Variability in the Ionosphere of Mars

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Variability – So What?

- Discover new phenomena
- Determine relationships of ionospheric properties to internal and external factors
- Provide more challenging tests of simulations
- Observe universal physical processes operating under martian conditions

Outline of this talk

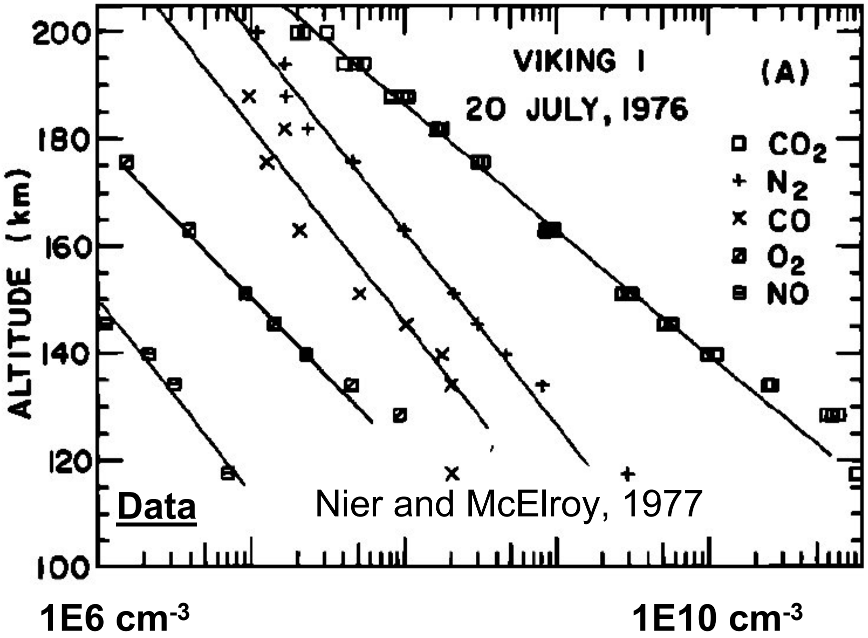
- (Brief) Introduction to the martian ionosphere
- Variability in the main ionospheric layer
- Variability below the main ionospheric layer
- Variability above the main ionospheric layer
- Variability in dynamics and chemistry
- Final remarks

(Brief) Introduction to the martian ionosphere

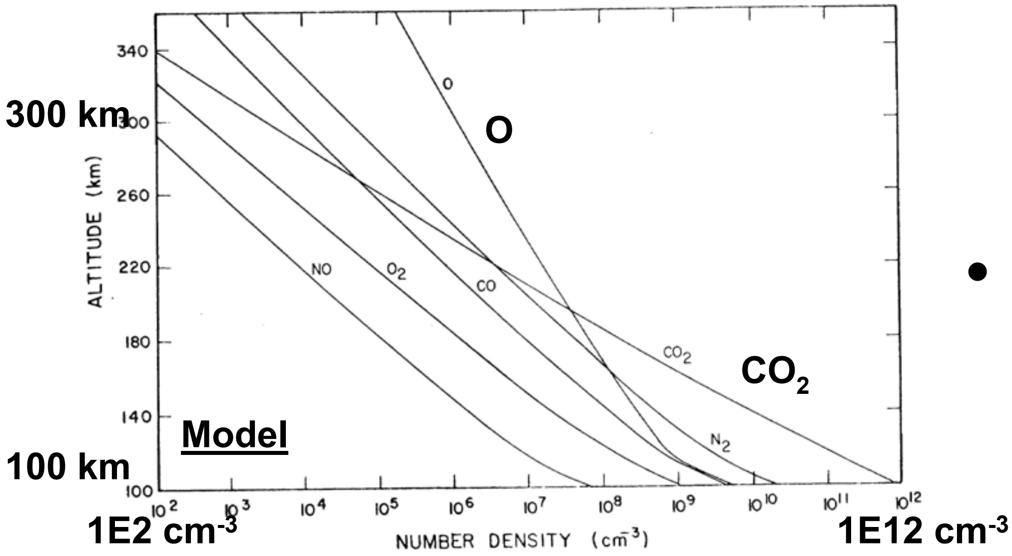
- Upper atmospheric composition
- Solar irradiance, CO_2 cross-sections, optical depth
- Typical ionospheric profile
- Significance of electron-impact ionization

Composition of the Upper Atmosphere

- Two Viking profiles
- Mostly CO_2
- Atomic O <u>inferred</u> to become dominant above ~200 km
- Viking could not measure O

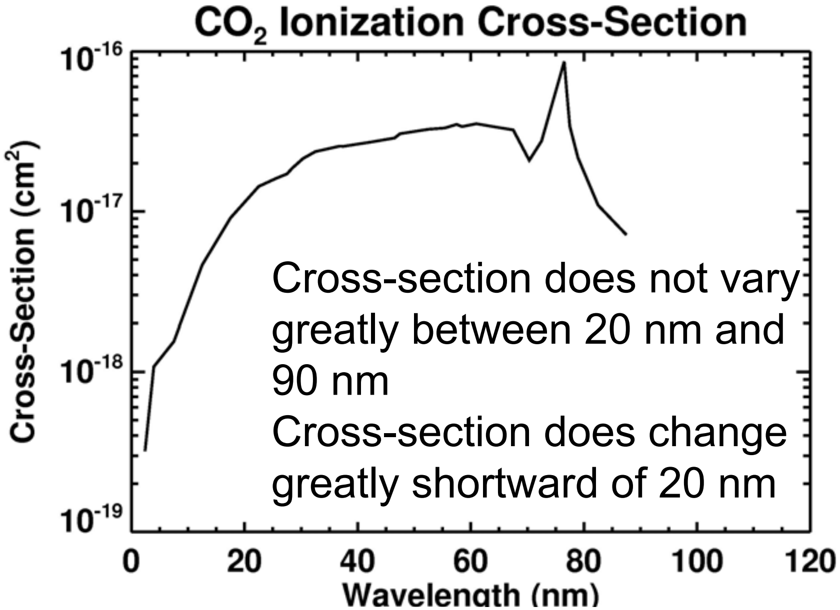


Nier and McElroy, 1977

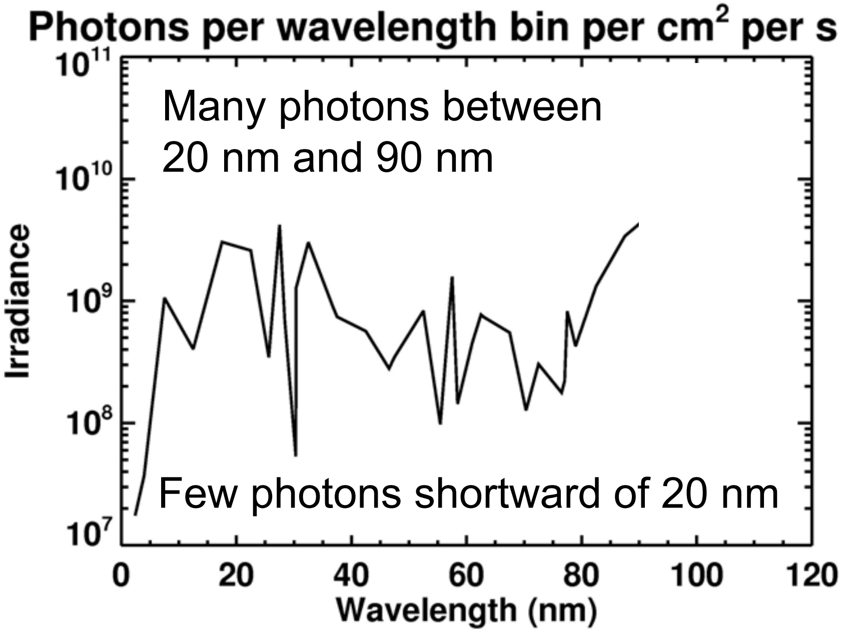


Chen et al., 1978

Cross-sections & Sun's spectrum affect ionosphere

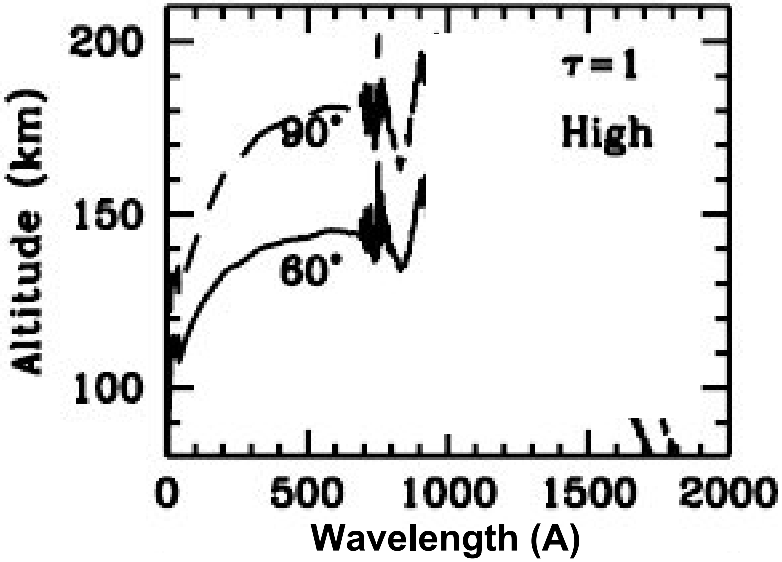


Cross-section does not vary greatly between 20 nm and 90 nm
Cross-section does change greatly shortward of 20 nm



Many photons between 20 nm and 90 nm

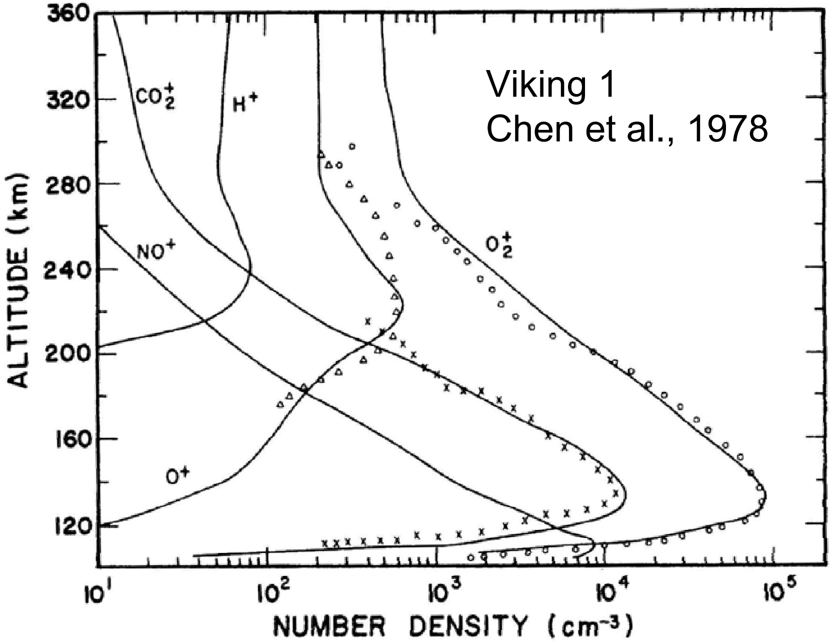
Few photons shortward of 20 nm



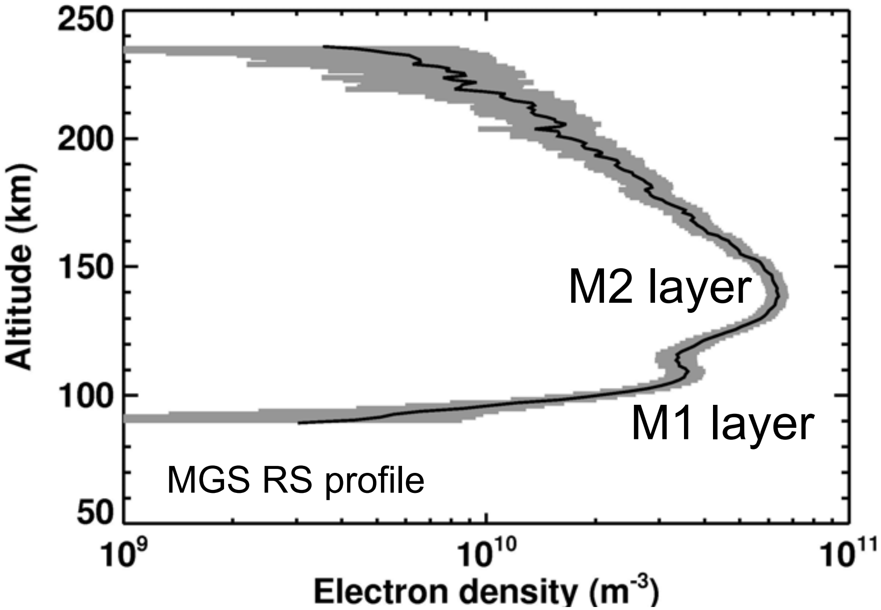
Fox and Yeager, 2006

Most ionizing photons have same altitude at which optical depth=1
Photons shortward of 20 nm penetrate deeper

Typical Ionospheric Profile



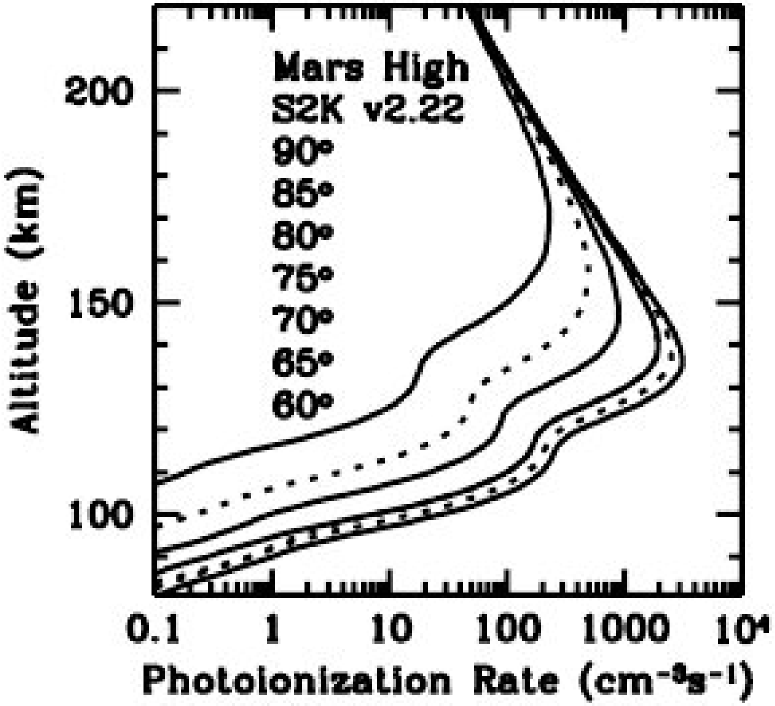
Viking 1
Chen et al., 1978



MGS RS profile

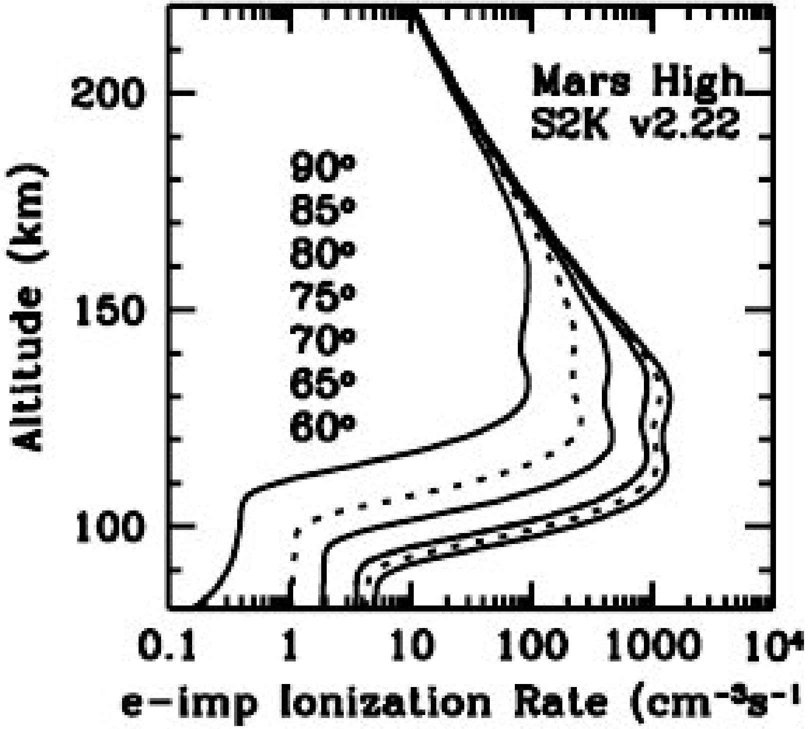
- Two Viking ion composition profiles
- Thousands of Ne(z)
- O_2^+ dominant, not CO_2^+
- O^+ and transport become significant in topside above ~200 km
- Small, variable M1 layer below M2 layer

Rate of production by photoionization



(Fox and Yeager, 2006)

Rate of production by electron impact



(Fox and Yeager, 2006)

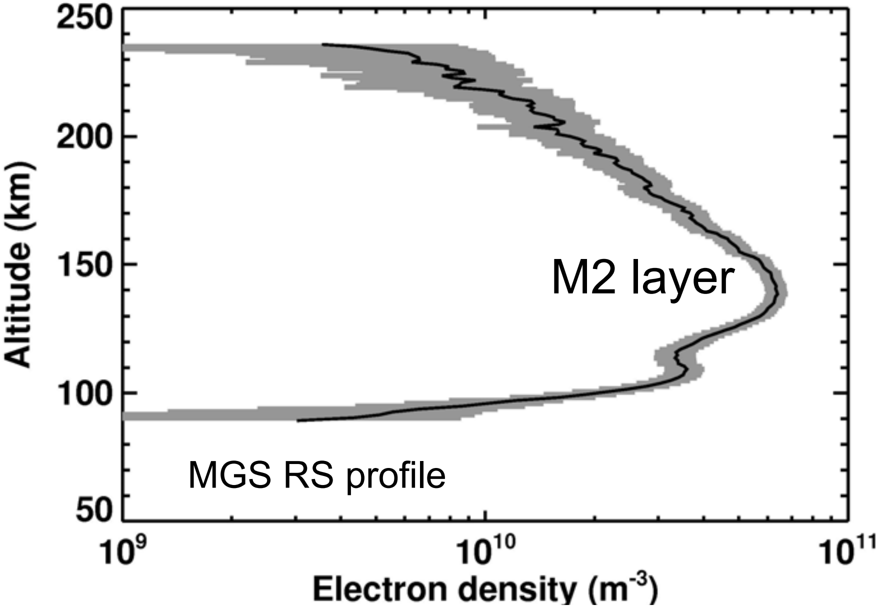
Why does M1 layer exist?

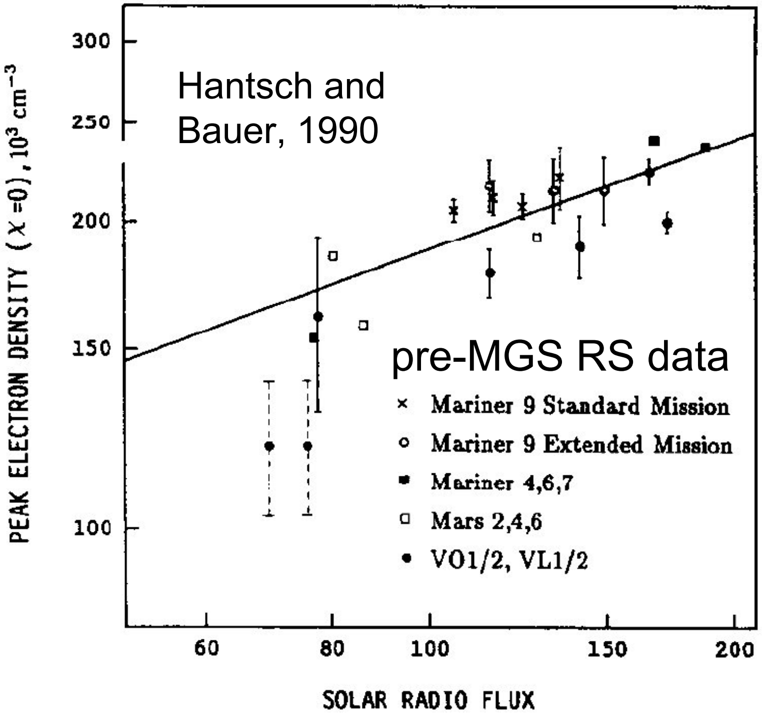
Photoionization rates suggest only a minor shoulder should exist.
However, one photon can produce more than one ion-electron pair due to electron impact ionization.
This process is hard to model accurately.

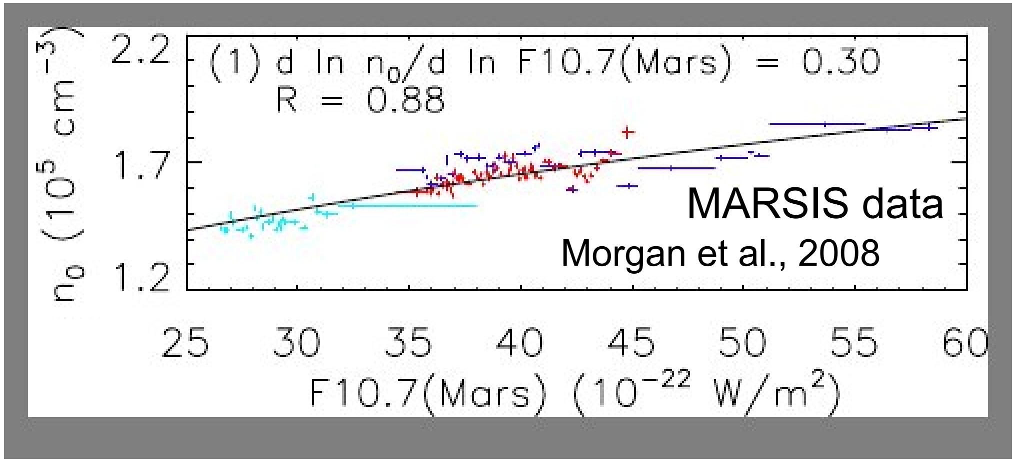
X-ray photons shortward of ~10 nm produce more ion-electron pairs than EUV photons
Each photon absorbed at the M2 layer produces ~1 ion-electron pairs
Each photon absorbed at the M1 layer produces ~10 ion-electron pairs!

Variability in the main ionospheric layer (M2)

- M2 Layer electron density
  - – Solar flux
    - 11 yr cycle
    - 27 day rotation
    - Flares
  - – Solar zenith angle
- M2 Layer altitude
  - – Solar zenith angle
  - – Tides
- M2 Layer width

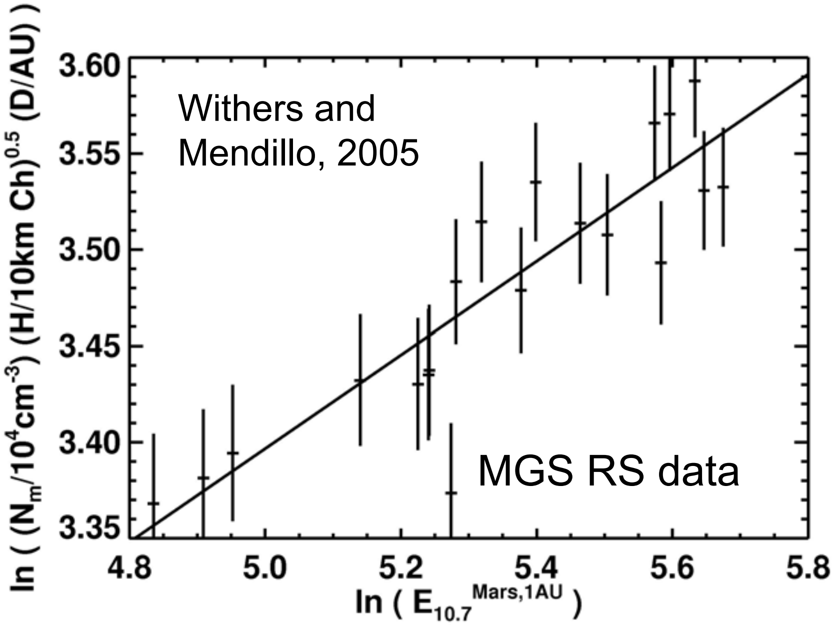


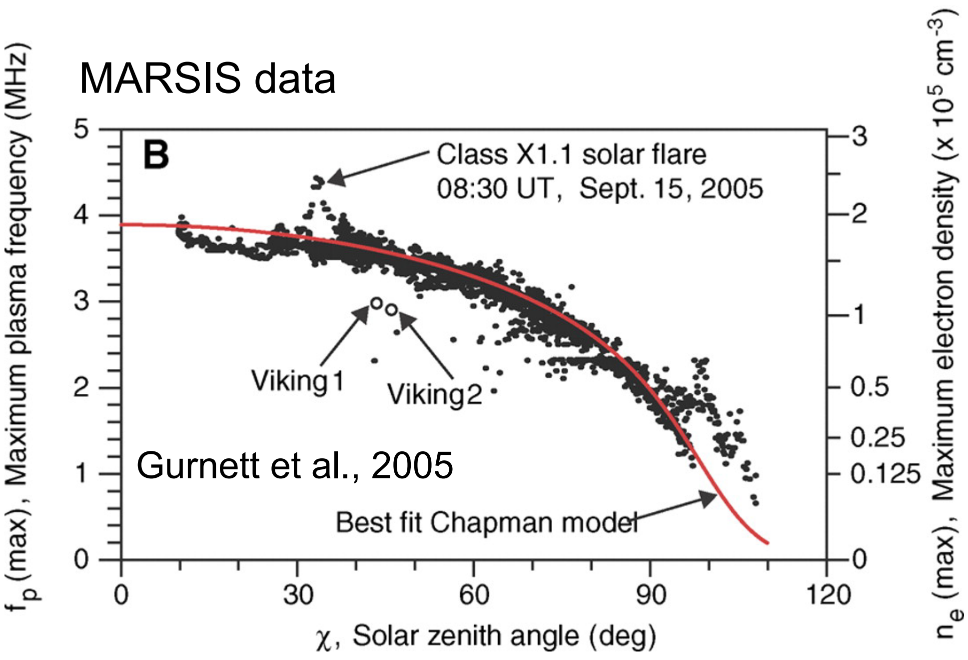




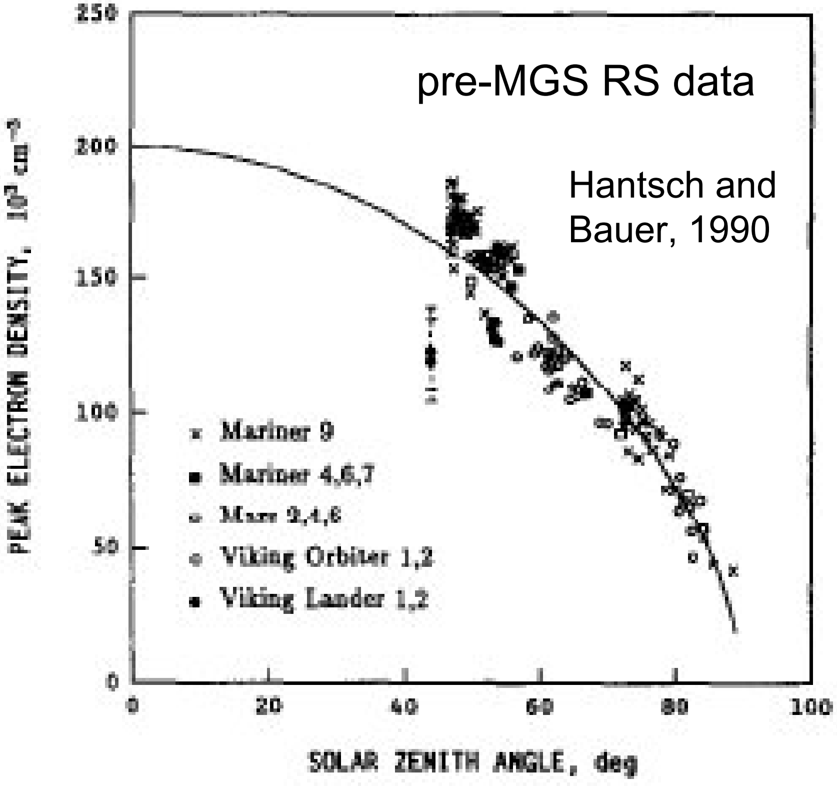
Peak electron density varies with solar EUV irradiance, often measured via F10.7

d ln N / d ln F ~ 0.3 in observations
Chapman theory predicts 0.5

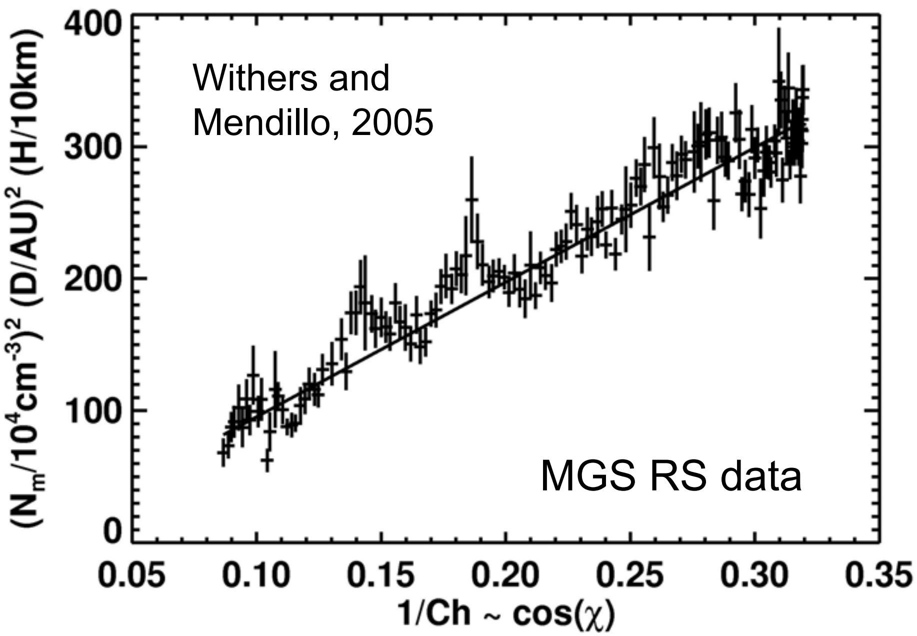



MARSIS data

Gurnett et al., 2005


pre-MGS RS data

Hantsch and Bauer, 1990


Withers and Mendillo, 2005

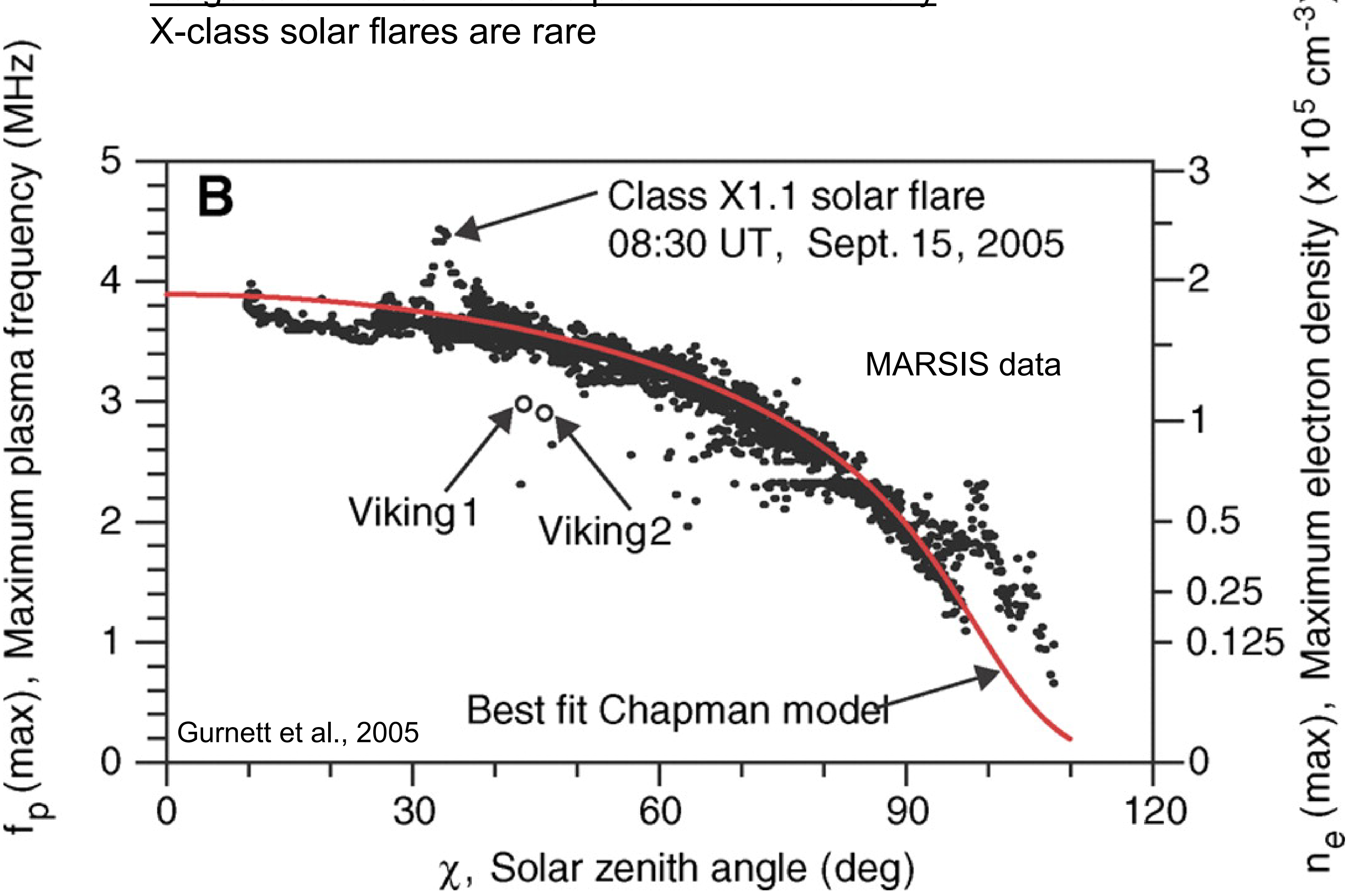
MGS RS data

<u>Peak electron density varies with solar zenith angle (SZA)</u>

Observations show that N is proportional to the square root of cosine of SZA (approximately)
This is consistent with Chapman theory

Large solar flares increase peak electron density

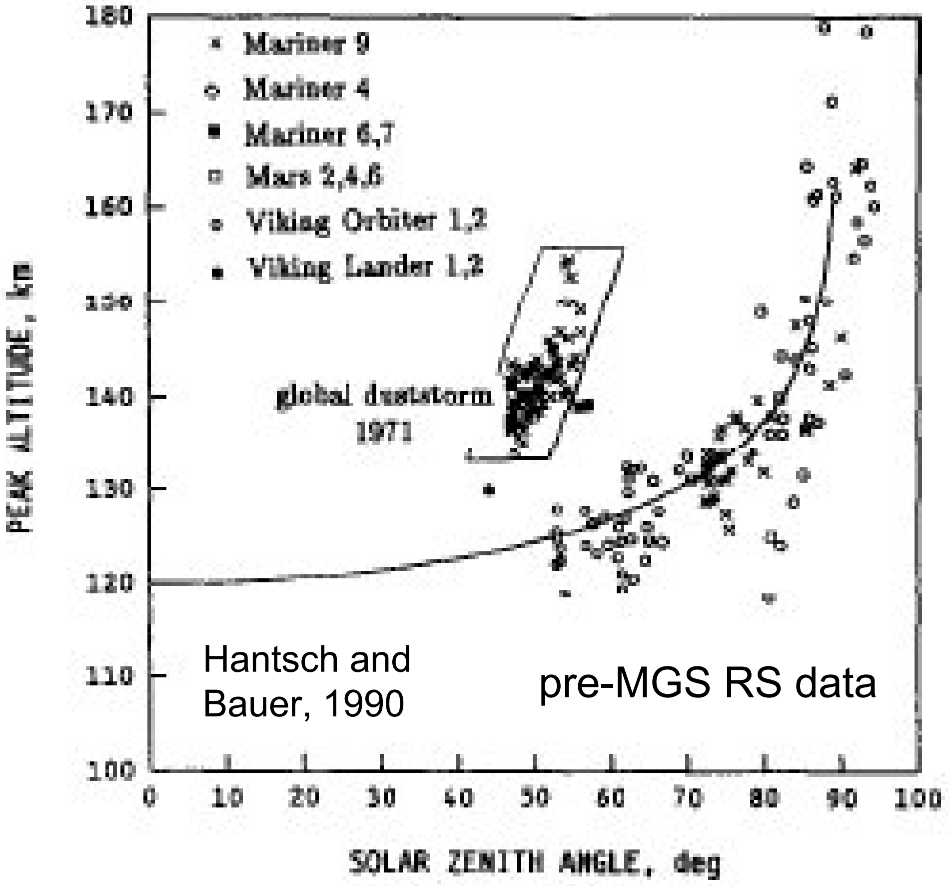
X-class solar flares are rare



MARSIS data

Gurnett et al., 2005

Peak altitude varies with SZA



Hantsch and Bauer, 1990

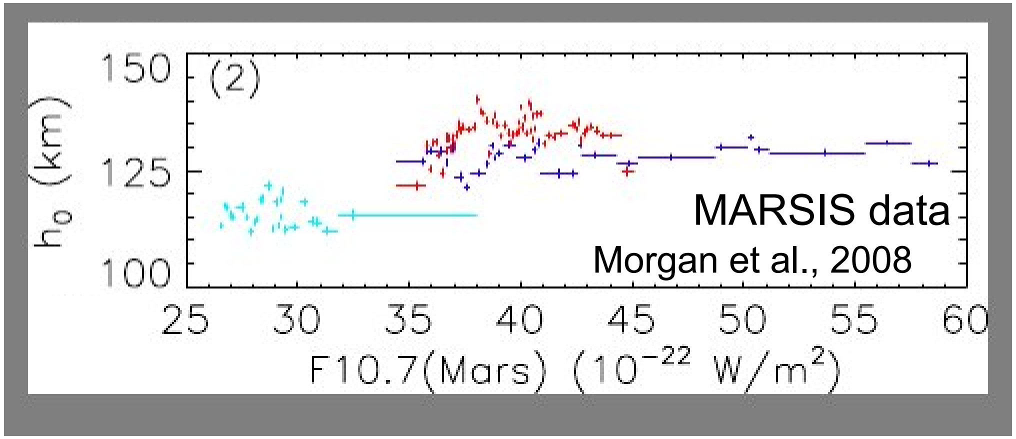
pre-MGS RS data

Observed variations are approximately consistent with Chapman theory, which predicts:

$z_{peak} = z_{subsolar} + H \ln \sec(SZA)$

$z_{subsolar}$ is predicted to satisfy:

$\sigma N(z_{subsolar}) H = 1$

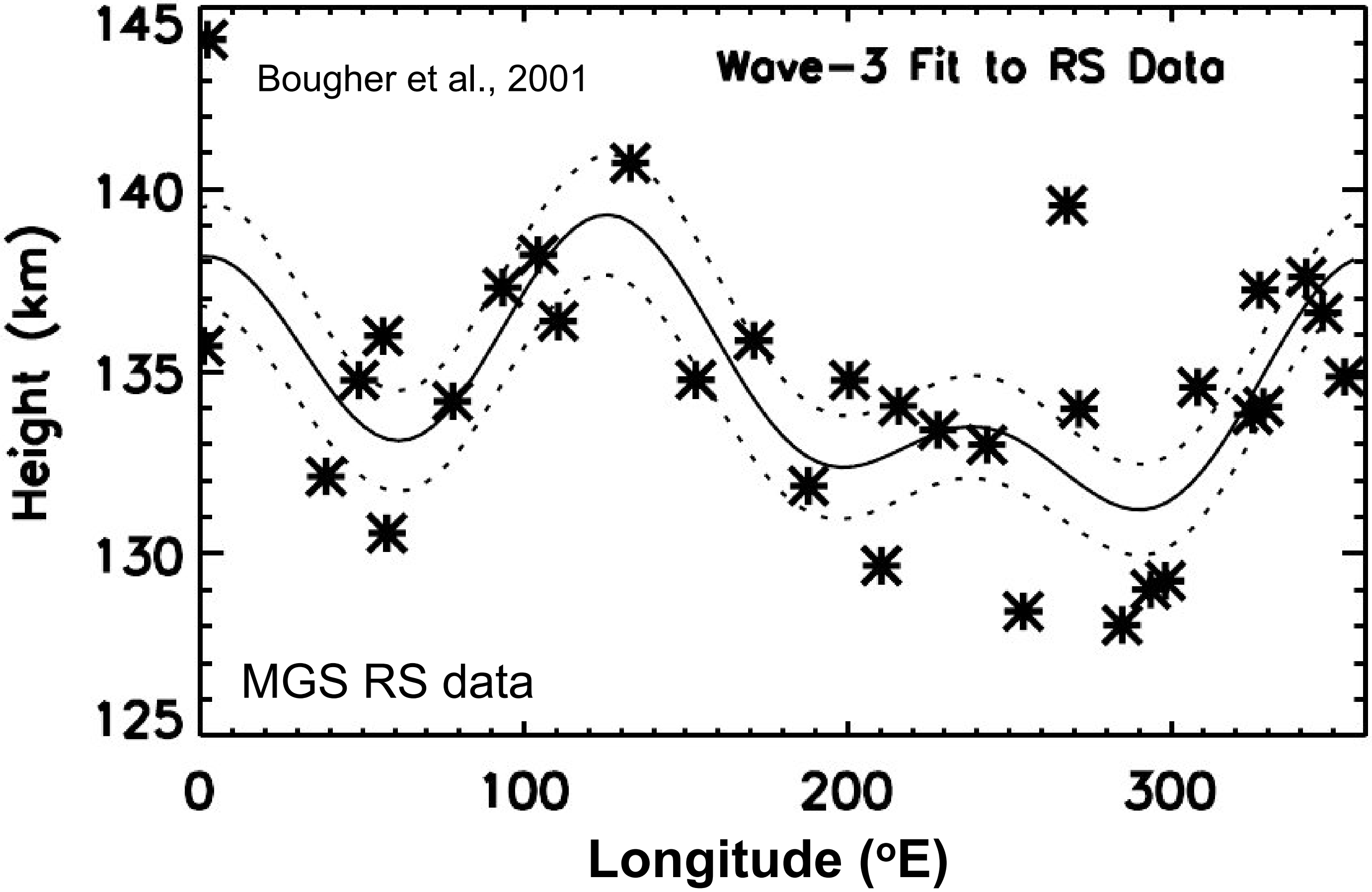


MARSIS data

Morgan et al., 2008

Recent MARSIS data suggest that $z_{subsolar}$ increases as F10.7 increases

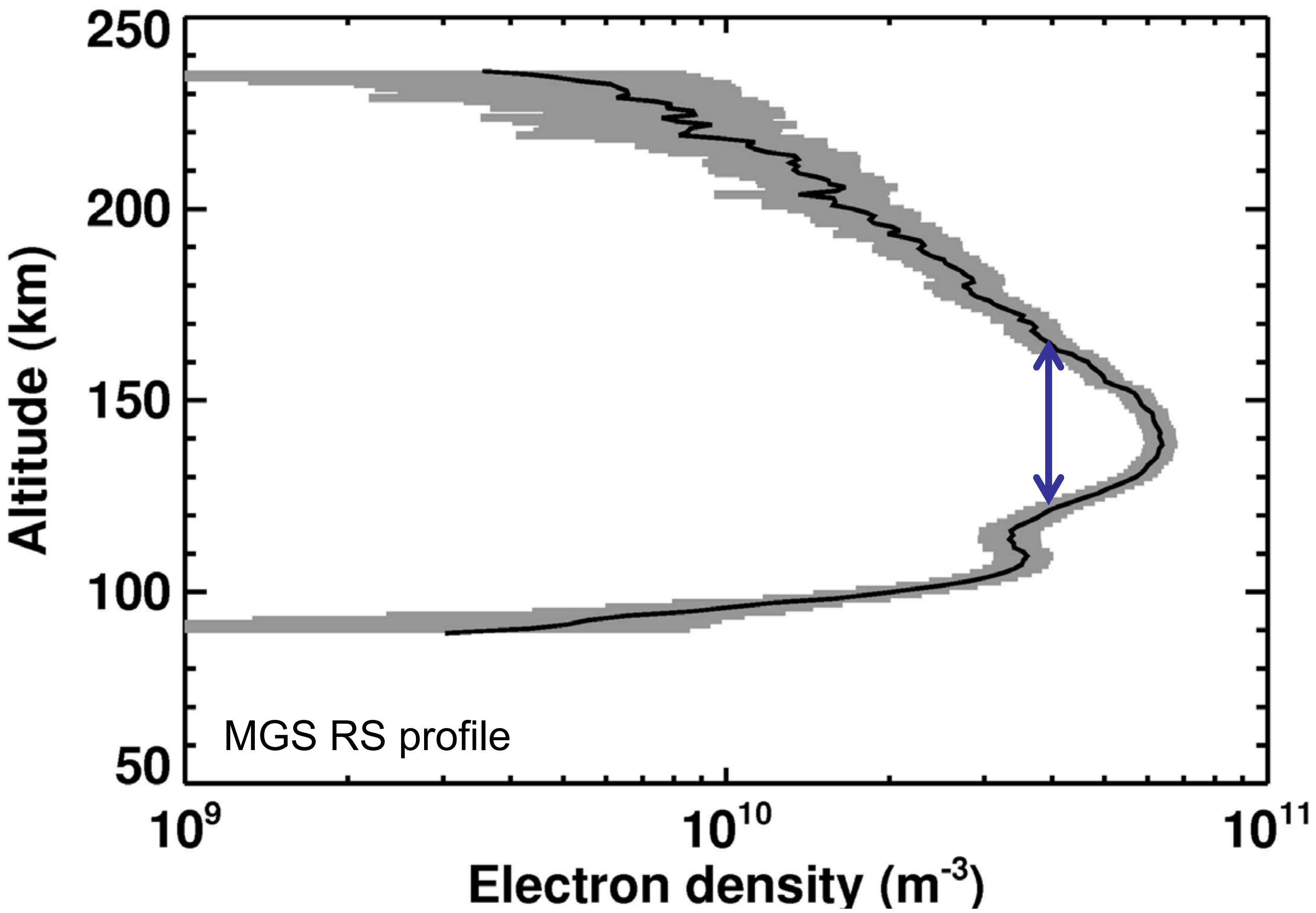
However, seasonal trends have not been removed



Height of M2 layer varies with longitude

Height of M2 layer is predicted to satisfy σ N H sec(SZA) = 1
These data points collected at same SZA, season, latitude, local solar time

Tides in the neutral atmosphere cause altitude of fixed density level to vary with longitude, and the height of the M2 layer varies as well



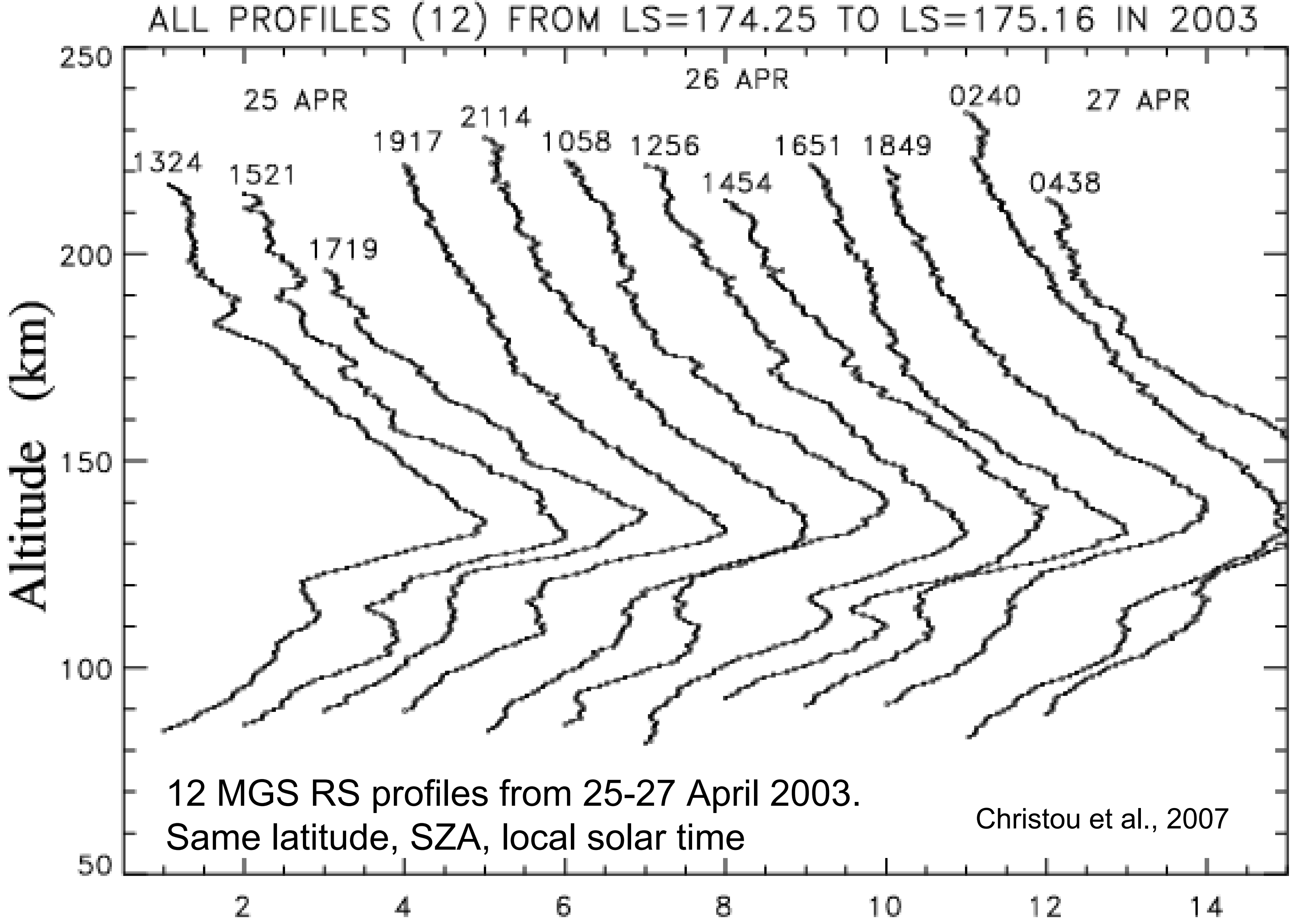
<u>Width of M2 layer is related to scale height of neutral atmosphere</u>

Full width at half maximum = 3.6 H according to Chapman theory

There have not been many studies of variations in the width of the M2 layer

Variability below the main M2 ionospheric layer

- M1 layer
  - Day-to-day variability
  - Solar flare
- Meteoric layer at 90 km
- Plasma far below 90 km?

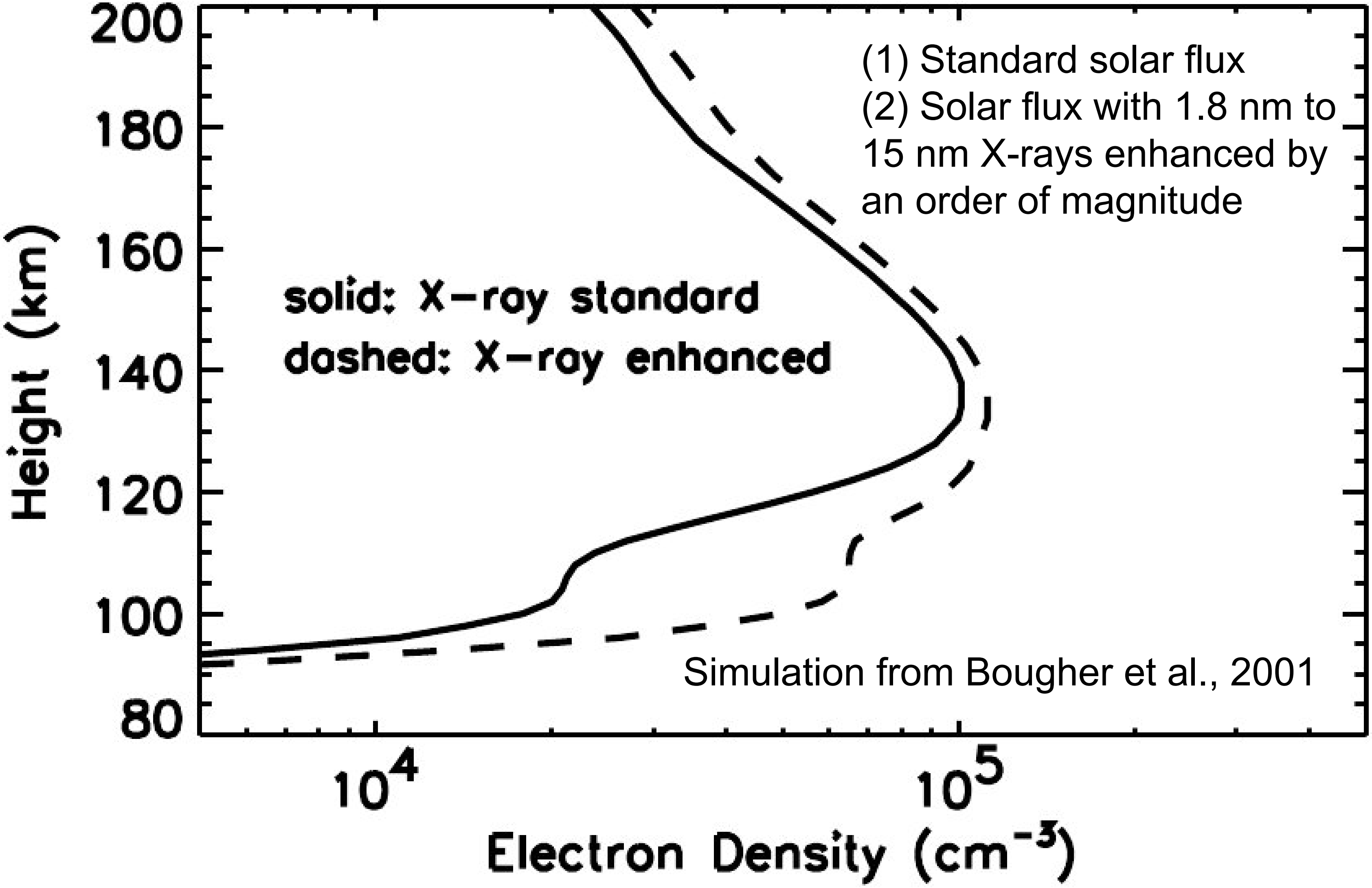


12 MGS RS profiles from 25-27 April 2003.
Same latitude, SZA, local solar time

Christou et al., 2007

<u>Shape, altitude and electron density of the M1 layer all vary on timescales of <hours</u>

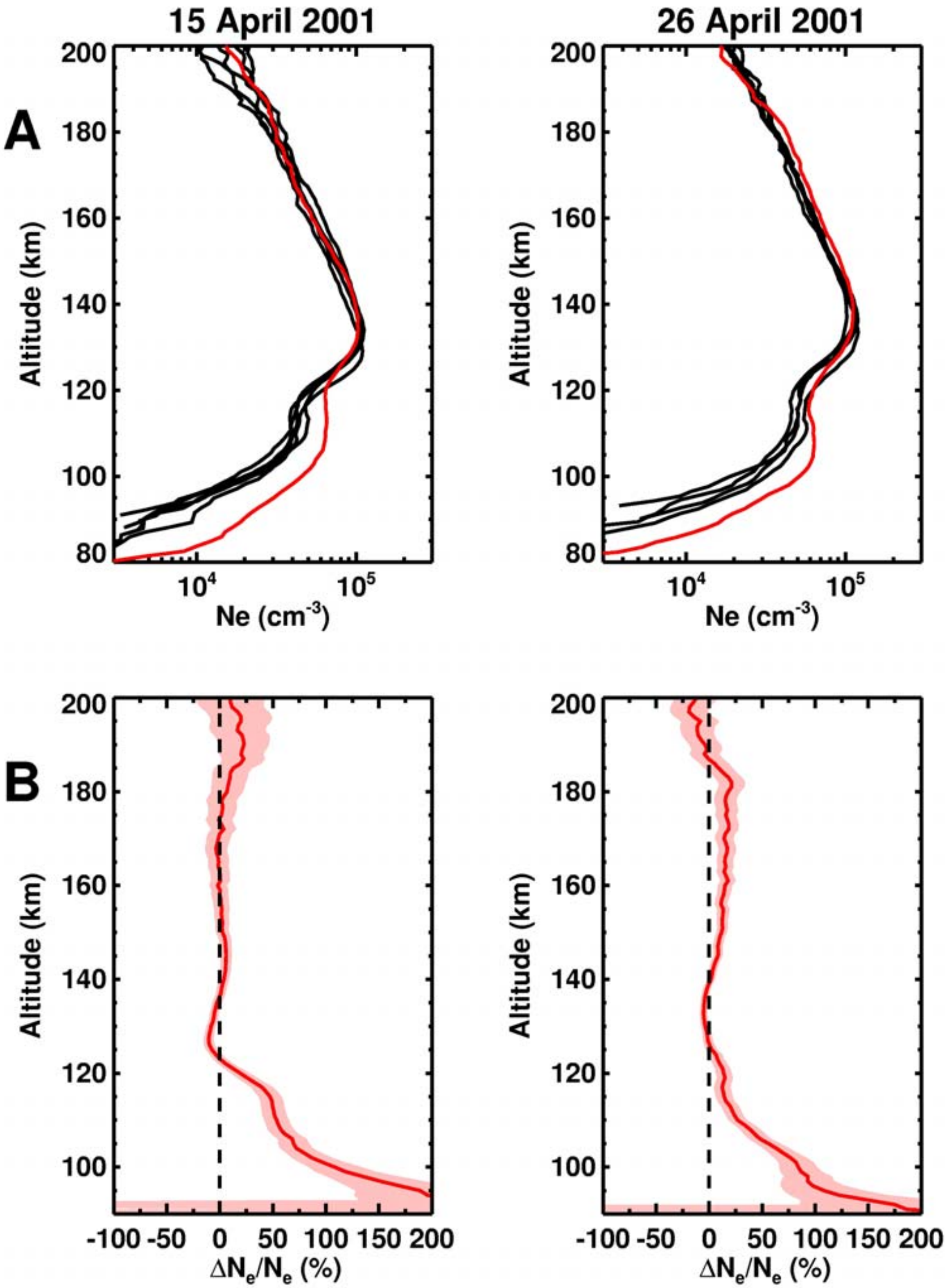
Fox and Yeager (2006) suggest that M1 electron density varies with SZA



(1) Standard solar flux
(2) Solar flux with 1.8 nm to 15 nm X-rays enhanced by an order of magnitude

Simulation from Bougher et al., 2001

Interpretation of M1 layer observations is complicated by
(A) Lack of knowledge of solar irradiance at appropriate wavelengths and cadences
(B) Difficulties of modelling electron-impact ionization



Mendillo et al., 2006

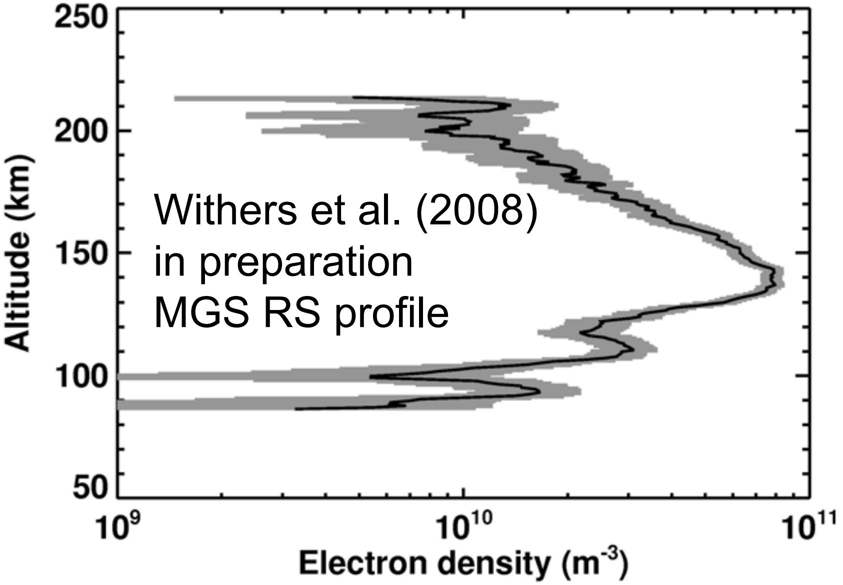
Solar flares have large effects below the main ionospheric layer

X14.4 solar flare on 15 April 2001
M7.8 solar flare on 26 April 2001

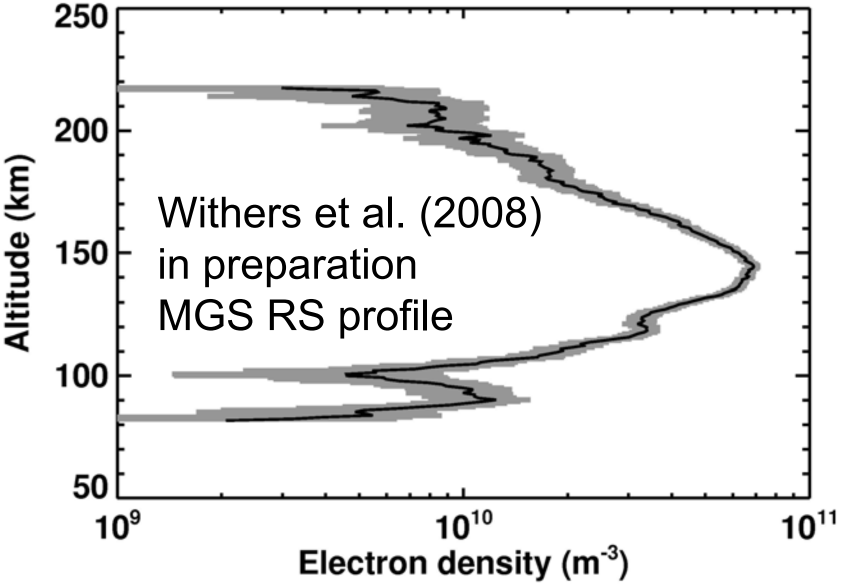
Electron densities below ~120 km are increased by a solar flare

Relative change in electron density increases as altitude decreases, which is consistent with hardening of spectrum during a solar flare

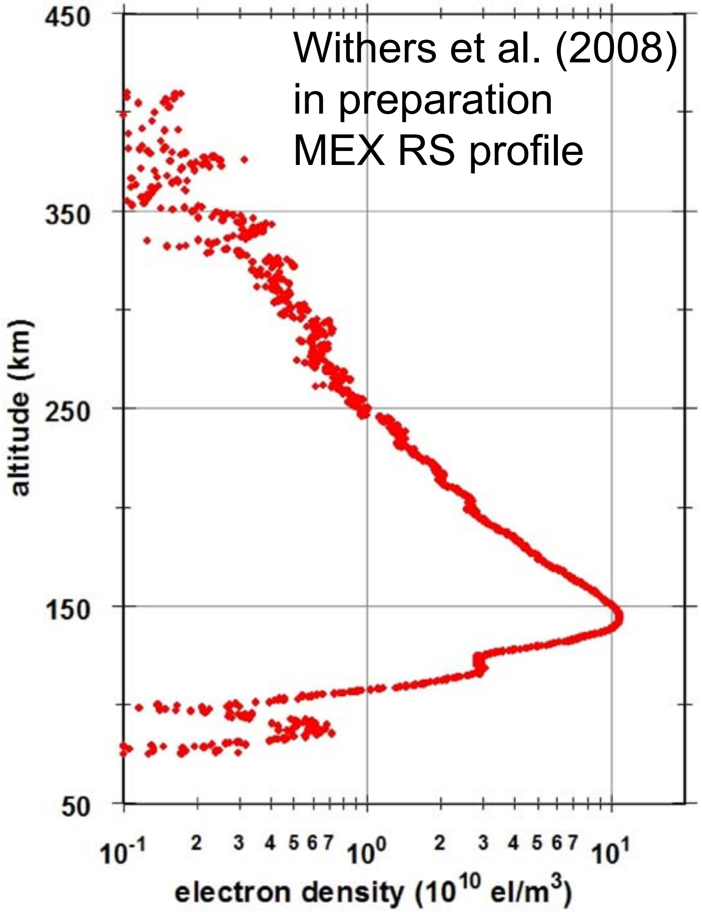
Shape of lower ionosphere changes during a solar flare



Withers et al. (2008)
in preparation
MGS RS profile



Withers et al. (2008)
in preparation
MGS RS profile

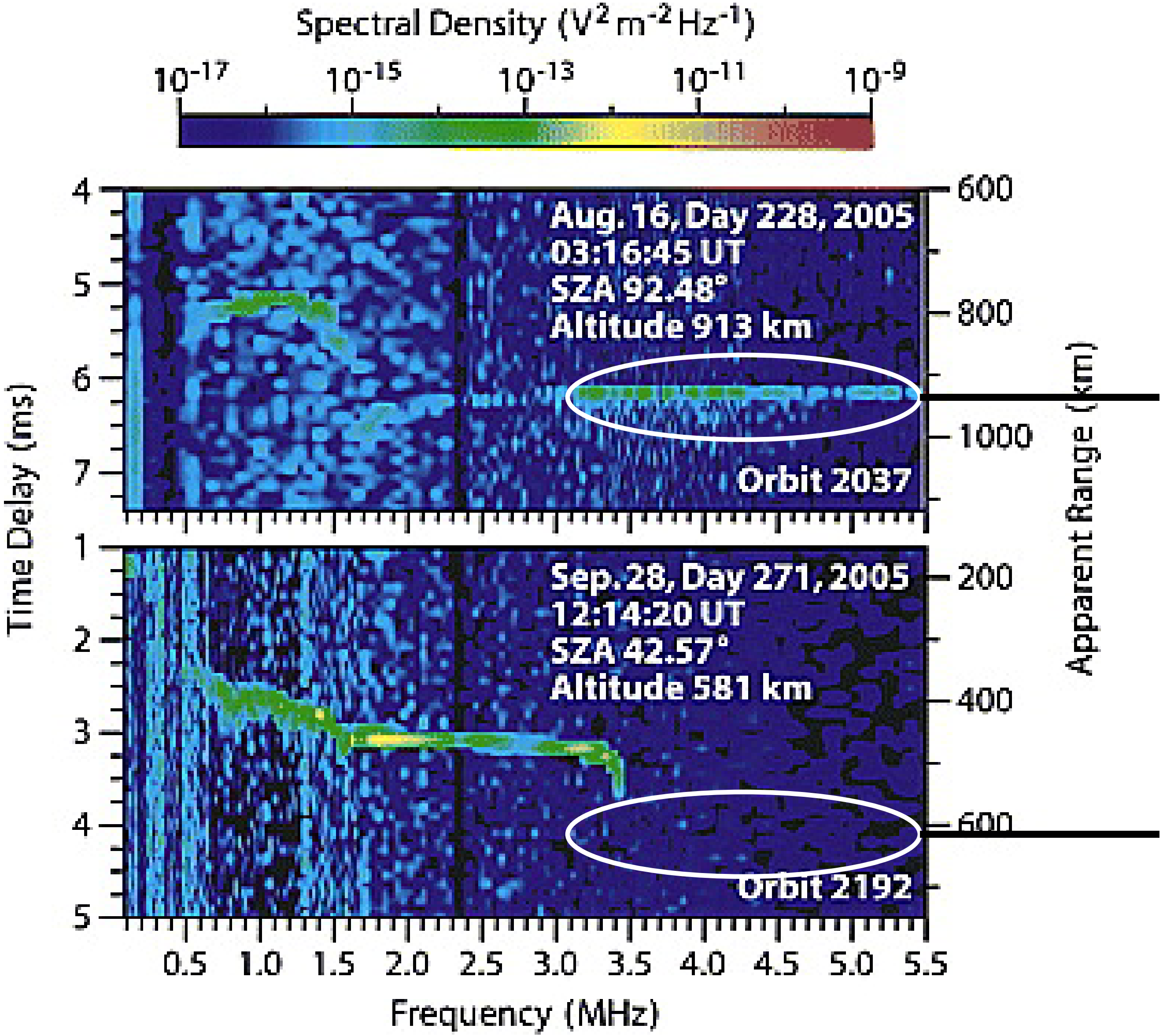


Withers et al. (2008)
in preparation
MEX RS profile

<u>Meteoroid influx creates a layer of plasma at 90 km</u>. This layer is not always detectable. Occurrence rate varies with season, consistent with control by meteor showers

Layer height, width and electron density are all correlated

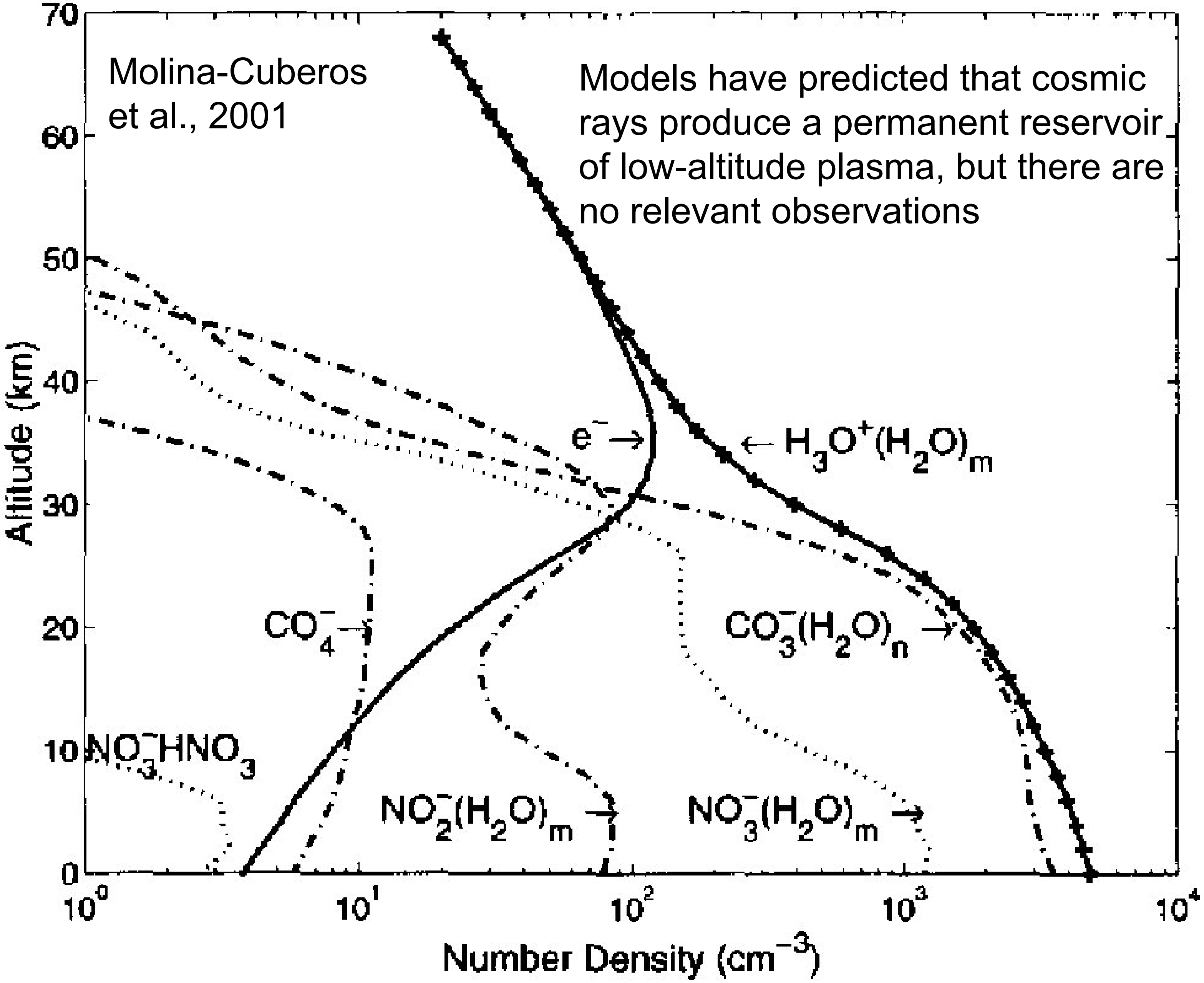
Morgan et al., 2006



<u>MARSIS detects reflections from the surface</u>

<u>MARSIS does not detect reflections from the surface</u>

Absence of surface reflections attributed to production of plasma at low altitudes by solar energetic particle events. Plasma persists for about a week.
Plasma in dense neutral atmosphere absorbs radio waves very effectively.

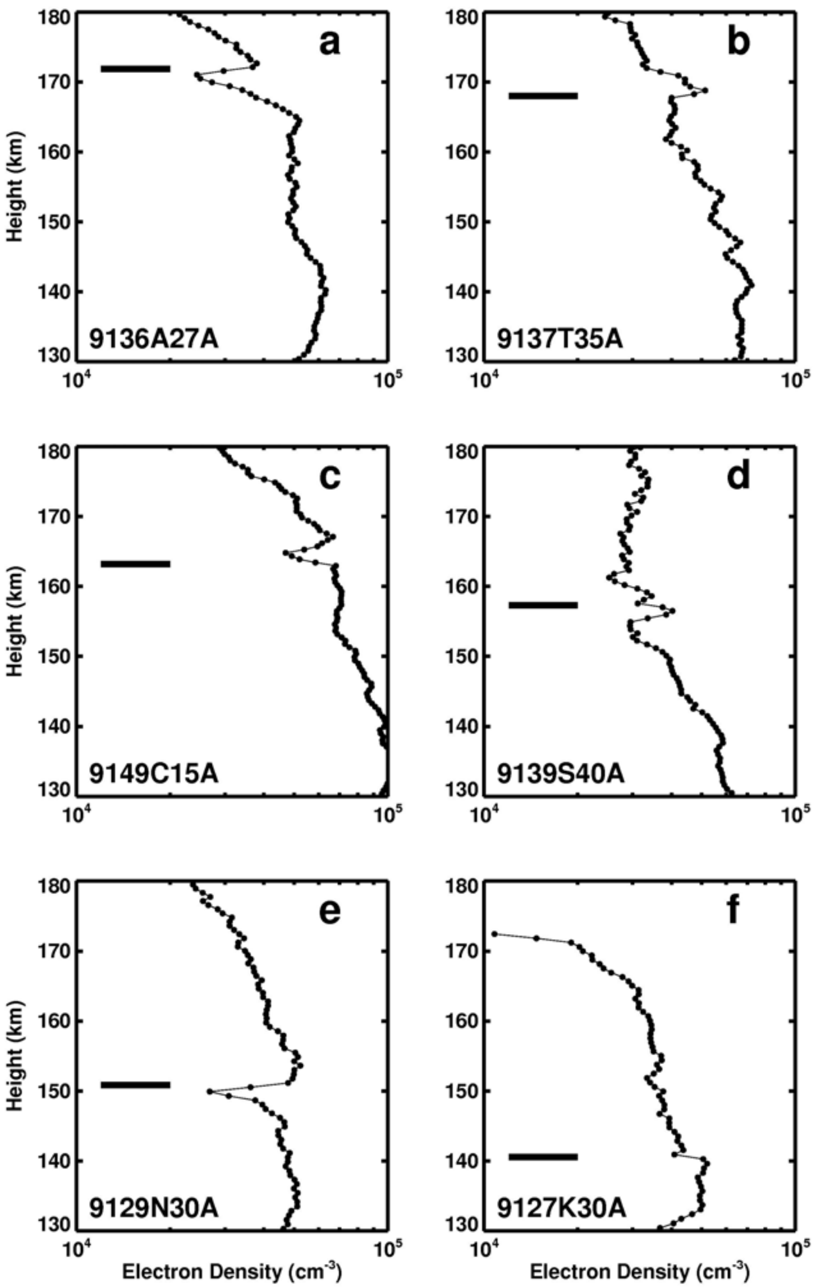


Molina-Cuberos et al., 2001

Models have predicted that cosmic rays produce a permanent reservoir of low-altitude plasma, but there are no relevant observations

Variability above the main M2 ionospheric layer

- Effects of crustal magnetic fields
  - Ionospheric structure
  - Electron temperatures
- Waves in topside ionosphere
- Ionopause



Six MGS RS profiles from Withers et al., 2005

These contain unusually large changes in electron density over a short vertical distance

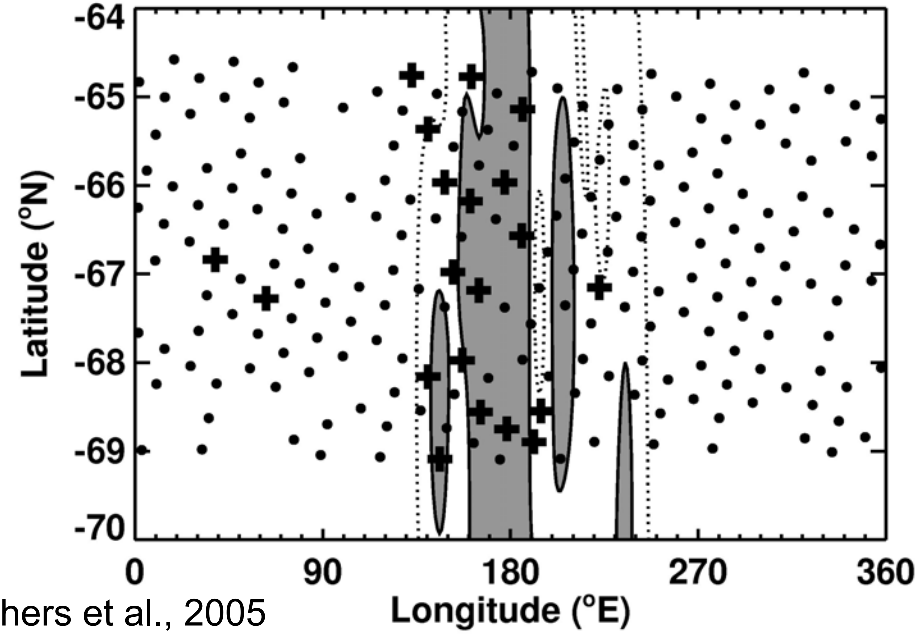
Some cases of localized decrease in electron density

Some cases of localized increase in electron density

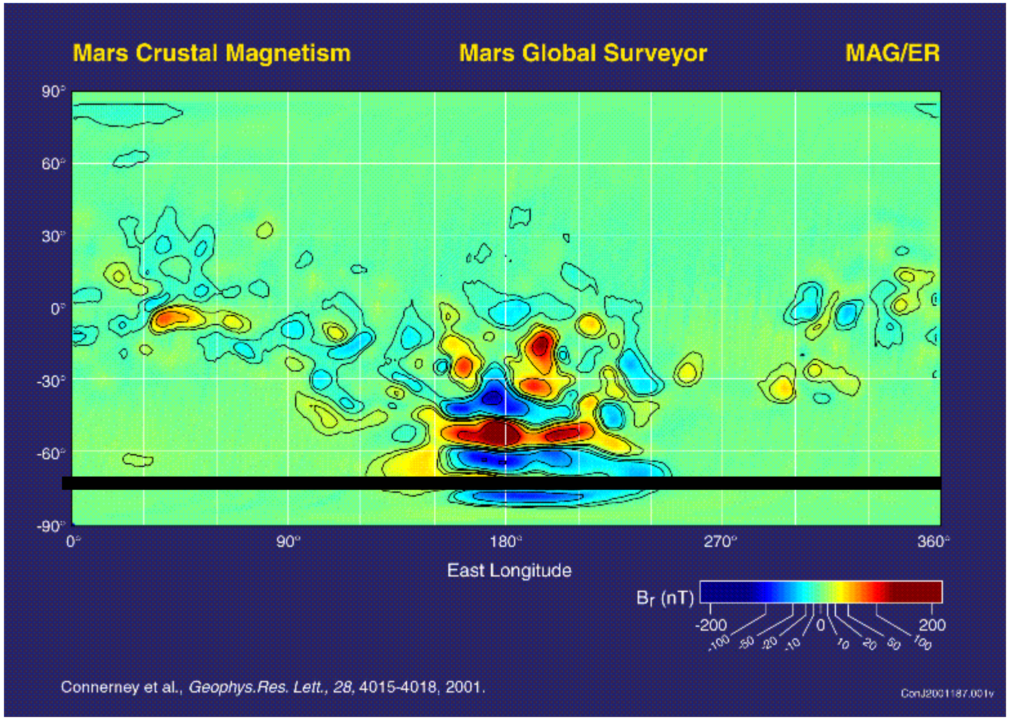
20 of 220 profiles from the southern hemisphere are anomalous

Only 5 of 3529 profiles from the northern hemisphere are anomalous

Anomalous profiles are located over regions of strong crustal magnetization



Withers et al., 2005



Connerney et al., *Geophys.Res. Lett.*, *28*, 4015-4018, 2001.

Based on first-principles equations, a magnetic field can affect an ionosphere in a limited number of ways

Plasma motion – Large scale dynamics

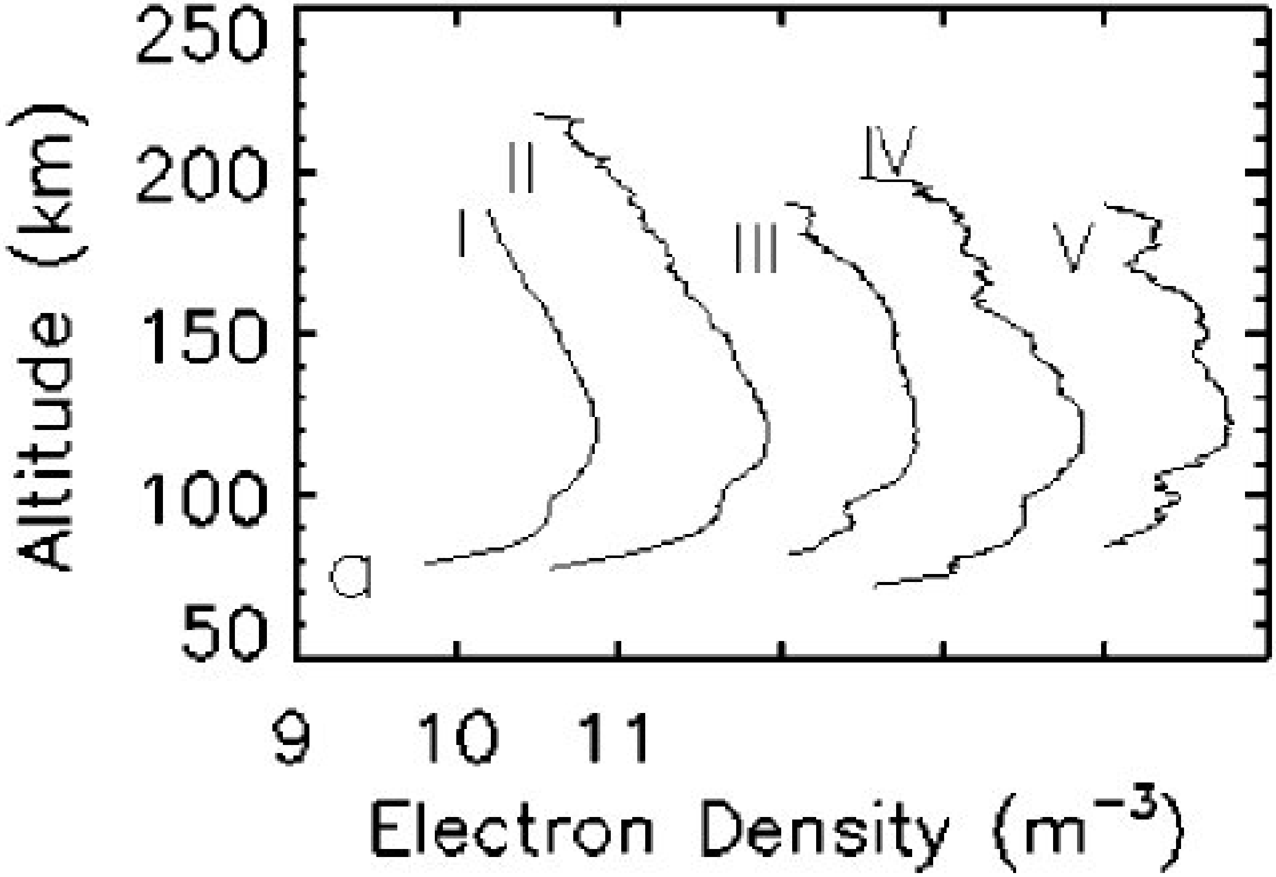
Plasma motion – Small scale instabilities

Boundary conditions – Connection to solar wind

Strong crustal magnetic fields can form mini-magnetospheres that isolate the ionosphere from solar wind plasma

Krymskii et al. (2003) suggested that electron temperatures are high within mini-magnetospheres

Wang and Nielsen, 2003



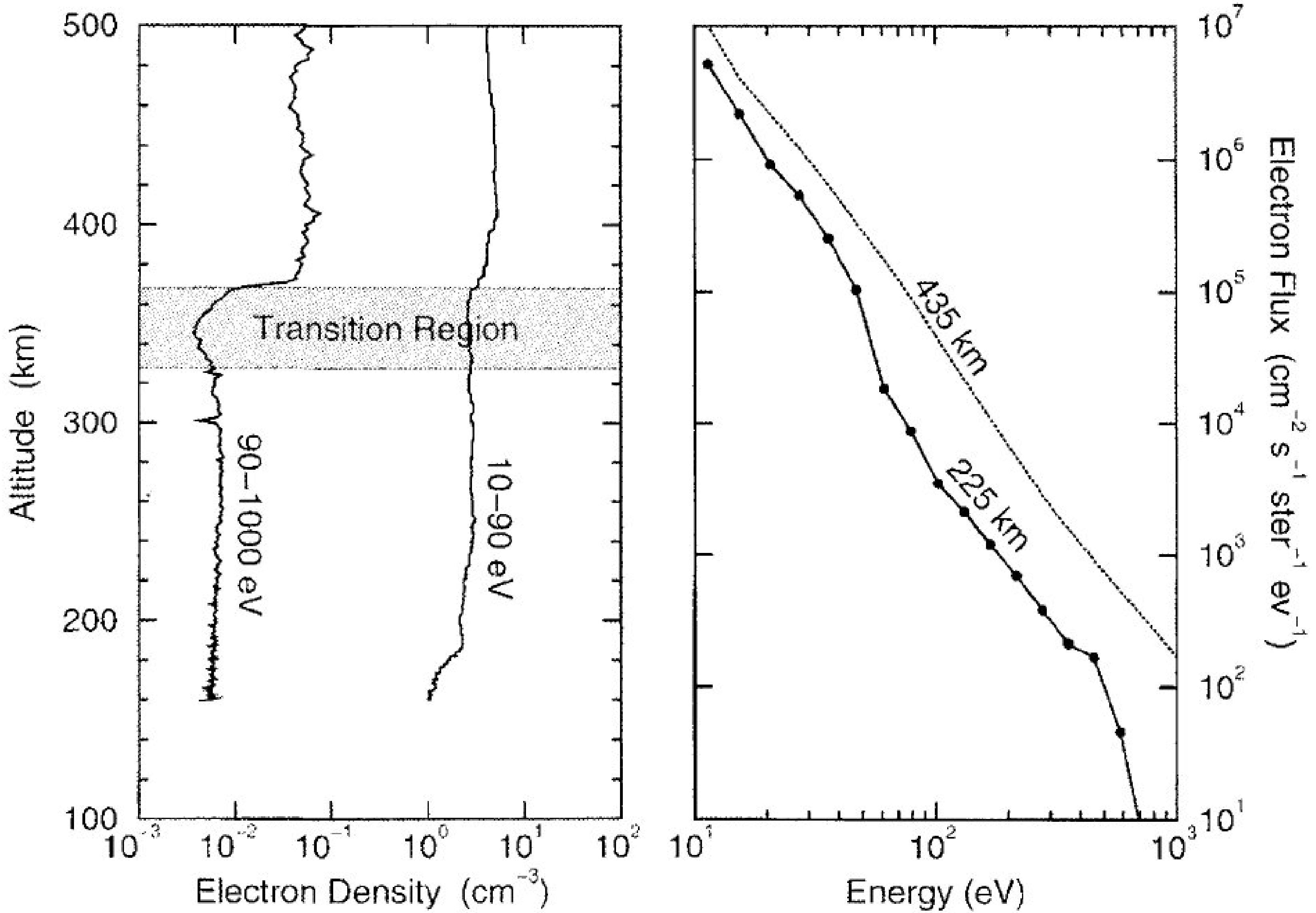
Five classes of electron density profile were identified by Wang and Nielsen

Based upon the waviness of the topside ionosphere

Attributed to the excitation of waves in the ionosphere by solar wind pressure

Topside ionosphere is highly variable.
Affected by solar zenith angle and solar wind conditions

Mitchell et al., 2001



The boundary (or boundaries) between the ionosphere and the solar wind are highly variable

Dynamics

- Plasma flow across the terminator
- Upward flow of plasma in topside ionosphere
- Effects of magnetic fields on three-dimensional plasma flow
- Small-scale plasma instabilities and their relation to magnetic fields
- Currents?

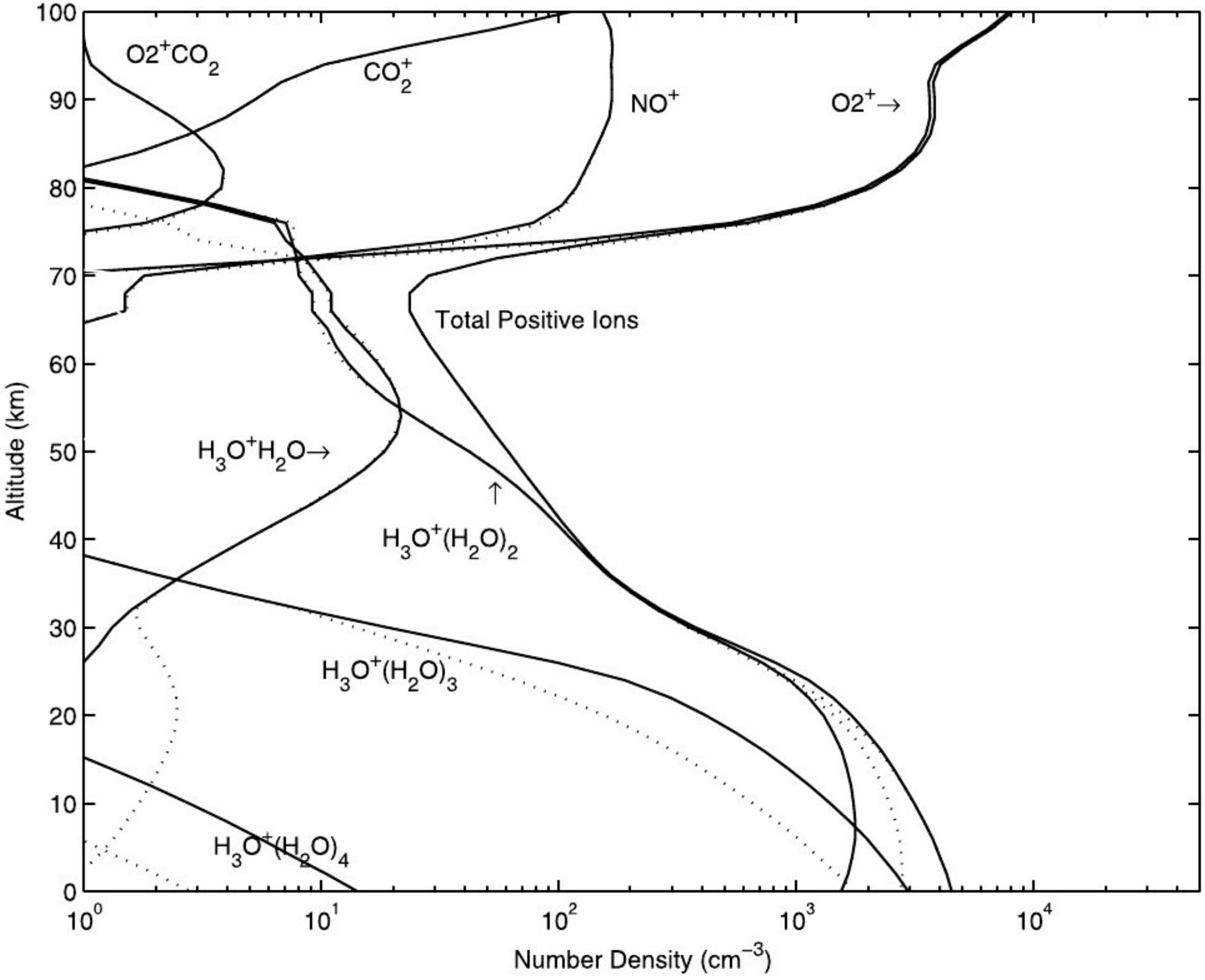
Chemistry

- Variations in O/CO_2 ratio with altitude, local solar time, solar cycle, etc.
- Does O^+ replace O_2^+ as the most abundant ion at high altitudes? Models differ.
- Importance of nitrogen-bearing ions, such as NO^+, at M1 layer and below?
- Possible presence of undetected trace species that play important roles in ionospheric chemistry?
- Chemistry of meteoric layers.

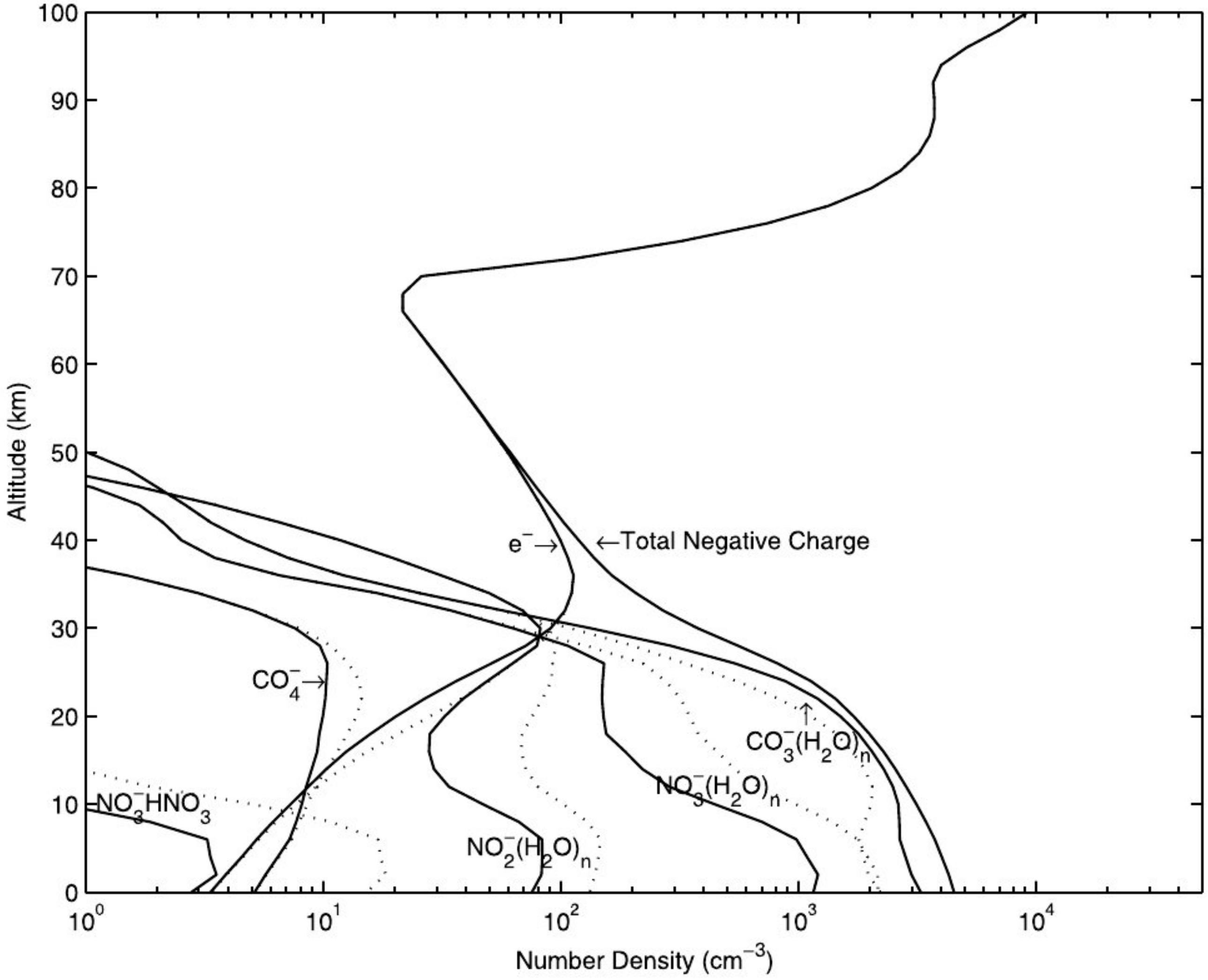
Conclusions

- Variations in solar EUV flux and in neutral atmospheric density are responsible for many of the observed variations in the M2 layer
- The M1 layer is highly variable due to variability in solar flux below 10 nm
- Variability of meteoric layers has not been explained in detail
- Magnetic fields cause spatial variability in the ionosphere
- Plasma dynamics and ionospheric chemistry are poorly constrained by present observations. There are multiple reasons why both are likely to vary.

Backup



Altitude (km)
Number Density (cm^{-3})
0
10
20
30
40
50
60
70
80
90
100
10^0
10^1
10^2
10^3
10^4
$O2^+CO_2$
CO_2^+
NO^+
$O2^+$→
Total Positive Ions
$H_3O^+H_2O$→
↑
$H_3O^+(H_2O)_2$
$H_3O^+(H_2O)_3$
$H_3O^+(H_2O)_4$


100
90
80
70
60
50
40
30
20
10
0
Altitude (km)
10^0
10^1
10^2
10^3
10^4
Number Density (cm^{-3})
e^-→
←Total Negative Charge
CO_4^-→
↑
$CO_3^-(H_2O)_n$
$NO_3^-(H_2O)_n$
$NO_3^-HNO_3$
$NO_2^-(H_2O)_n$

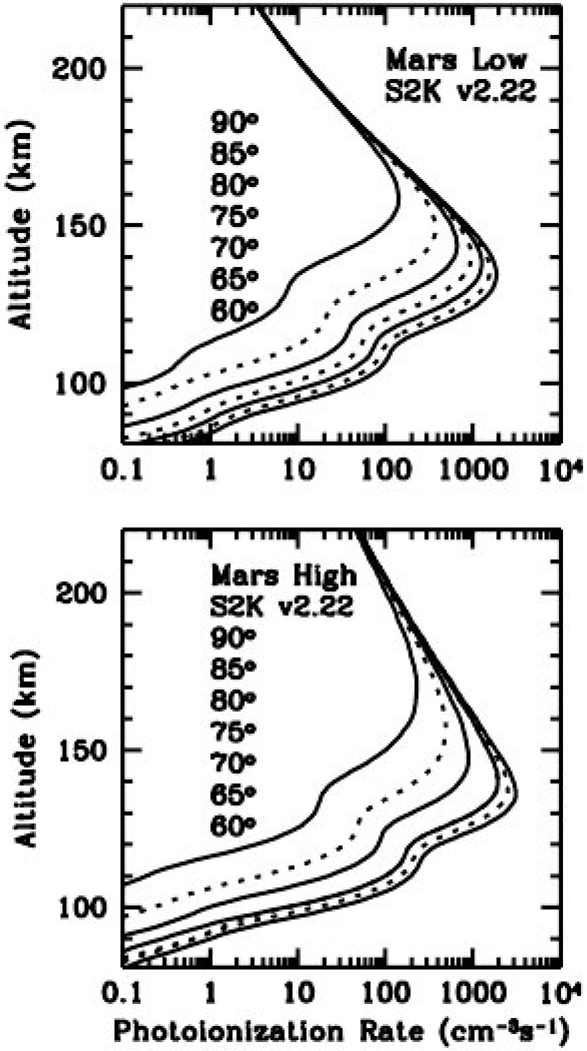


Figure 7. Altitude profiles of the photoionization rates for all the models. The curves are, in order of decreasing peak photoionization rate and increasing peak altitude, those for the 60, 65, 70, 75, 80, 85, and 90° models. (top) Low solar activity. (bottom) High solar activity.

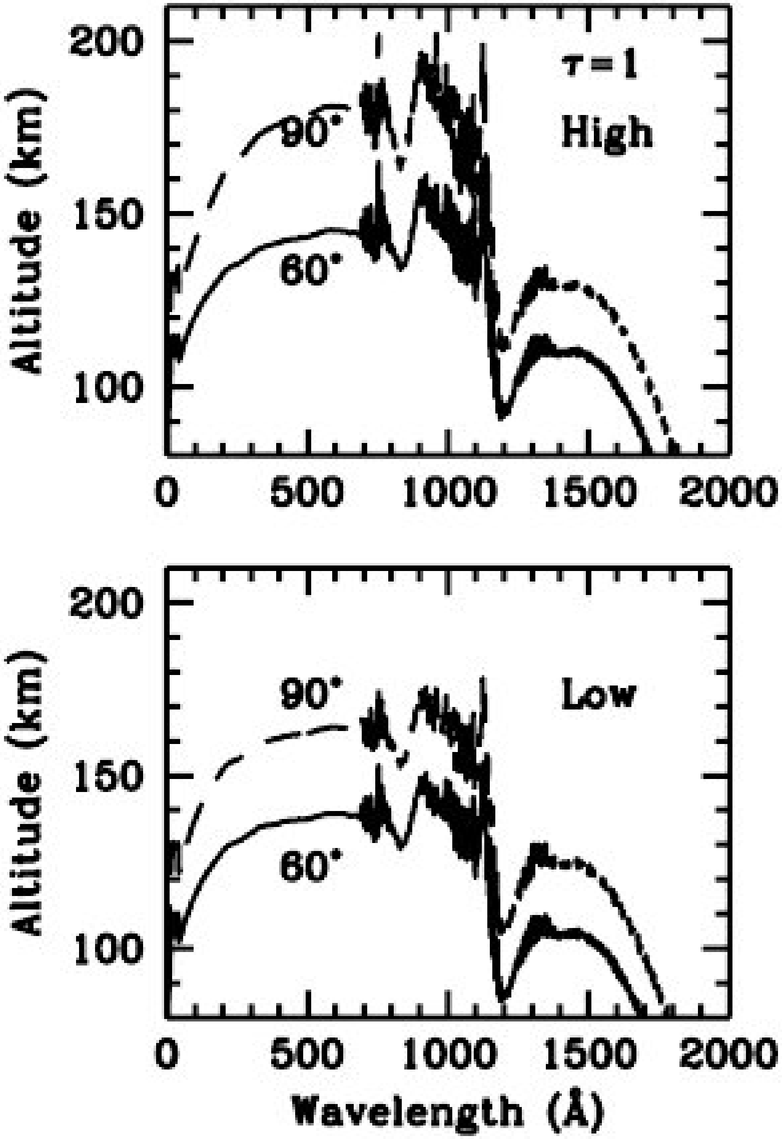


Figure 2. Optical depth unity as a function of wavelength for the interval 0 to 2000 Å for the 60 and 90° SZA models. (top) High solar activity. (bottom) Low solar activity.

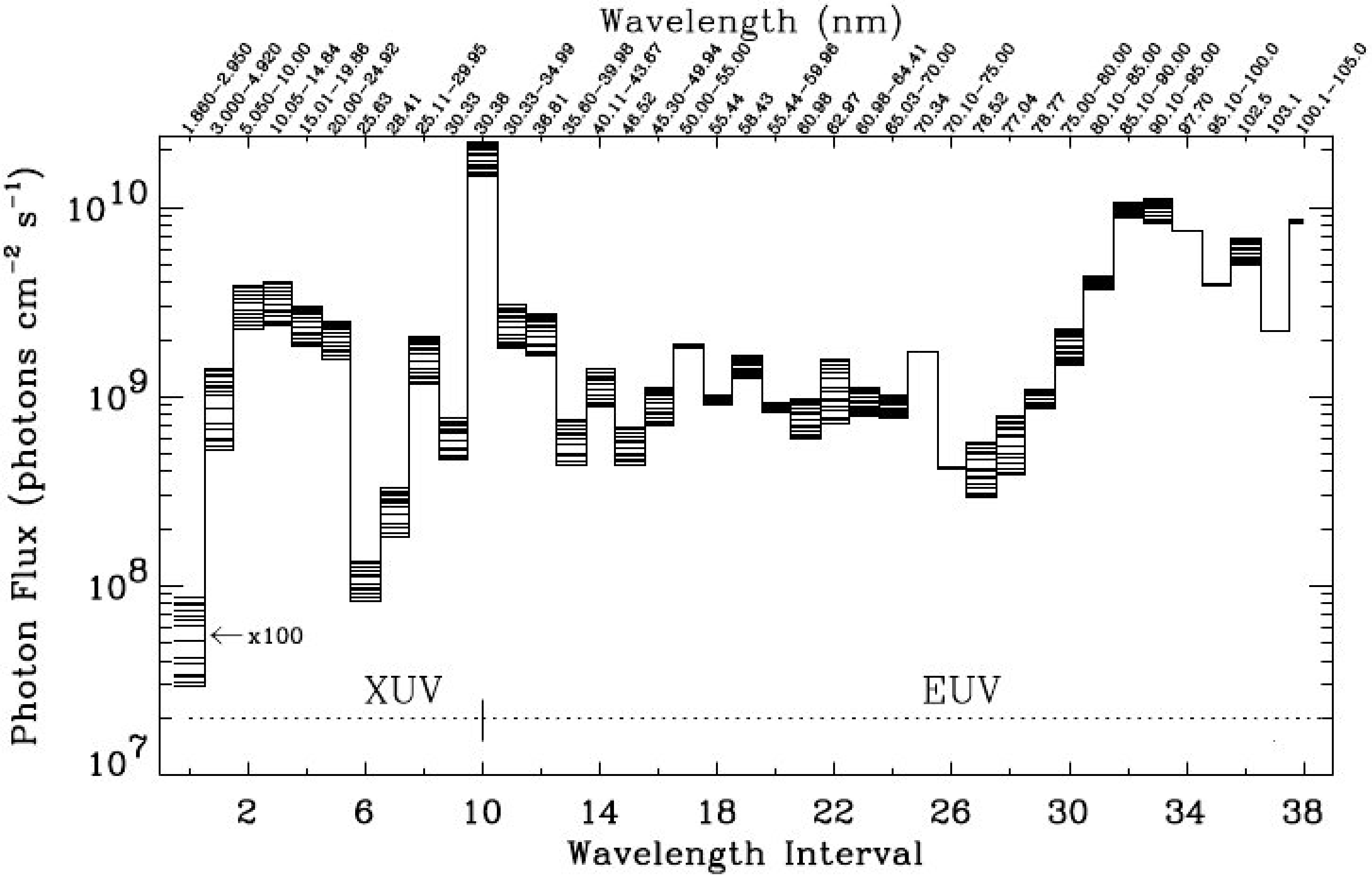
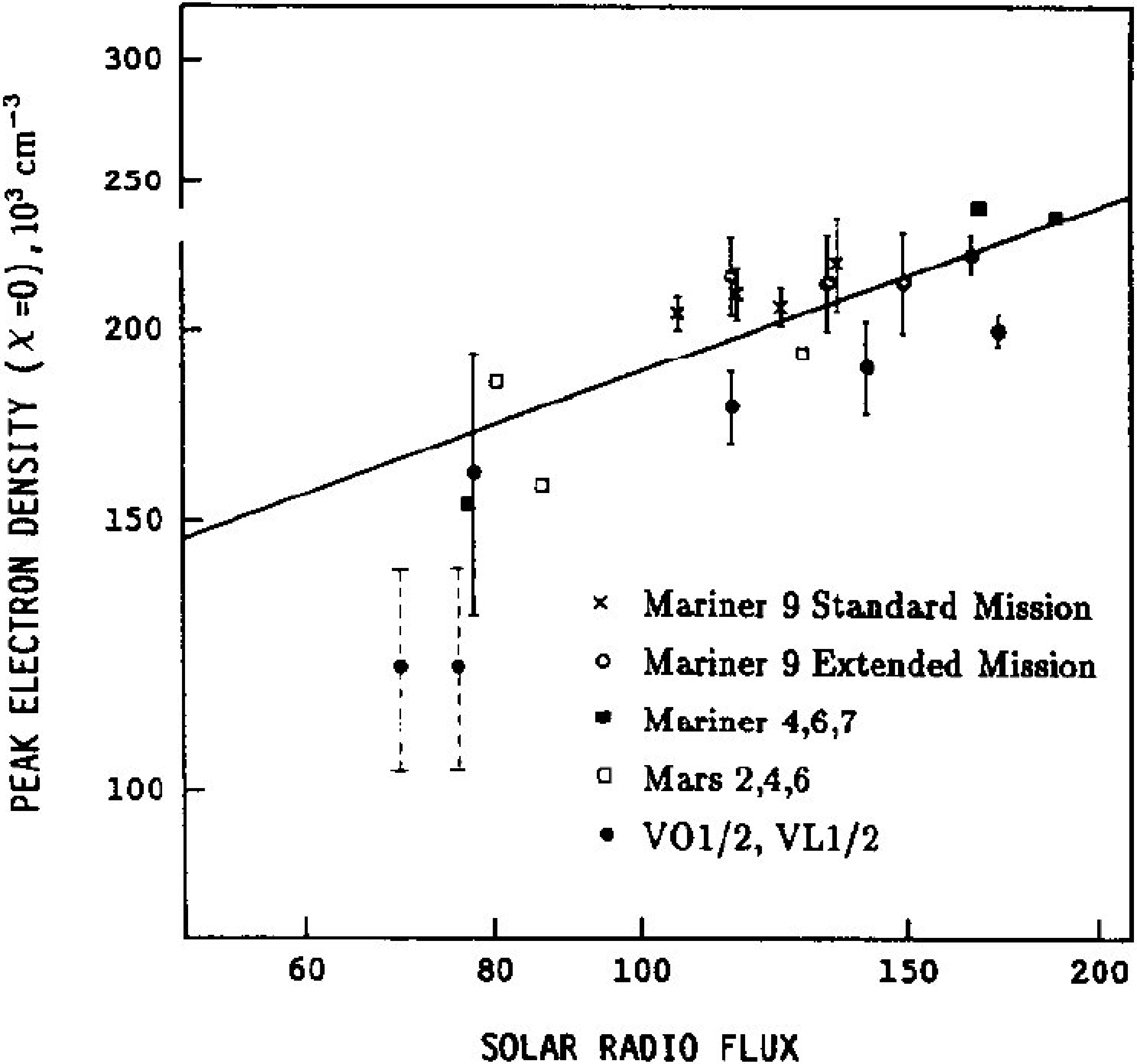
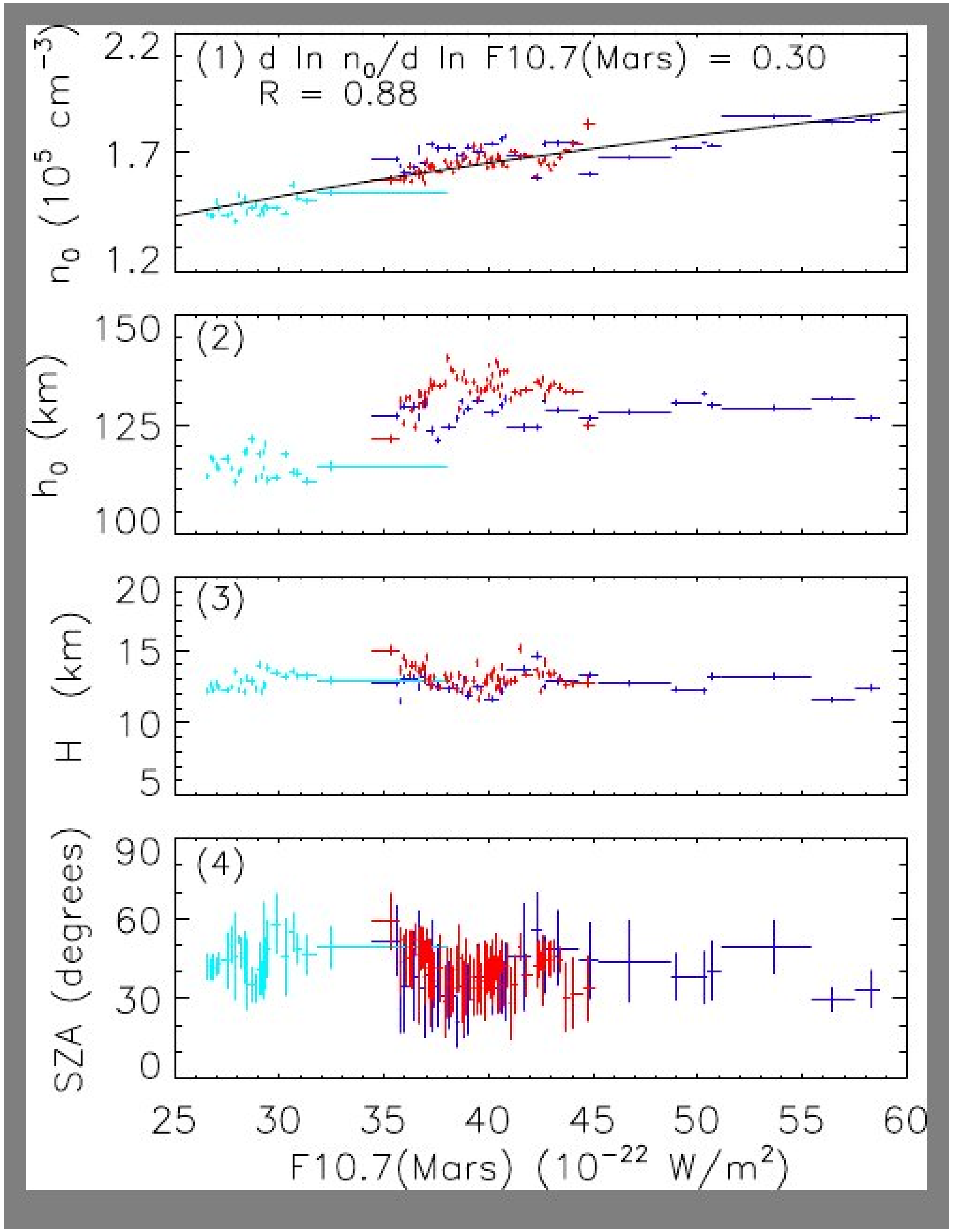
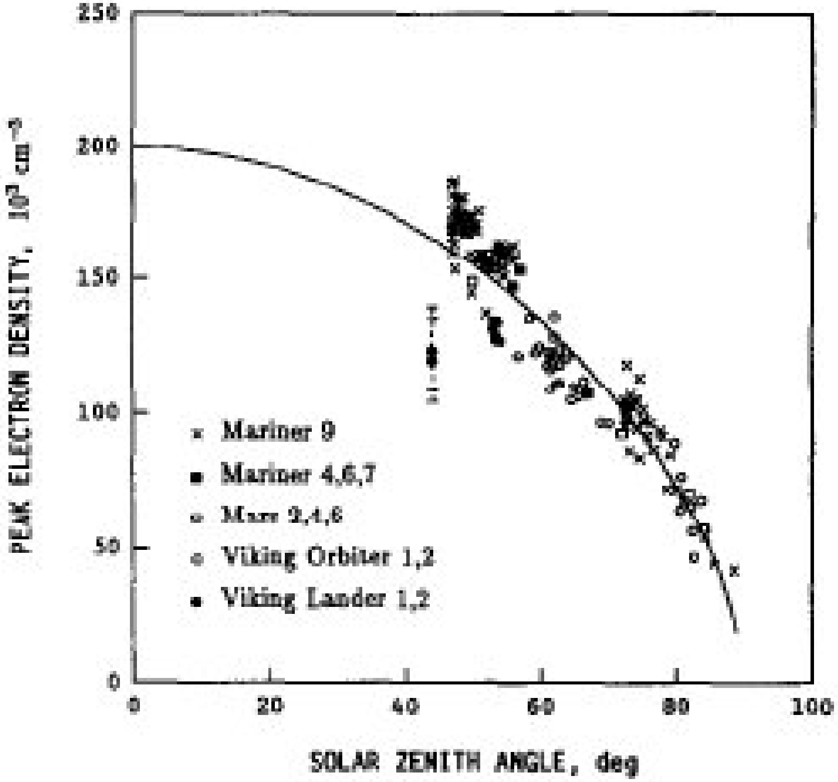


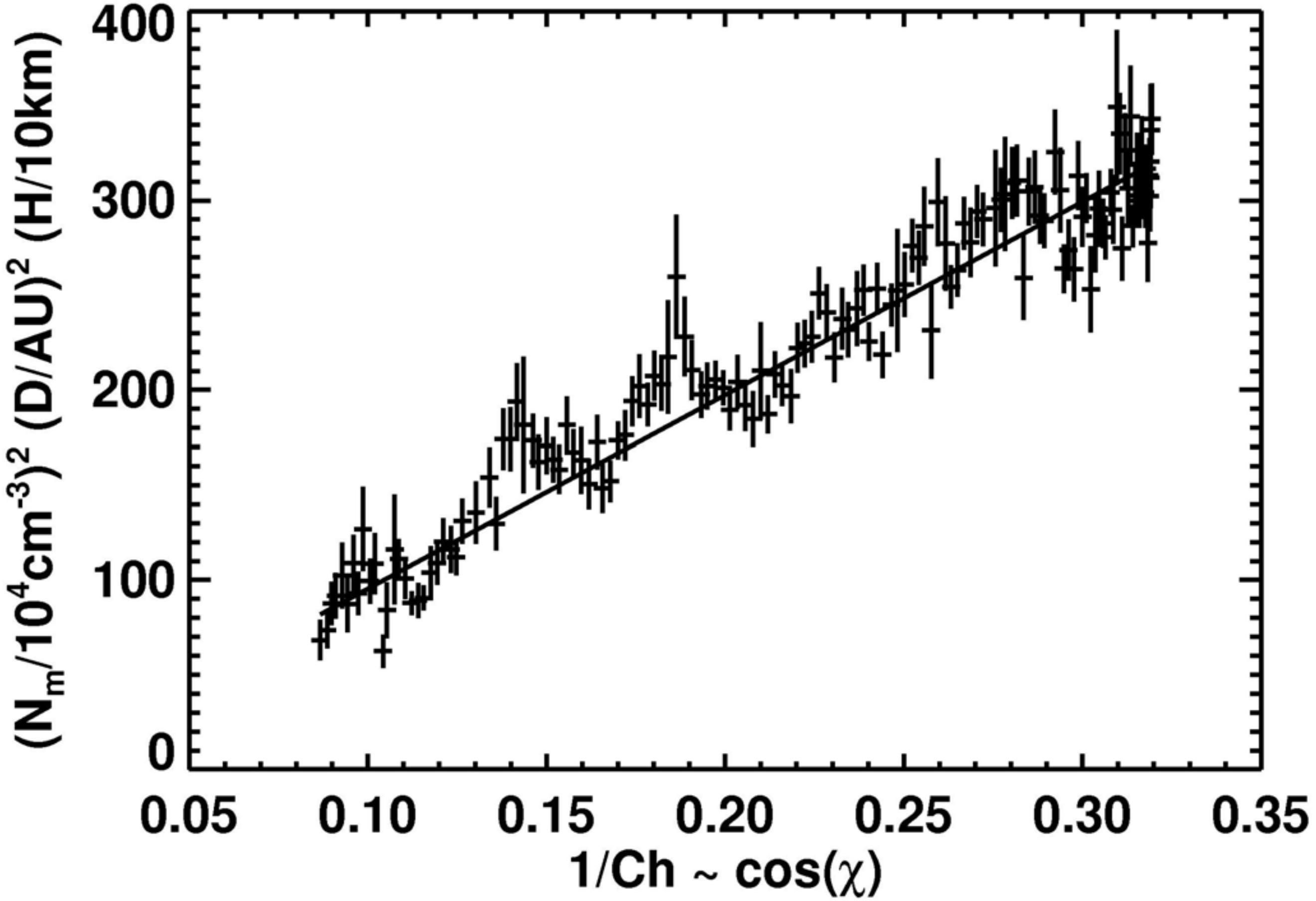
Figure 4. Solar photon flux versus wavelength from SOLAR2000 model for the 9–27 March 1999 period. The XUV spectral range includes wavelengths from 1.8 to 30 nm. The EUV range goes from 30 to 100 nm. The first wavelength bin has been multiplied by 100 for display purposes.


PEAK ELECTRON DENSITY (χ=0), 10^3 cm^{-3}
300
250
200
150
100
60
80
100
150
200
SOLAR RADIO FLUX
× Mariner 9 Standard Mission
○ Mariner 9 Extended Mission
■ Mariner 4,6,7
□ Mars 2,4,6
● VO1/2, VL1/2


(1) d ln n_0/d ln F10.7(Mars) = 0.30
R = 0.88
n_0 (10^5 cm^{-3})
2.2
1.7
1.2
(2)
h_0 (km)
150
125
100
(3)
H (km)
20
15
10
5
(4)
SZA (degrees)
90
60
30
0
25
30
35
40
45
50
55
60
F10.7(Mars) (10^{-22} W/m^2)



PEAK ELECTRON DENSITY, 10^3 cm^{-3}
250
200
150
100
50
0
0
20
40
60
80
100
SOLAR ZENITH ANGLE, deg
× Mariner 9
■ Mariner 4,6,7
○ Mars 2,4,6
○ Viking Orbiter 1,2
■ Viking Lander 1,2


$(N_m/10^4 cm^{-3})^2\ (D/AU)^2\ (H/10km)$
400
300
200
100
0
0.05
0.10
0.15
0.20
0.25
0.30
0.35
$1/Ch \sim \cos(\chi)$