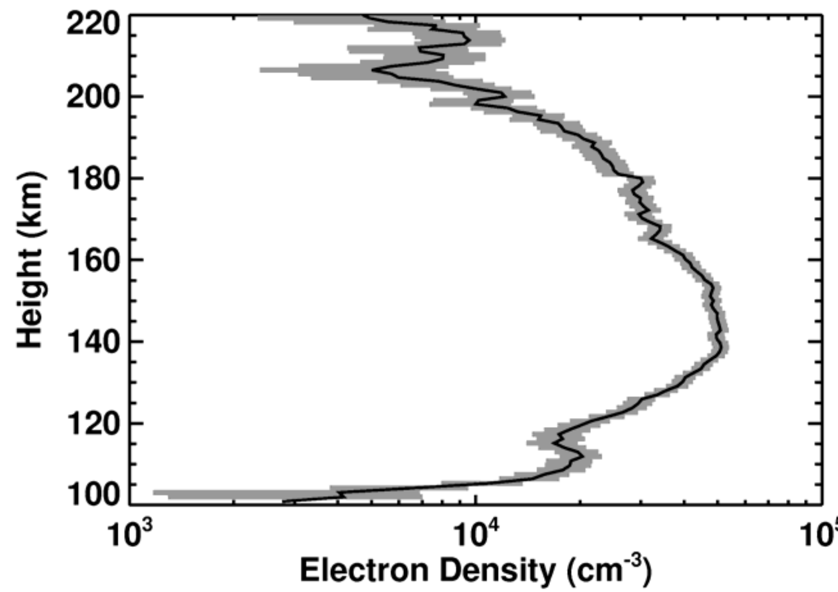
Fall AGU 2005, #SA53B-1165
San Francisco, 2005.12.09

# Abstract

Disturbances on the Sun affect the other bodies in the solar system and their environments. Solar flares cause sudden ionospheric disturbances at Earth and coronal mass ejections cause geomagnetic storms and auroral displays at Earth and other planets. We present the first observations of the effects of a solar flare on the upper atmosphere of another planet. A large solar flare on 15 April 2001 caused electron densities in the bottomside martian ionosphere to increase by 100 to 200 percent. Electron densities in the terrestrial ionosphere also increased in response to the flare. Comparative studies of events such as these will improve our knowledge of the solar X-ray spectrum and secondary ionization yields from the interaction of X-rays and molecules.

# Typical Ionospheric Profiles



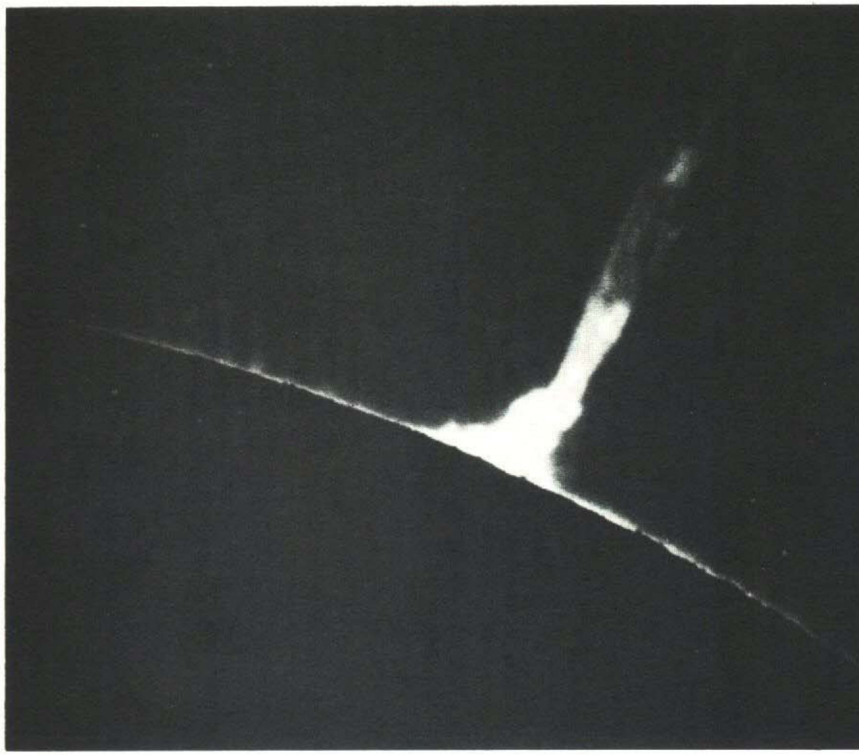




Earth (Hargreaves, 1992)
F layer due to EUV photons
E layer due to soft X-rays
D layer due to hard X-rays

Soft ~ 10 nm, hard ~ 1 nm

Mars (MGS RS data)
Main peak at 150 km due to EUV photons
Lower peak at 110 km due to X-rays. Lower peak is very variable and often absent

# Solar Flares

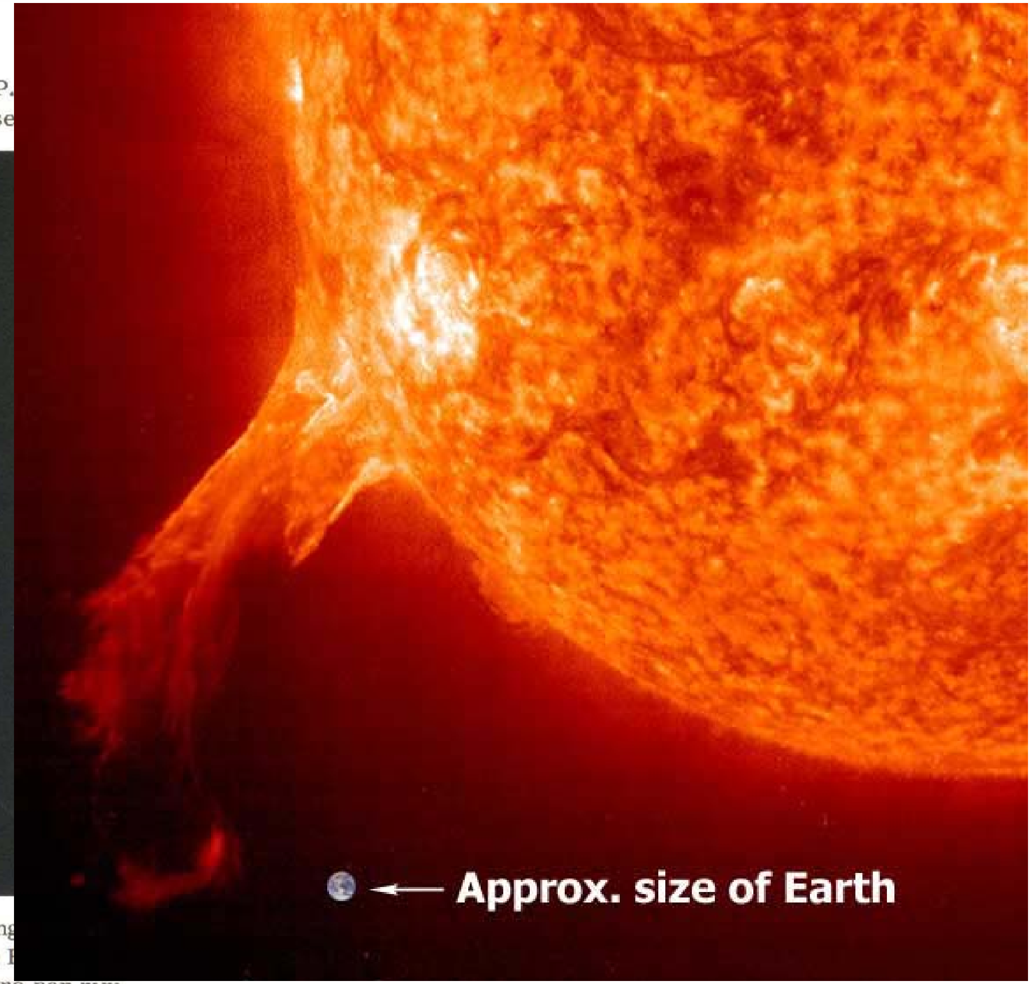


*SOLAR FLARE PHOTOGRAPHED AT BOYDEN OBSERVATORY*
*ON THE 11TH AUGUST 1972, AT 14h44m SAST*

The accompanying photograph, taken by Mr. H. Bacik and Mr. J. P. … has been sent to us by Prof. A. H. Jarrett, Director of the Boyden Obse…

The photograph was taken with a 15 cm aperture solar telescope using … ference filters in series giving an effective halfwidth of 15Å centred on … 6563Å. The scale on the original 35 mm negative was 6.4 seconds of arc per mm, the photograph being enlarged ten times. The film was Kodak infrared high speed 2481, and exposure time four seconds.

A Fabry-Perot interferometer was placed between the filters and the camera to investigate the tem… fringe halfwidths - some of the H alpha fringes can be seen on the photograph to the left of the flare. (The photograph has been processed to emphasize the flare itself rather than the fringes which cross it).




http://www.assabfn.co.za/pictures/solar_boydenflare_historical_articles.jpg

http://rednova.com/news/stories/1/2003/10/24/story002.html

# Changes in Flux during a Flare

- At a given wavelength, flux increases from background level to a maximum in a time ~ minutes, then decreases to background level in a time ~ hours. Timescales do not depend much on wavelength

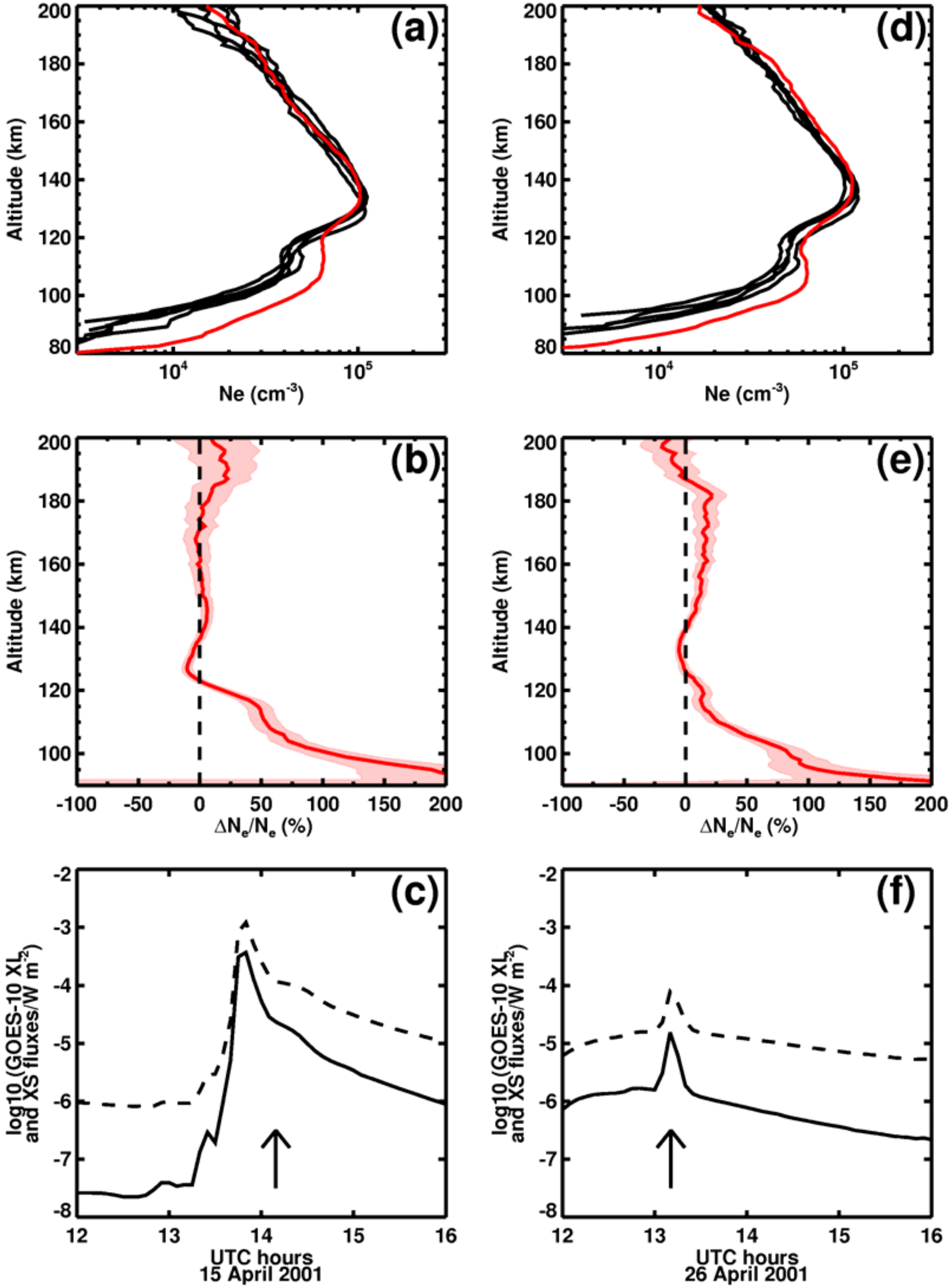
- Flux changes more at short wavelengths than at long wavelengths

- EUV flux barely increases, soft X-ray flux increases by a factor ~ tens, hard X-ray flux increases by a factor ~ hundreds

# Effects of Solar Flares on an Ionosphere

- X-rays penetrate into regions where plasma transport is negligible and photochemical processes dominant
- Shorter wavelengths penetrate deeper

- D region time constant ~ 30 min (daytime)
- E region time constant ~ 10 min (daytime)
- Mars time constant ~ few minutes at 110-150 km (daytime)




(a) MGS RS electron density profiles from 15 April 2001. Electron densities are enhanced at low altitudes for one profile, marked in red.

(b) Percentage difference between the red, enhanced profile and the mean of the black, non-enhanced profiles

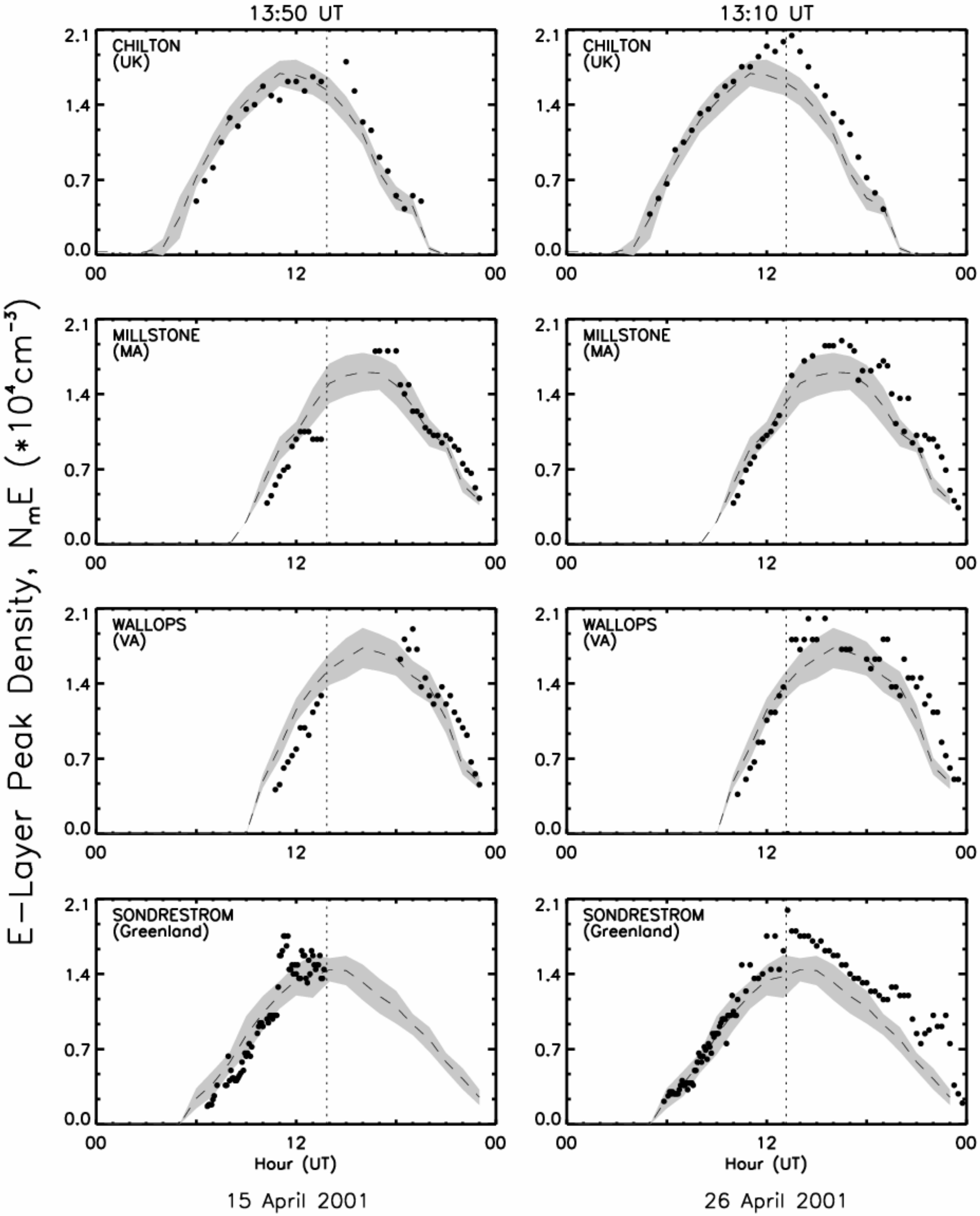
(c) X-ray fluxes at Earth on this day between 0.5-3 A (solid, XS) and 1-8 A (dashed, XL). Arrow marks observation time of enhanced profile. Data from GOES satellites

(d), (e), (f)

As (a), (b), (c) but for 26 April 2001

# Two clear ionospheric responses to solar flares

- In both cases, the increase in electron density is largest at low altitudes, consistent with the relative increase in flux being greatest for the most penetrating, short wavelength, X-rays
- Observed X-ray fluxes increased by orders of magnitude during flare – why did electron density only increase by 50-100%?
  – Because ionization around 100 km is caused by ~5 nm photons, but GOES only observes X-rays shorter than 0.8 nm. It is very plausible that fluxes at ~5 nm increased by $1.5^2$ to $2.0^2$, or 2.25 to 4.0



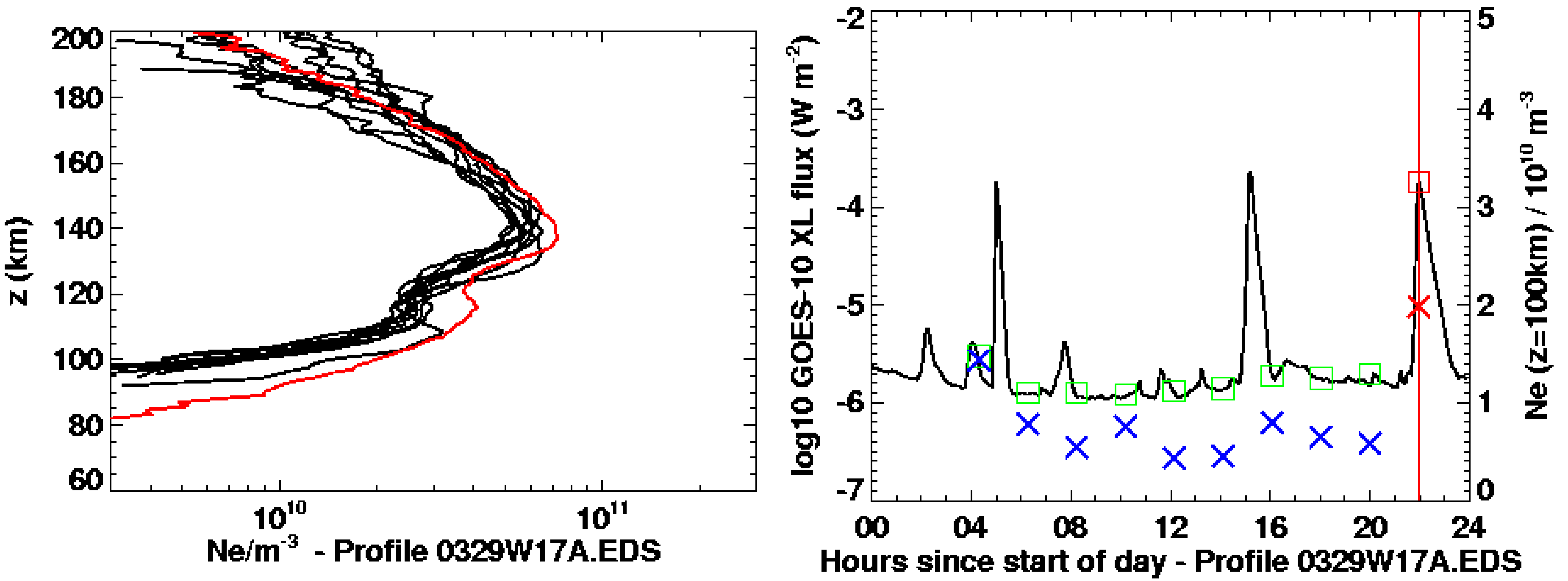

Measurements of the terrestrial ionosphere on 15 and 26 April 2001, left and right columns respectively. Dots are observations, dashed lines and shaded areas are average values for the month. Vertical lines show times of peak flare fluxes.

The 15 April flare, X14.4 magnitude, was so strong that the ionosonde's radio signal was absorbed by increased electron densities in the D region and the E region was not observable

The 26 April flare, M7.8 magnitude, did lead to increased E region densities

# Additional observations of similar ionospheric enhancements

- We have found 30 additional examples of ionospheric enhancements at Mars in the 3749 profiles archived by MGS using an automatic detection algorithm.
- We have compared the changes in electron density in the 32 enhanced profiles at Mars, the solar X-ray flux at Earth, and the Earth-Sun-Mars angle.
- We find that:
  - Large X-ray fluxes at Earth are more likely to be coincident with enhanced electron densities at Mars if the Earth-Sun-Mars angle is small than if it is large.
  - The increase in electron density is large when the increase in solar flux is large, but small when the increase in solar flux is small.
  - The increase in electron density increases as altitude decrease
- Short wavelength X-ray fluxes observed at Earth are not always large when enhanced electron density is observed at Mars
- We conclude that enhanced bottomside electron densities on Mars are caused by increases in solar flux. Models suggest that photons of 1-5 nm are responsible.



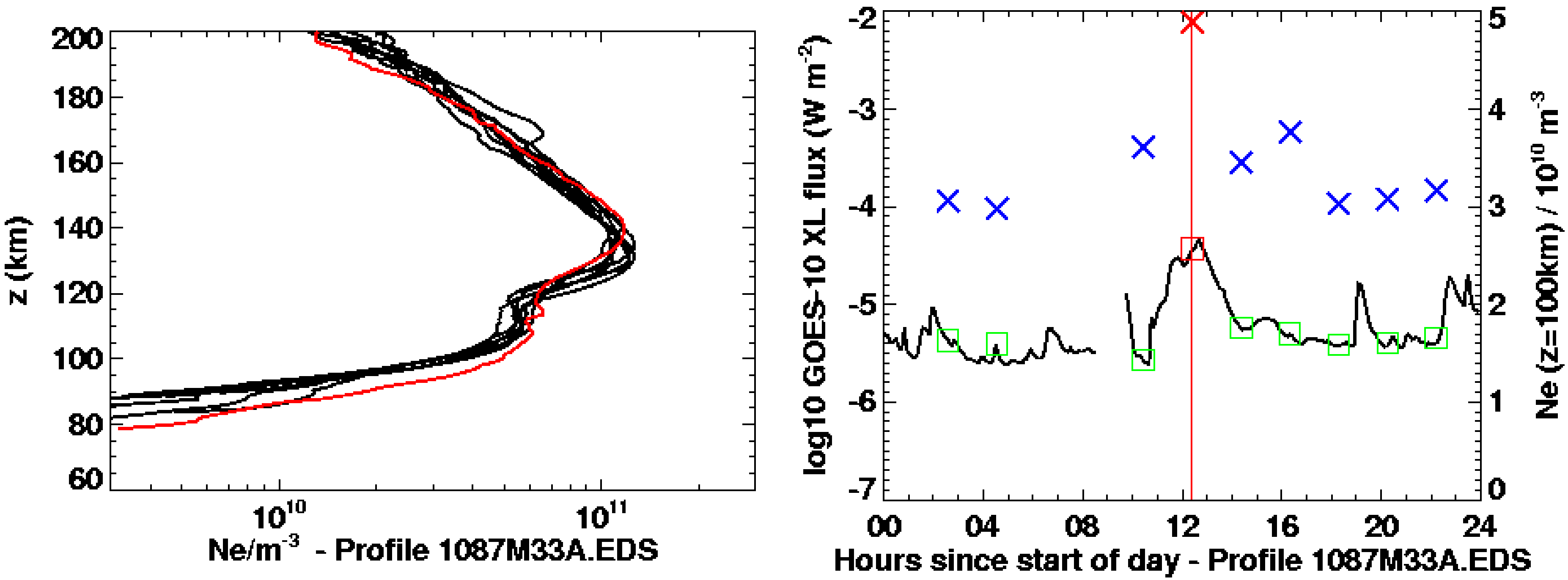

Left panel. Profile with enhanced electron density (red line) and other profiles from that day (black lines)

Right panel. GOES 1-8 A flux at Earth (black line), with values during occultations at Mars highlighted by green squares.

Blue crosses show electron density at 100 km. Red symbols indicate values from the red profile in the left panel.

Very clear enhancement in electron density below 120 km

Coincident with large increase in flux at Earth

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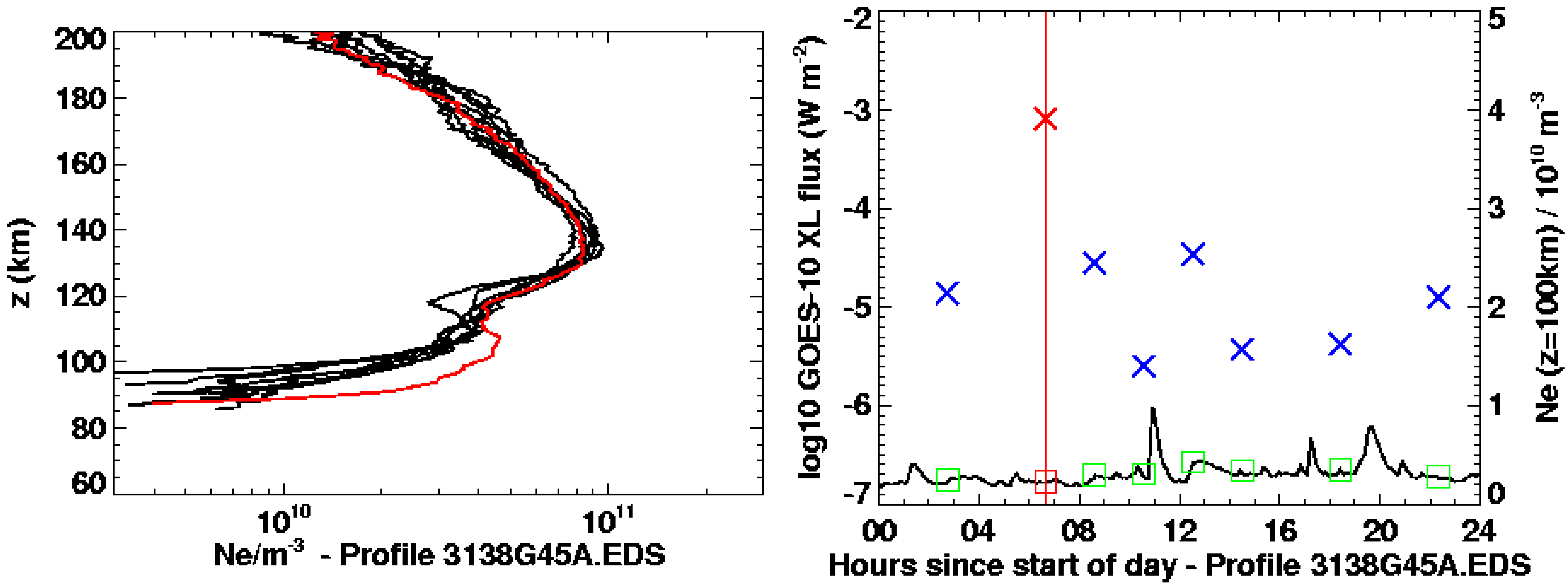
Right panel. GOES 1-8 A flux at Earth (black line), with values during occultations at Mars highlighted by green squares. Blue crosses show electron density at 100 km. Red symbols indicate values from the red profile in the left panel.

Enhancement in electron density below 110 km
Coincident with slight increase in flux at Earth

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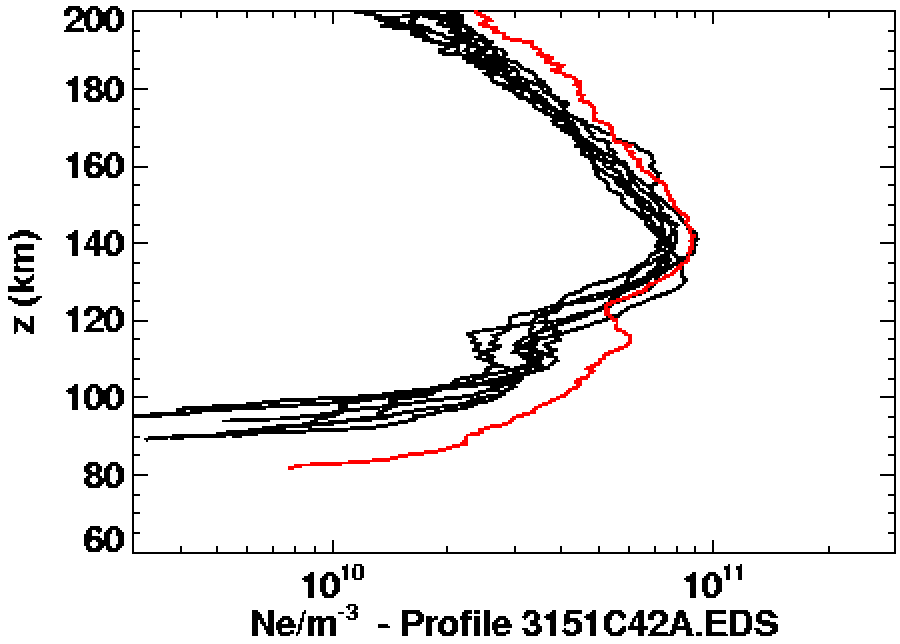
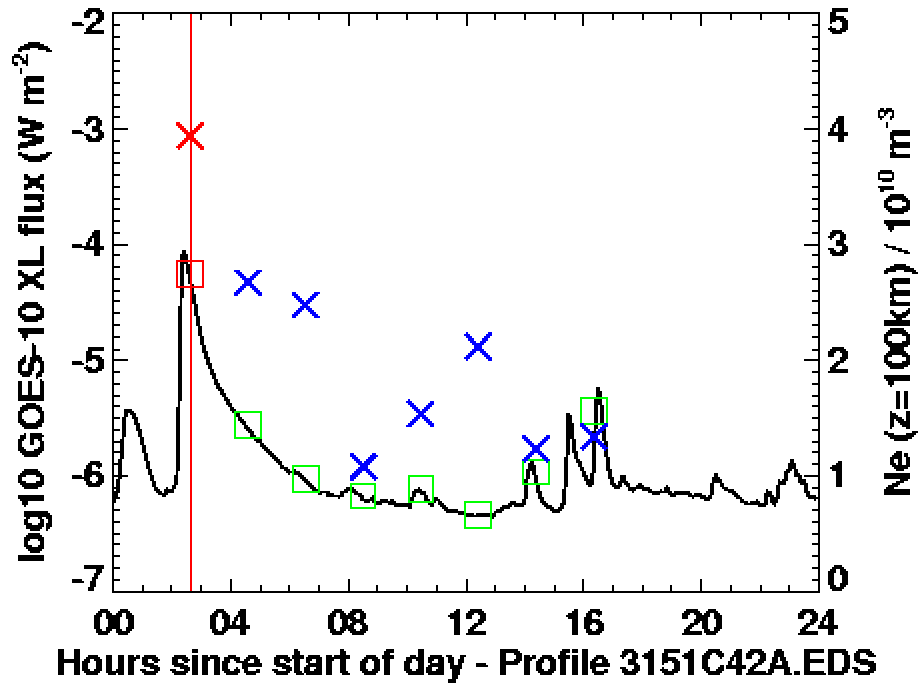
Right panel. GOES 1-8 A flux at Earth (black line), with values during occultations at Mars highlighted by green squares.
Blue crosses show electron density at 100 km. Red symbols indicate values from the red profile in the left panel.

Clear enhancement in electron density below 110 km
No increase in flux seen at Earth

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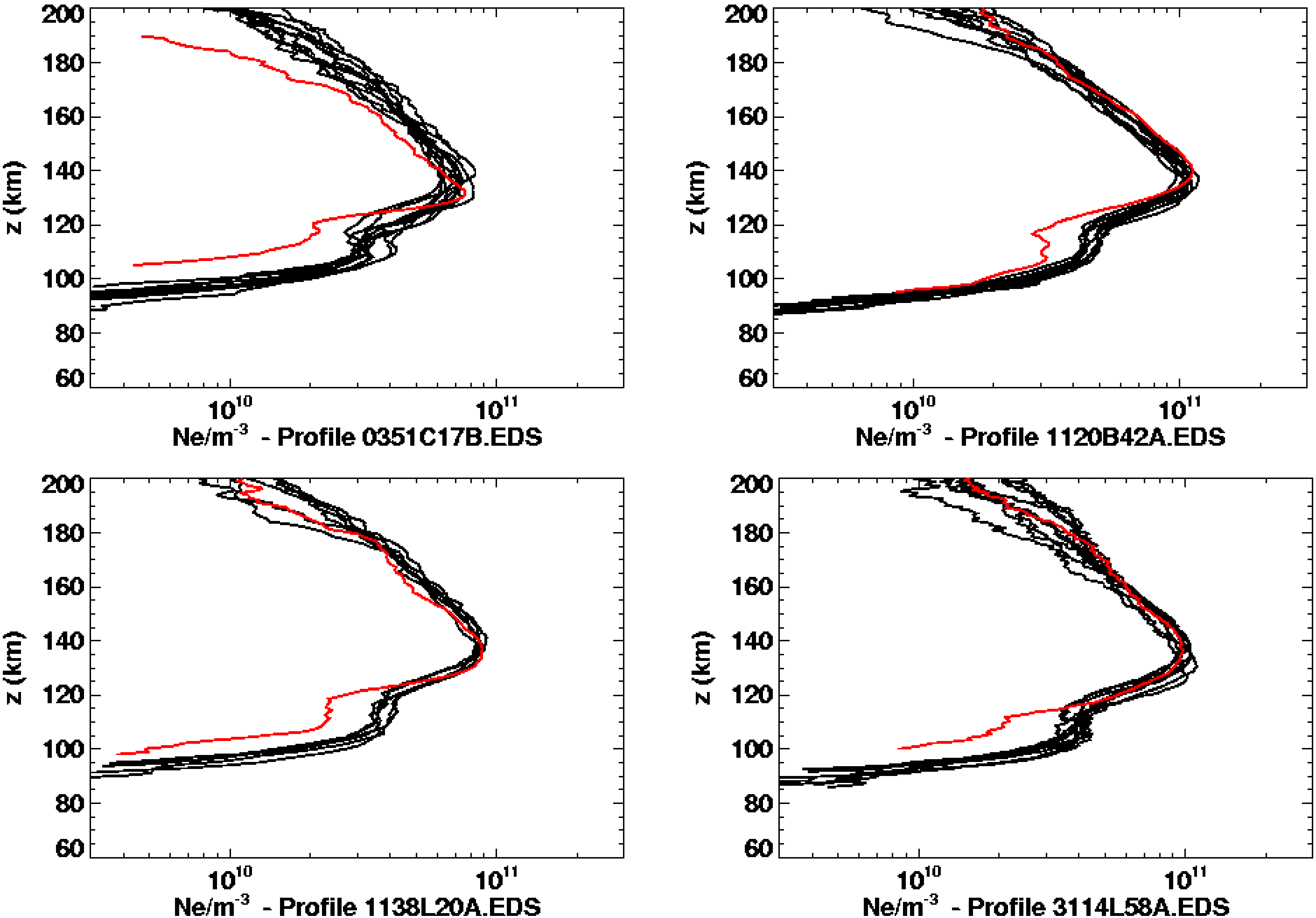
Very clear enhancement in electron density below 120 km

Coincident with large increase in flux at Earth




“Anti-flares” – Low electron densities around 110 km, cause unknown

# Ongoing Work

- Fitting simple models to observations to determine fluxes and other properties
- Comparing the responses of the terrestrial and martian ionospheres to the same X-ray fluxes in order to understand secondary ionization on Mars better
- Investigating the “anti-flare” profiles

- Secondary ionization due to X-rays is very hard to model, but forms many ion-electron pairs per photon. One common modelling approach is to specify the number of ion-electron pairs formed per X-ray photon absorbed, but this leads to the following problem: How can we distinguish 10 X-ray photons that each produce only 1 ion-electron pair from 1 X-ray photon that produces 10 ion-electron pairs?
- Solution is either measure flux accurately or understand secondary ionization very well – neither is possible for Mars
- Our approach

# A simplistic ionospheric model - 1

1) $n(z) = n_0 \exp [ (z_0 - z)/H ]$
2) $F_{total} = F_E + F_X$
3) $F_E(z) = F_E(\text{top of atm}) \times$
   $\exp(-\tau_E(z)/\cos(SZA))$
4) $\tau_E(z) = n(z)\, \sigma_E\, H$ same for $F_X$, $\tau_X$
5) $q_E = \sigma_E\, n(z)\, F_E(z)$ and $q_X = \sigma_X\, n(z)\, F_X(z)$
6) $q_{total} = q_E(1+S_E) + q_X(1+S_X)$
7) $N_e(z) = [\, q_{total} / \alpha \,]^{1/2}$

# A simplistic ionospheric model - 2

1) Neutral atmosphere has fixed H and composition
2) Solar flux contains only two wavelengths, EUV and X-ray photons
3) This flux is attenuated by absorption
4) The absorption is wavelength-dependent
5) The rate of direct photo-production of ions equals the product of the cross-section, the neutral number density, and the flux
6) For every ion-electron pair produced by direct photo-production, a specified number of secondary ion-electron pairs are also created
7) Production by direct and secondary ionization is balanced by loss due to dissociative recombination

- Specify $z_0$, SZA, $\sigma_E$, and $\alpha$.
- Remaining parameters affecting $N_e(z)$ are: $n_0$, H, $F_E$(top), $S_E$, $\sigma_X$, $F_X$(top), and $S_X$
- Specify $S_E$ and $S_X$
- Vary $n_0$, H, $F_E$(top), $\sigma_X$, and $F_X$(top) to get best fit to observations
- Interpret results

# Untangling $F_X$ and $S_X$

- This approach can only determine the product of $F_X$ and $(1+S_X)$, it cannot determine them individually.
- In future work, we will look at simultaneous observations of the terrestrial ionosphere in detail. Since the parameterization of secondary ionization in the terrestrial ionosphere is known accurately, we will use similar methods to determine $F_X$ at Earth.
- This extra piece of information is sufficient to separate $F_X$ and $(1+S_X)$ at Mars.
- At present, we set $S_E$=1 and $S_X$=10