Simulations of the response of the Mars ionosphere to solar flares and solar energetic particle events

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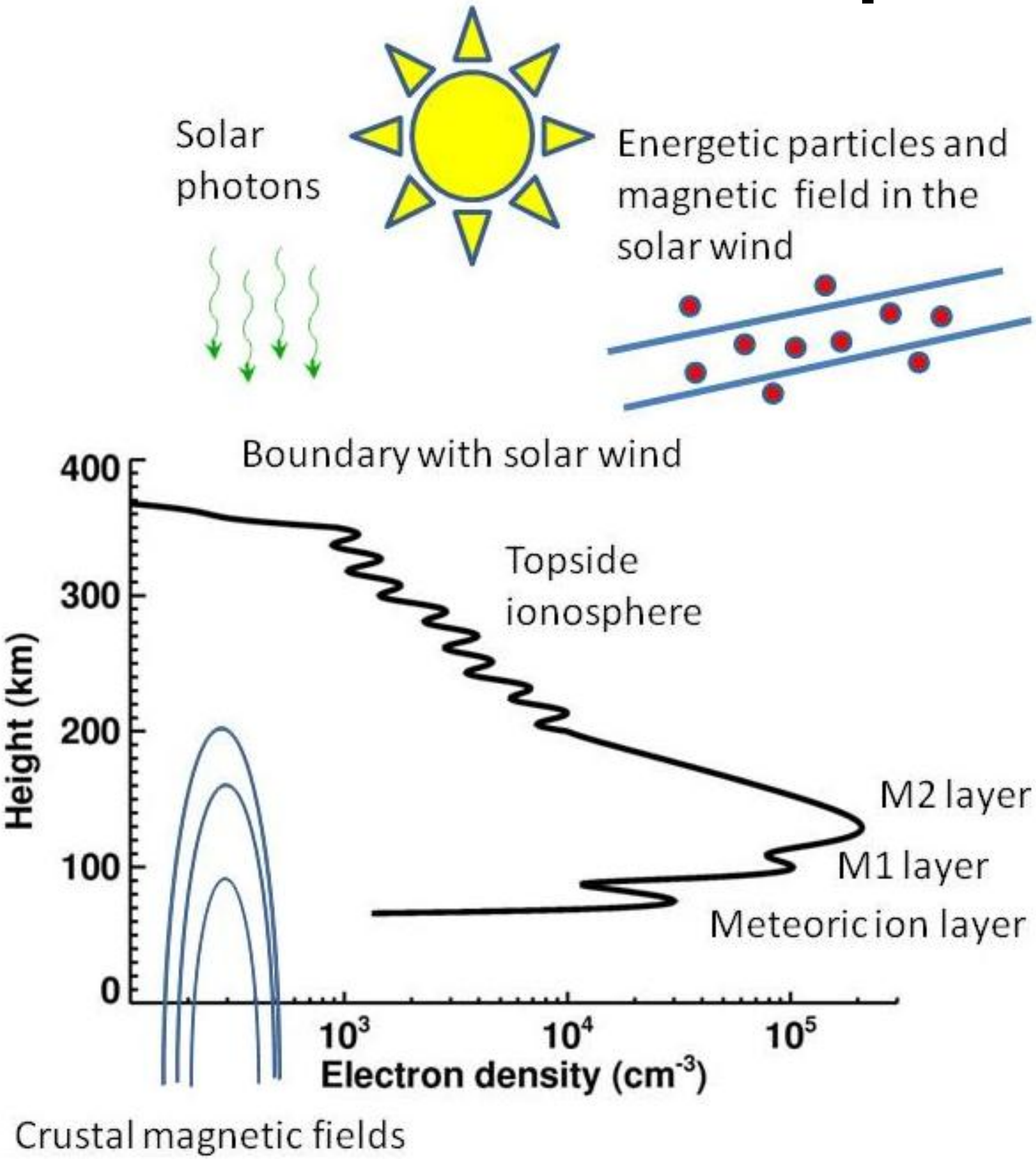
The ionosphere of Mars



Withers et al. (2009) Decadal Survey white paper

Neutral atmosphere is mainly CO_2, O becomes significant at high altitudes

O_2^+ is main ion (?) at all altitudes

EUV photons responsible for main M2 layer

Soft X-ray photons and secondary ionization responsible for lower M1 layer

Transport only important in topside ionosphere

Solar X-rays increase during a flare

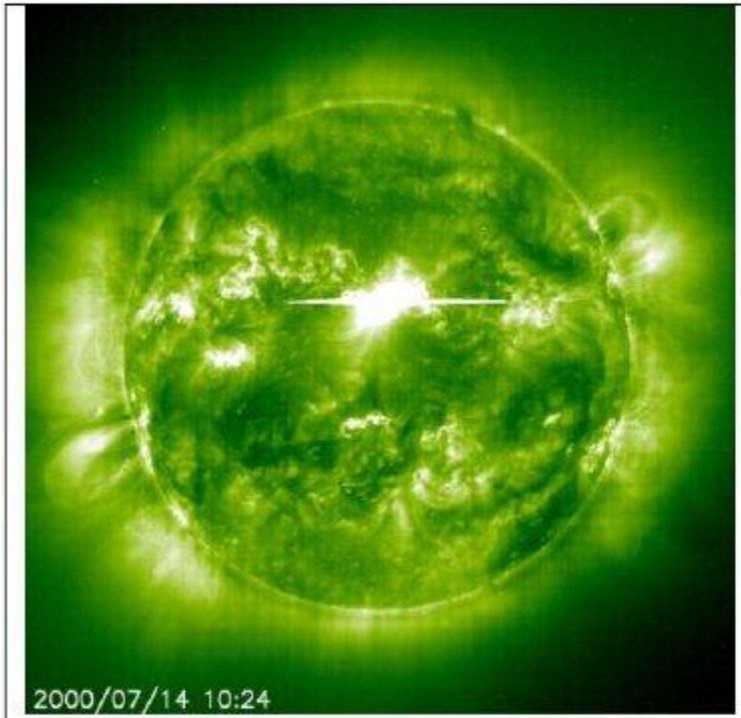


Fig 2. SOHO EIT 195 A image of the Sun at 10:24 on 14 July 2000. The saturated region is an X6 flare.

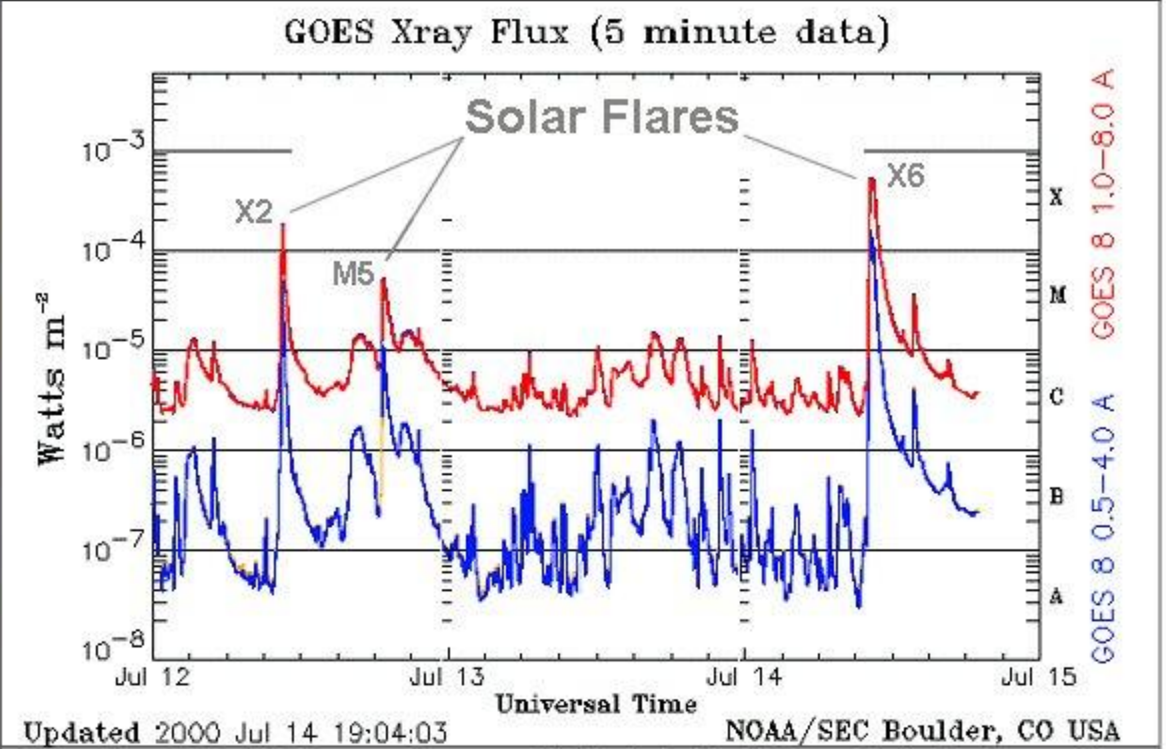


Fig 3. GOES X-ray fluxes (0.5-4 A in blue, 1-8 A in red) on 12-14 July 2000. The solar X-ray flux rises by orders of magnitude during the highlighted X6 flare.

Mars is affected by solar flares

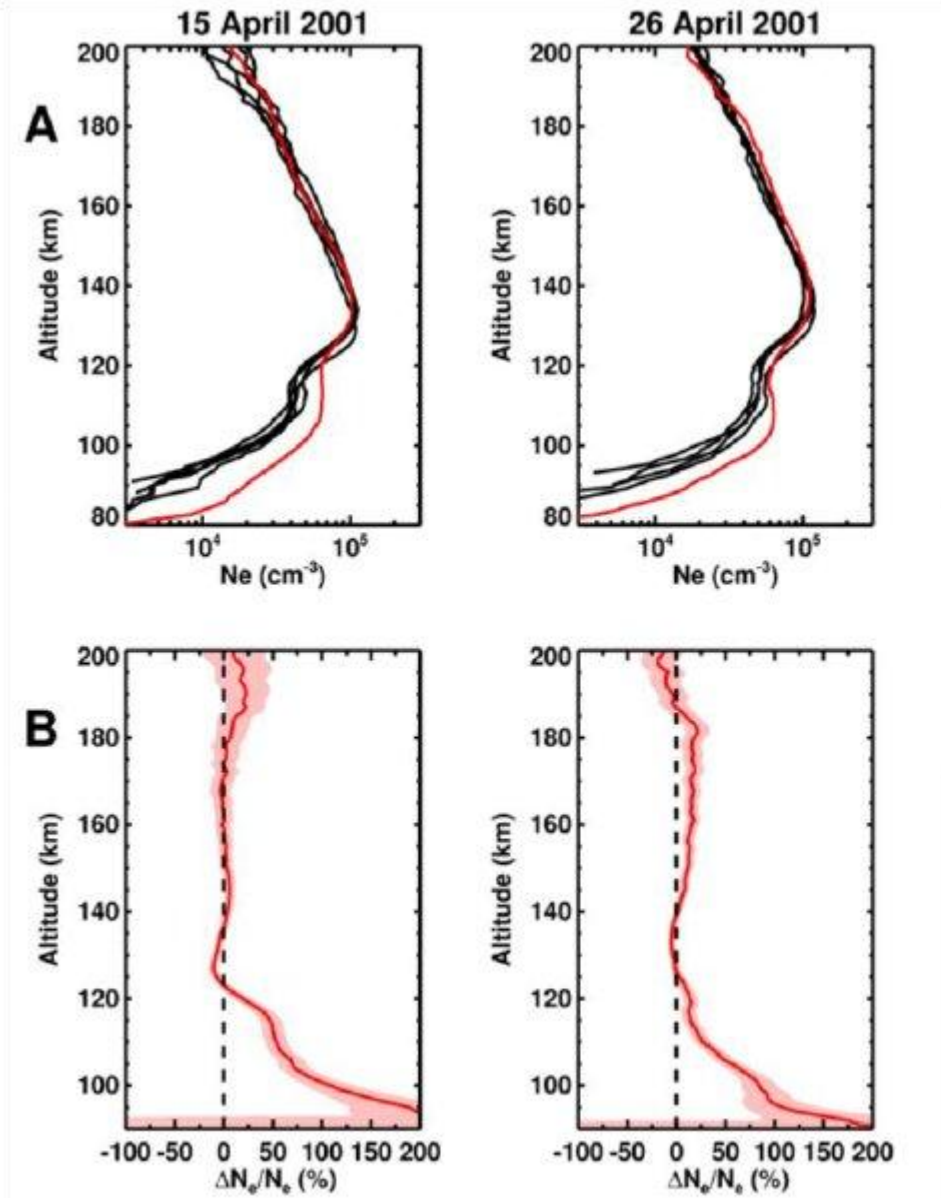
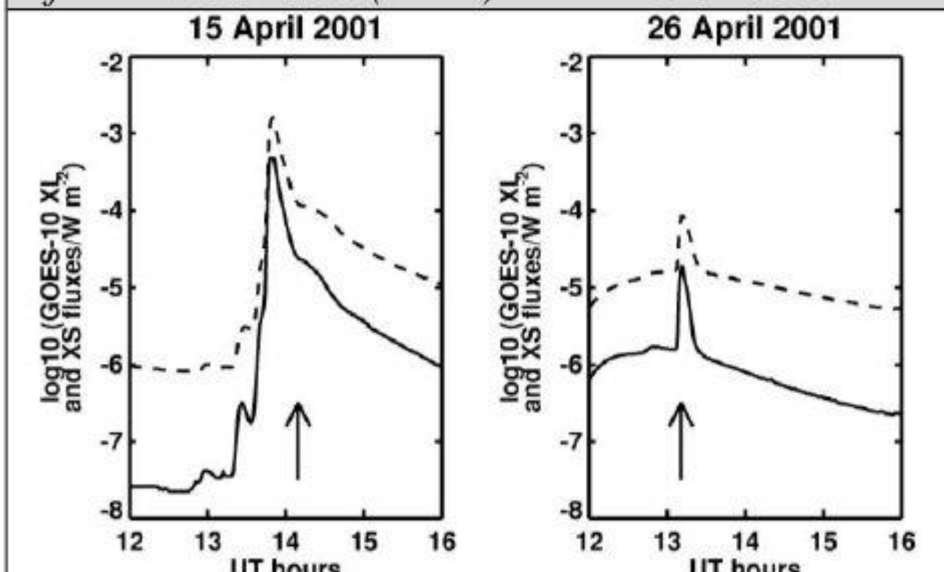


Fig 7. (top row) Electron density profiles from 15 and 26 April 2001. One profile, shown in red, from each day has enhanced electron densities at low altitudes. (bottom row) The ratio of the change in electron density in the flare-affected profiles to the unperturbed electron density, showing greatest enhancements in electron density at low altitudes. Fig 1 of Mendillo et al. (2006).

Fig 8. Corresponding 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. Arrows indicate times of flare-affected profiles. Fig 2 of Mendillo et al. (2006).



Solar spectrum changes in a flare

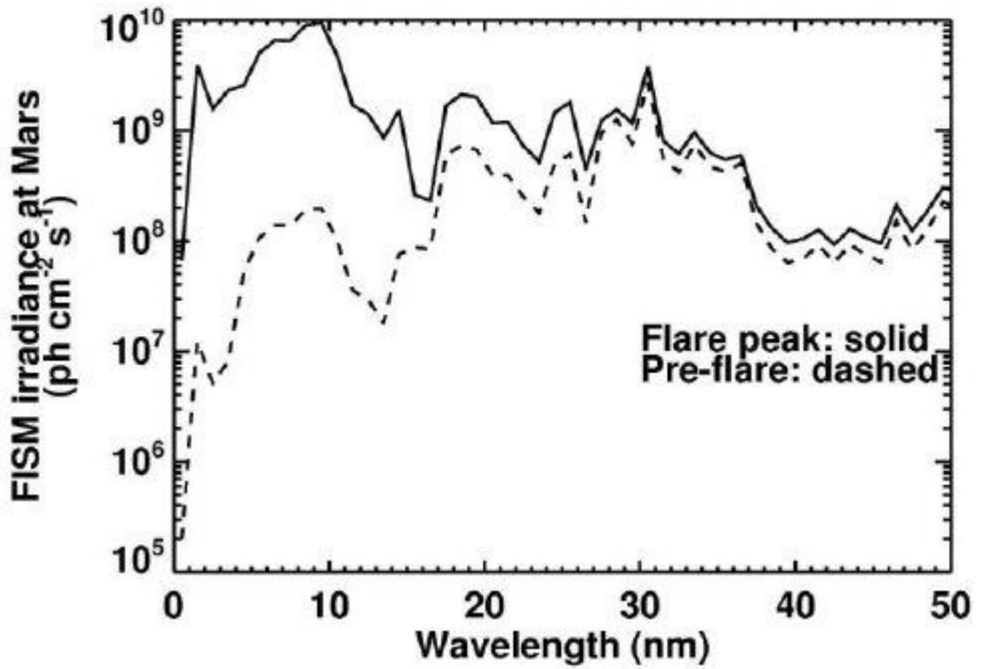
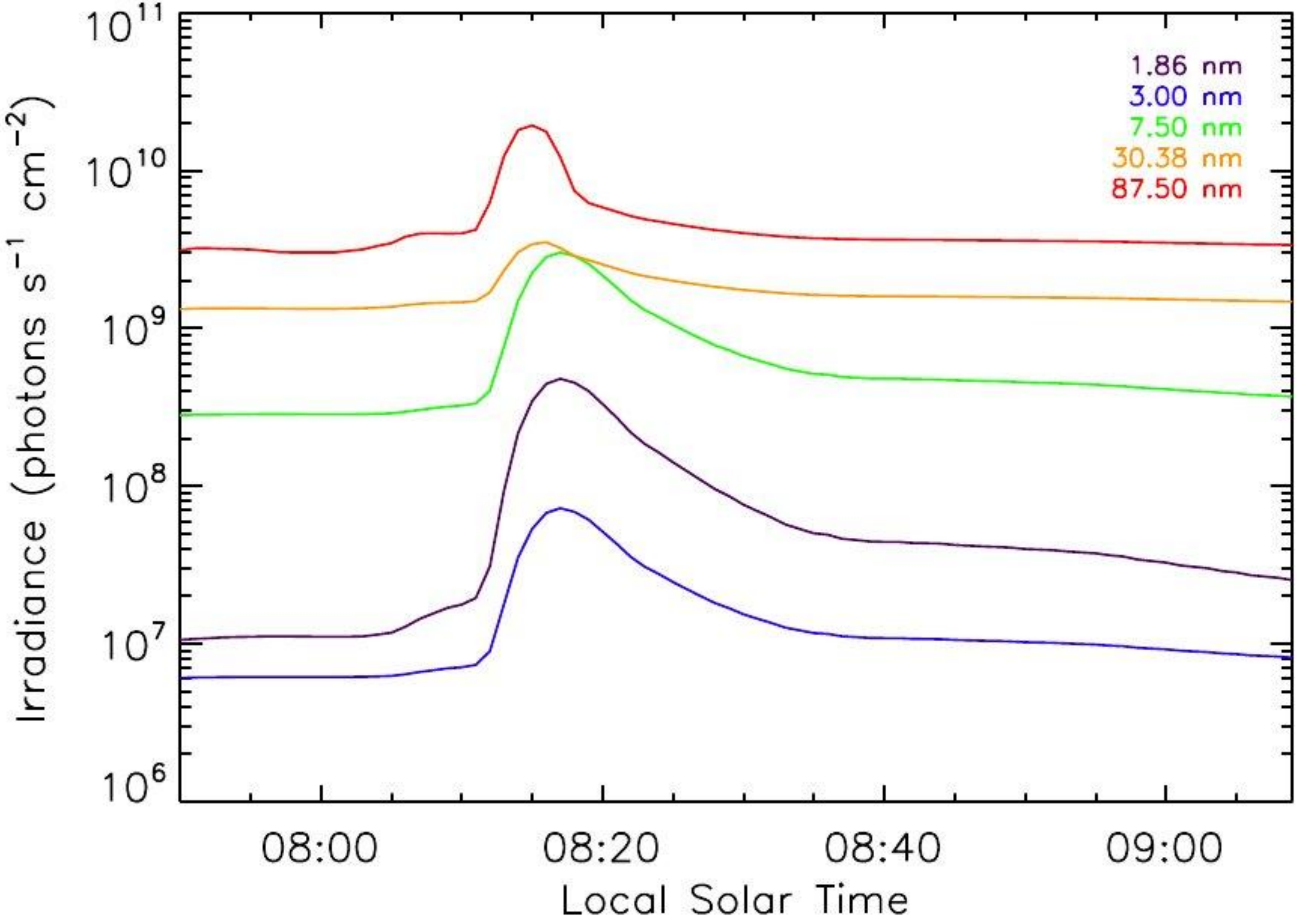
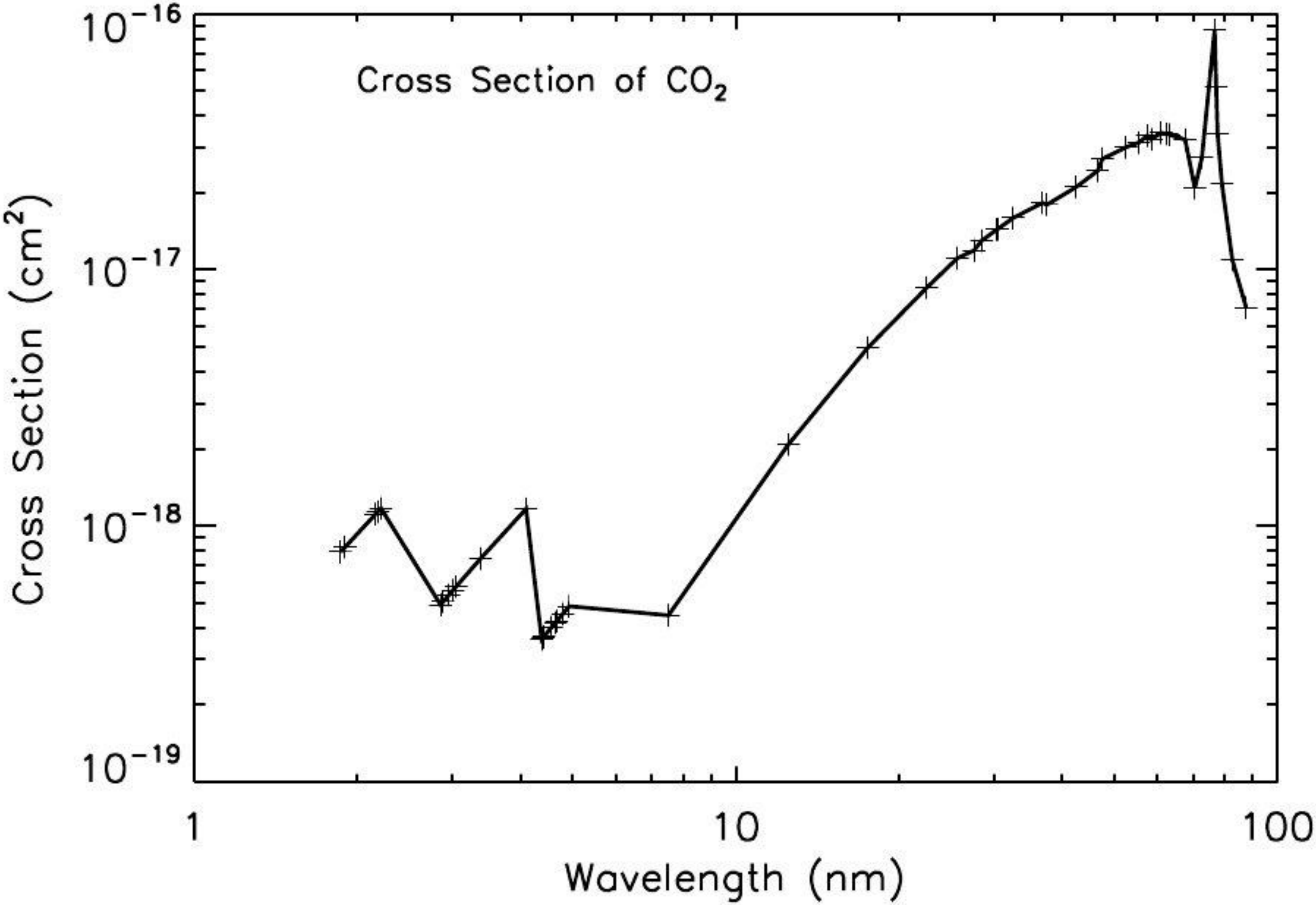


Fig 15. FISM irradiances in 1 nm intervals shortward of 50 nm at a pre-flare time and 10 mins after the flare peak time on 15 April 2001. Irradiances longward of 30 nm are increased only slightly at this time, but irradiances at shorter wavelengths are increased by up to two orders of magnitude. Electron impact ionization causes each short wavelength photon to produce many ion-electron pairs, so the effect on ion production is dramatic even when EUV fluxes are barely increased.

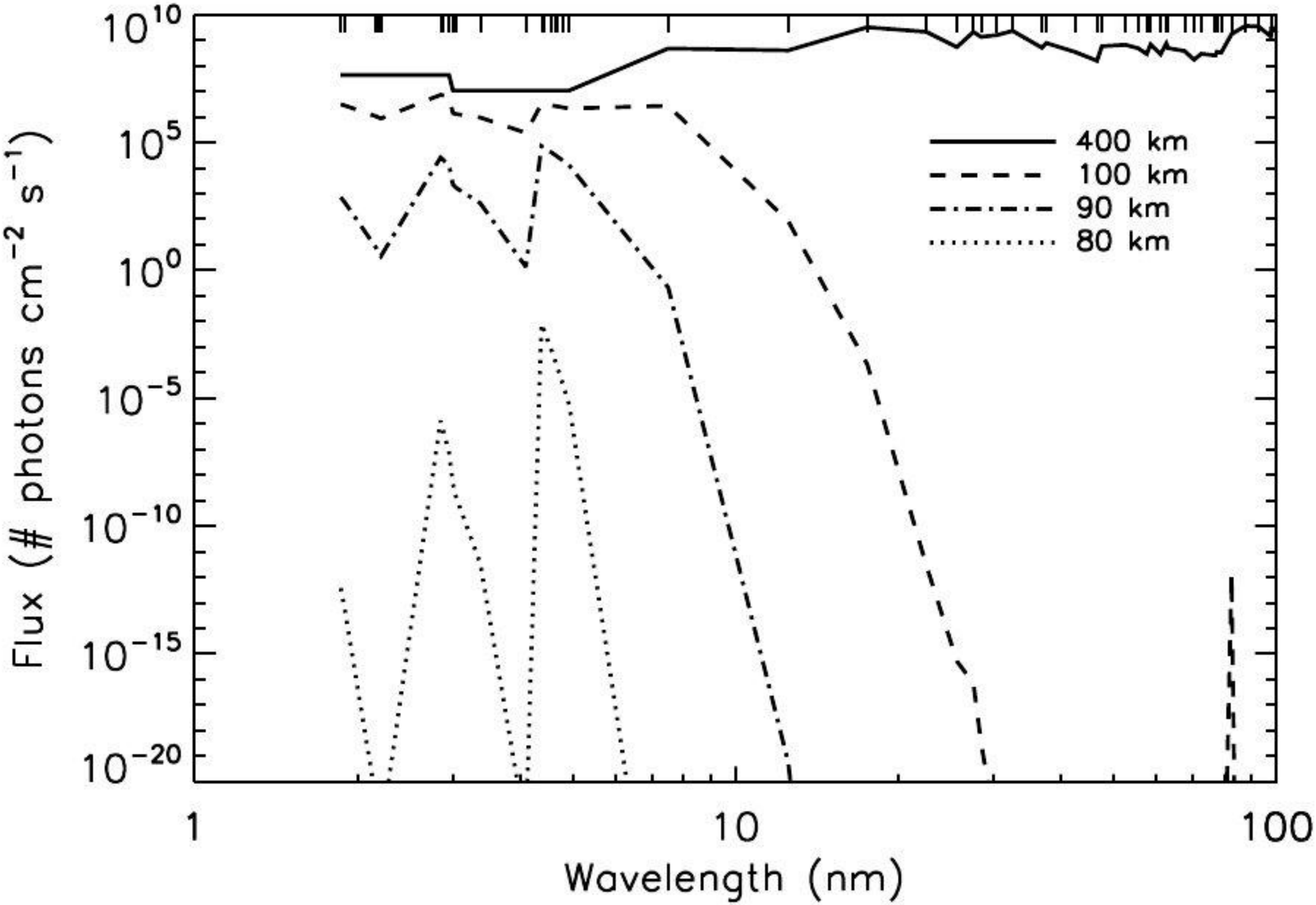
Solar spectrum on 15 April 2001



Unusual behaviour of CO_2 at 1-5 nm



Flux is greatly affected by this

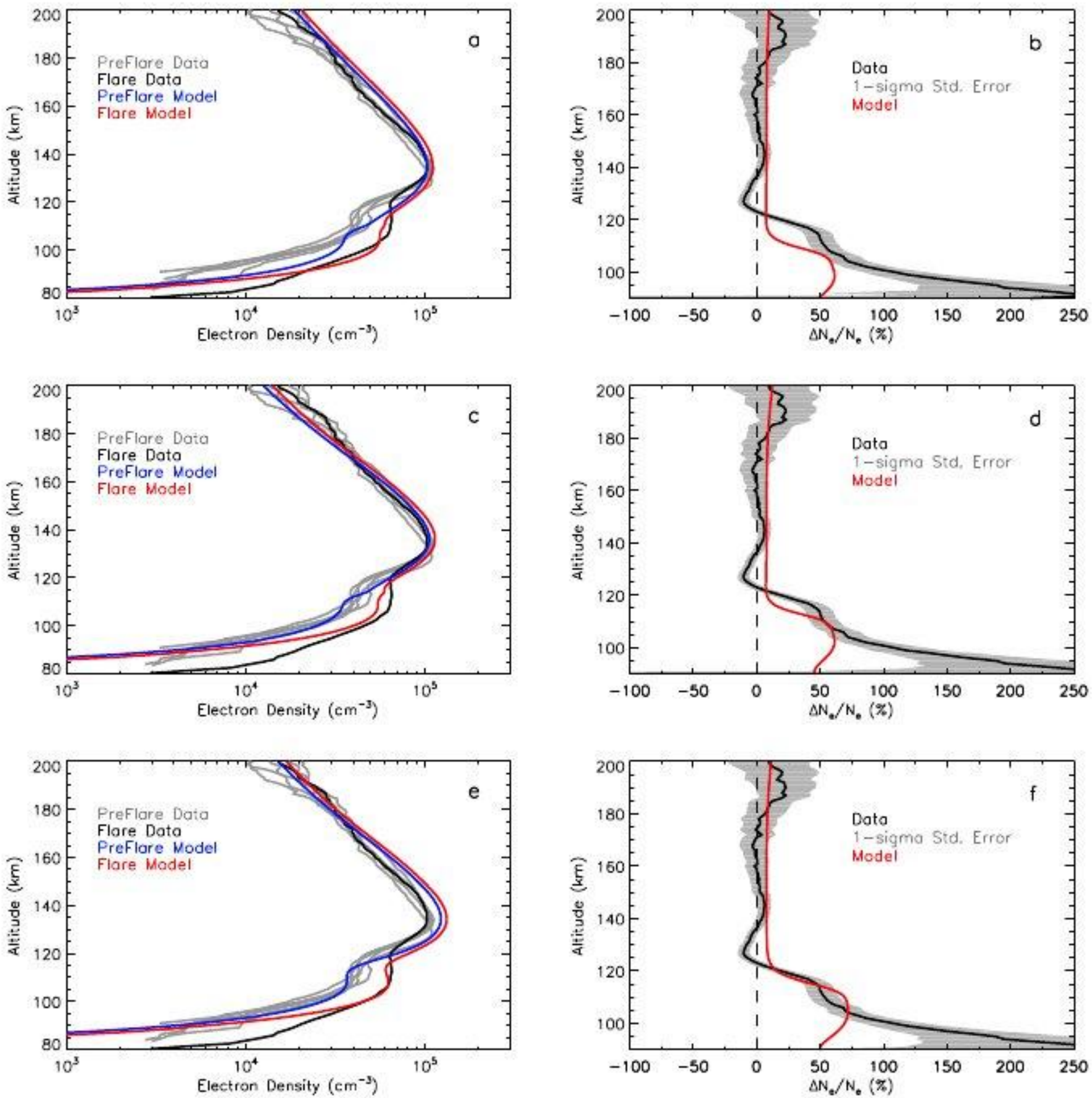


BU Mars Ionosphere Model

- 1-D, 80-400 km with 1 km vertical resolution
- Neutral atmosphere derived from Mars Climate Database at 80 km and assumed temperatures
- Temperatures adjusted until ionospheric layer altitudes and widths reproduced accurately
- Electron temperatures parameterized from neutral temperatures
- Time-varying solar spectrum from FISM with 1 minute and 1 nm resolutions

Electron impact ionization

- CO_2 can be ionized by 90 nm photons
- Where does extra energy of 3 nm photons go?
- Suprathermal photoelectron which ionizes many other molecules as it slows down via collisions
- How many ion-electron pairs produced by this mechanism for each photon absorbed?
- We assume that this number is equal to the ratio of the excess energy to some energy, W
- Theory suggests W values in range of 20-40 eV



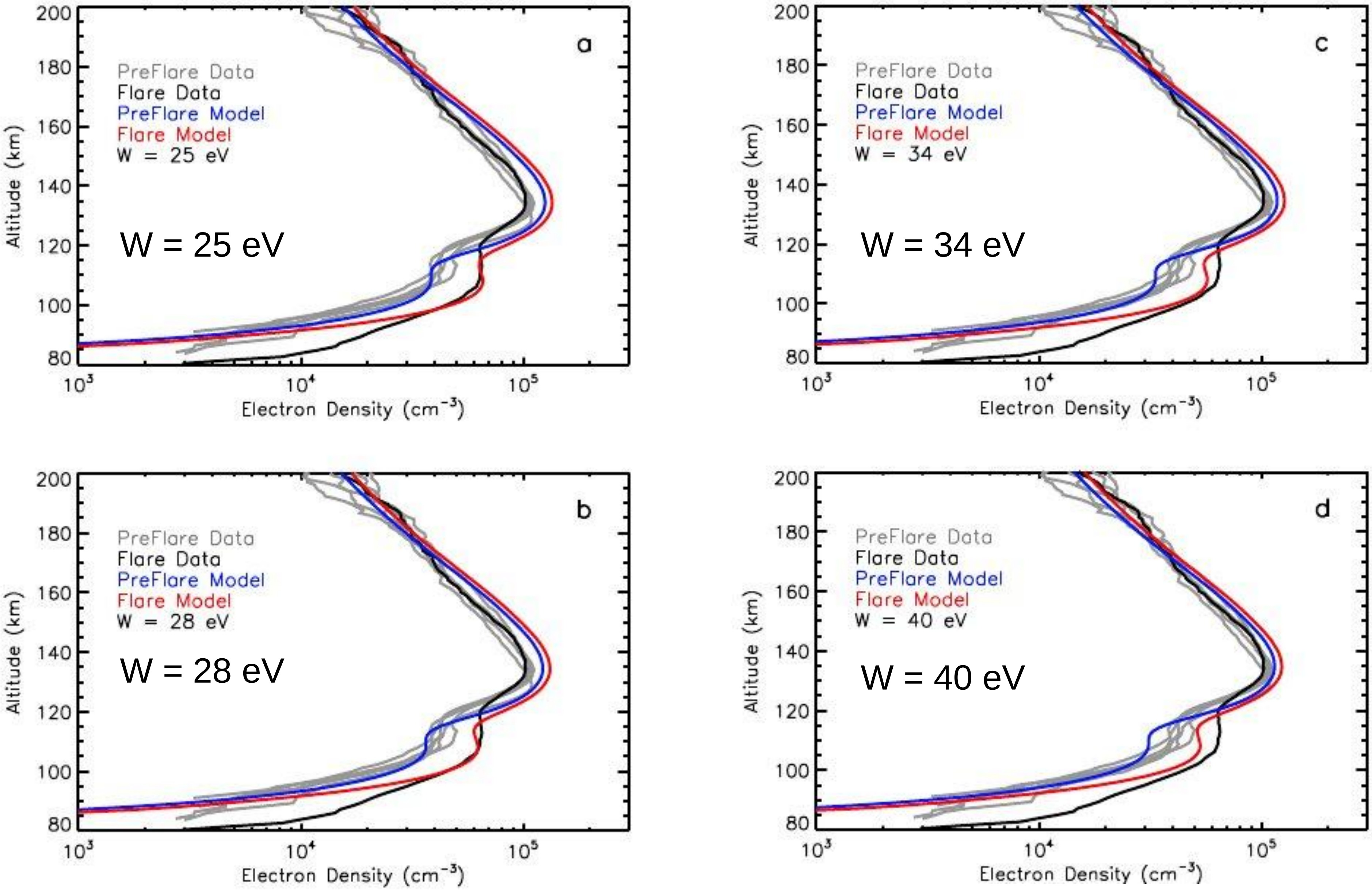
Model parameters and inputs are optimized to reproduce observations

Neutral atmosphere and electron impact ionization as in Mendillo et al. (2011)

Modification to neutral atmosphere to get altitude and width of main peak OK

Modification to electron impact ionization to get altitude and density of lower peak OK

W value of 28 eV gives best results



Final results for 15 April 2001 flare

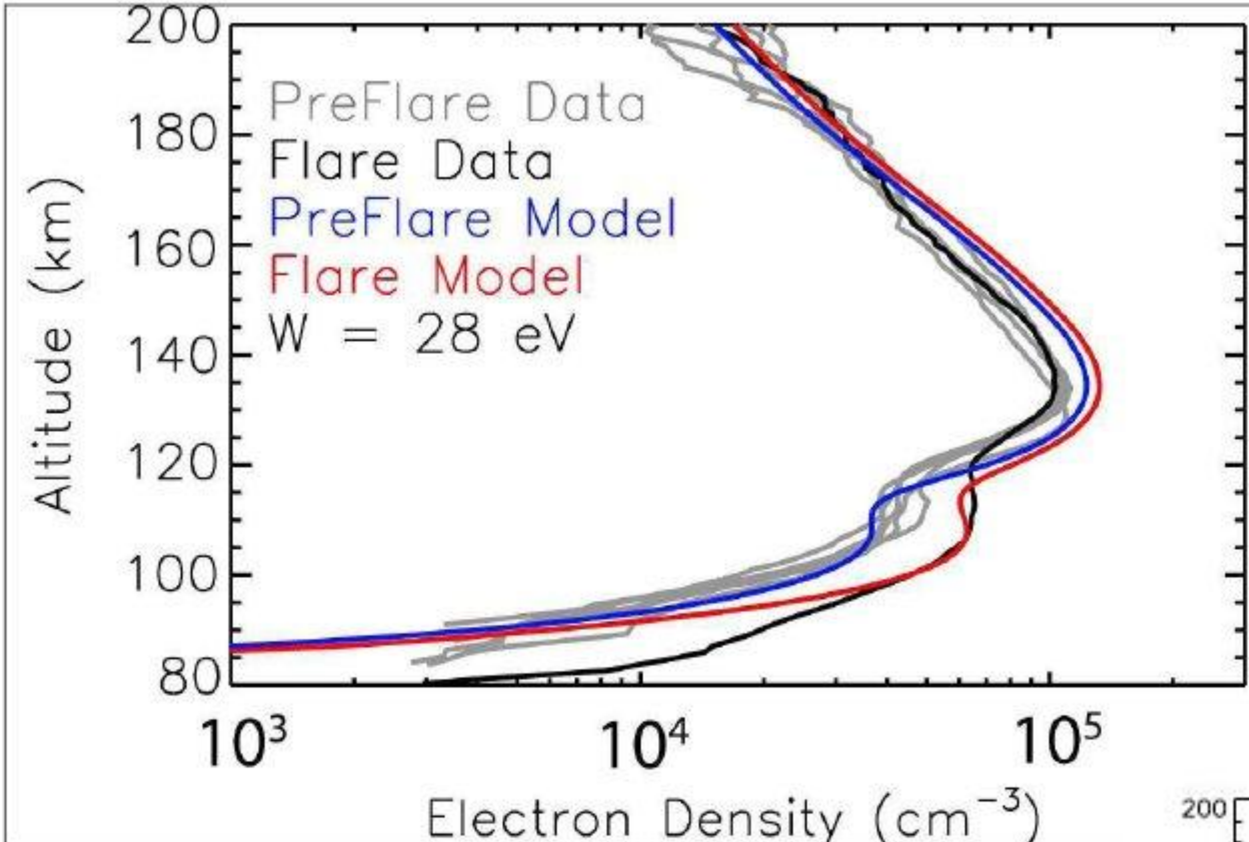
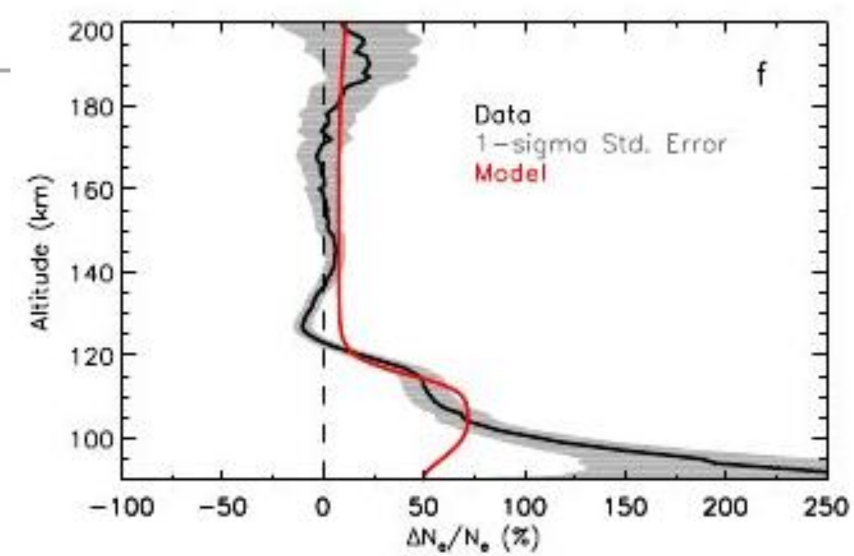
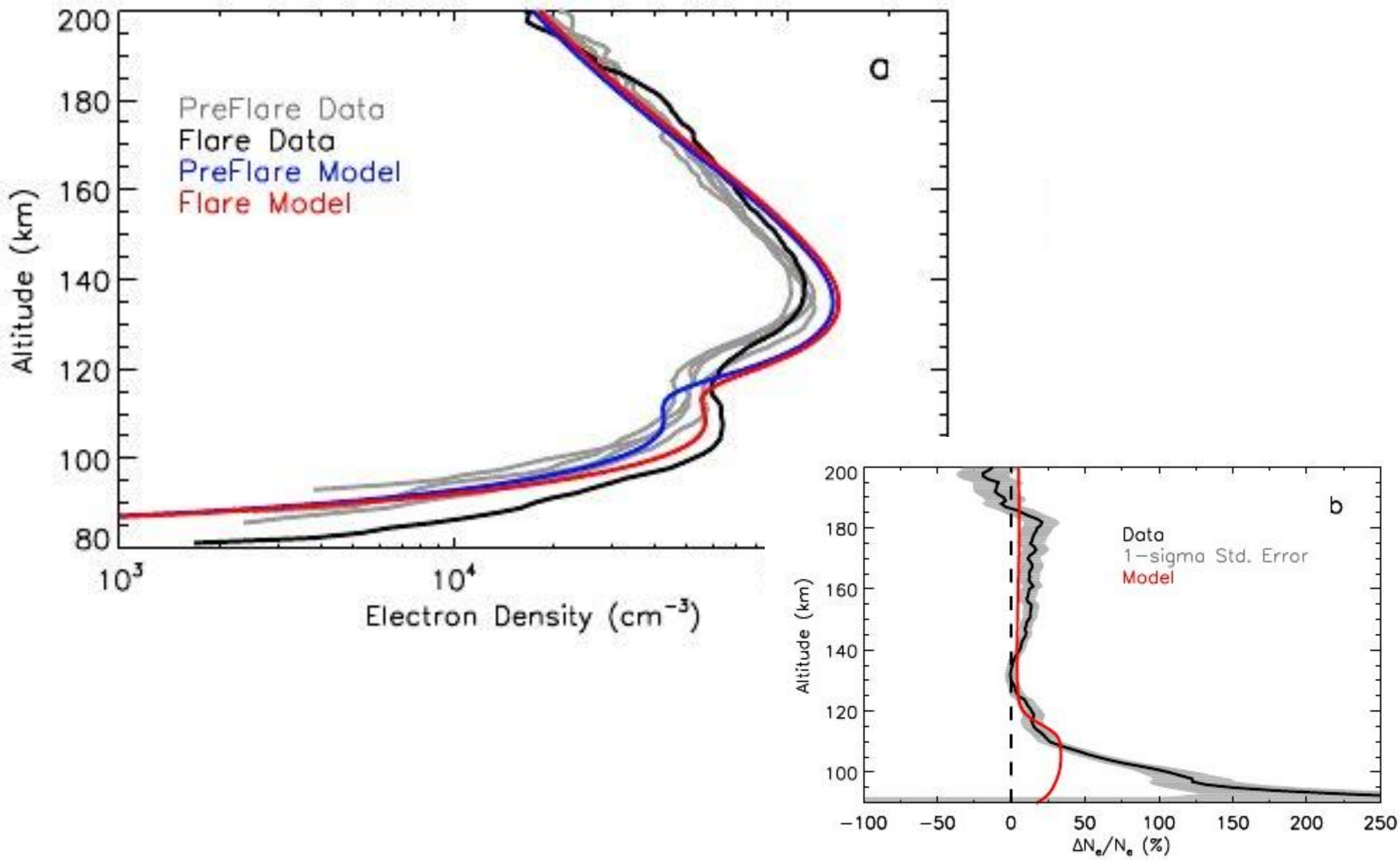


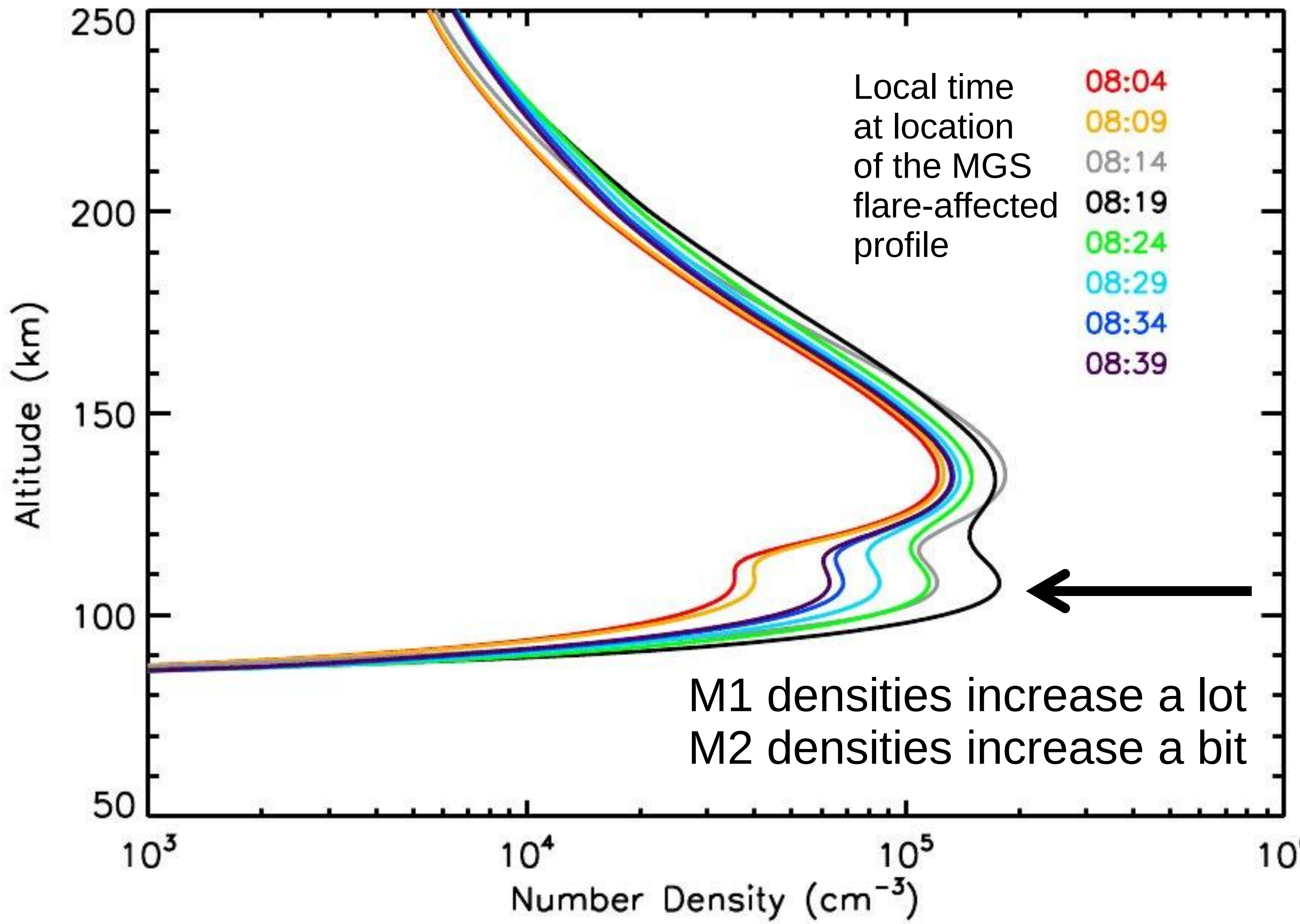
Figure 17: Profiles of simulated and observed electron density during the April 15, 2001 solar flare. Observations are shown in grey (pre–flare) and black (during the flare) and results from the 1-D BU Mars Ionosphere Model are shown in blue (pre–flare) and red (during the flare). Adapted from Fig 6 of Lollo et al. (2012).



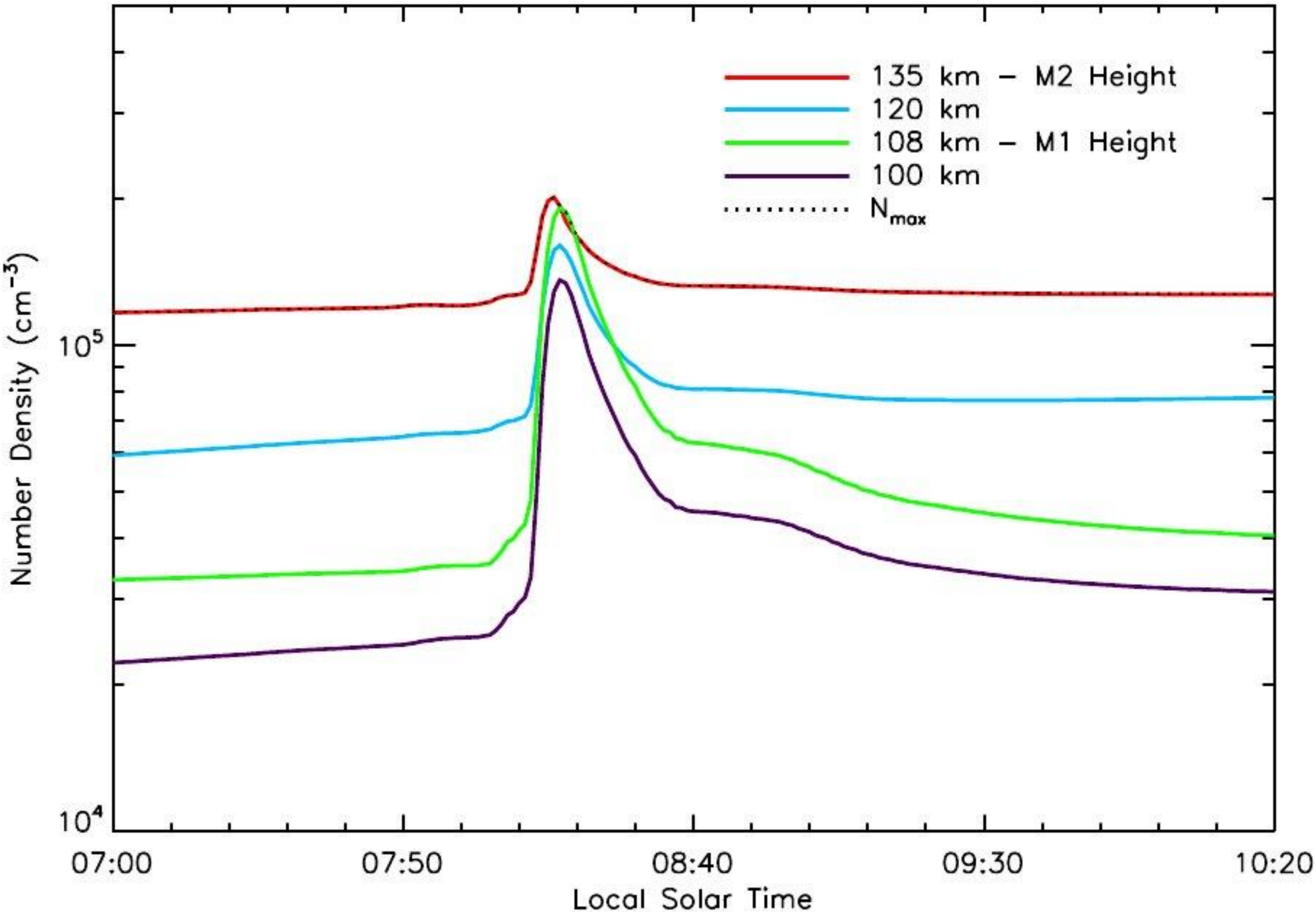
Final results for 26 April 2001 flare



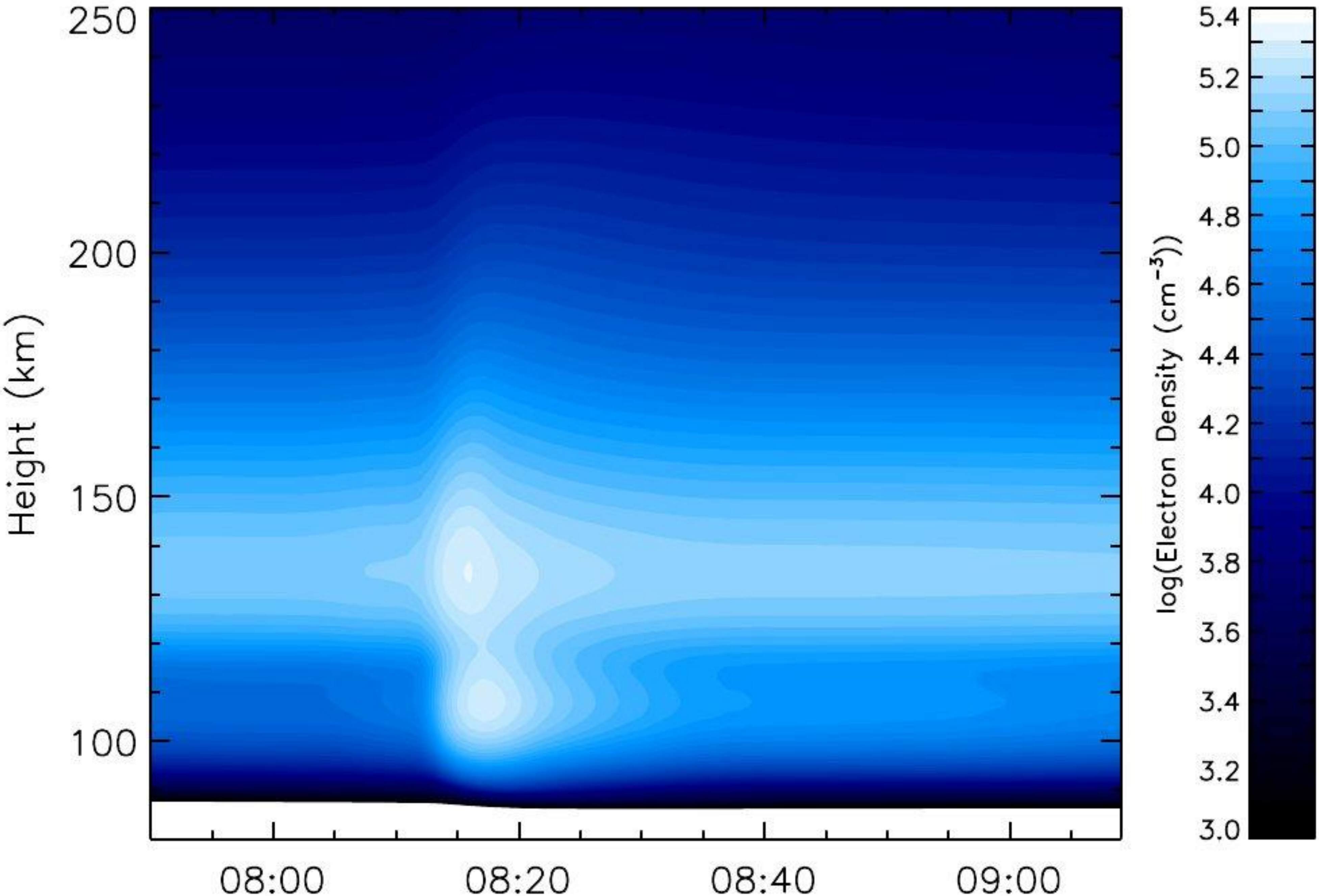
Large changes in electron density profile during the 15 April flare



Duration and magnitude of changes in electron density



Effects at all altitudes on 15 April 2001



Conclusions for flares

- Simulations are good with one exception – electron densities below 100 km for the flare-affected profile are underpredicted
- Is this caused by the changes in CO_2 cross-section at 2.3 nm (O) and 4.3 nm (C)? How accurately can we assign photons to one or other side of these thresholds?
- Simon-Wedlund et al. (2011) prediction of W-value of 28 eV for Mars, unlike the 34-35 eV common on Earth, is supported by our work

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Numerical simulations of the ionosphere of Mars during a solar flare

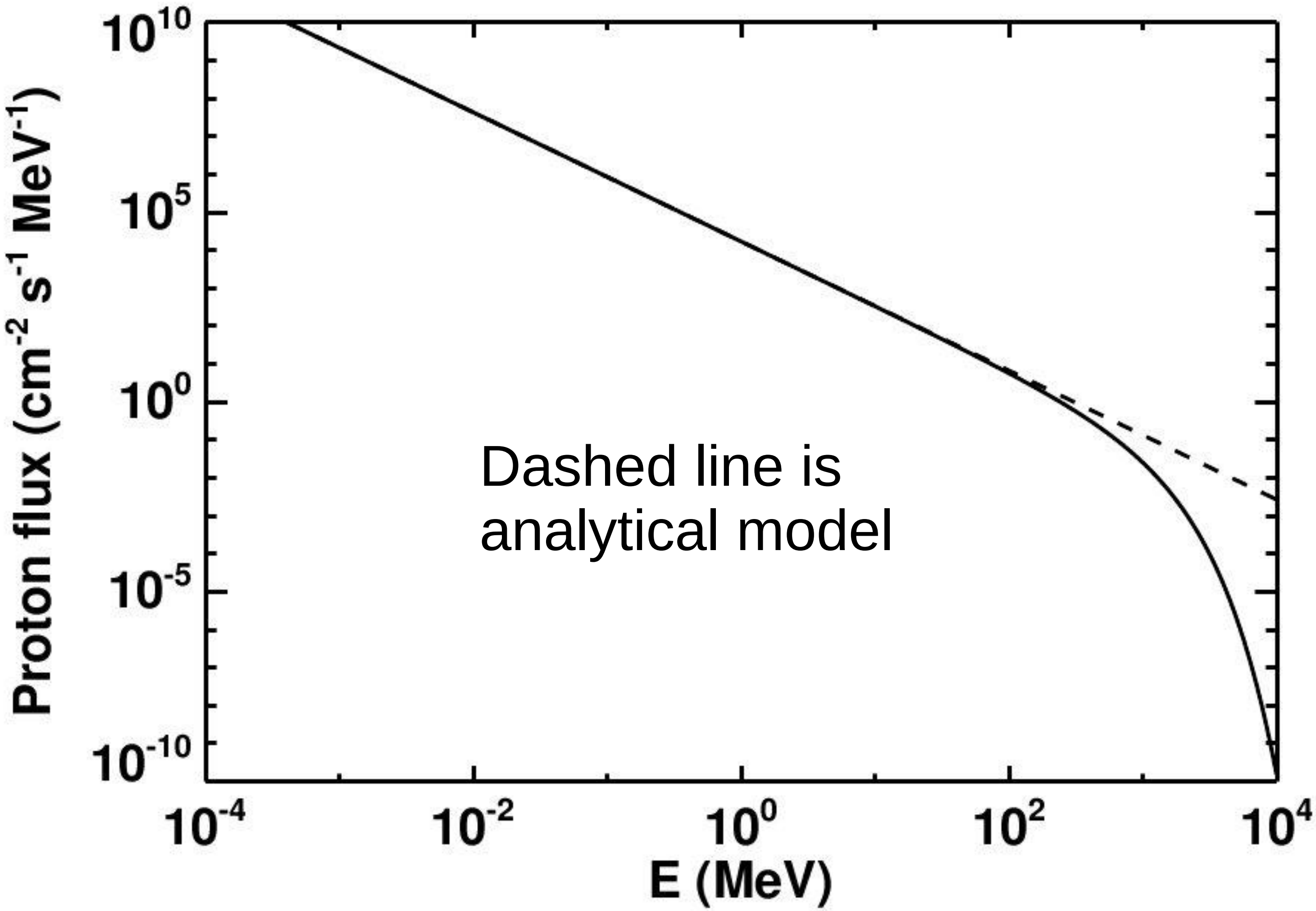
Anthony Lollo[1,2], Paul Withers[1], Kathryn Fallows[1], Zachary Girazian[1], Majd Matta[1] and P. C. Chamberlin[3]

In press at JGR Space Physics
DOI:10.1029/2011JA017399

Effects of solar energetic particle (SEP) events

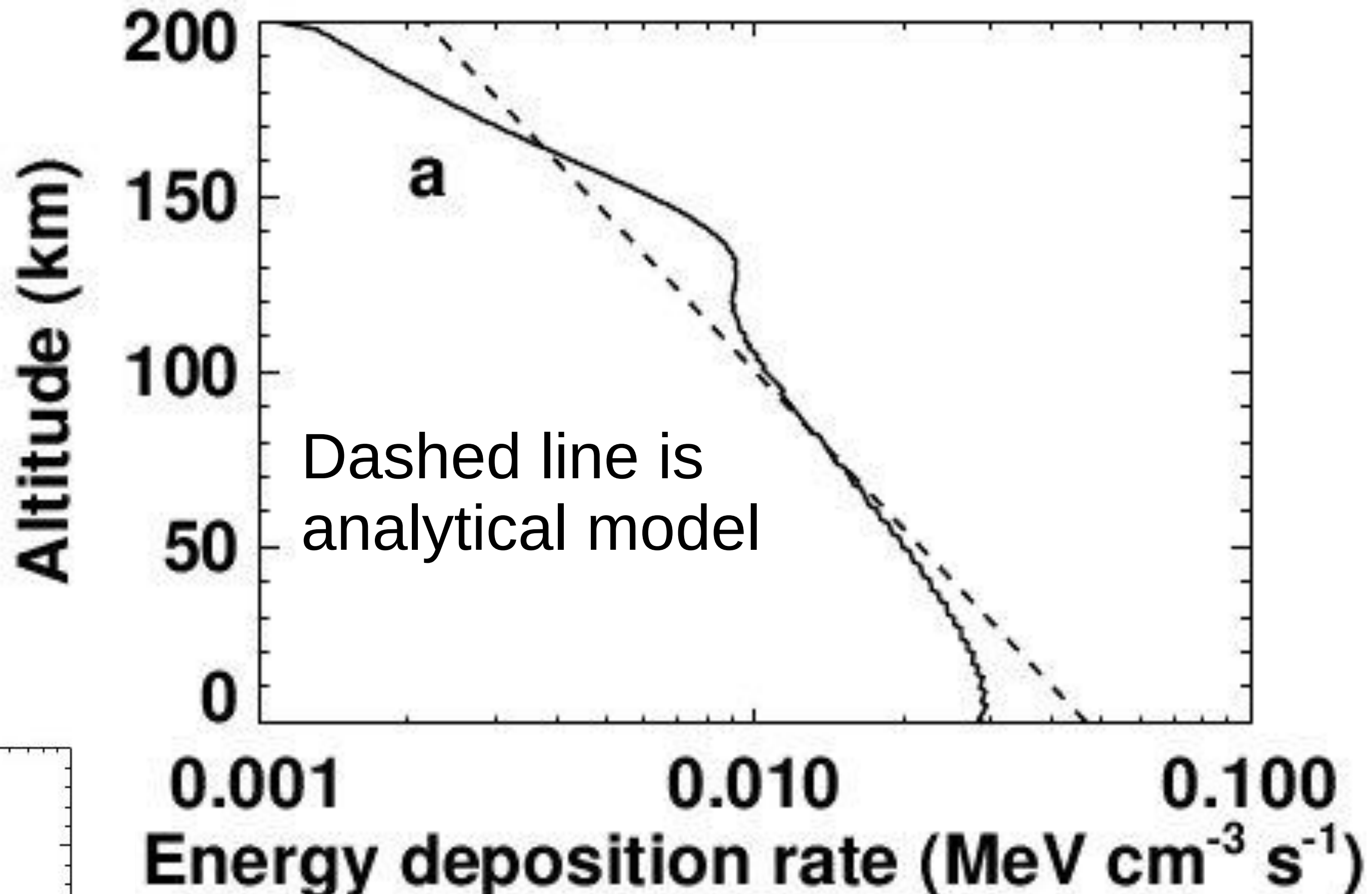
- MARSIS data show that electron densities somewhere below the main peak are enhanced by some amount during SEP events
- Does a model of the ionospheric effects of Sep events support this inferred association or not?
- We simulate the ionosphere during a large SEP event (29 September 1989) to test if sufficient plasma is produced to affect MARSIS data

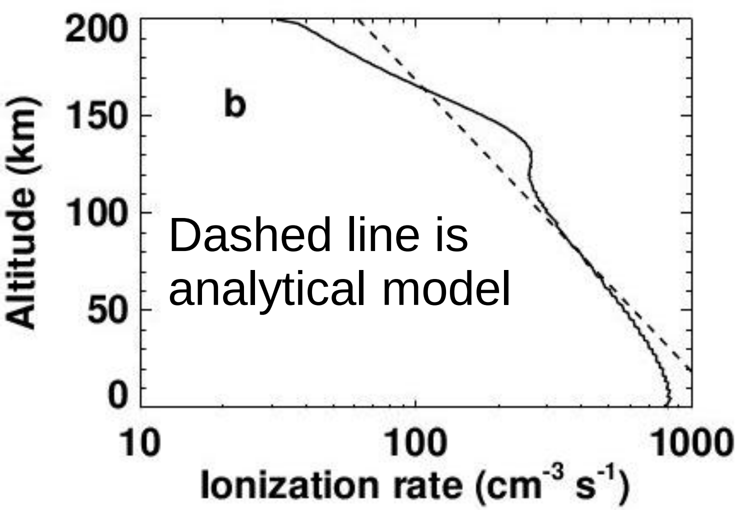
Assumed proton energy spectrum



Protons slowed by the atmosphere

Energy deposition rate for continuous slowing down approximation using tabulated ranges of protons in CO_2





Resultant ionization rate assuming one ion-electron pair produced for every 35 eV of energy deposited

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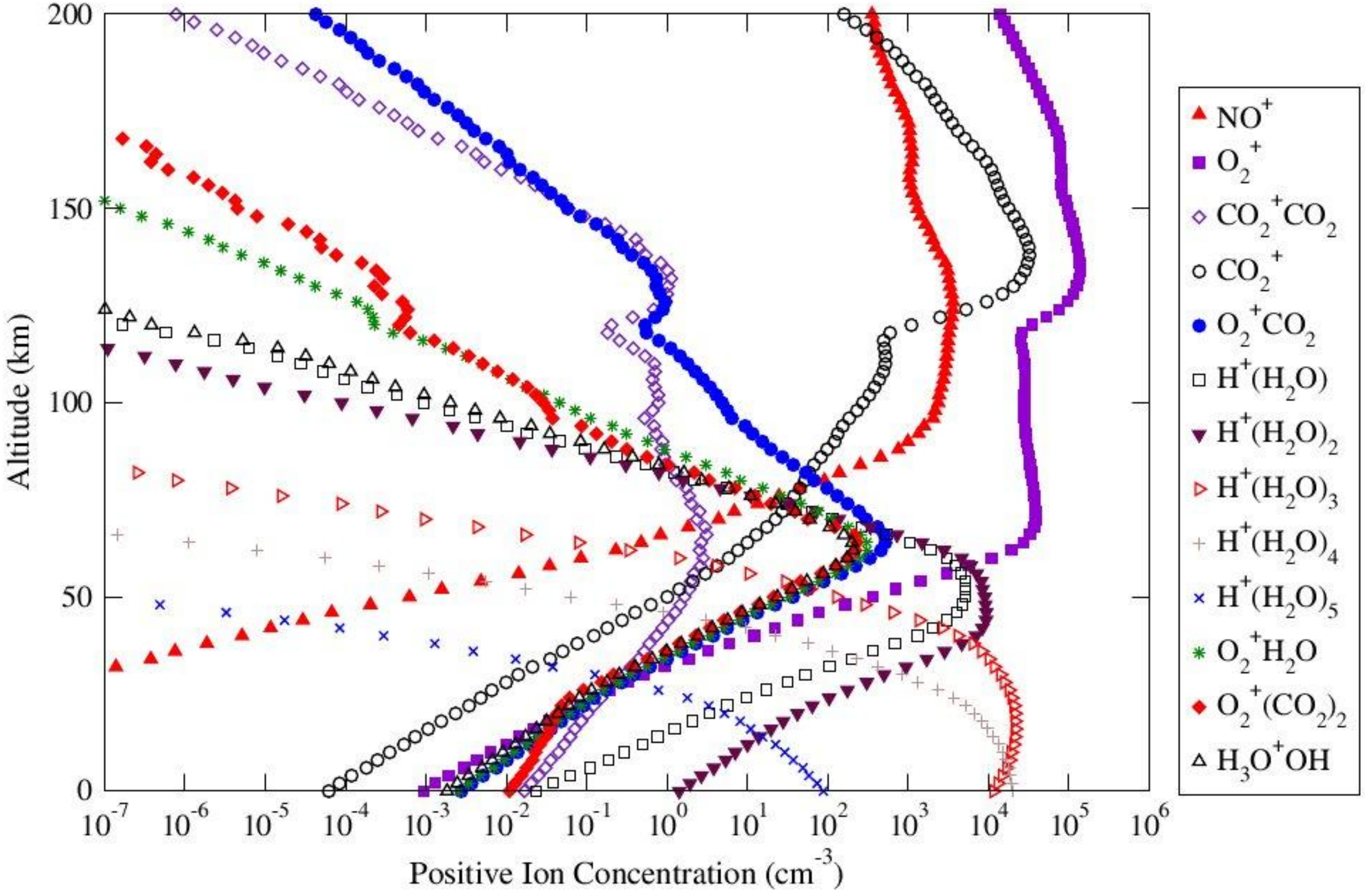
1 **Numerical simulation of the effects of a solar**
2 **energetic particle event on the ionosphere of Mars**

Varun Sheel,[1] S. A. Haider,[1] Paul Withers[2], K. Kozarev[2], I. Jun[3], S. Kang[3],

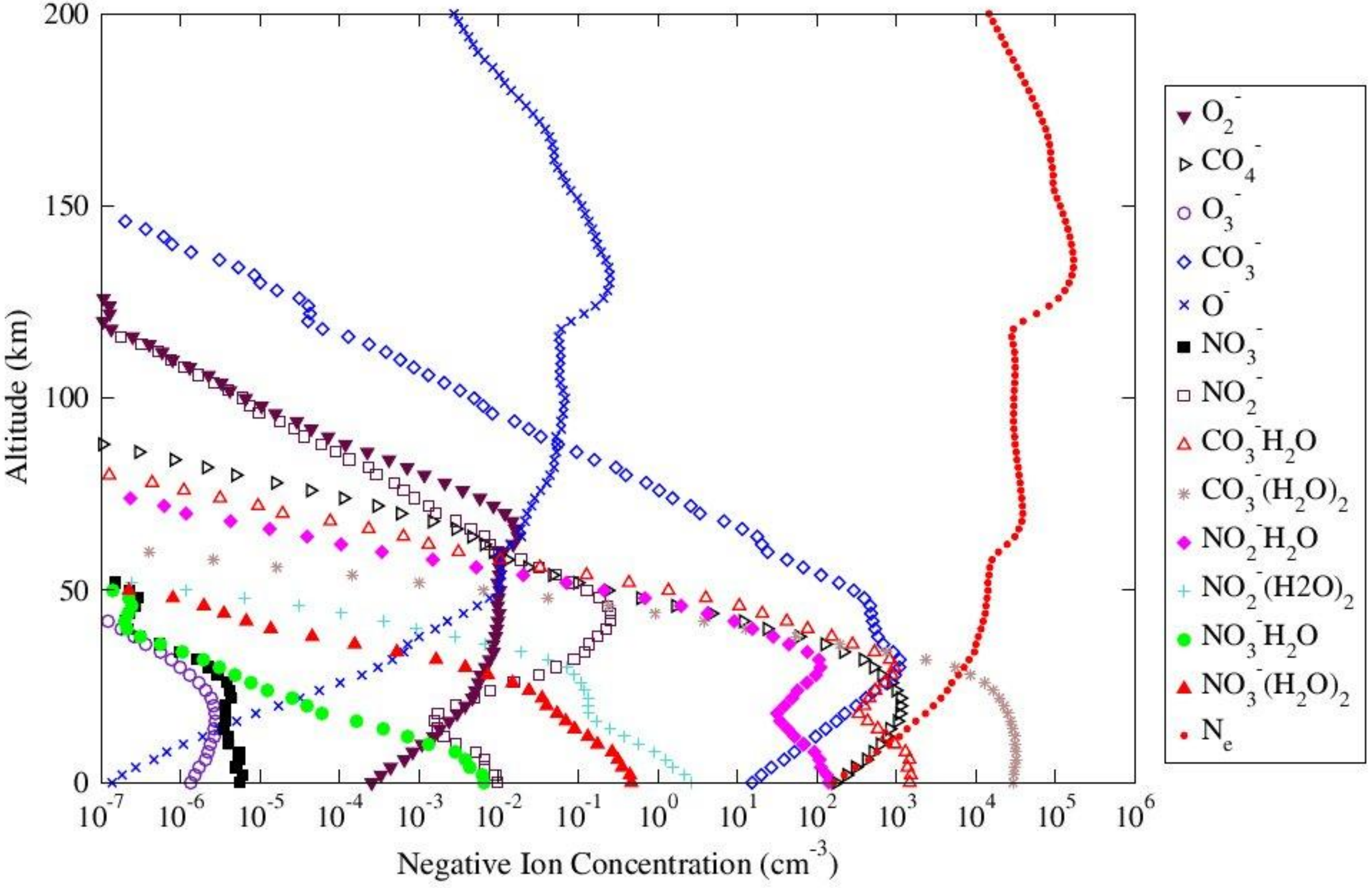
G. Gronoff[4], and C. Simon Wedlund[5]

In press at JGR Space Physics
DOI:10.1029/2011JA017455

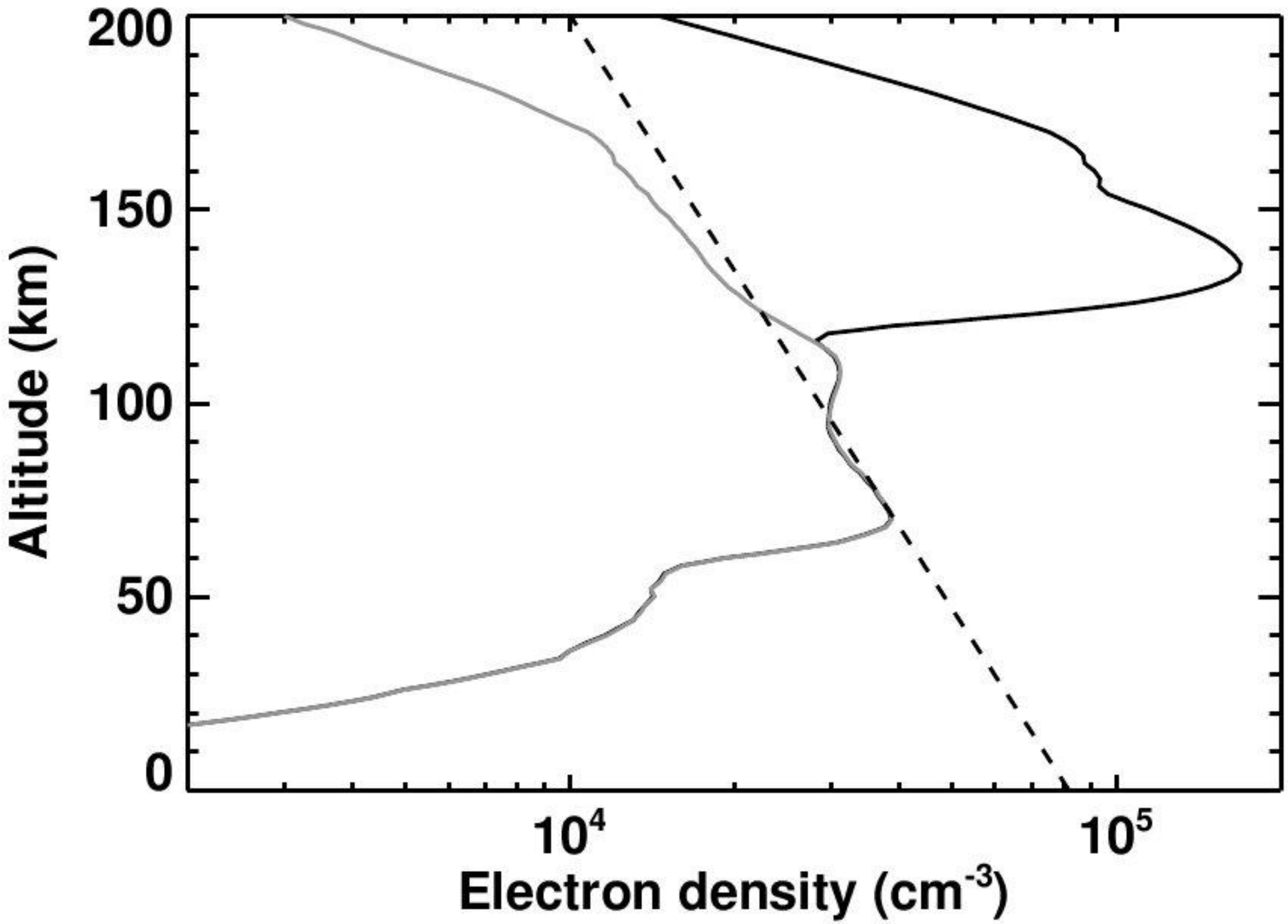
Simulated positive ion densities (including photoionization)



Simulated negative ion densities (including photoionization)



Simulated electron density profile



Grey line has ion production from protons only

Black line includes photoionization as well

Dashed line is analytical model to proton only case
Very accurate in 70-170 km region

Conclusions for SEP events

- This proton-only simulation has 462 dB of attenuation at 5 MHz, more than enough to explain the MARSIS observations (13 dB)
- SEP events can cause MARSIS blackouts
- Increased TEC during SEP events confirmed by Lillis et al. (2010)
- Enhanced electron densities at 90 km during SEP events not identified in radio occultation data yet
- Analytical simplification of model works well for certain focused purposes, but not perfect