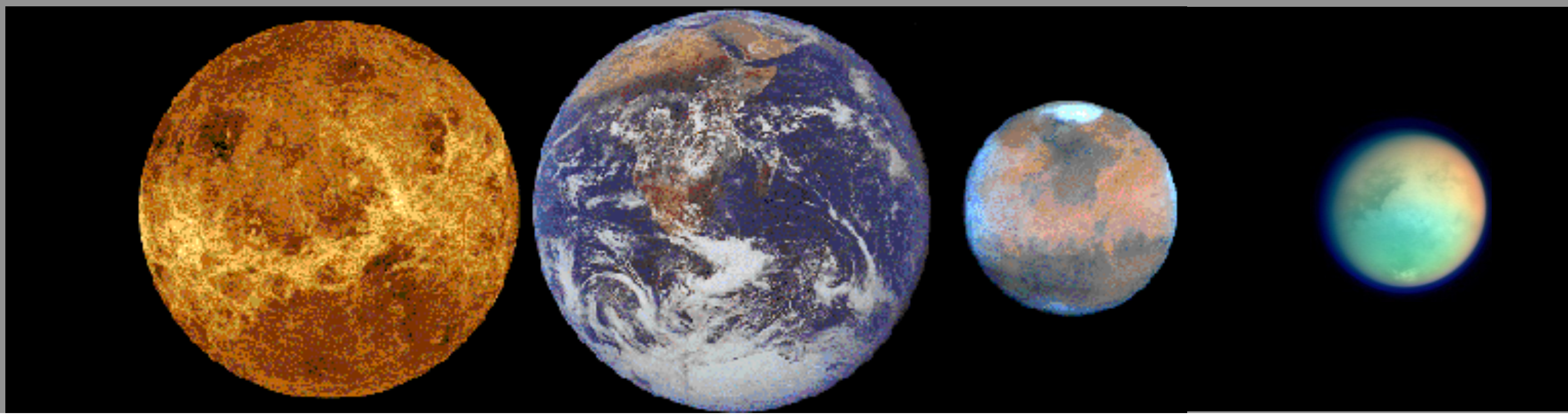
The ionosphere of Mars

A.J.Coates[1]
Mullard Space Science Laboratory, UCL, UK

With thanks to O.Witasse, ESTEC for some slides



4 lectures in ‘aeronomy’ topic – also Wing Ip evening talk

- The ionosphere of Mars
- The Mars-solar wind interaction
- Atmospheric escape
- Comparative plasma interactions
- Space weather at Mars (W.-H. Ip)

The Martian ionosphere

- Concepts from Earth's ionosphere
- Mars atmosphere and thermosphere
- Mars ionosphere
  - Production and loss mechanisms
  - Composition
  - Structure
- Emissions – including aurora (X-rays in next talk)

MEX instruments contributing to upper atmospheric studies

MEX experiments	Measurements
ASPERA	- Electron fluxes in the energy range 0.01–20 keV - Ion measurements in the energy range 0.01–30 keV/q for H^+, He^{++}, He^+, O^+, O_2^+ and CO_2^+ - Energetic neutral atoms measurements
Radio-science	Vertical electron density profile in the altitude range 80-600 km, in the solar zenith angle range 50-120 degrees
MARSIS	- Total Electron Content in the atmosphere every 2 seconds when operating in subsurface mode - Vertical electron density profiles (above the main ionization peak), local electron density, and magnitude of the local magnetic field when operating in the Active Ionosphere Sounding mode
SPICAM	- Upper atmosphere CO_2 and O_2 densities and temperatures in the altitude range 60-140 km - Exospheric densities and temperatures - Ultraviolet airglow and auroras, in the wavelength range 118-320 nm
OMEGA	Visible and NIR airglow

Some concepts from Earth's ionosphere

Ionospheric structure - 1

- The ionosphere is the upper atmosphere region containing large concentrations of electrons & ions due to ionisation of the atmosphere by solar UV & X-rays
- Such a plasma has a characteristic (i.e. resonant) frequency of oscillation
  - Ions are much more massive than electrons, so we can neglect ion motion
  - If the electrons in the plasma are moved from their equilibrium locations, an oscillation occurs at the *plasma frequency* ω_p, given by

$$\omega_p^2 = \frac{N_e Q_e^{\,2}}{\varepsilon_0 m_e}$$

where N_e = *the undisturbed electron density*
Q_e = *the charge on an electron*
m_e = *the mass of an electron*
ε_0 = *the vacuum permittivity*

- Electromagnetic waves are reflected if their frequency is $\leq \omega_p$
- Thus the ionosphere was discovered when radio waves were transmitted and received over much larger distances around the curved surface of the Earth than could be explained by simple wave propagation.
  - The waves had to be reflected from an ionised layer in the upper atmosphere

Ionospheric structure - 2

- Earth's ionosphere has been probed extensively by radar methods:
  - Send pulses of gradually increasing frequency upwards
  - Then measure the delay until the reflected pulse is detected.
  - The frequency at which reflection ceases gives the density
  - The delay gives the height

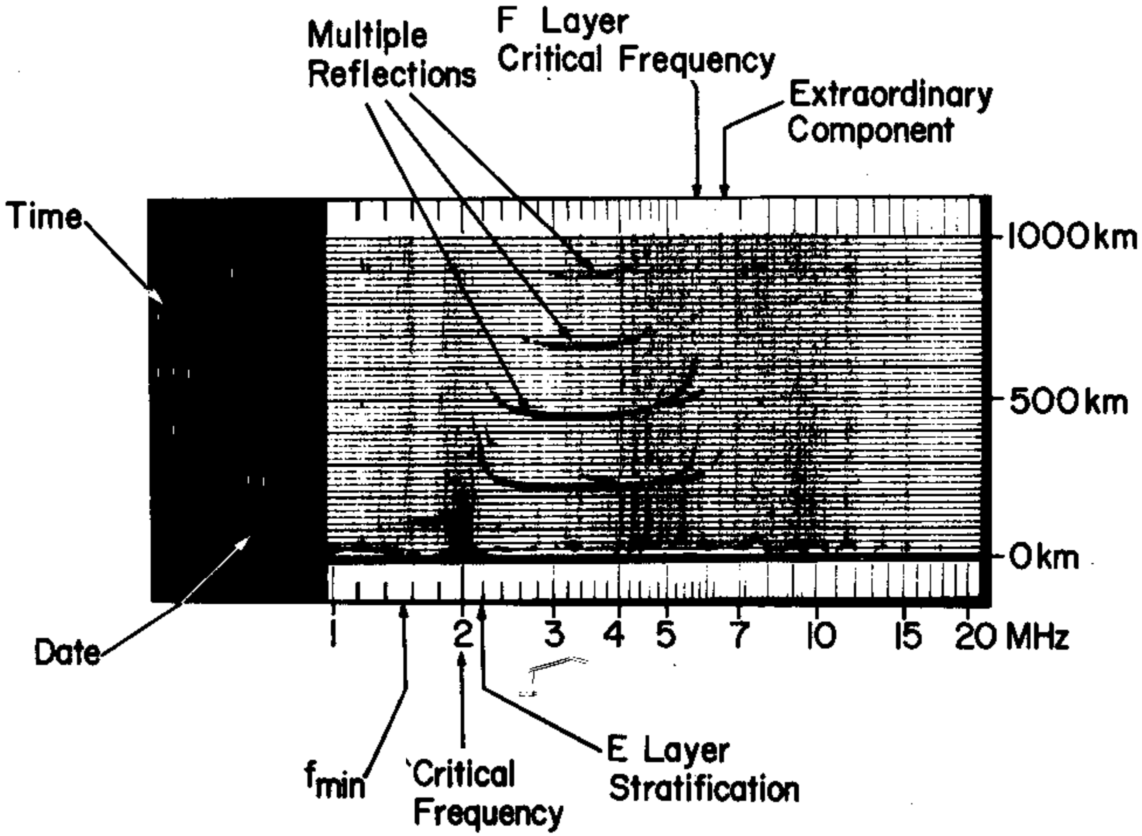


Fig from Chamberlain & Hunten

Ionospheric structure - 3

Fig from Tascioni, Introduction to the space environment

- Several layers have been identified and called D, E, FI and F2
- Different layers form because:
  - a) the solar spectrum ionises at various heights depending on the absorption characteristics.
  - b) the recombination rate depends on the density, and there is more than one recombination process.
  - c) the atmospheric composition changes

Note: The D layer and the F1 layer disappear at night

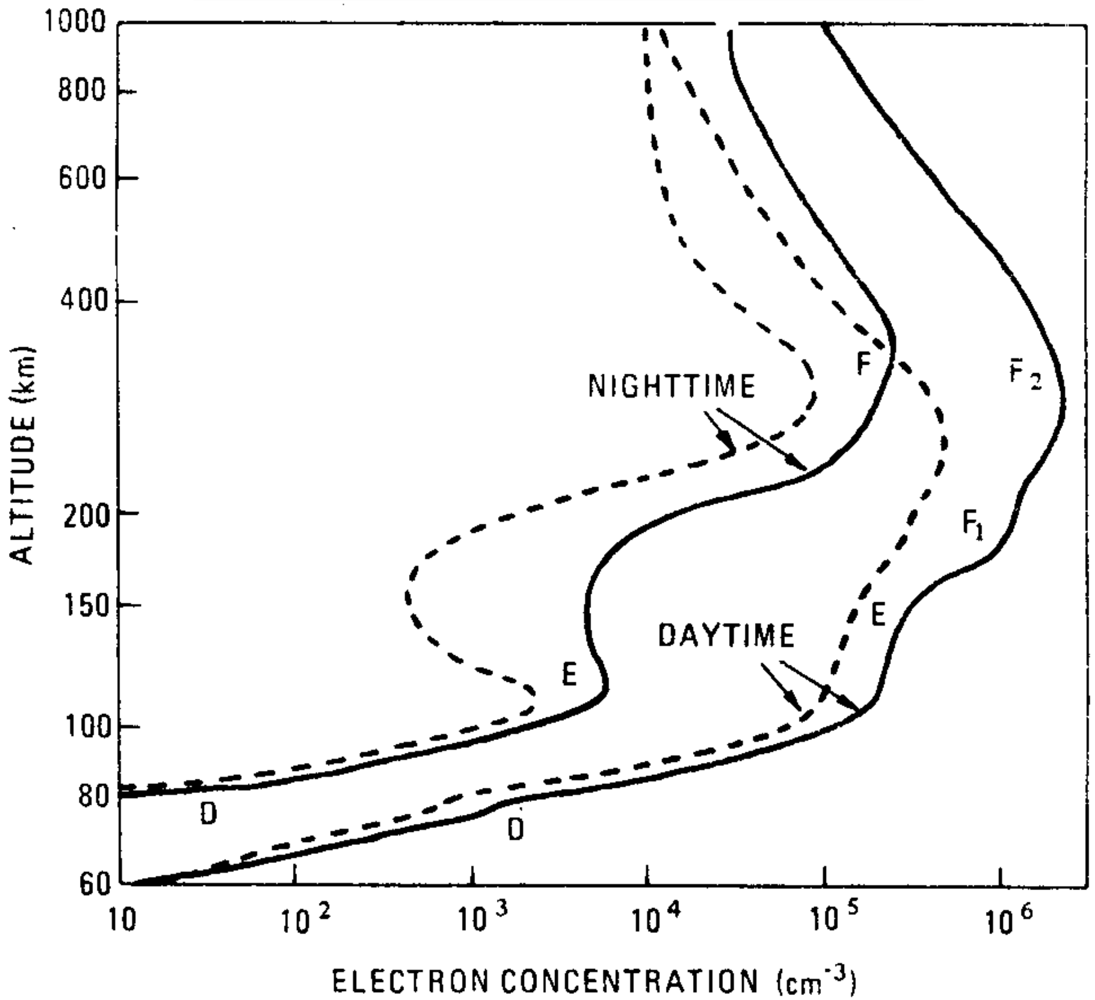


Figure 7.1 Typical midlatitude daytime and nighttime electron density profiles for sunspot maximum (solid lines) and minimum (dashed lines).

Ionospheric structure - 4

- The rate of change of electron density N_e is the difference between the production & loss rates:

$$\frac{dN_e}{dt} = q - \alpha_{eff} N_e^2$$

where q = production rate, dependent on solar UV/X-ray flux

α_{eff} = effective ion-electron recombination coefficient

- If we now assume that:
  - the atmosphere is plane and parallel and isothermal
  - solar flux ionisation rate & absorption coefficient are independent of wavelength

then an expression can be found for electron density N_e as a function of height z:

$$N_e(z,\theta) = \left(\frac{q_m}{\alpha_{eff}}\right)^{1/2} \exp\left\{\tfrac{1}{2}\left[1 - z_1 - \exp(-z_1)\right]\right\}$$

where q_m = production rate at the peak of the layer (proportional to $\cos\theta$)

θ = solar zenith angle

$z_1 = (z - z_m)/H$

z_m = height of the peak in electron density

H = scale height

- This is known as a Chapman layer

- This Chapman layer approximation results in a broadly peaked layer as shown in the diagram.
  - Its characteristic feature is that the peak density varies as $(\cos\theta)^{1/2}$ (see Fig)
    - This determines the daily, seasonal & latitudinal variation
    - This can be easily tested by observing the variation of peak density during the day.
  - Problems with this Chapman model:
    - a) not good at sunrise & sunset where the atmosphere is not plane parallel
    - b) the atmosphere has a time lag
    - c) the atmosphere is not isothermal

Fig from Tascioni, introduction to the space environment

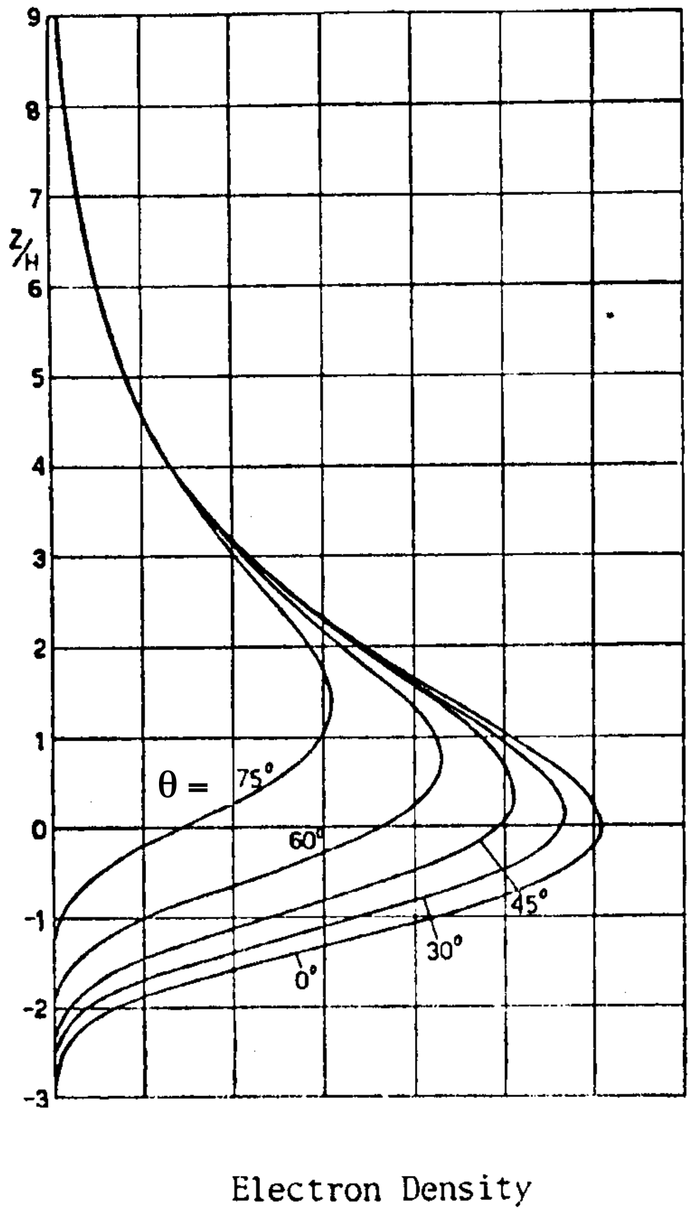


Figure 7.2 Distribution of electron density versus zenith angle *(after Rawer, 1952)*.

Real ionospheres - 1

Fig from Tascioni, introduction to the space environment

- Earth
  - Main layers on Earth are the E, F1 and F2 layers
  - E & F1 are reasonable Chapman layers as shown
  - F2 is not:
    - Because of the very low atmospheric density:
      - recombination becomes proportional to N_e, not N_e^2
      - vertical electron diffusion is important

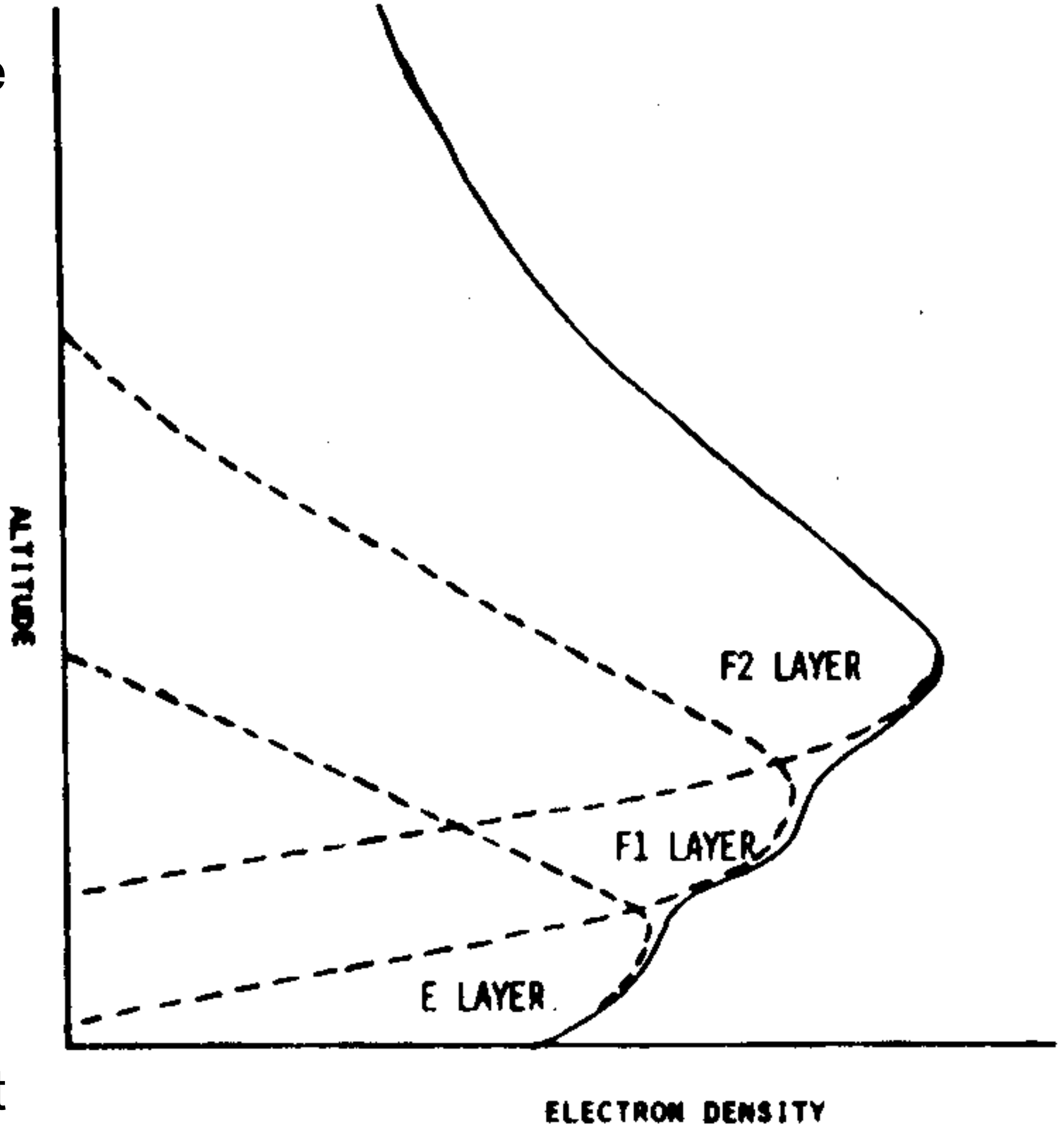


Figure 7.3 Electron density profile as the sum of the E, F1, and F2 Chapman layer contributions.

8.2 Real ionospheres - 5

Venus & Mars

•Both have basically Chapman-type ionospheres

•For example, CO_2^+ is a major species involved (see Fig) as follows:

- Photoionisation

  $CO_2 + h\nu \rightarrow CO_2^+ + e$ (< 90nm)

- Dissociative recombination

  $CO_2^+ + e \rightarrow CO + O$

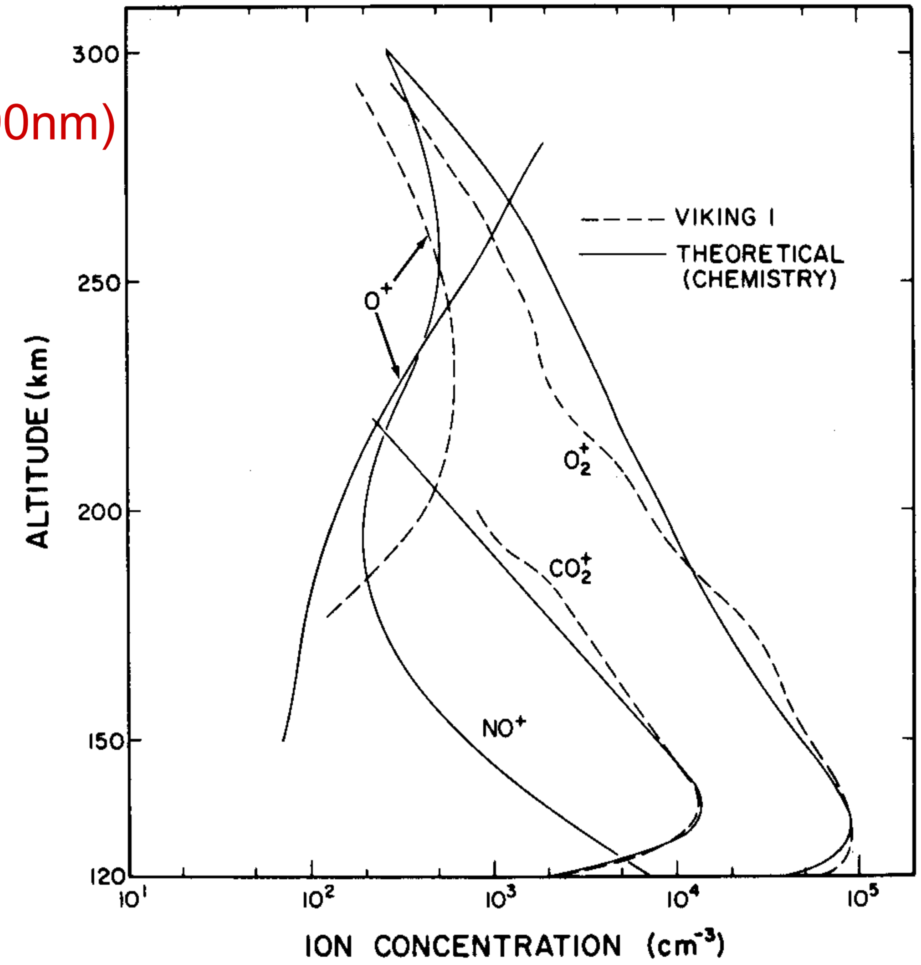


Fig. 5.11 Ion densities for Mars, observed by Viking 1 (dashed lines) and calculated profiles (solid lines). [From HANSON *et al.* (1977)].

Thermosphere

Neutral Atmosphere of Mars

- Neutral Composition of the Thermosphere:

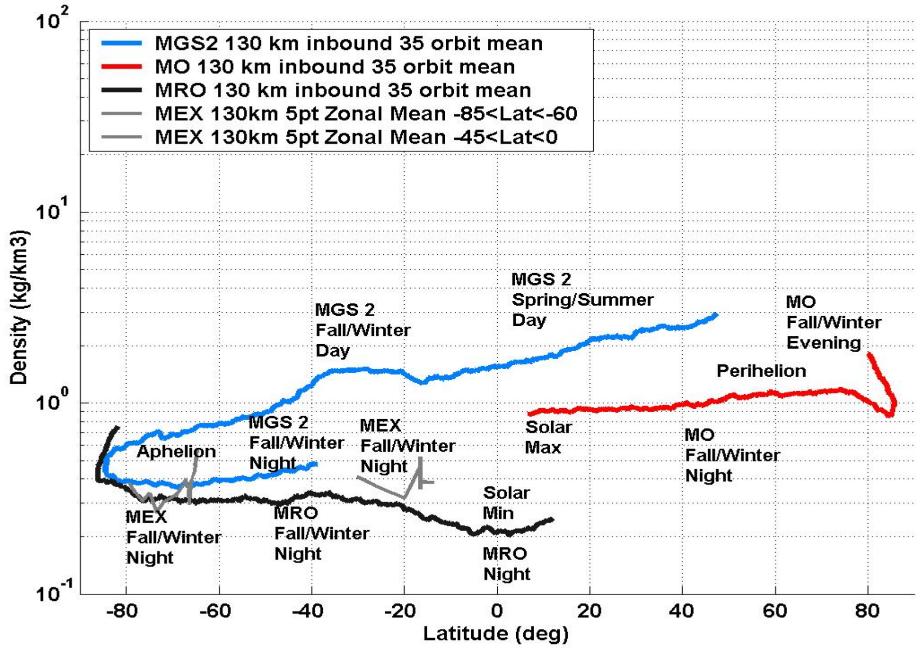
CO_2, CO, O, N_2, O_2, NO, He, H_2, H

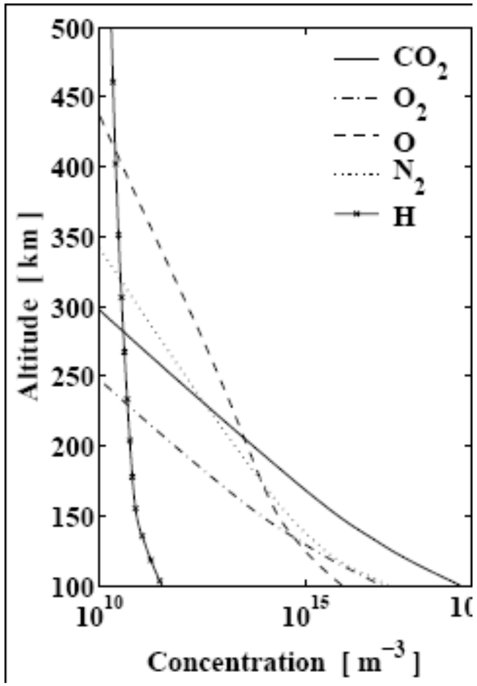
- Temperatures: 200-400 K
- Winds: largely unconstrained by any observations. Can reach 300 m/s.

Important: variability

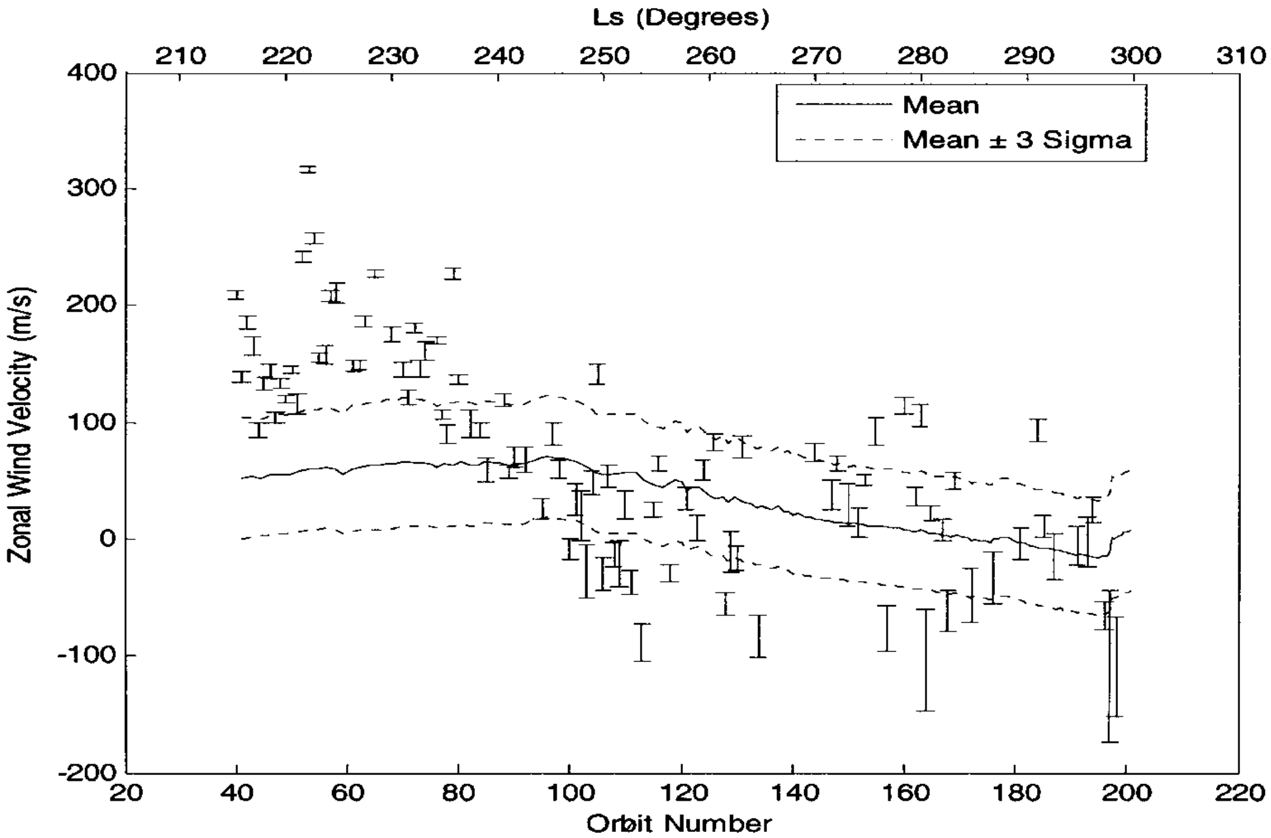
- Inflation/contraction of entire atmosphere due to seasonal varying (solar) and episodic dust storm heating
- Upward propagating tidal, planetary scale and gravity waves. Seasonal.
- Seasonal differences (perihelion to aphelion)

Densities and composition



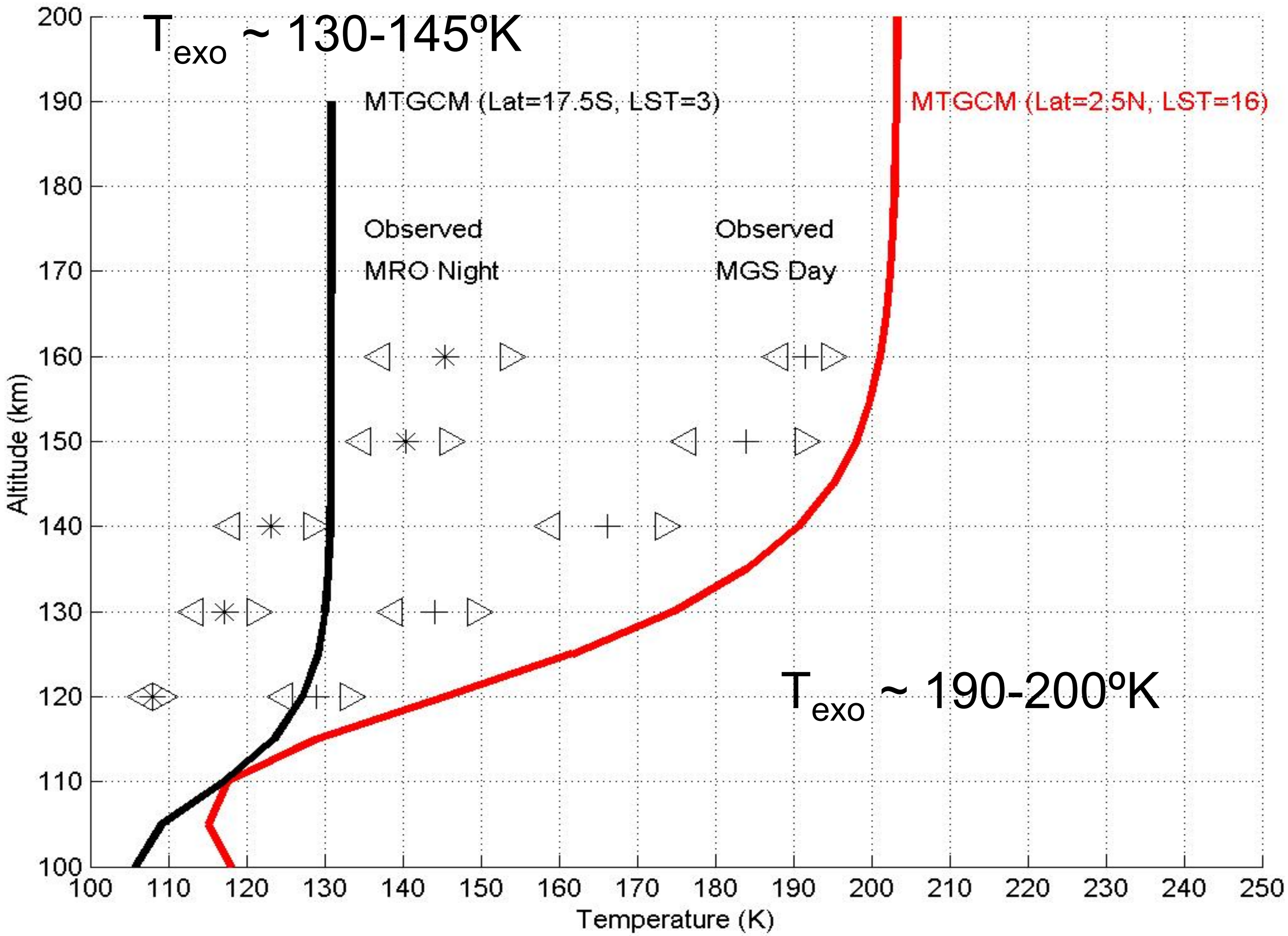


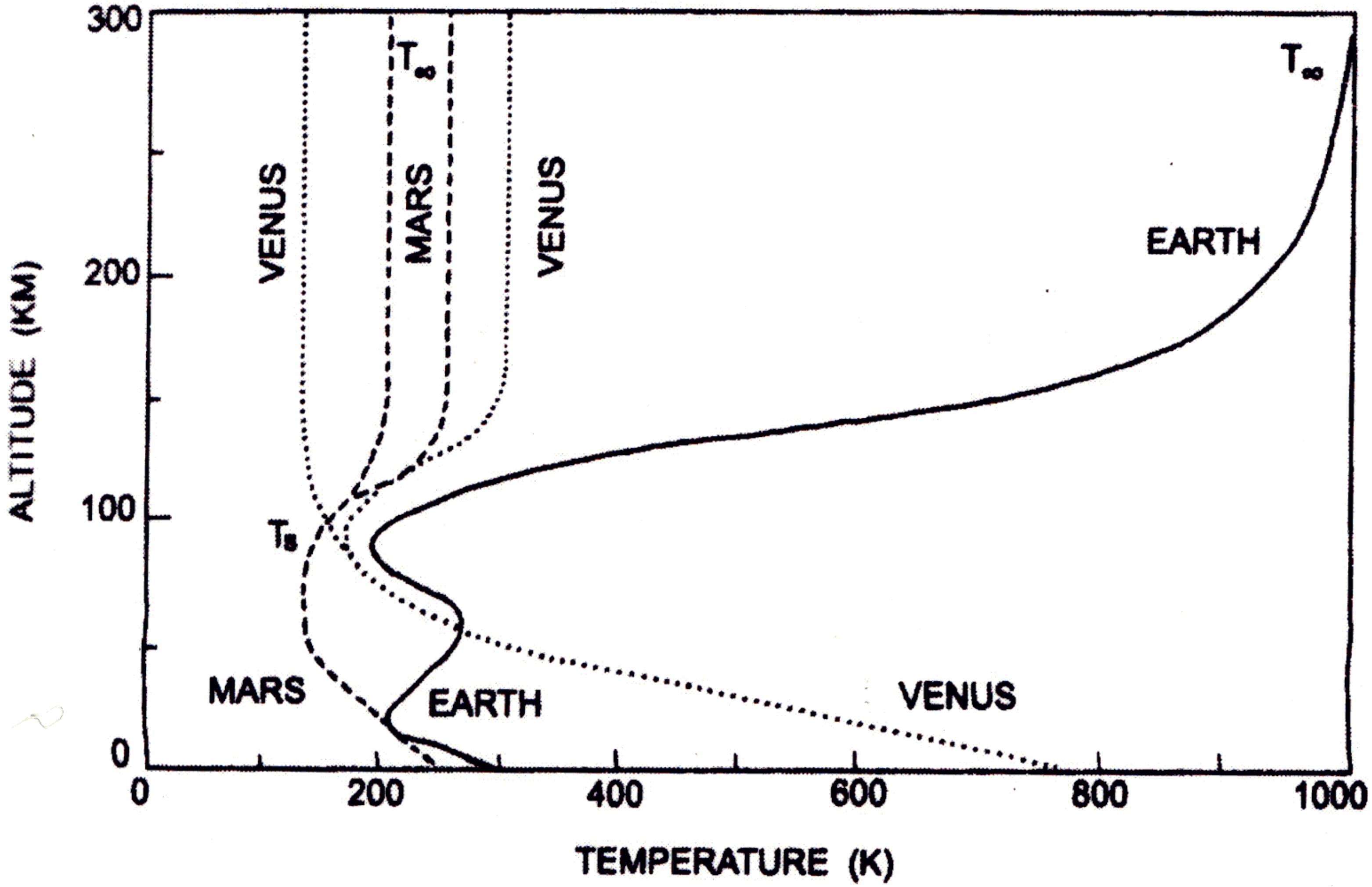
Zonal wind



Recently measured with a very original method, using the gyroscopes and accelerometers during aerobraking.

Temperature Profiles Derived from Accelerometers (Keating et al., 2008; 2009)




300
200
100
0
ALTITUDE (KM)
0
200
400
600
800
1000
TEMPERATURE (K)
VENUS
MARS
VENUS
T_∞
T_∞
EARTH
T_S
MARS
EARTH
VENUS

IONOSPHERE

Photo-Chemical Equilibrium

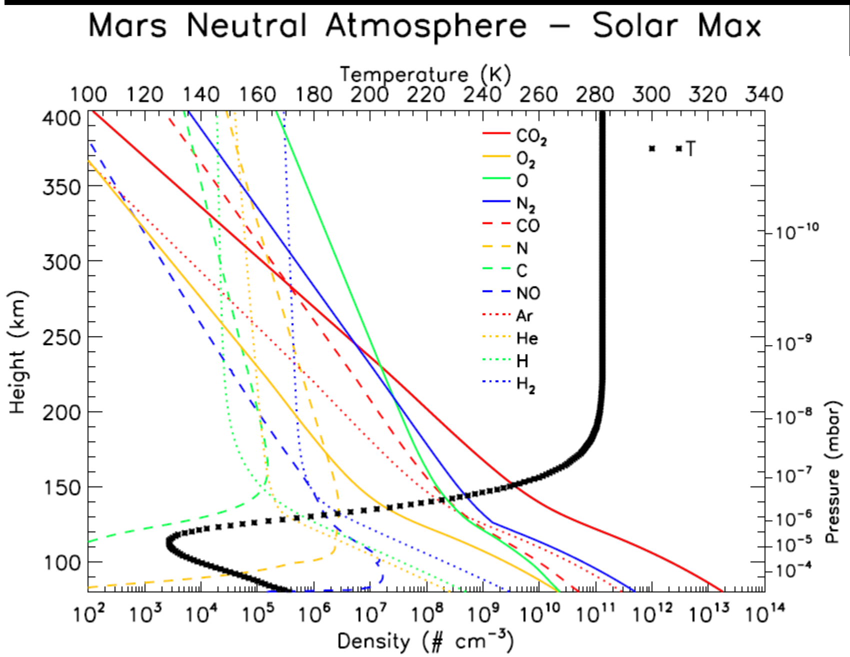
	MARS	EARTH
Production (P_o):	$CO_2 + h\nu \rightarrow CO_2^+ + e^-$	$N_2 + h\nu \rightarrow N_2^+ + e^-$
Transformation:	$CO_2^+ + O \rightarrow O_2^+ + CO$	$N_2^+ + O \rightarrow NO^+ + N$
Loss (L):	$O_2^+ + e^- \rightarrow O + O$	$NO^+ + e^- \rightarrow N + O$

For $P_o = L$ $\quad P_0 = \alpha N_e^2$

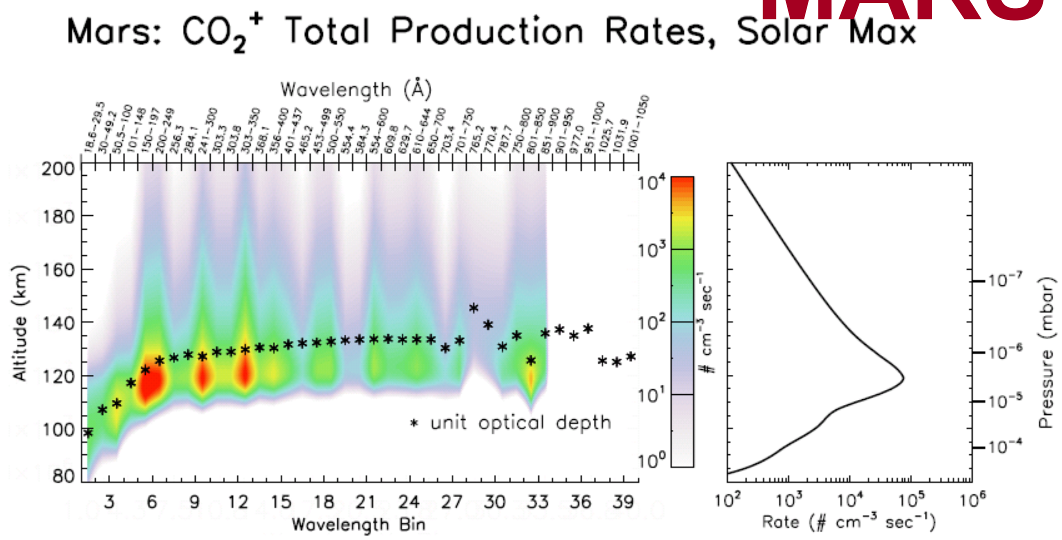
For $\quad P_0 \propto \Phi_{SUN} \propto \dfrac{1}{d^2}$

Giving $\quad N_e(d) \propto \dfrac{1}{d}$

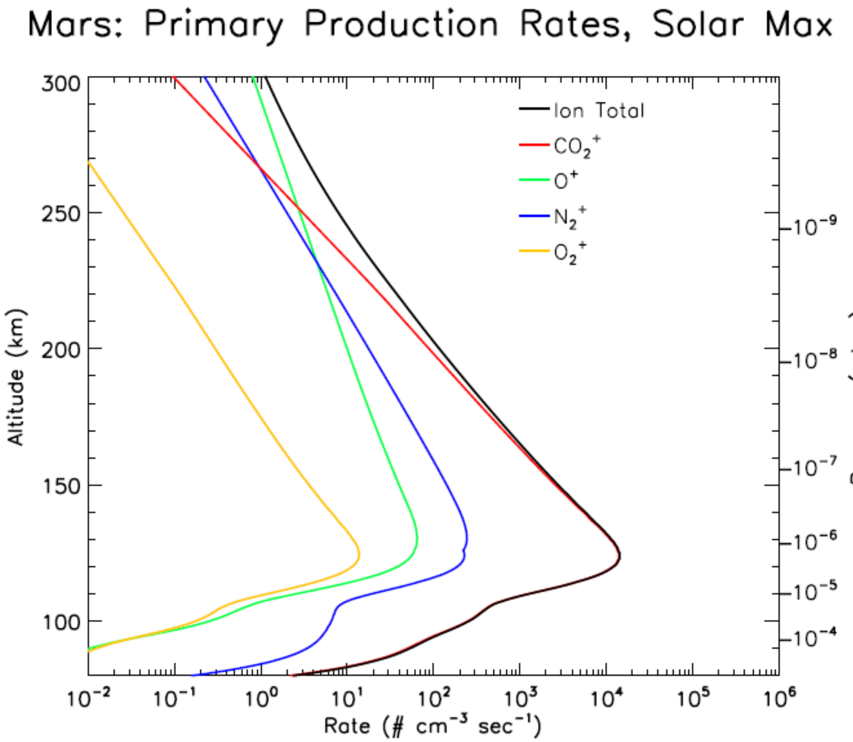
UCL MARS



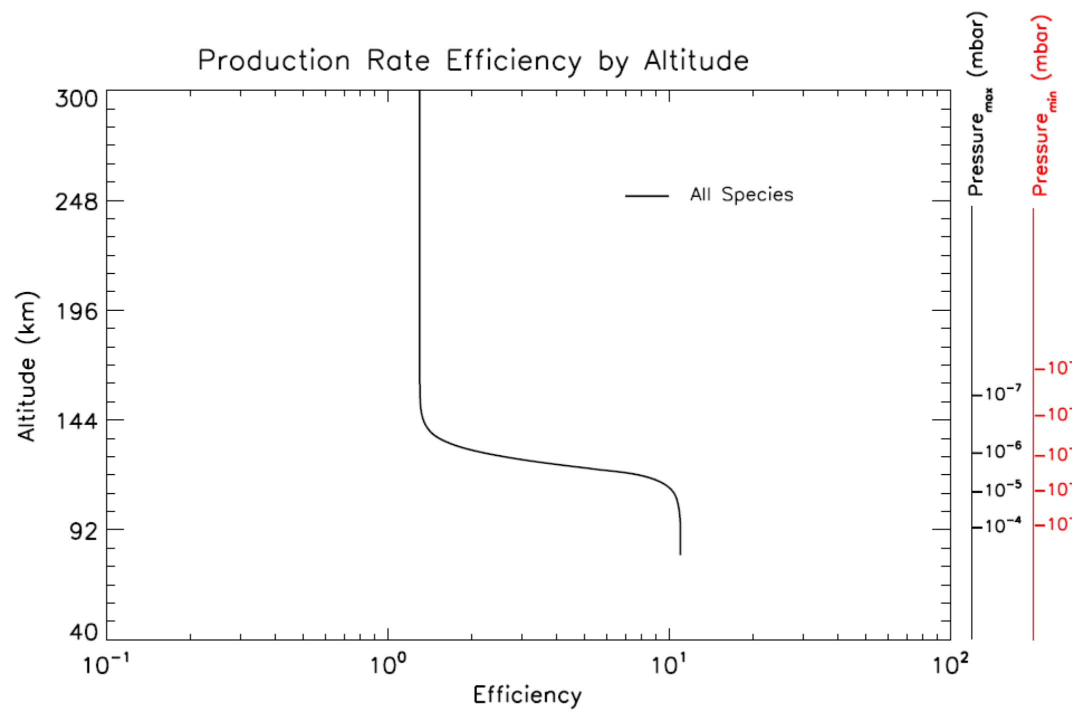
Mars Neutral Atmosphere – Solar Max
Temperature (K)
100 120 140 160 180 200 220 240 260 280 300 320 340
Height (km)
400
350
300
250
200
150
100
CO2
O2
O
N2
CO
N
C
NO
Ar
He
H
H2
T
Pressure (mbar)
10^-10
10^-9
10^-8
10^-7
10^-6
10^-5
10^-4
10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14
Density (# cm^-3)



Mars: CO2+ Total Production Rates, Solar Max
Wavelength (Å)
Altitude (km)
200
180
160
140
120
100
80
3 6 9 12 15 18 21 24 27 30 33 36 39
Wavelength Bin
* unit optical depth
# cm^-3 sec^-1
10^4
10^3
10^2
10^1
10^0
Rate (# cm^-3 sec^-1)
10^2 10^3 10^4 10^5 10^6
Pressure (mbar)
10^-7
10^-6
10^-5
10^-4

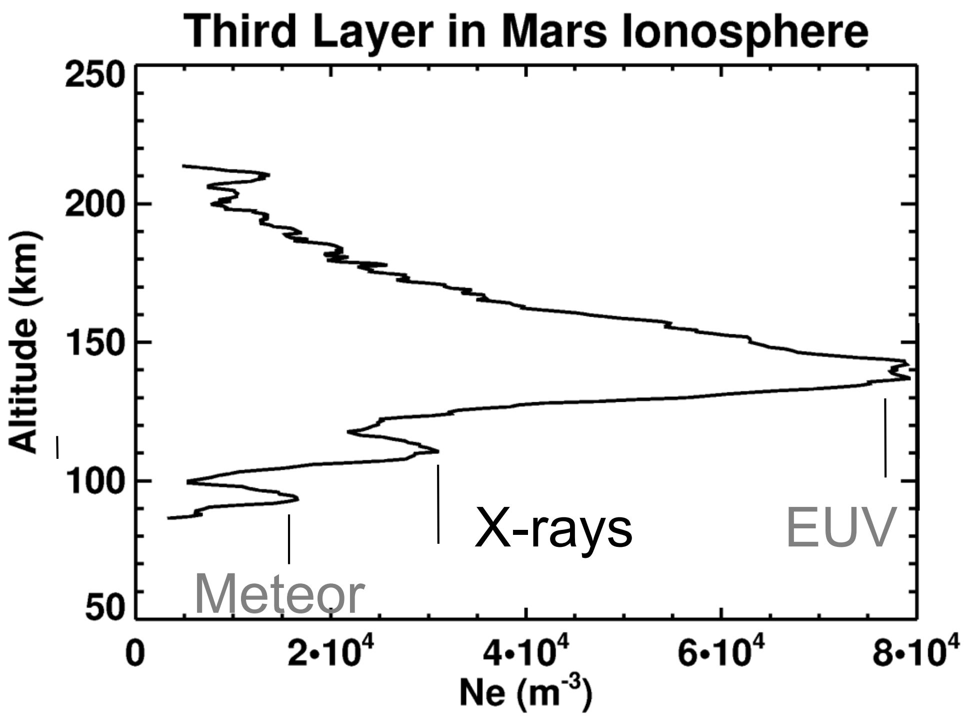


Mars: Primary Production Rates, Solar Max
Altitude (km)
300
250
200
150
100
Ion Total
CO2+
O+
N2+
O2+
Pressure (mbar)
10^-9
10^-8
10^-7
10^-6
10^-5
10^-4
10^-2 10^-1 10^0 10^1 10^2 10^3 10^4 10^5 10^6
Rate (# cm^-3 sec^-1)

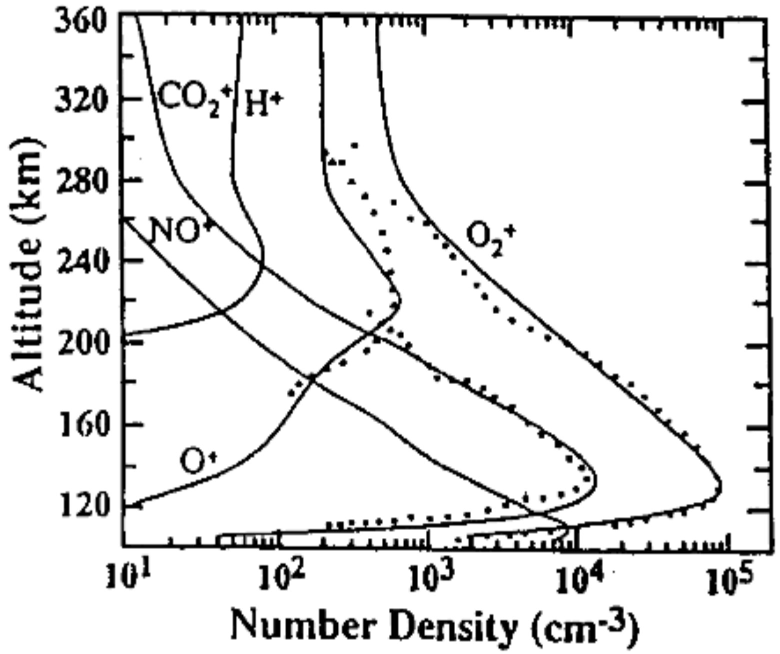


Production Rate Efficiency by Altitude
Altitude (km)
300
248
196
144
92
40
All Species
10^-1 10^0 10^1 10^2
Efficiency
Pressure_max (mbar)
Pressure_min (mbar)
10^-8
10^-7
10^-6
10^-5
10^-4

Densities and composition

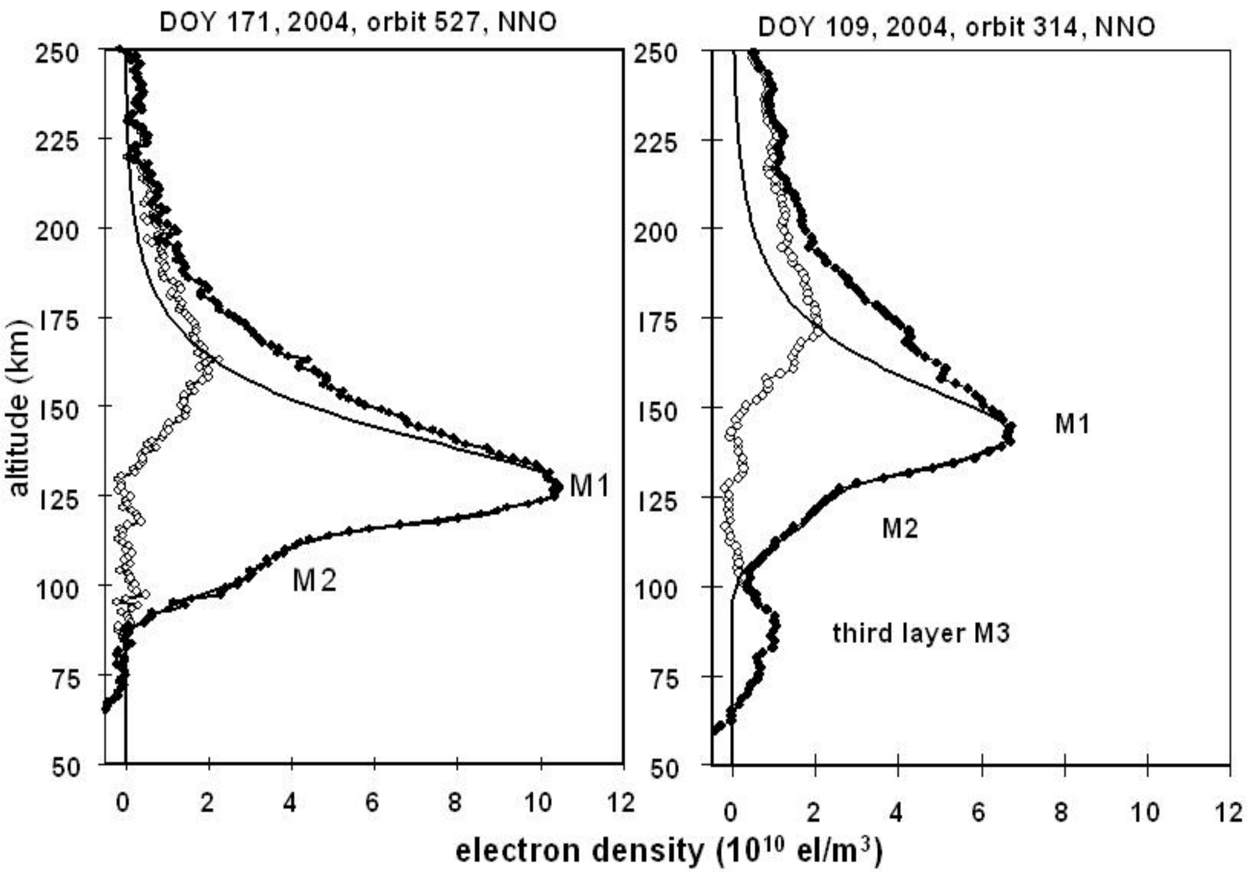


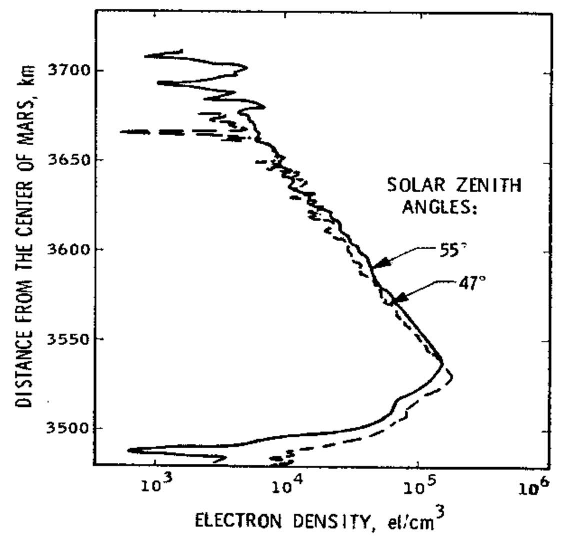
From Paul Withers (MGS data)



Fox and Dalgarno 1979

A 3rd layer in the ionosphere

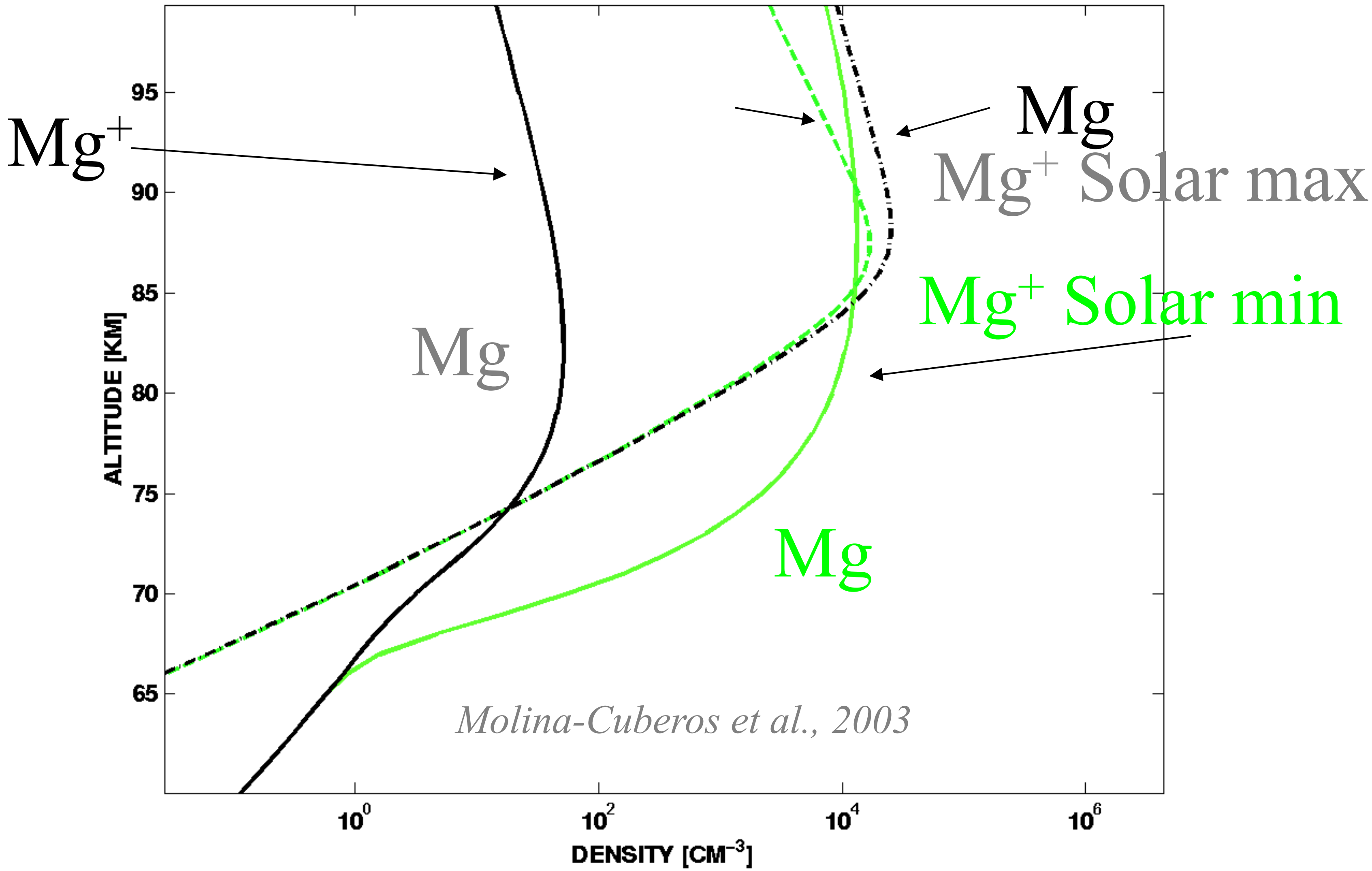




Kliore, 1972

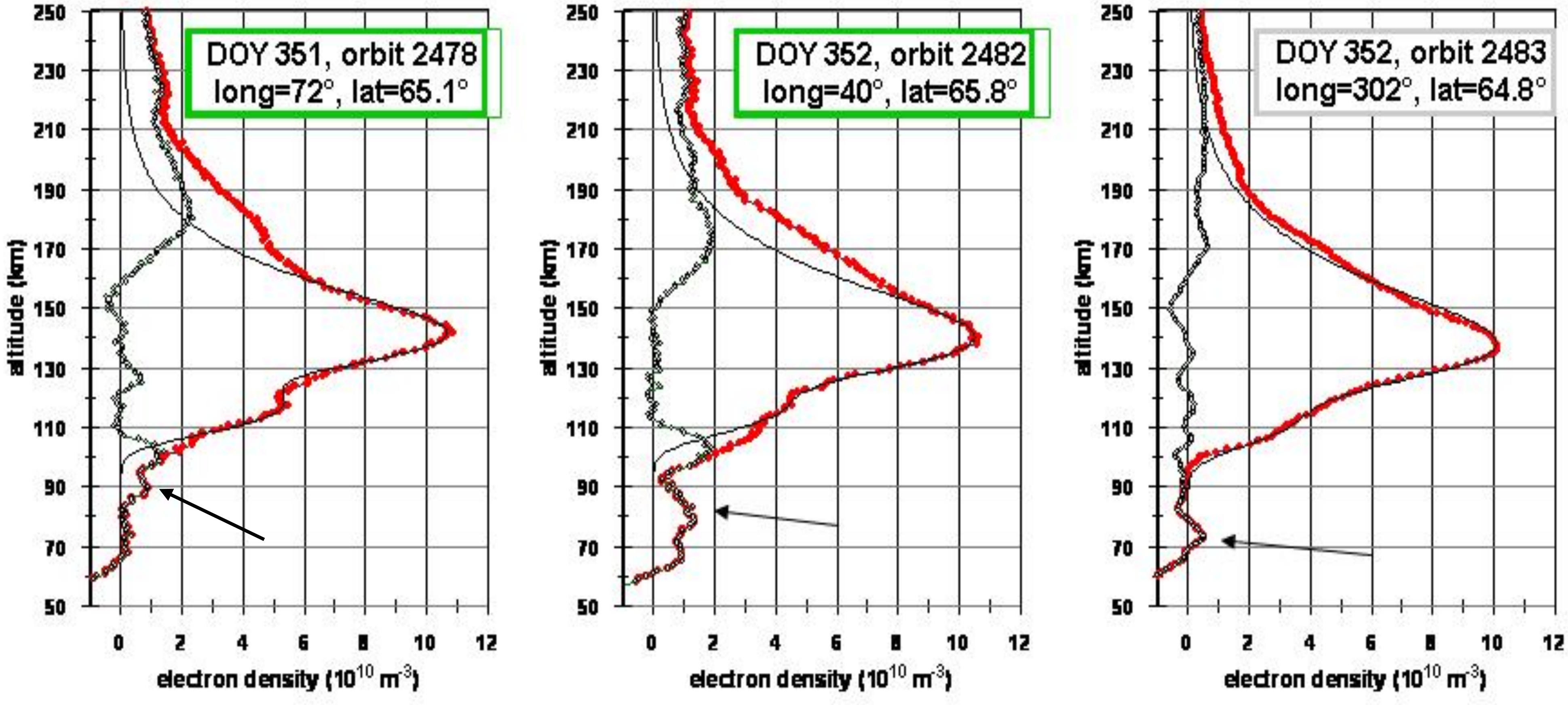
Pätzold et al., 2005

Mg and Mg⁺ densities day and night



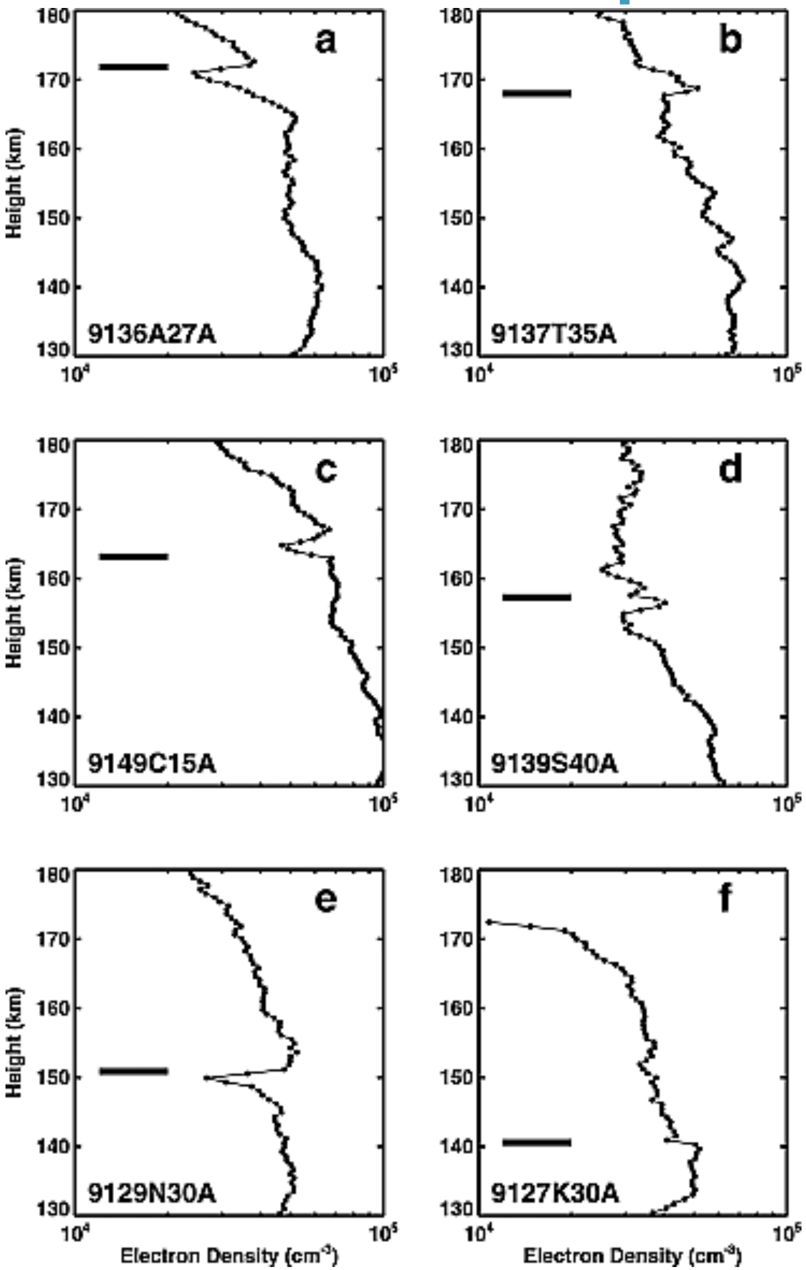
UCL

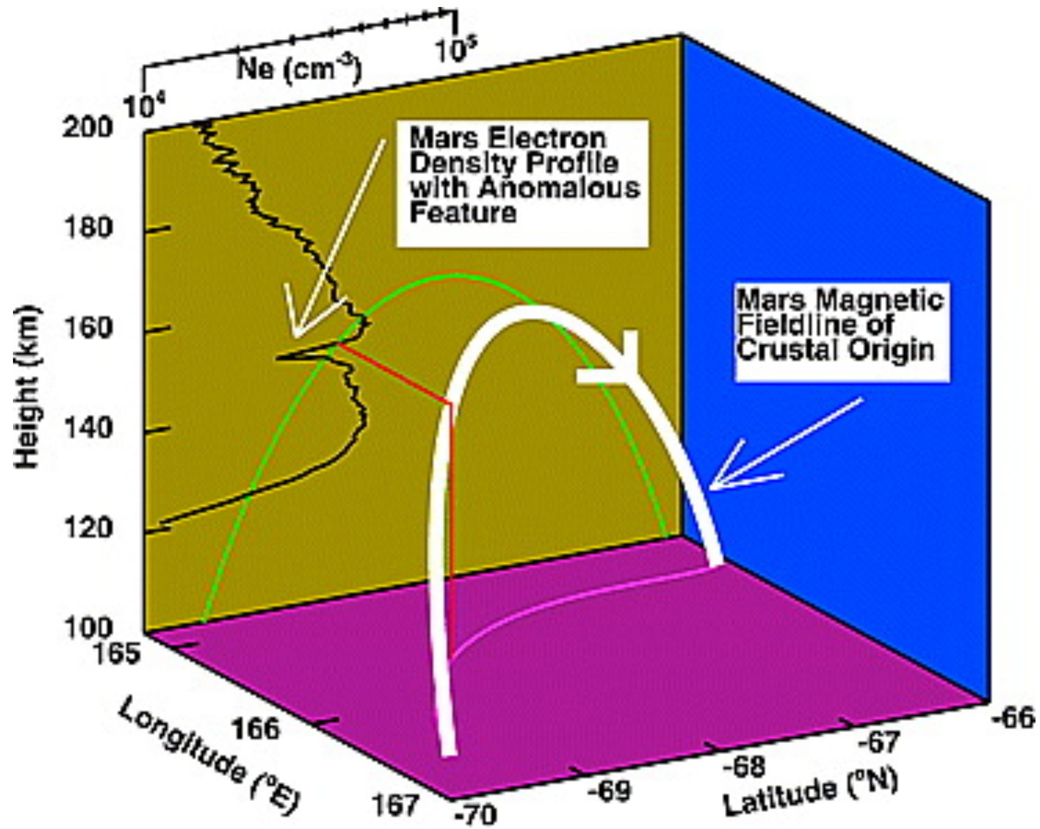
Third layer: Long lifetime?



Paetzold, personnel communication

Mars ionosphere: anomalous profiles

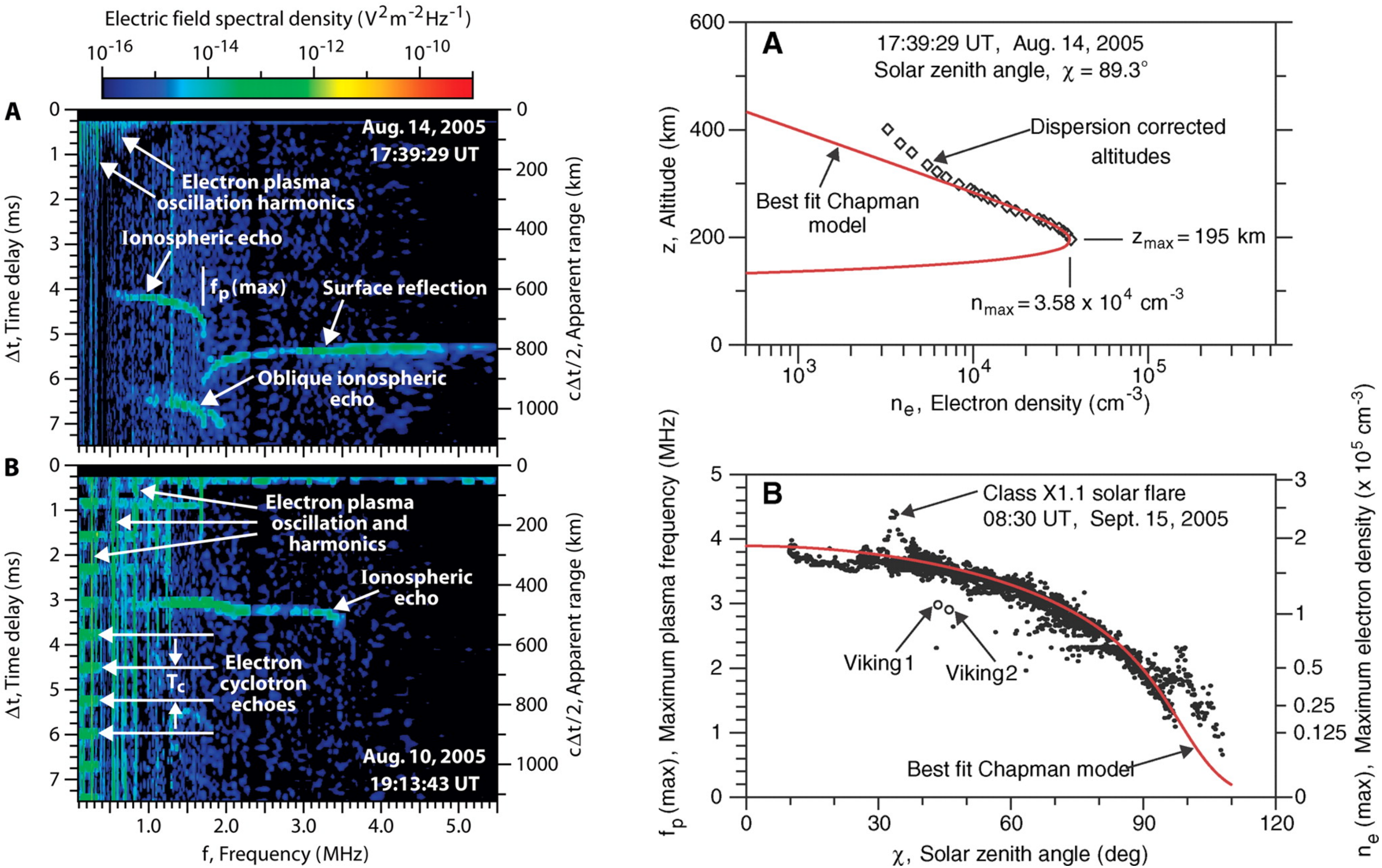




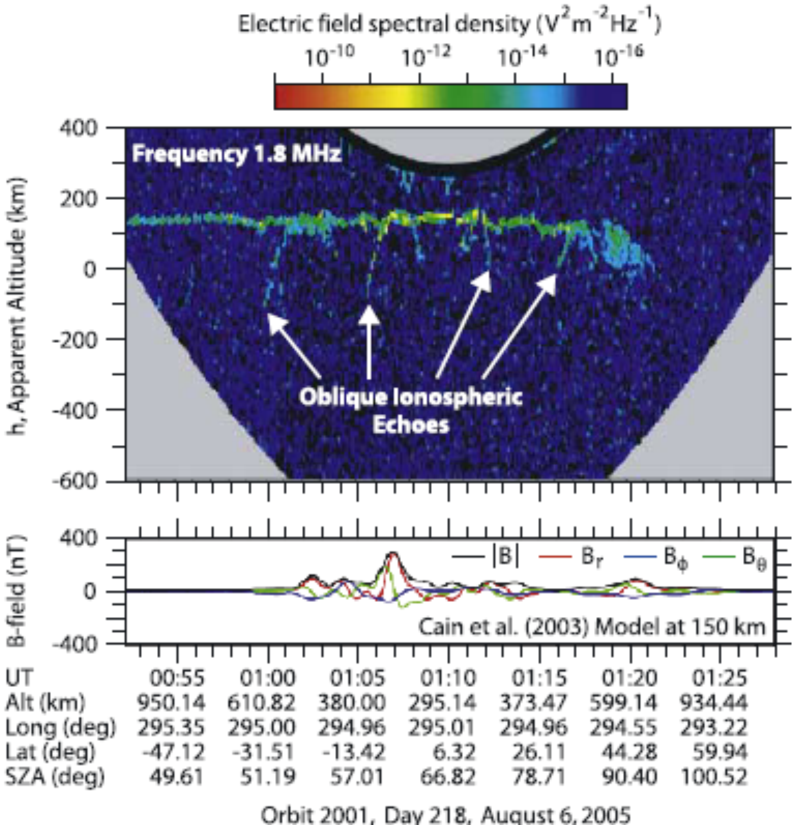
Withers et al.

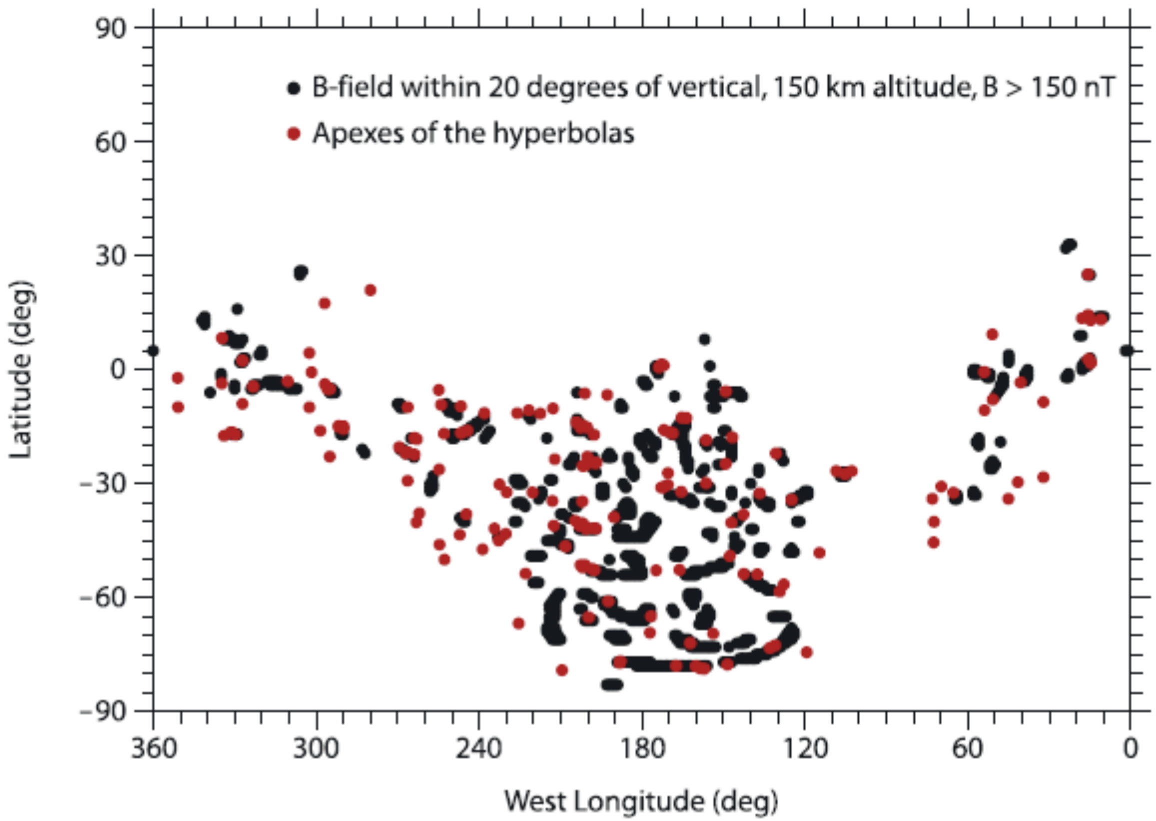
Mars ionosphere: first MEX radar results

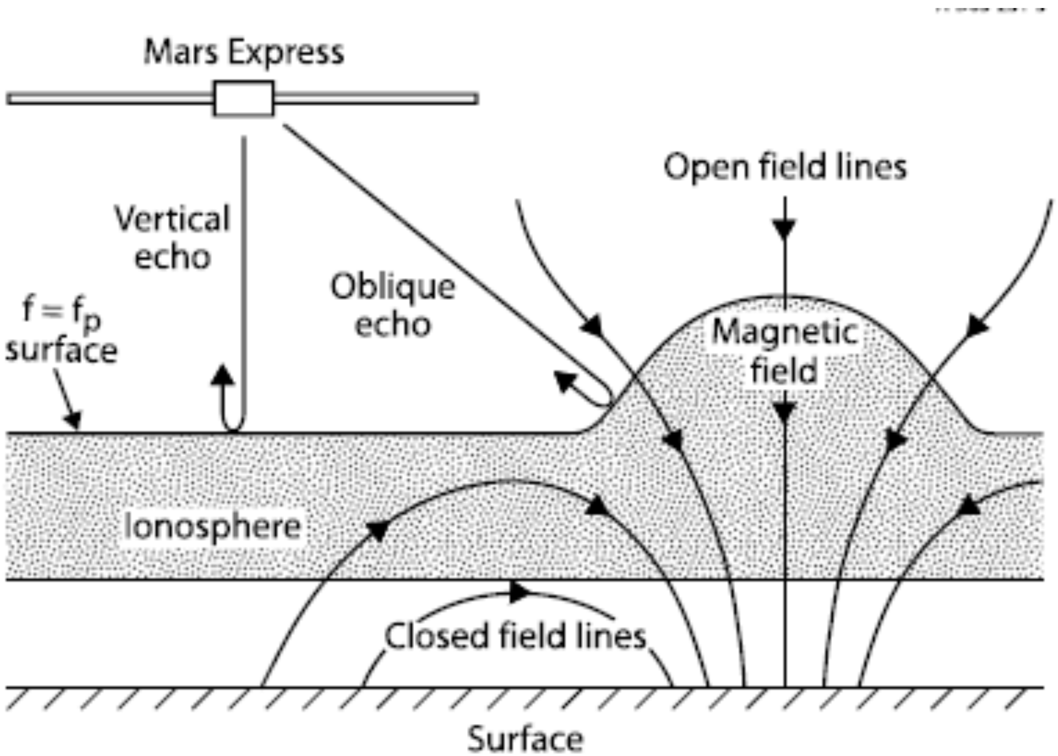
Gurnett et al, 2005



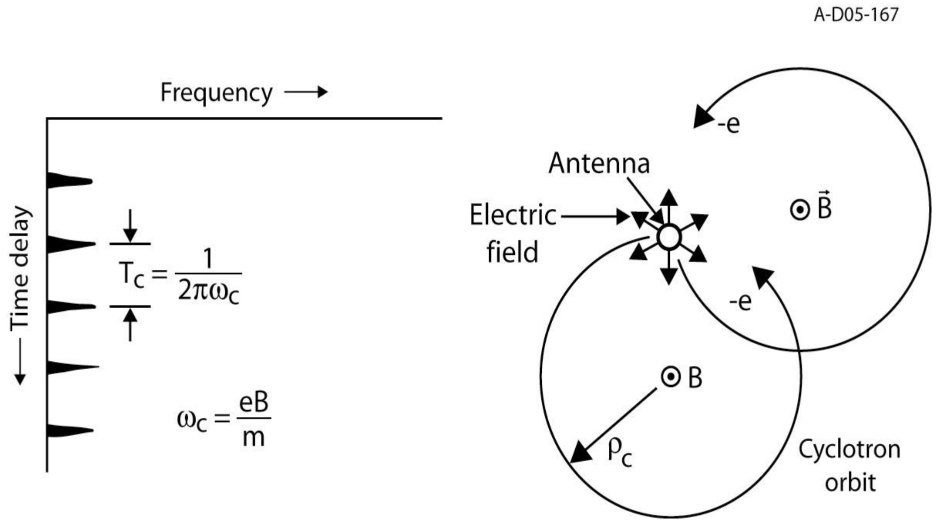
Mars ionosphere: Magnetically controlled structures *Duru et al, 2006*






Mars Express
Open field lines
Vertical echo
Oblique echo
$f = f_p$ surface
Magnetic field
Ionosphere
Closed field lines
Surface

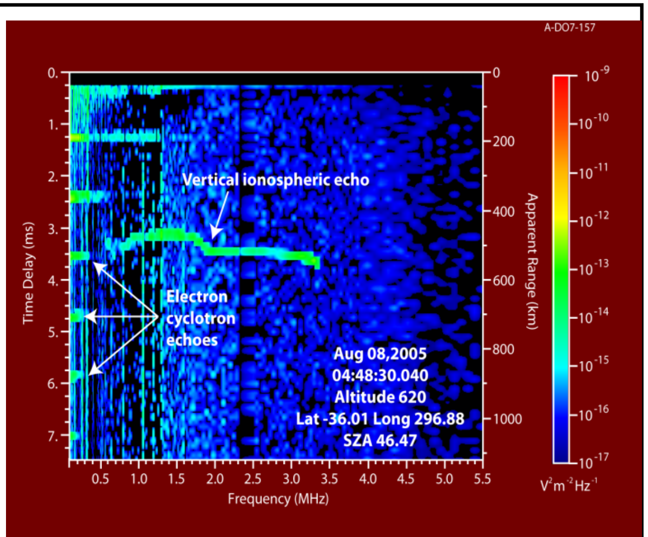
The MARSIS team has demonstrated a simple and accurate technique for measuring the magnetic field around Mars using the ionospheric sounder onboard Mars Express, which has no onboard magnetometer. Knowledge of the magnetic field is a crucial element in the understanding of the space environment near Mars.



<u>Magnetic field measurement principle</u>:

- The MARSIS pulses accelerate electrons, locally.
- The accelerated electrons execute cyclotron orbits in the local magnetic field.
- Every time these electrons return to the vicinity of the spacecraft, a short broadband voltage pulse is induced on the antenna, thereby producing the horizontal echoes on the ionogram.
- The magnetic field strength is calculated by assuming that the observed repetition rate is equal to the electron cyclotron frequency.
- This was totally unexpected!

Electron cyclotron echo visible in the Marsis ionograms (on the left)

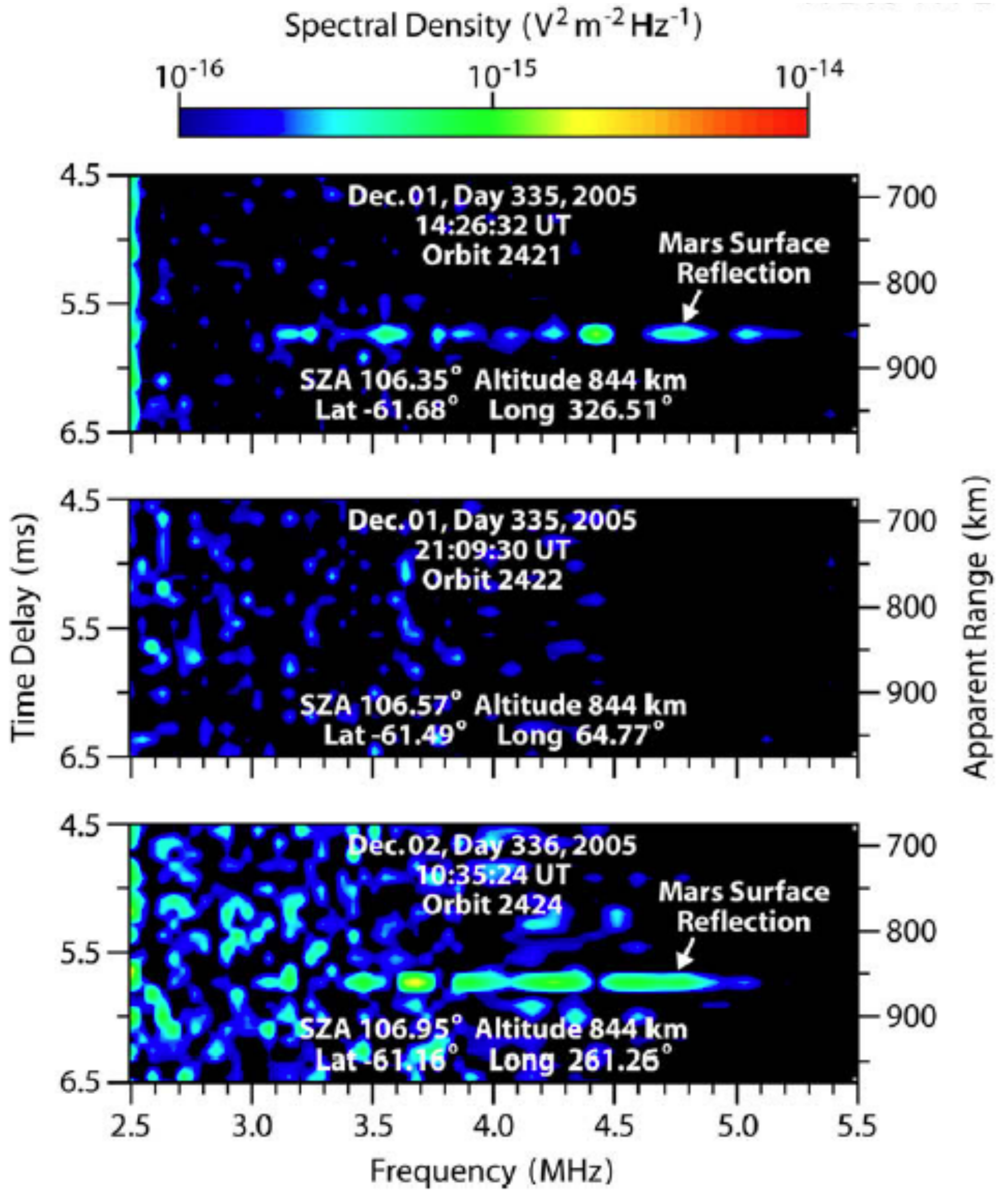


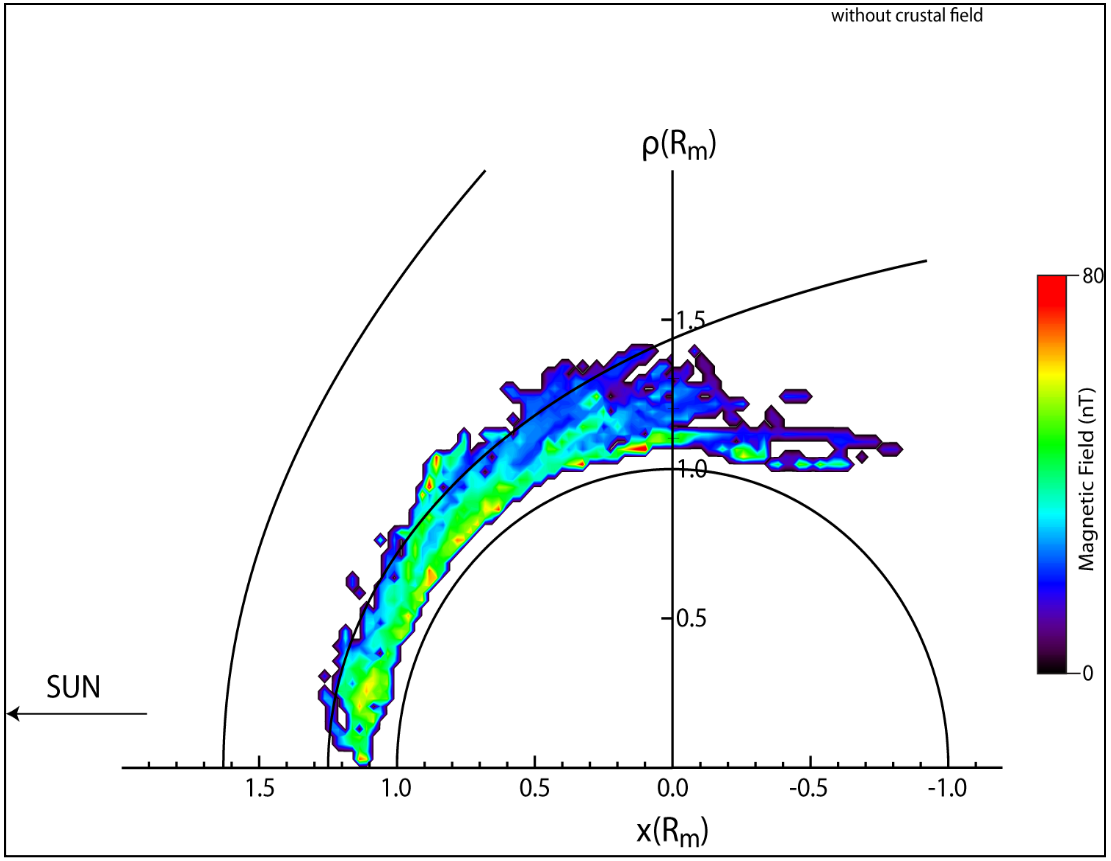
Mars ionograms used to look at effect on Mars surface reflection of solar energetic particles

Enhanced ionization

Possible space weather probe

Morgan et al., Icarus 2010





Distribution of magnetic field strength around Mars, with intense crustal fields removed. The positive horizontal axis is along the Mars-Sun direction. The vertical axis shows the distance from the Mars-Sun axis. The sun is to the left. The color bar represents the magnetic field strength in nT. Bow shock and magnetic pile-up boundary (inclined lines) are from a model.

The measured magnetic field intensity is seen to be at a maximum near the lowest sampled altitudes, decreasing with Increasing altitude, and usually undetectable outside the magnetic pileup boundary.

References: Akalin *et al*., Icarus, 2010

Mars ionosphere: effect of dust storms

Topic for YingHuo-1?

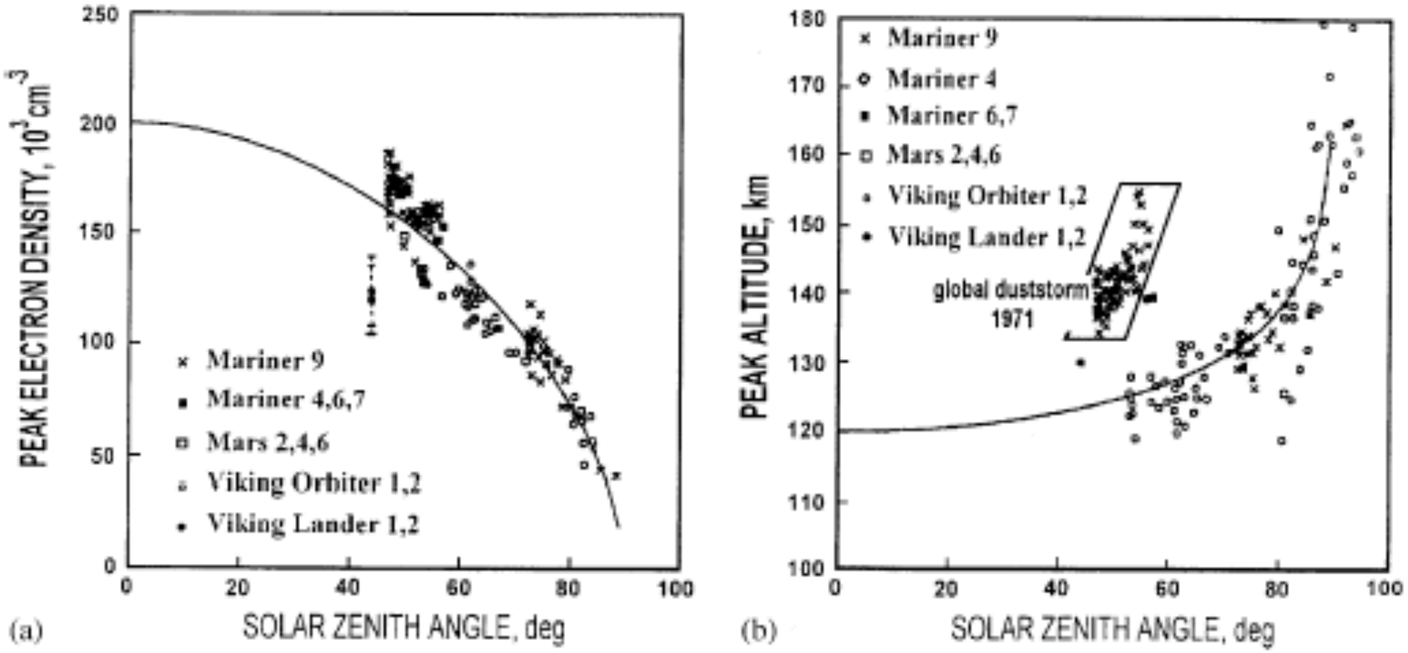
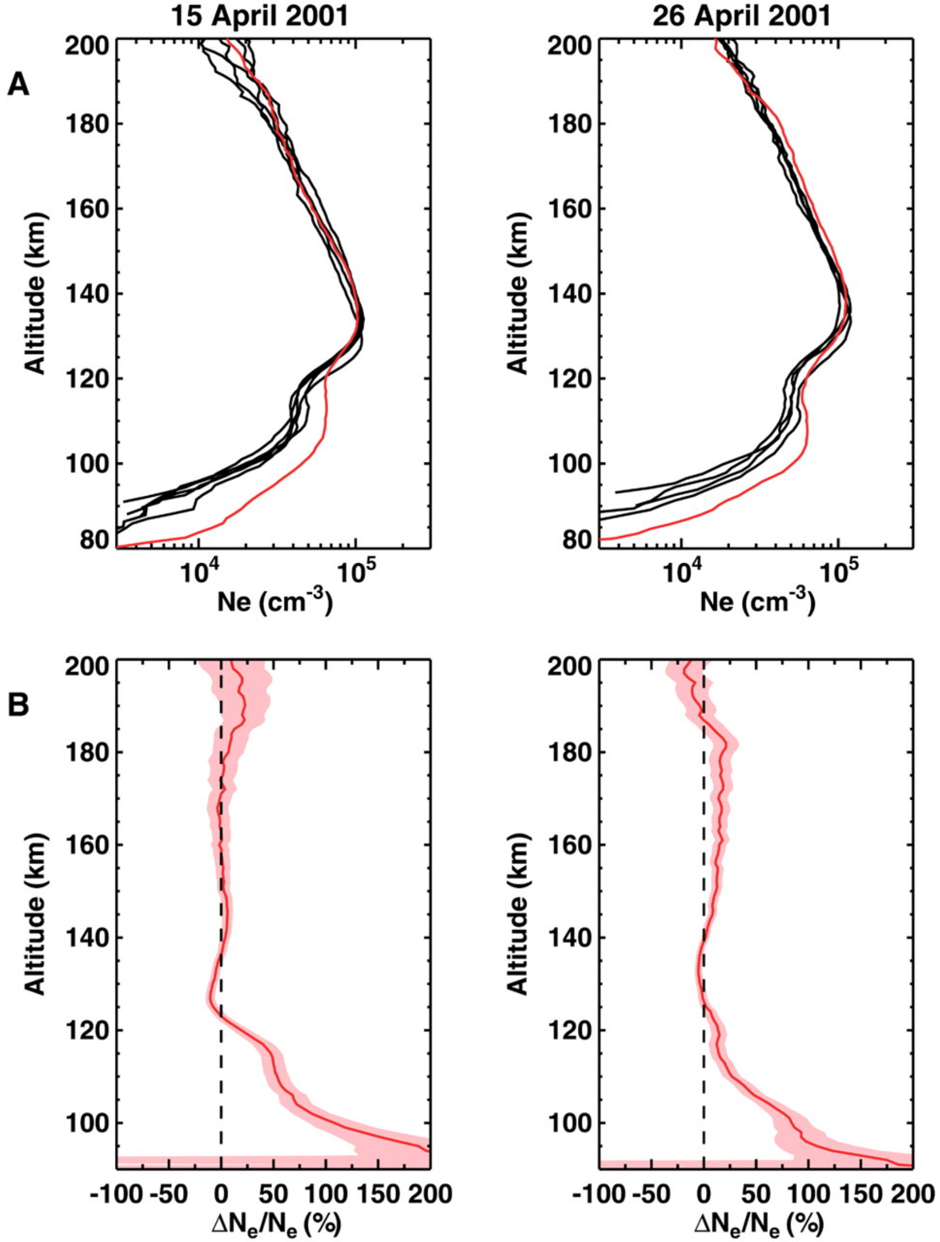


Fig. 1. Maximum values (a) and peak altitudes (b) of electron densities observed at Mars. The curve in (a) corresponds to $n_m = 200\cos^{0.57}\chi$, and that in (b) to $h_m = 120 + 10\ln(\sec\chi)$ (from Hantsch and Bauer, 1990).

Nielsen et al. 2007 PSS

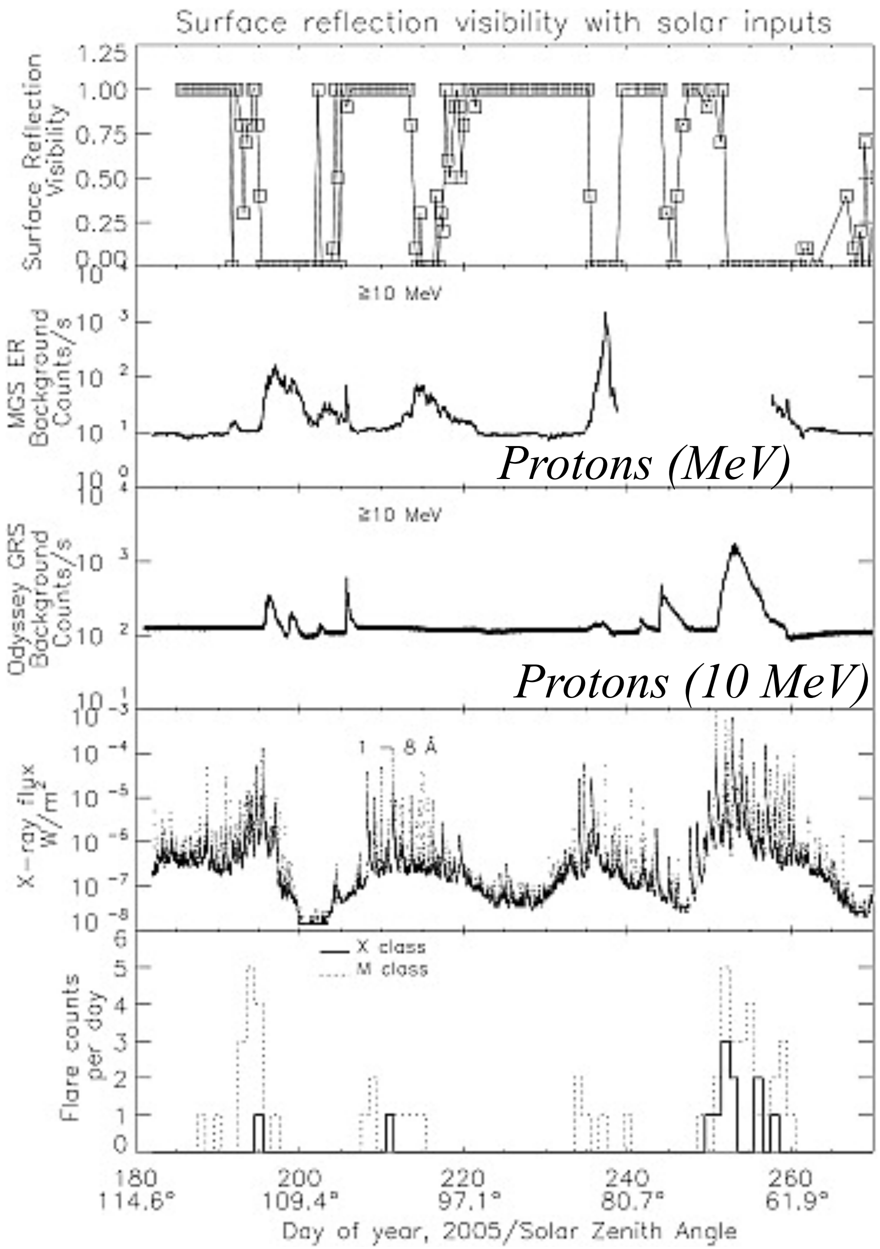
Mars ionosphere: effect of solar flares

Mendillo et al, 2006



Mars ionosphere: radio-wave attenuation

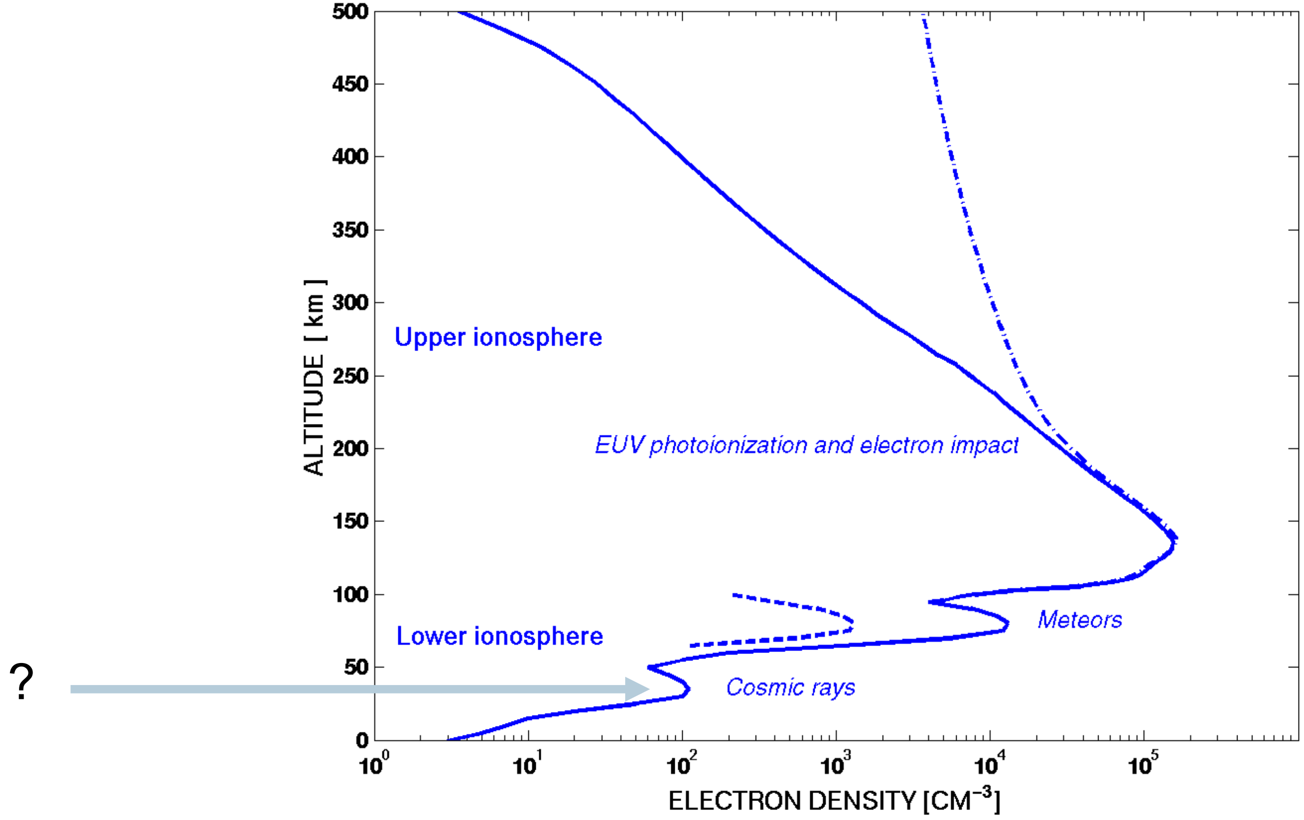
Morgan et al, 2006
Espley et al., 2007
Nielsen et al., 2007



Attenuation due to:

- Influx of solar protons (night)
  or
- Infall of cosmic dust (day/night?)
  or
- Layer created by soft-X rays (day)
  or
- Dust storm
  or
- Meteors

A totally unknown region of the ionosphere



Other recent (2011) results on the Martian ionosphere

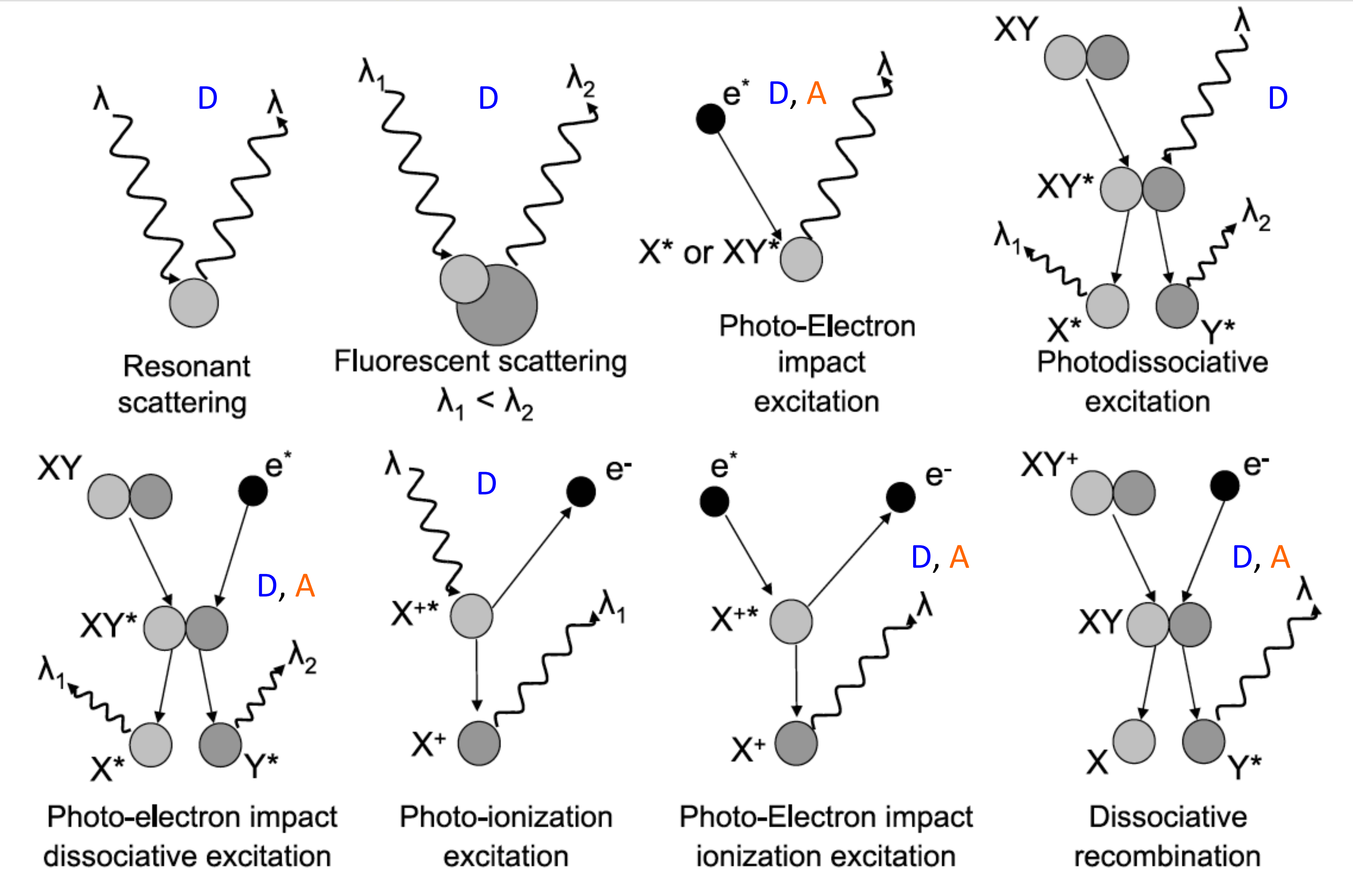
- Coates et al Ionospheric photoelectrons (part of Friday talk)
- Nemec et al, Dayside ionosphere: Empirical model based on MARSIS data. 2 regions – up to 5 scale heights above peak, Chapman-like: >10 scale heights, diffusion dominates
- Trantham et al., Photoelectrons on closed crustal field lines at Mars
- Halekas et al, sawtooth oscillations
- Nemec et al, Enhanced ionization regions on nighside
- Najib et al, multifluid modelling
- Stenberg et al, alpha particle capture
- Lundin et al., low altitude acceleration of ions
- Withers et al, wave atttenuation – MARSIS application
- Hara et al, heavy ion enhancements during CIR
- Lundin et al, crustal field effect on escape
- 2010 includes Fraenz et al., transterminator ion flow

Ionosphere: to remember

- Very interesting and rich physics
- While the region around the main peak (135 km height) is relatively well studied, many unknown remain concerning: the upper part (= the ionopause) and the lower part (below 100 km).
- Extreme variability at all altitudes.
- The knowledge of the ionosphere is important for telecommunication and radio-link (surface-surface, surface-orbiter).

Airglow

Dayside airglow (and aurora) emission processes



From Leblanc et al., 2006

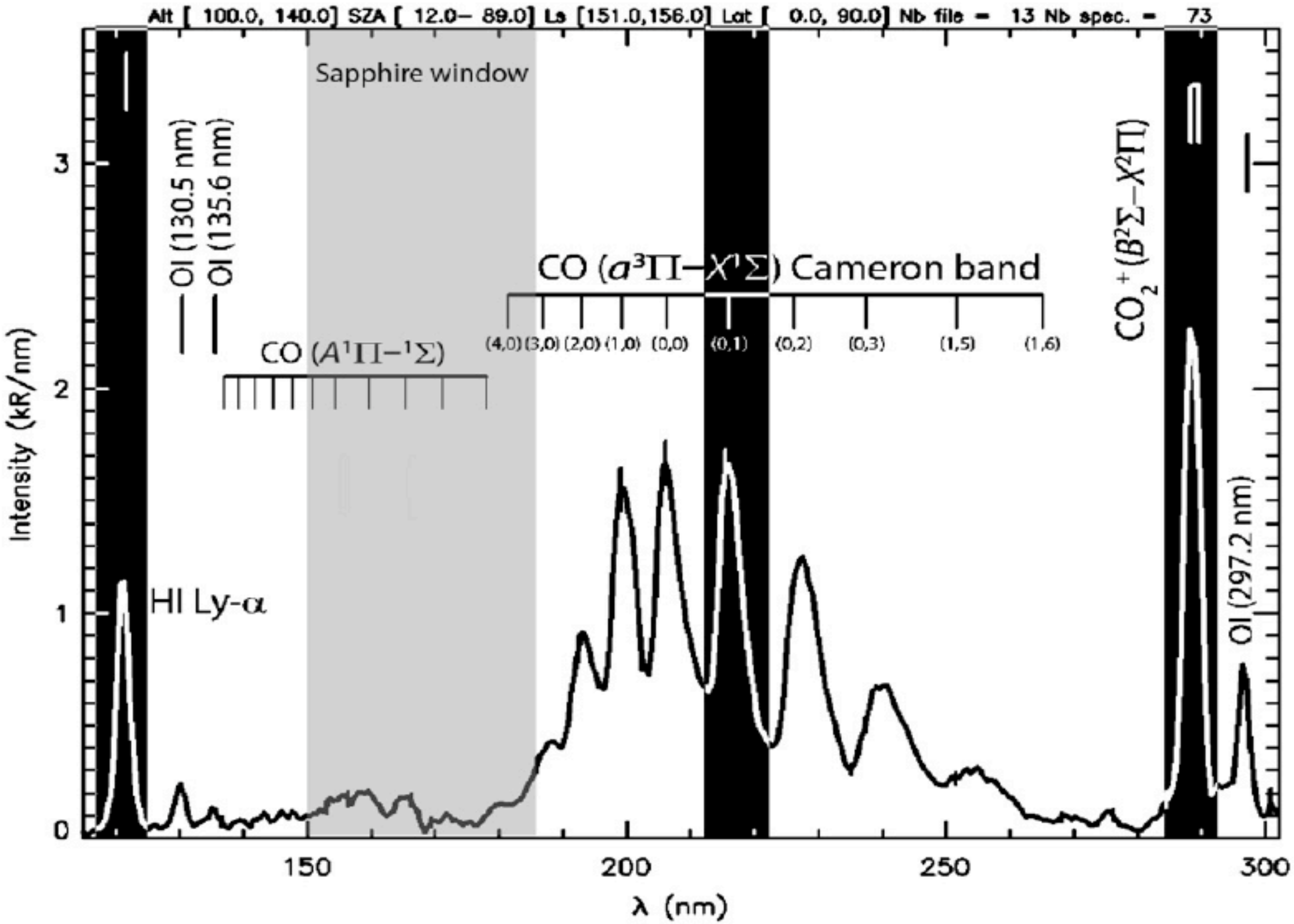
Why observe planetary airglows and auroras ? ? ?

Once the sources et sinks of the emitting excited species are known, airglow observations provide a quantitative tool to **remotely sense** :

- Atmospheric densities
- Temperature
- Dynamical processes (wind, turbulent transport, waves)

In addition, aurora provides insight into the energy and spatial characteristics of the precipitated particles and of acceleration processes

SPICAM – Mars FUV

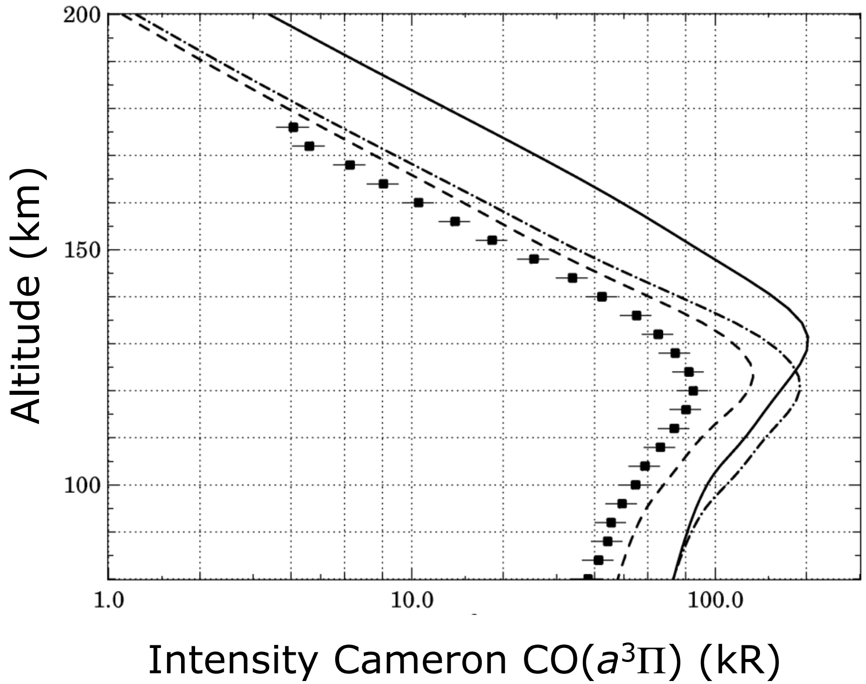


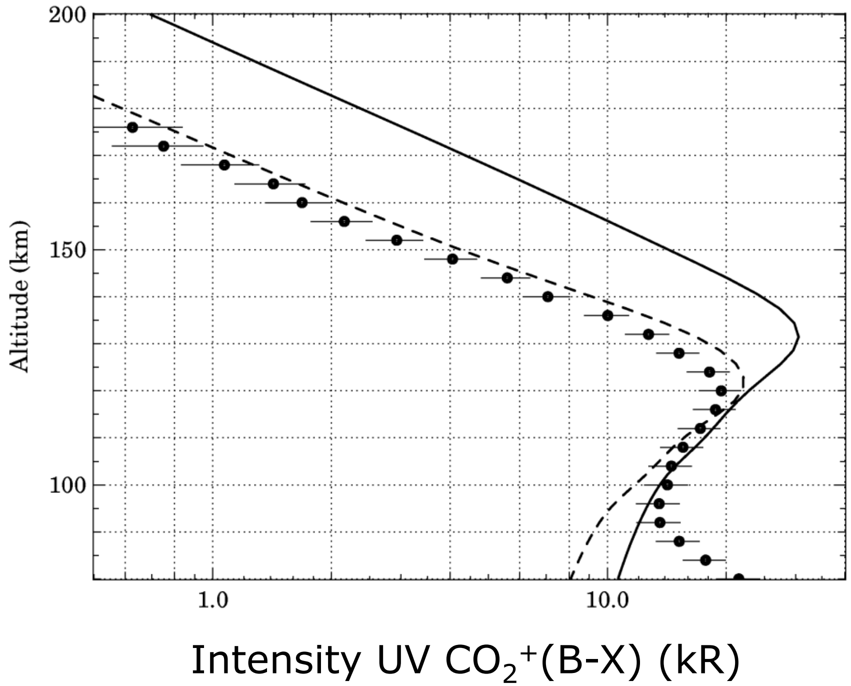
Vertical profiles of ultraviolet emissions

Comparison with model, for the Cameron bands of CO, and CO2+(2890Å).

→Neutral atmosphere (CO2) needs to be divided by **<u>3</u>** compared to what was expected for solar minimum conditions.

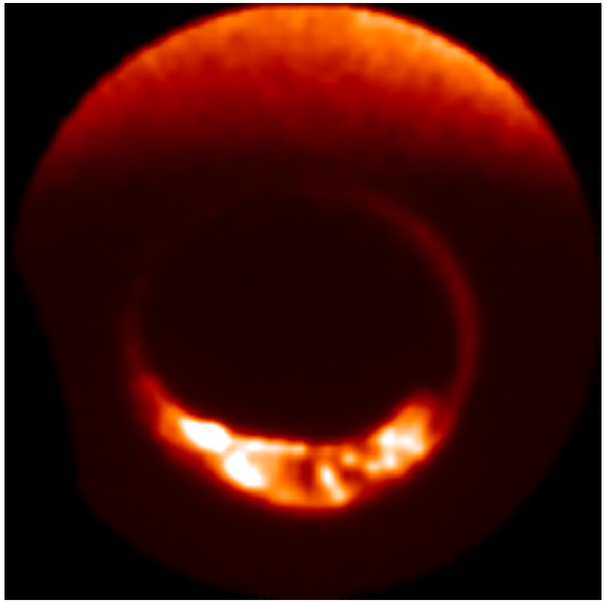
→ Neutral atmosphere very variable.

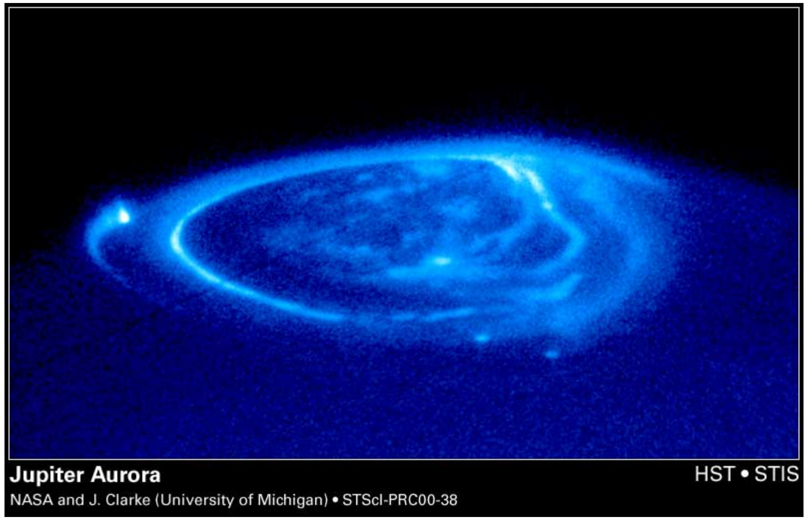


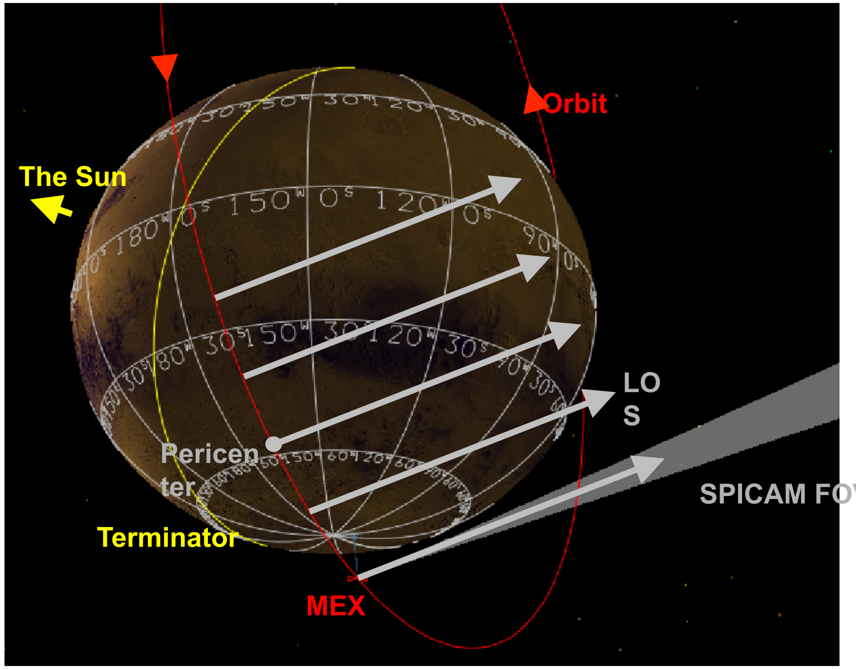


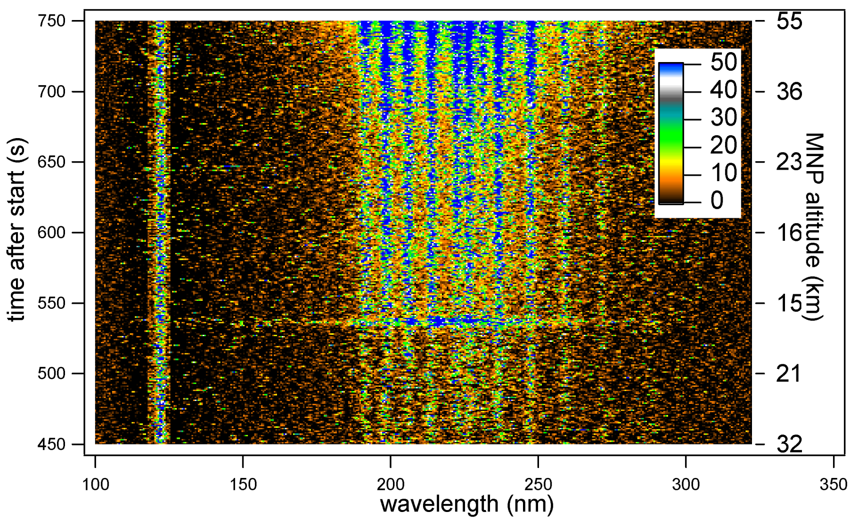
Aurora

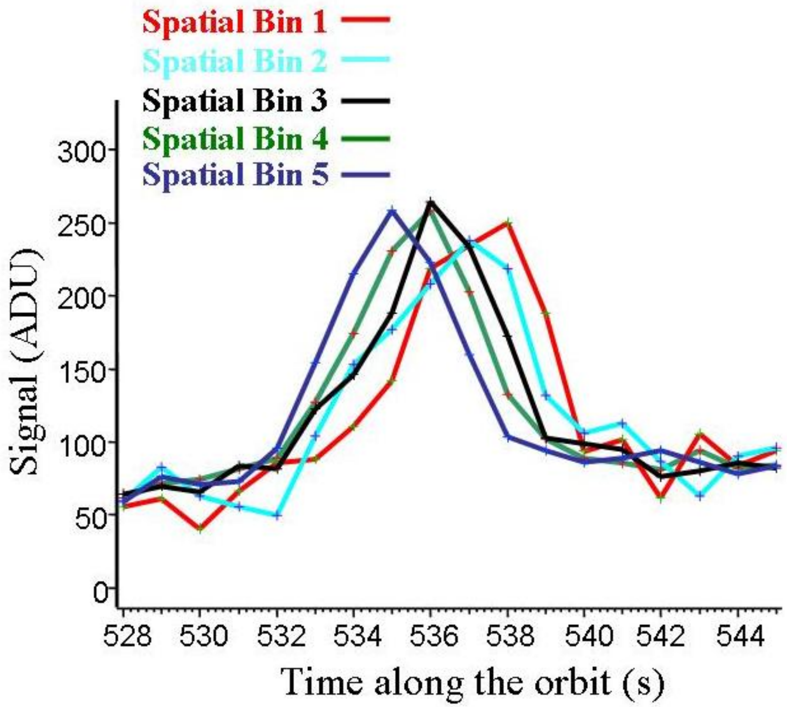
Aurora




Jupiter Aurora
HST • STIS
NASA and J. Clarke (University of Michigan) • STScI-PRC00-38

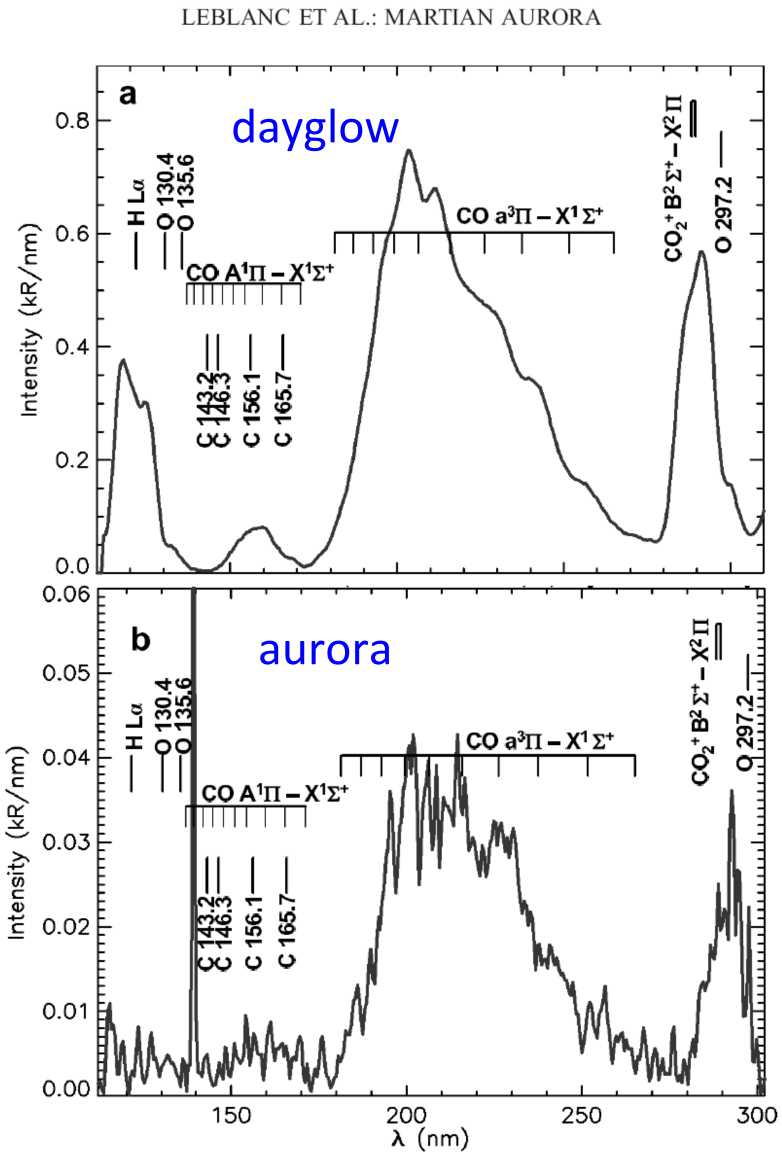




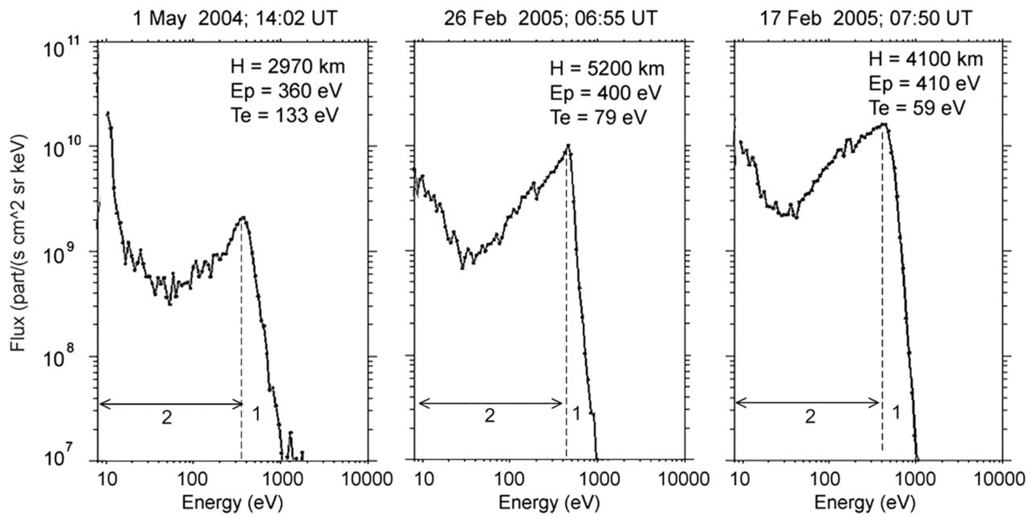


Bertaux et al. 2005

Mars aurora



The Mars auroral UV spectrum (Bertaux et al.) is very similar to the dayglow emission since electron Impact plays a major role in the excitation of the CO and CO_2^+ bands. The characteristics of the UV spectrum suggest an intense flux of soft (tens of eV) electron precipitation (Leblanc et al., 2008)



The auroral electron energy spectrum is similar to that observed on Earth in inverted-V events, with characteristic energies of 50-150 eV. This suggests that these electrons are associated with upward field-aligned currents generated near the boundary of open and closed crustal field structures.

Mars has some remanent crustal magnetism, concentrated in the Southern hemisphere -- Mars Global Surveyor magnetometer data.

J.E.P. CONNERNEY ET AL.

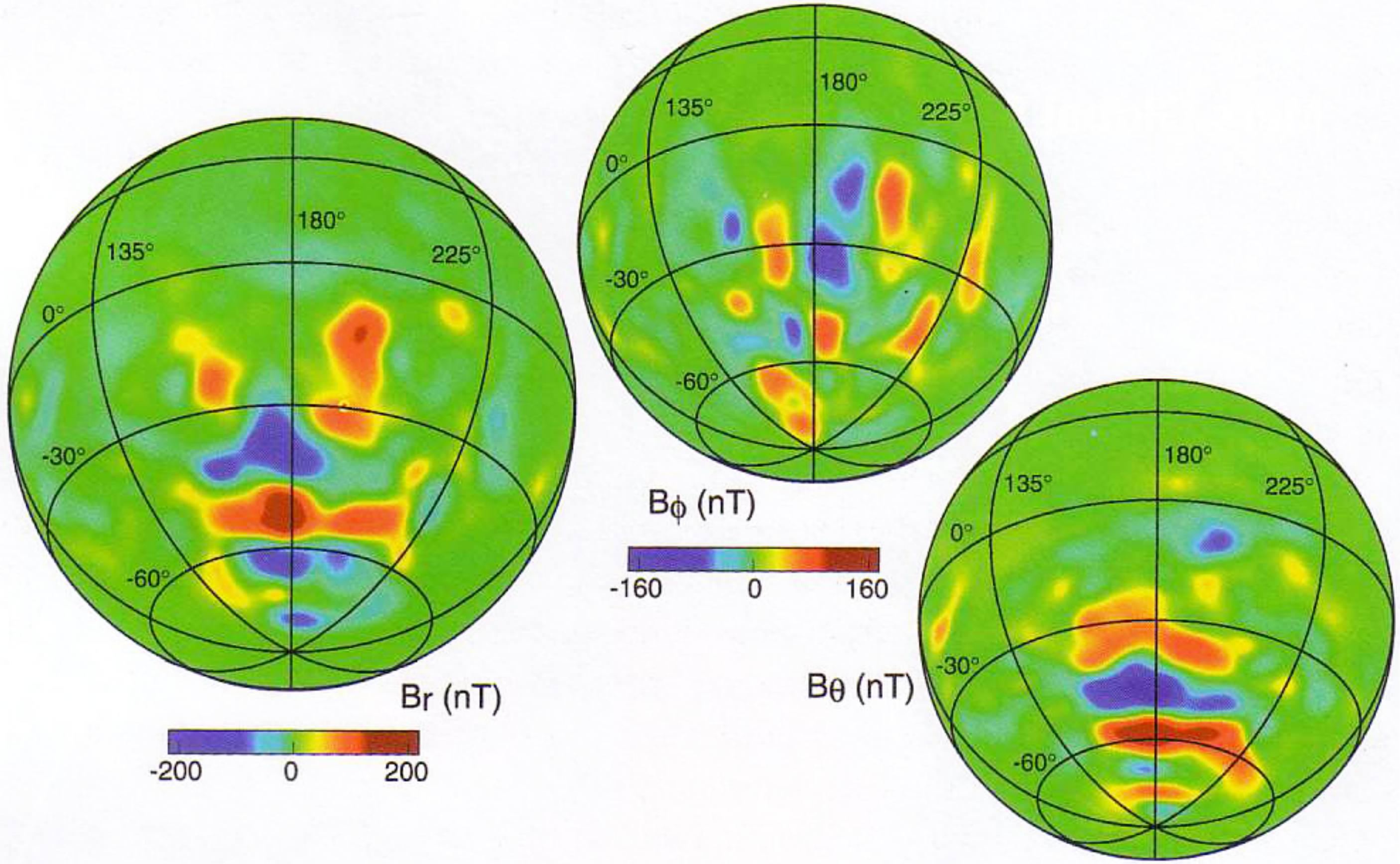
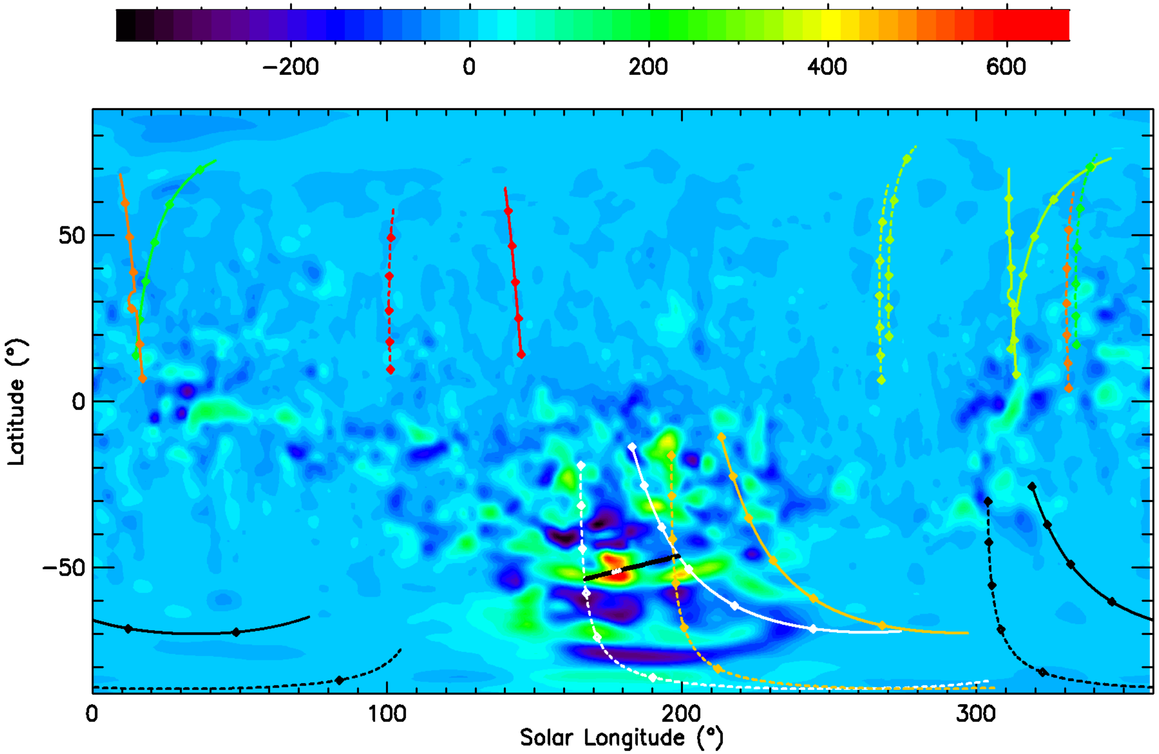
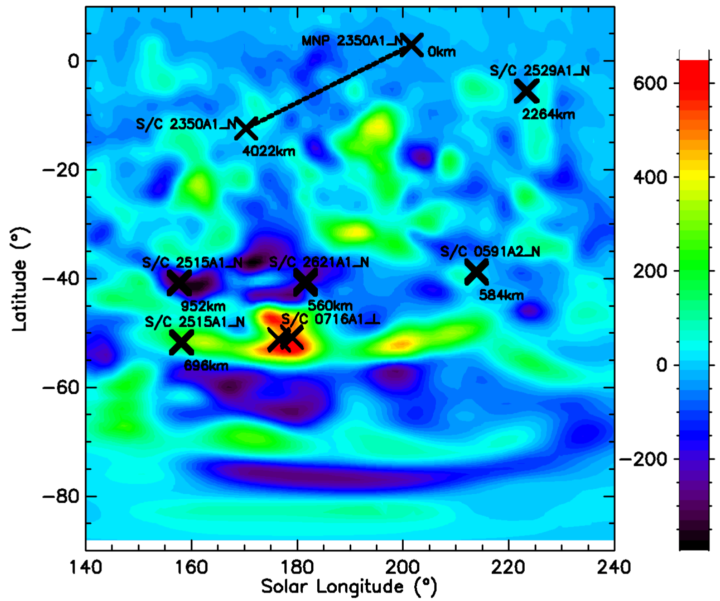


Figure 2. Orthographic projections of the three components of the magnetic field (B_r, B_θ, B_ϕ) at a nominal 400 km mapping orbit altitude, viewed from 30 deg S and 180 deg East longitude (after Connerney *et al.*, 2001).

Martian aurora

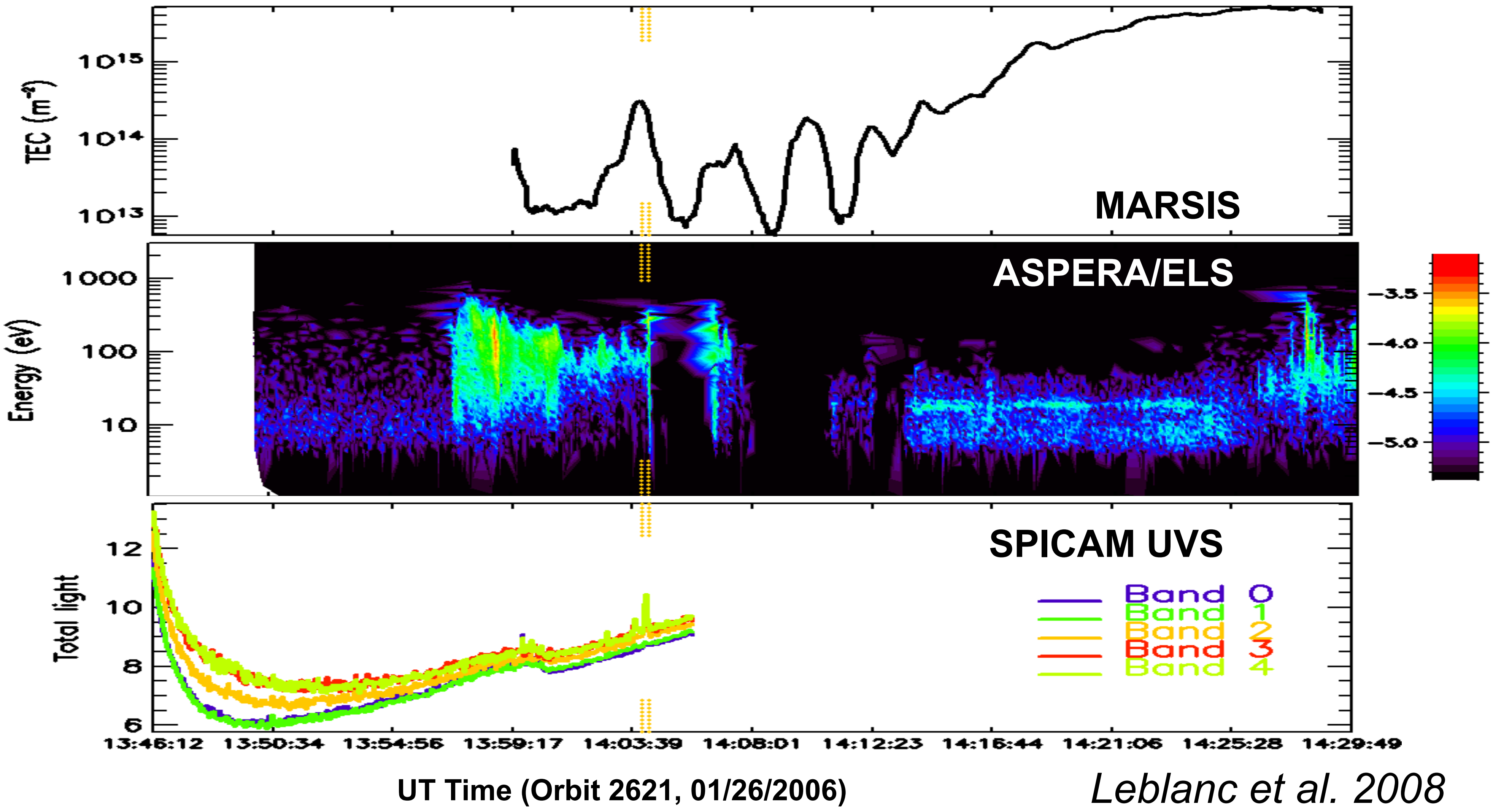
Magnetic anomalies and locations of auroras





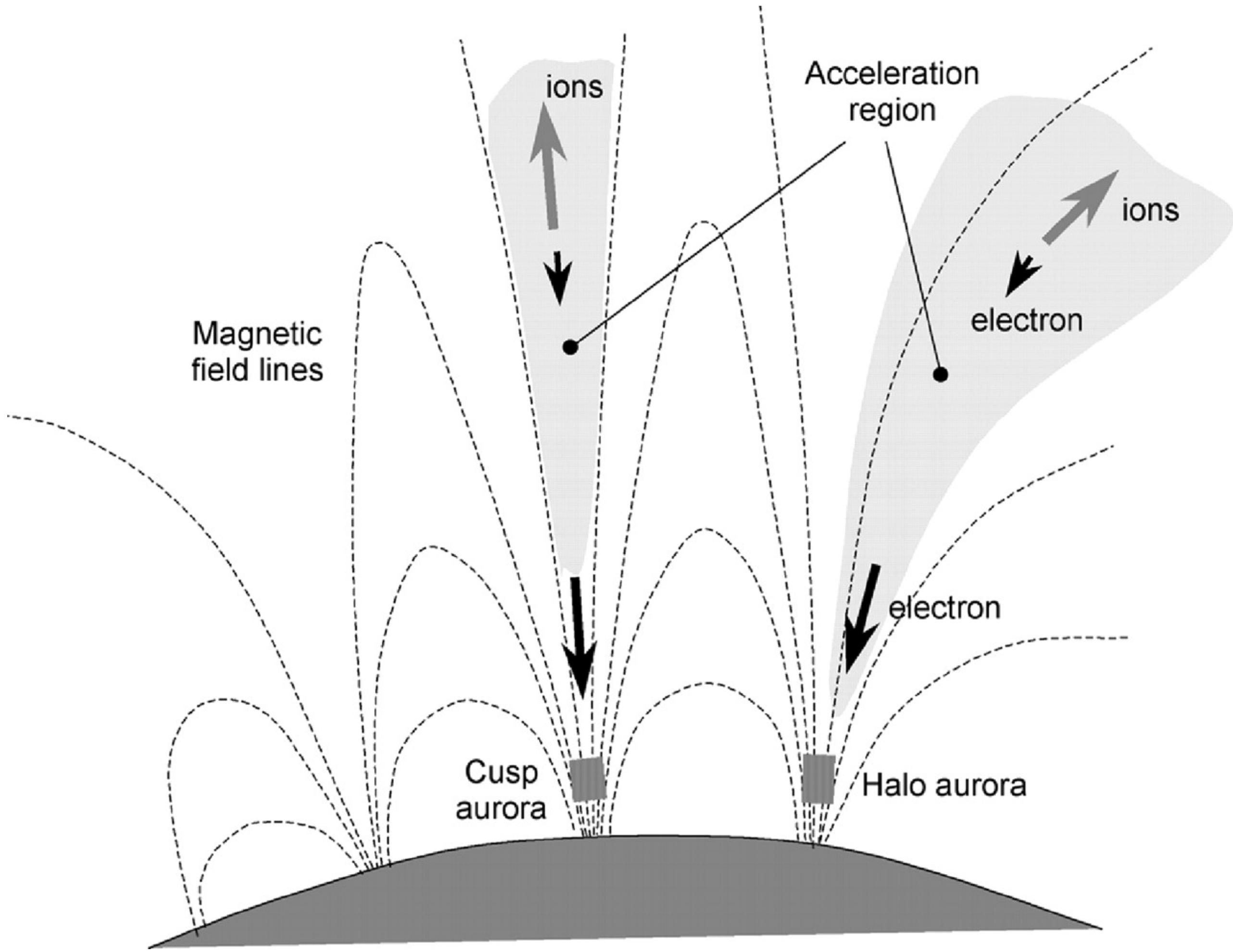
Area characterized by crustal magnetic anomalies

Mars ionosphere: multi-instrument study of the crustal magnetic field regions: SPICAM-MARSIS-ASPERA



Leblanc et al. 2008

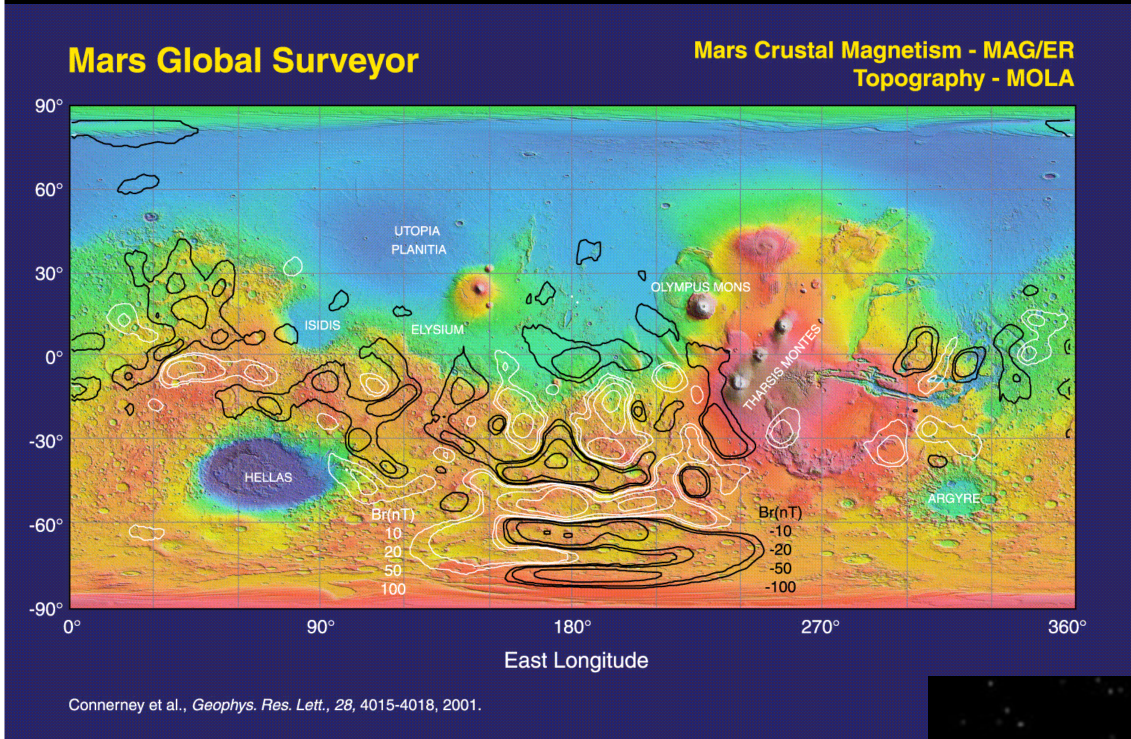
Mars aurora



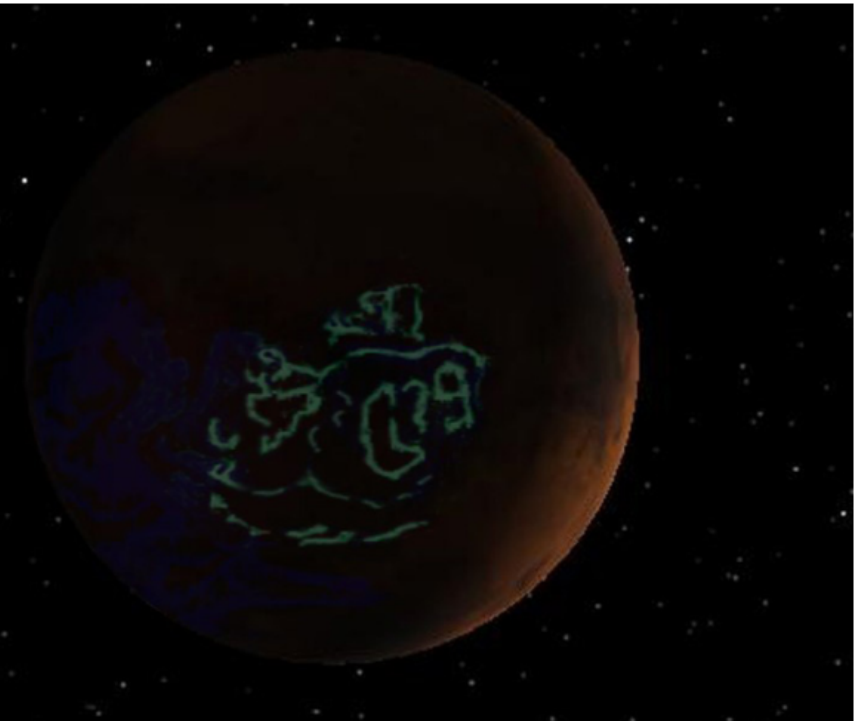
Lundin et al., 2006

Simultaneous SPICAV and Aspera-3 observations show that all UV aurora detections are associated with regions of crustal magnetic field. It appears that cusp-like structures can trigger the auroral features identified by SPICAM UVS.

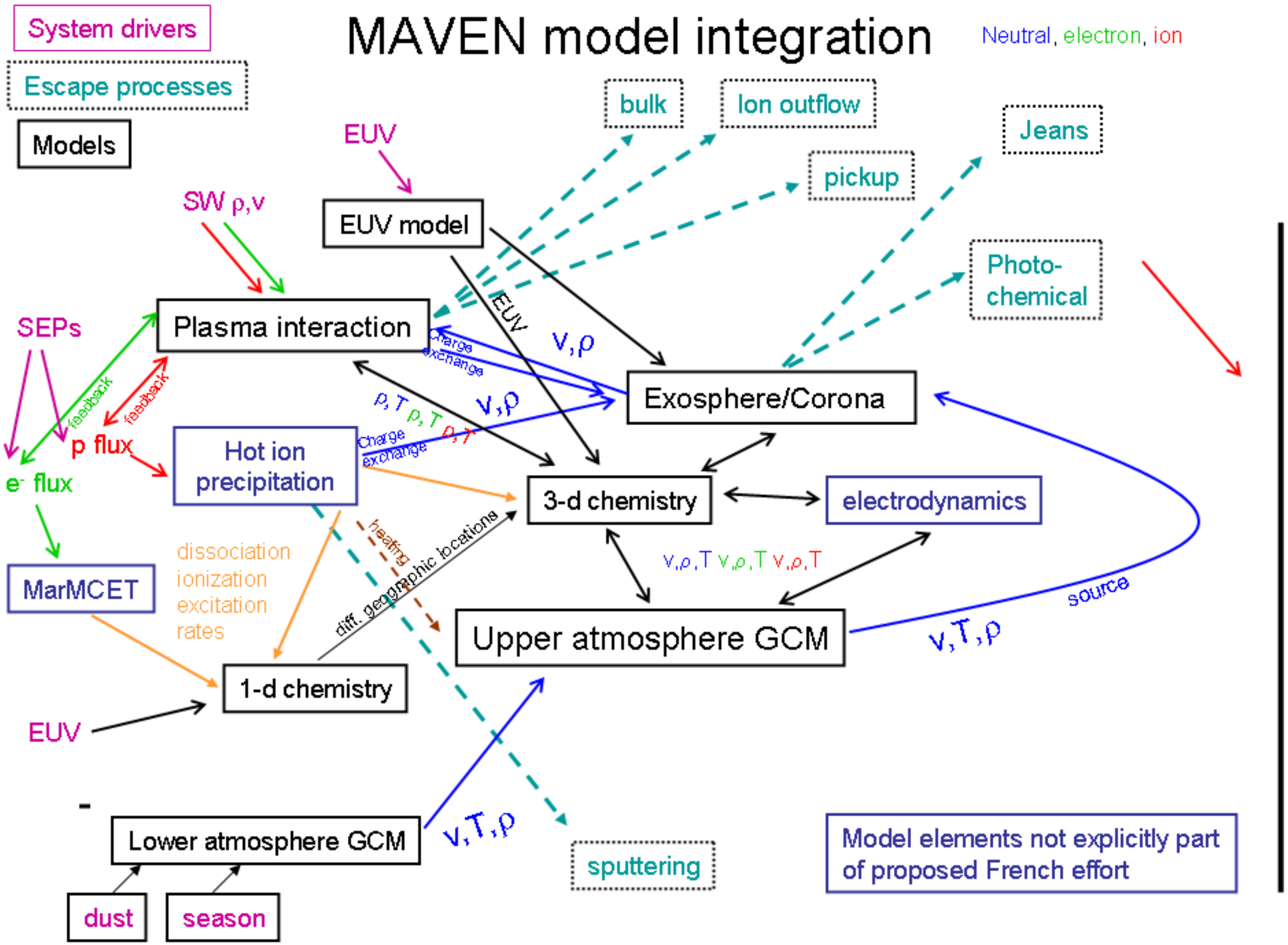
Aurora and global solar wind interaction



Crustal anomalies – effects of associated **aurora** seen by MEx – IR limb measurements by SPICAM - need to image directly and determine extent of solar wind control



Artist's impression of Mars aurora near crustal fields


MAVEN model integration
System drivers
Escape processes
Models
Neutral, electron, ion
bulk
Ion outflow
Jeans
pickup
EUV
EUV model
SW ρ,v
Photo-chemical
SEPs
Plasma interaction
charge exchange
v,ρ
EUV
Exosphere/Corona
feedback
feedback
p flux
Hot ion precipitation
ρ,T ρ,T ρ,T
v,ρ
charge exchange
e- flux
3-d chemistry
electrodynamics
heating
diff. geographic locations
MarMCET
dissociation
ionization
excitation
rates
v,ρ,T v,ρ,T v,ρ,T
Upper atmosphere GCM
source
v,T,ρ
1-d chemistry
EUV
Lower atmosphere GCM
v,T,ρ
sputtering
Model elements not explicitly part of proposed French effort
dust
season

- Nagy, A.F., Banks, P.M., 1970. Photoelectron fluxes in the ionosphere. J. Geophys. Res. 75, 6260–6270.
- Mantas, G.P., Hanson, W.B., 1979. Photoelectron fluxes in the Martian ionosphere. J. Geophys. Res 84, 369–385..
- Fox, J.L., Dalgarno, A., 1979. Ionization, luminosity, and heating of the upper atmosphere of Mars. J. Geophys. Res. 84, 7315–7333.
- Mitchell, D.L., et al., 2001. Probing Mars' crustal magnetic field and ionosphere with the MGS Electron Reflectometer. J. Geophys. Res. 106, 23419–23428.
- Lundin, R., et al., Ionospheric Plasma Acceleration at Mars: ASPERA3 results, Icarus, Volume 182, Issue 2, p. 308-319. 2006**.**
- Witasse, O., et al., 2008. Solar system ionospheres. Space Sci Rev. 139, 235–265.
- Bertaux, JL, et al., Discovery of an aurora on Mars, NATURE Volume: 435 Issue: 7043 Pages: 790-794, 2005.