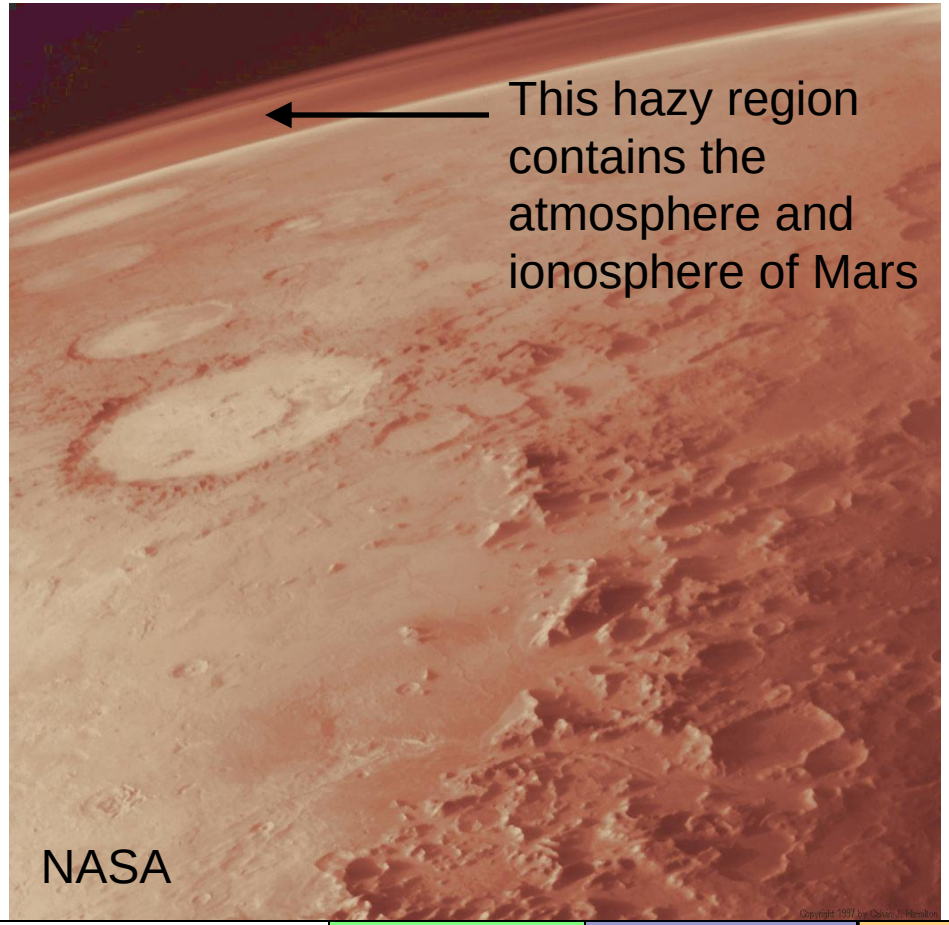
How the ionosphere of Mars works



Paul Withers
Boston University
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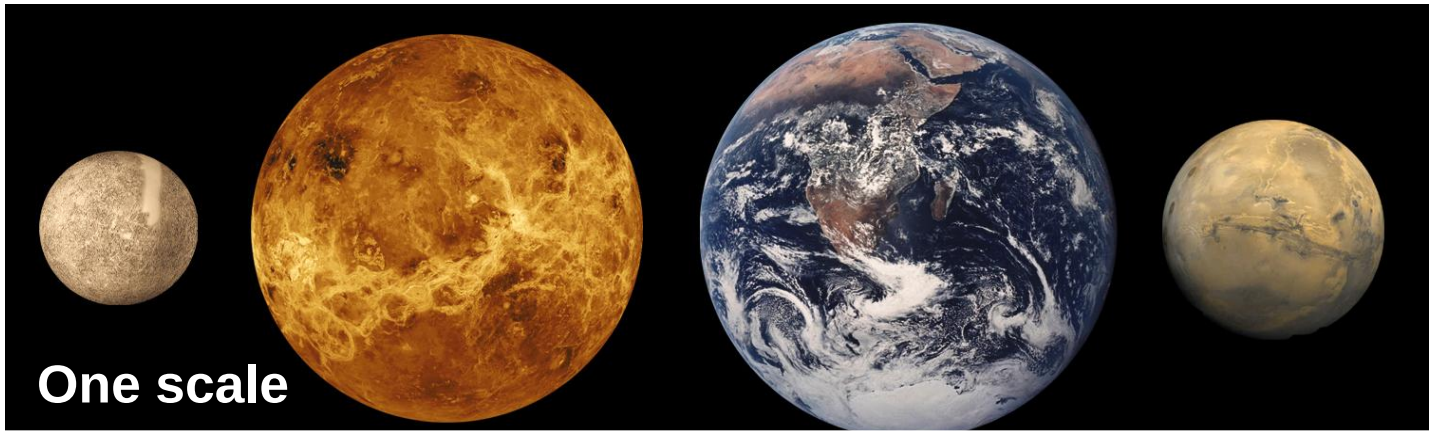
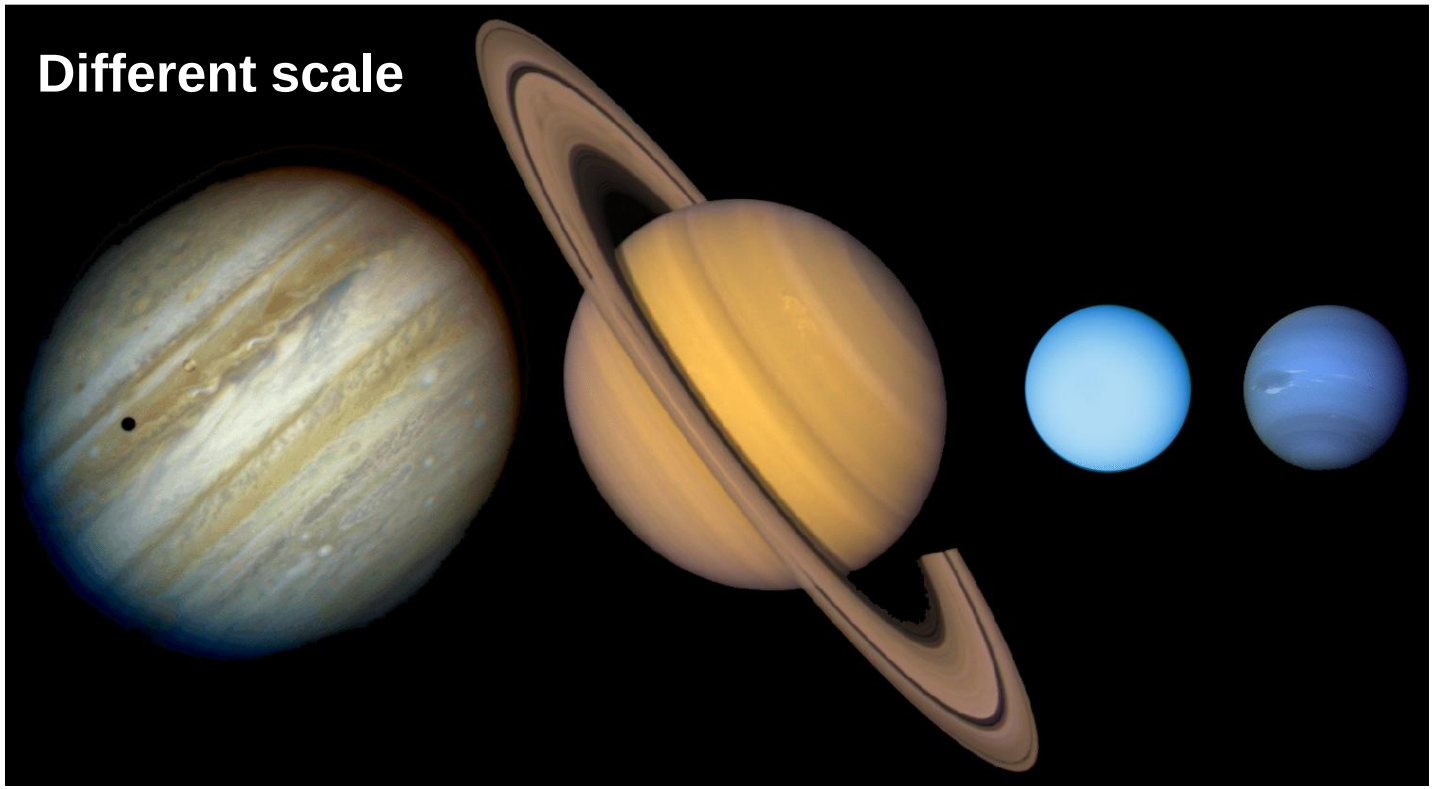
Department Lecture Series, EAPS, MIT

Wednesday 2012.02.08
16:00-17:00





www.solarviews.com

This is ⟵ Mars

0.5 x R-Earth

1.5 AU from Sun

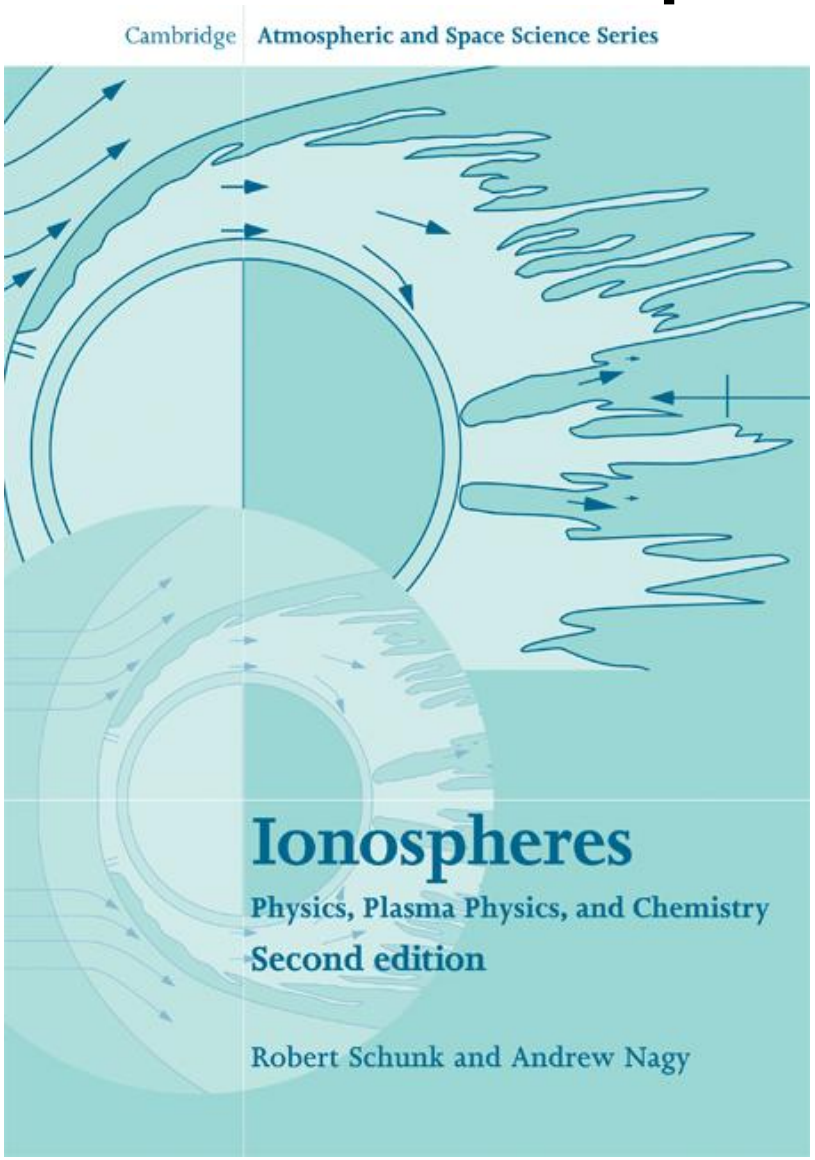
Same rotation rate as Earth

Carbon dioxide atmosphere

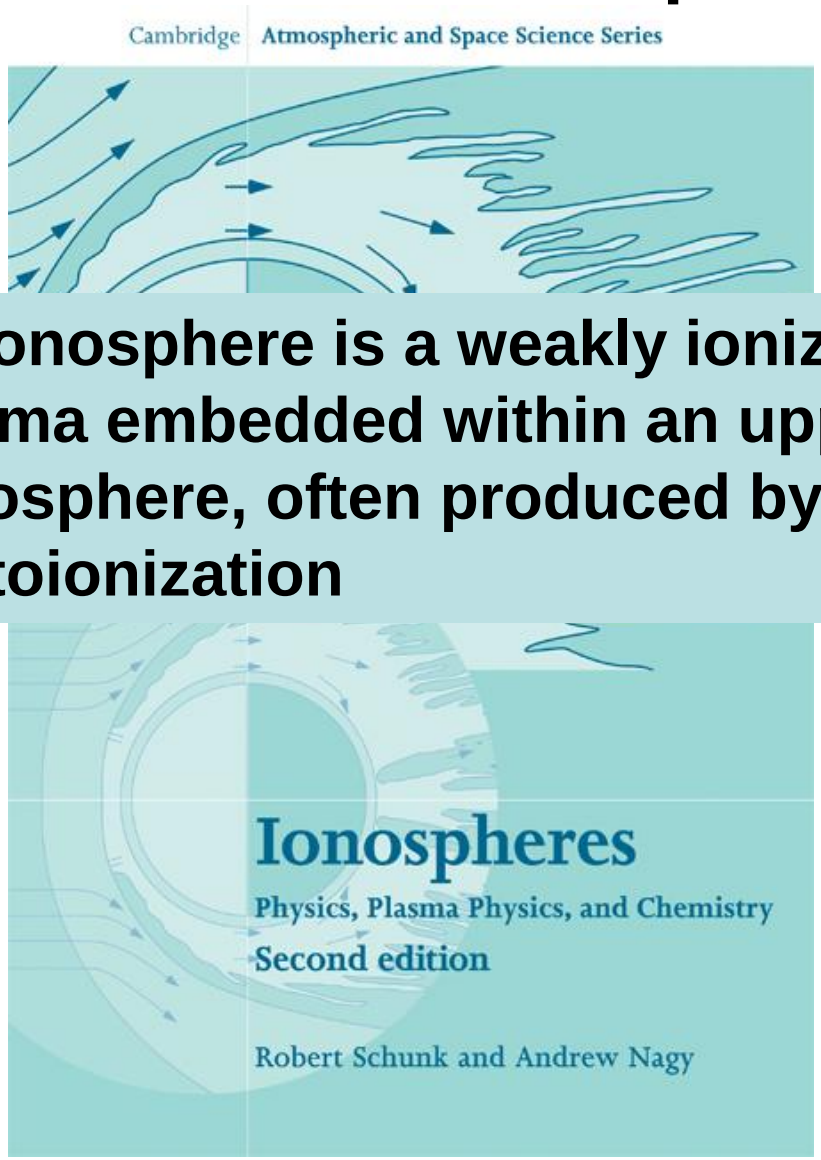
100x smaller surface pressure

Target of many spacecraft in last 15 years

What is an ionosphere?



What is an ionosphere?



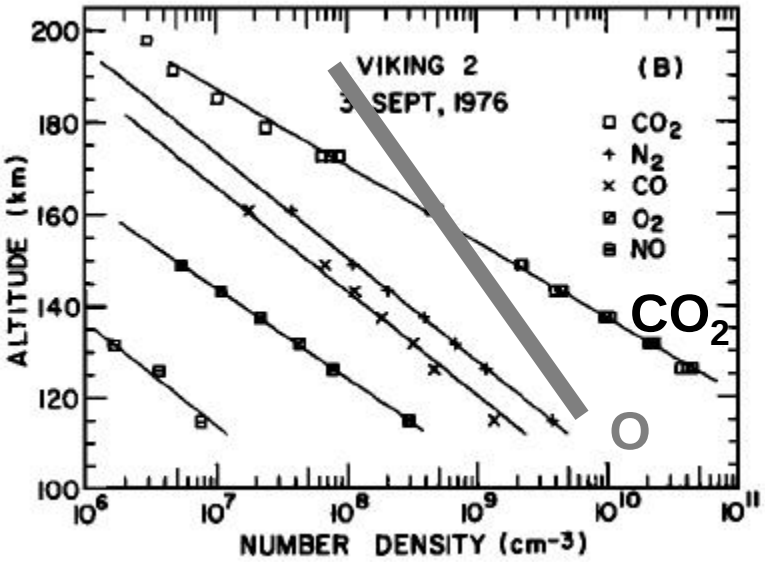
An ionosphere is a weakly ionized plasma embedded within an upper atmosphere, often produced by photoionization

What does that actually mean?

	Atmosphere	Ionosphere	Space physics
Chemistry			
Gravity			
Sunlight			
Magnetic fields			
Composition	Neutrals	Ions, electrons, and neutrals	Protons and electrons

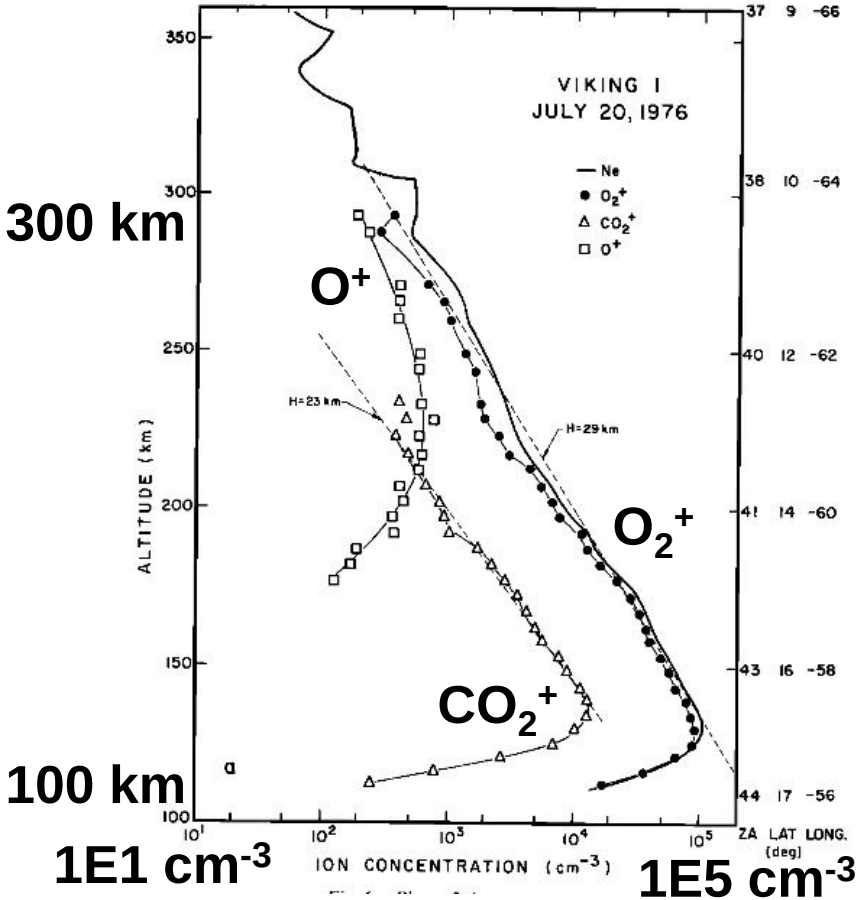
What we know about composition

Neutral species



Nier et al. (1977)

Ion species



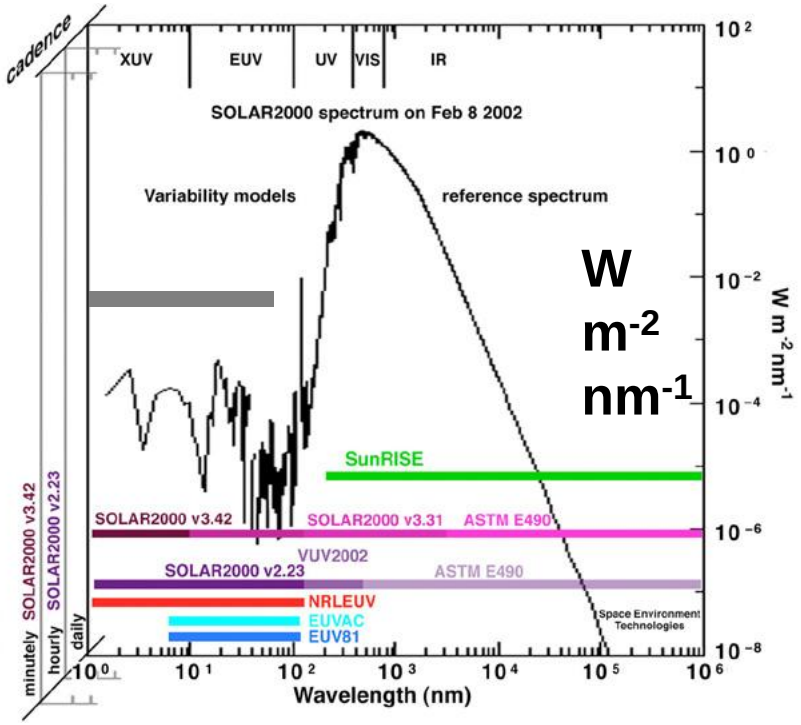
Hanson et al. (1977)

1E1 cm^{-3}

1E5 cm^{-3}

Making ions – Start with sunlight

Solar spectrum

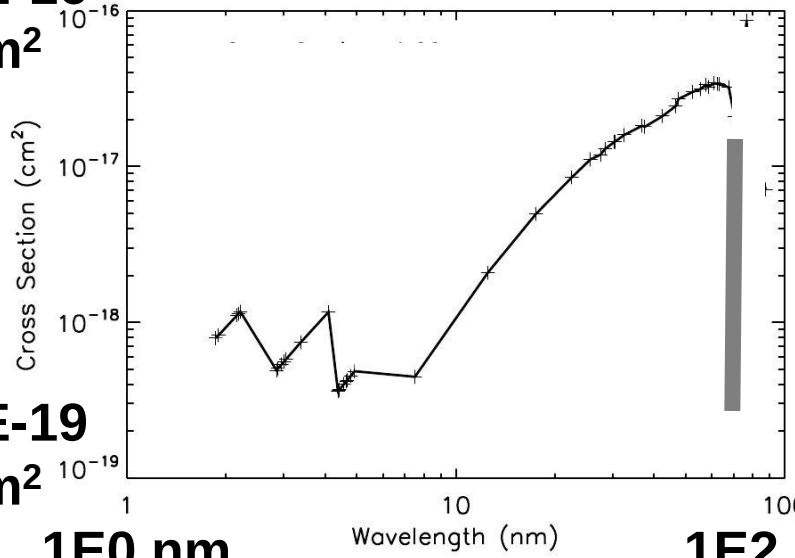


W m^{-2} nm^{-1}

1E0 nm **1E6 nm**

www.spacewx.com

Cross-section of CO_2



1E-16 cm^2

1E-19 cm^2

1E0 nm **1E2 nm**

Soft X-ray (XUV) = 1-10 nm
Extreme ultraviolet (EUV) = 10-100 nm

Making ions – From the top down

- Optical depth(z) = n(z) σ H

- n = neutral number density
- σ = cross-section of carbon dioxide
- H = scale height of neutral atmosphere

Making ions – From the top down

- Optical depth(z) = n(z) σ H
- Flux = Flux-at-infinity x exp(-optical depth)

Making ions – From the top down

- Optical depth(z) = n(z) σ H
- Flux = Flux-at-infinity x exp(-optical depth)
- Number of ions produced cm^{-3} s^{-1} = F σ n

- Flux x cross-section x neutral density

  cm^{-2} s^{-1} cm^{2} cm^{-3}

Making ions – From the top down

- Optical depth(z) = n(z) σ H
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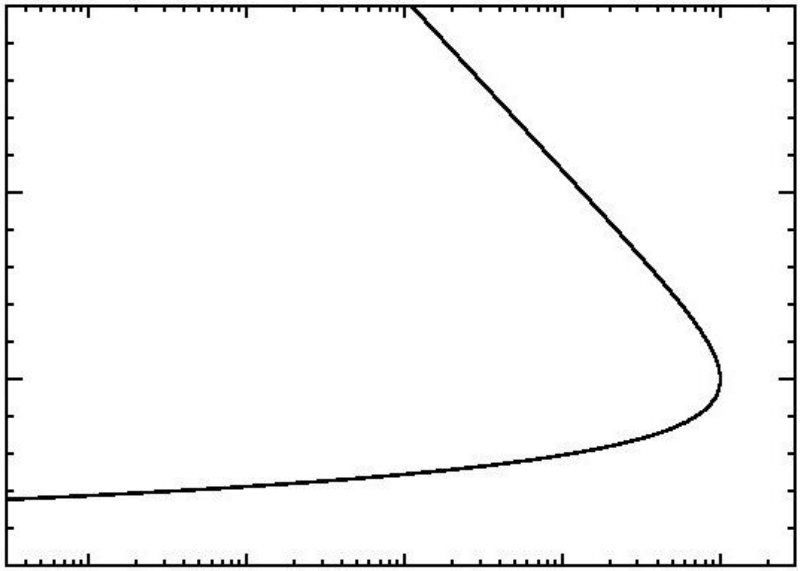
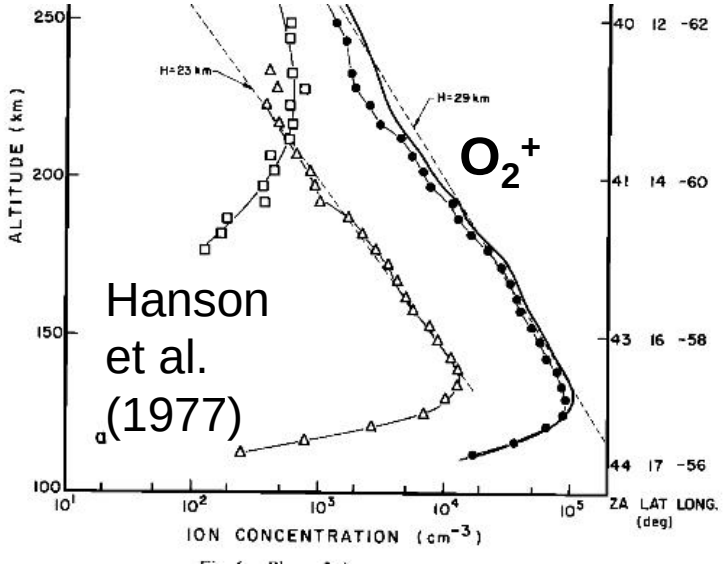
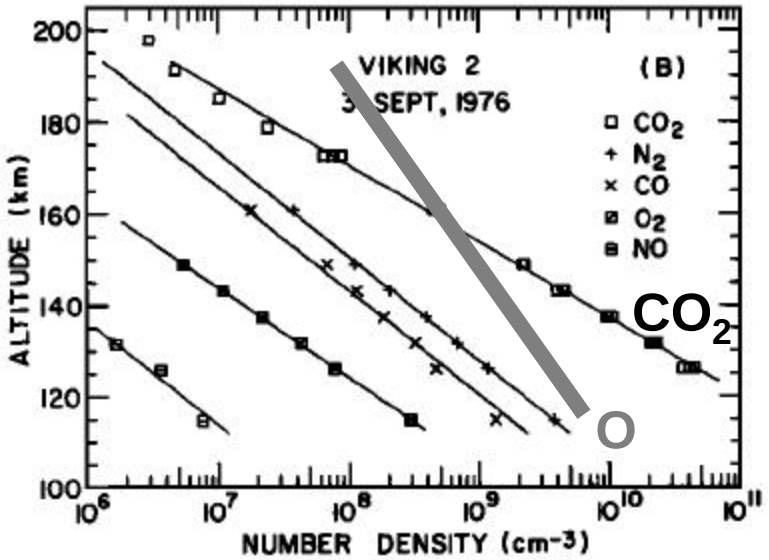


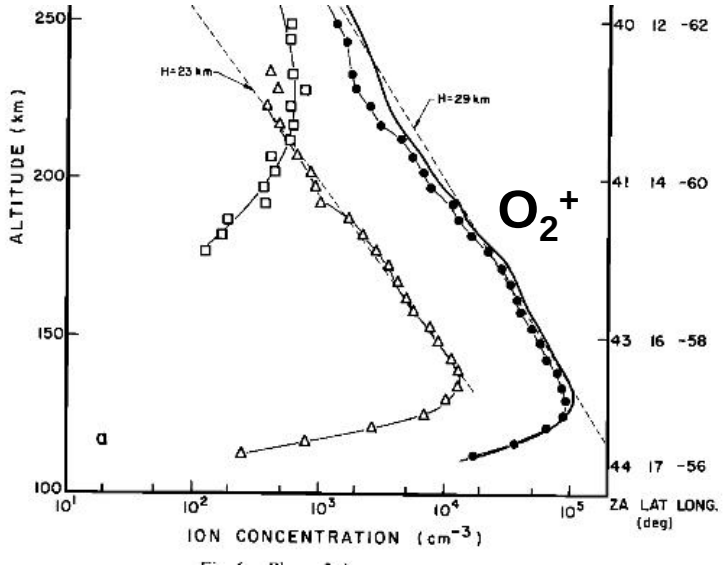


Losing ions

- $CO_2^+ + O \rightarrow O_2^+ + CO$ very fast
- $O_2^+ + e \rightarrow O + O$ few minutes

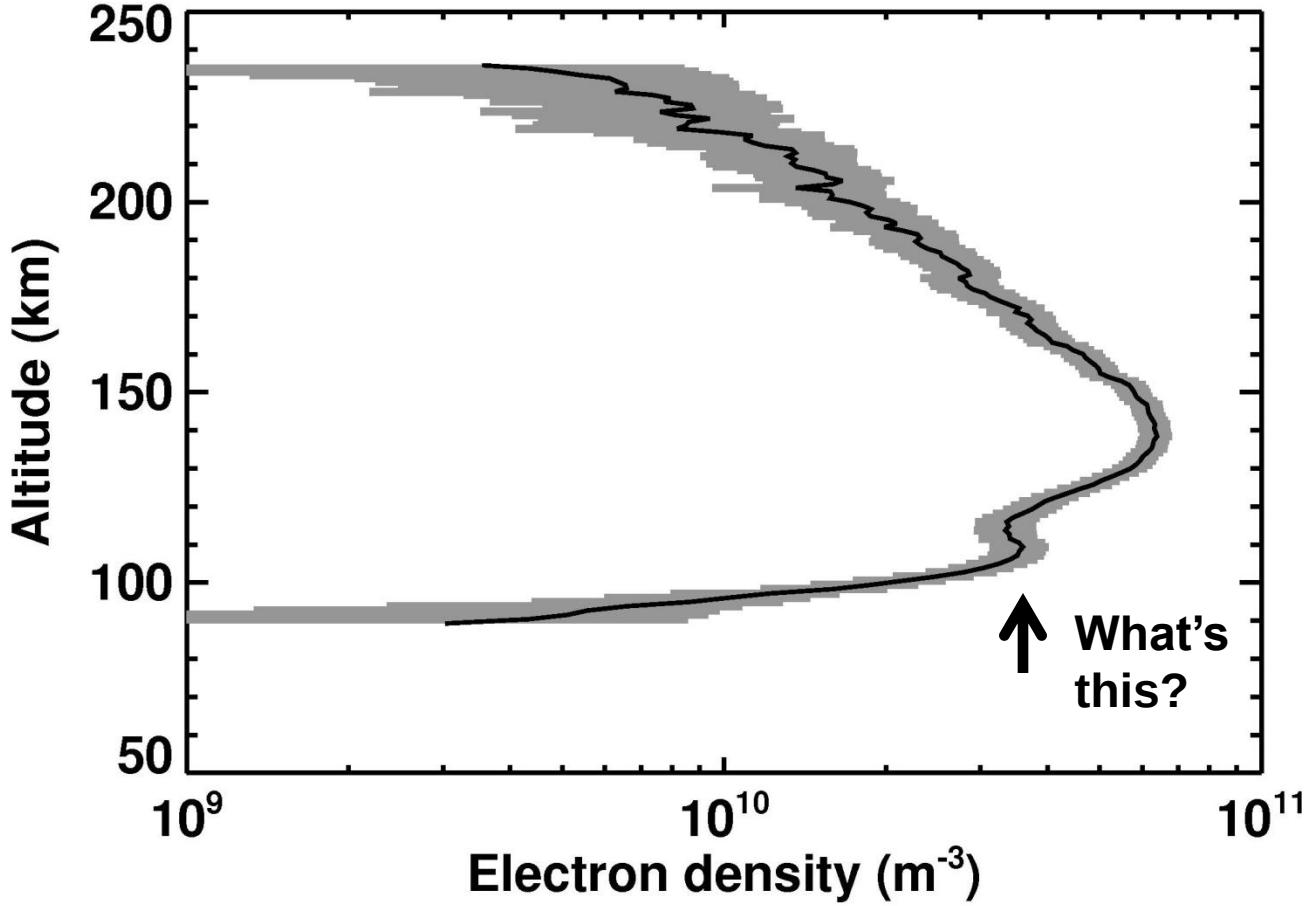


Nier et al. (1977)



Hanson et al. (1977)

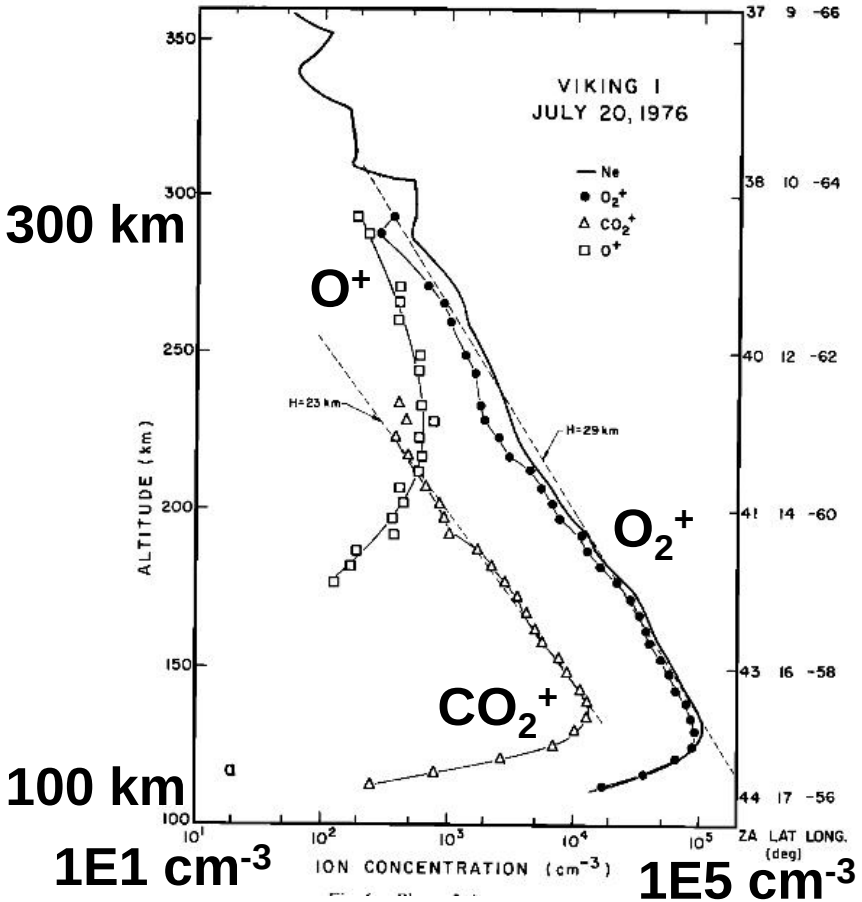
Vertical structure



Things are different at the top

- Composition
- No longer pure O_2^+

- Transport
- Density gradients always drive motion, but can be impeded by collisions with neutrals



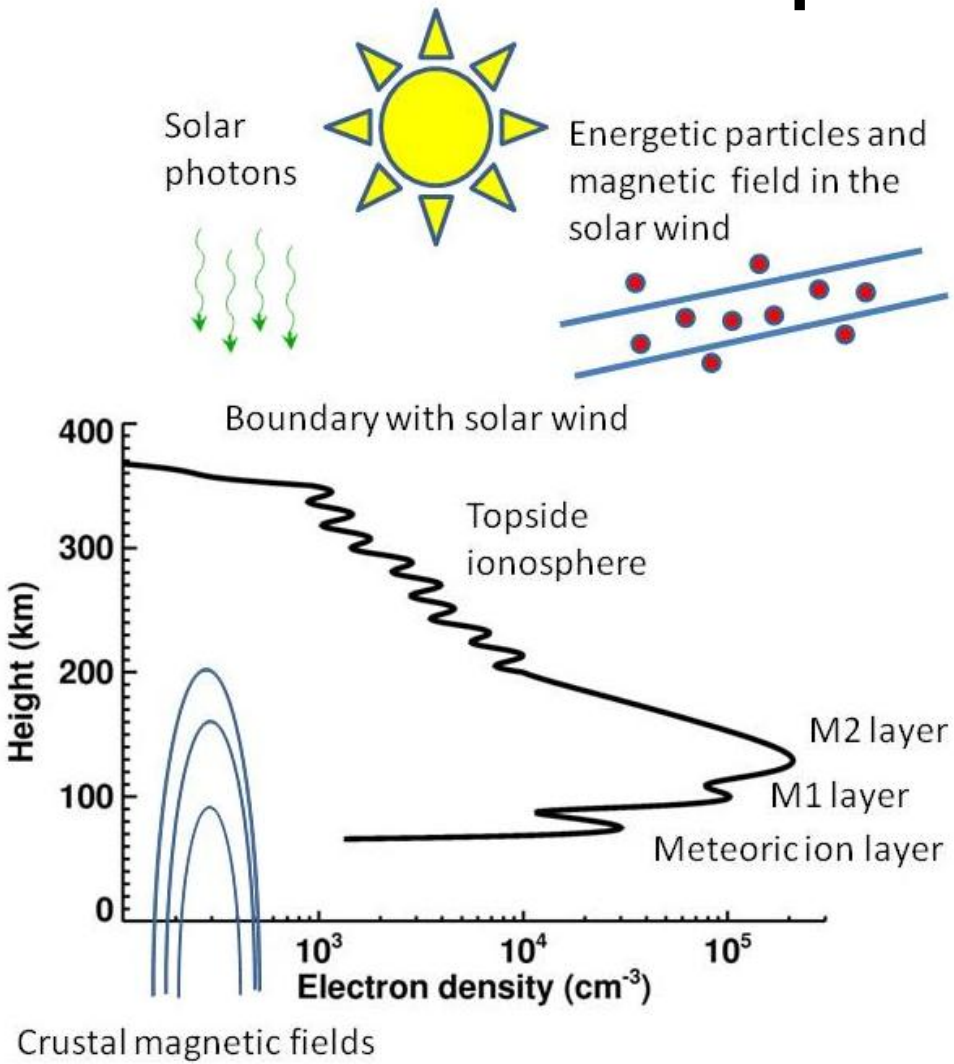
Hanson et al. (1977)

“Three wise men”

	Low altitude	High altitude
Production	X-ray solar photons (1-10 nm)	Extreme ultraviolet (EUV) solar photons (10-100 nm)
Composition	Molecular ions	Atomic ions
Transport	Negligible	Important - and can be influenced by magnetic fields

What does “low” and “high” mean in each case?

The ionosphere of Mars



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

Withers et al. (2009) Decadal Survey white paper

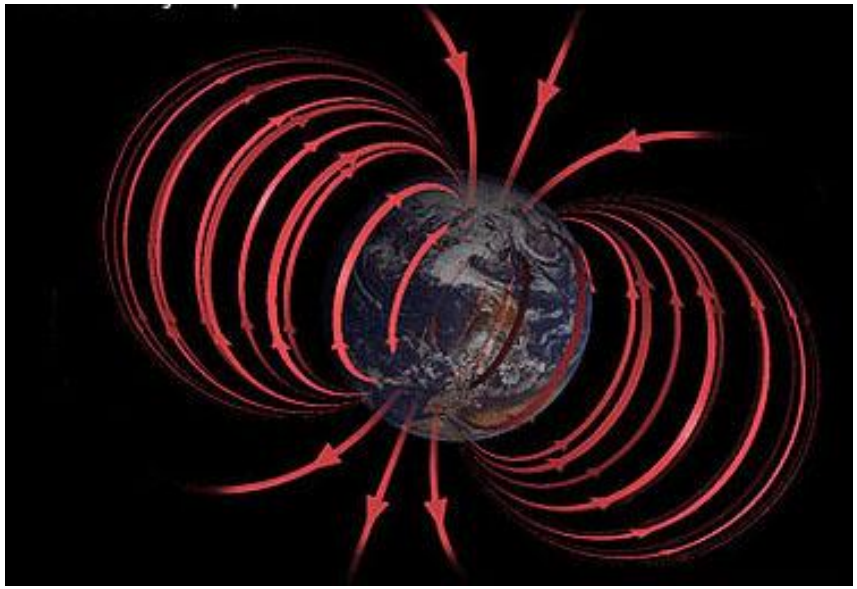
Where have we got to?

- 1978
- No useful observations from 1978 to 1998

- Next…
- Effects of magnetic fields
- Wide range of observations that don’t fit into the basic template

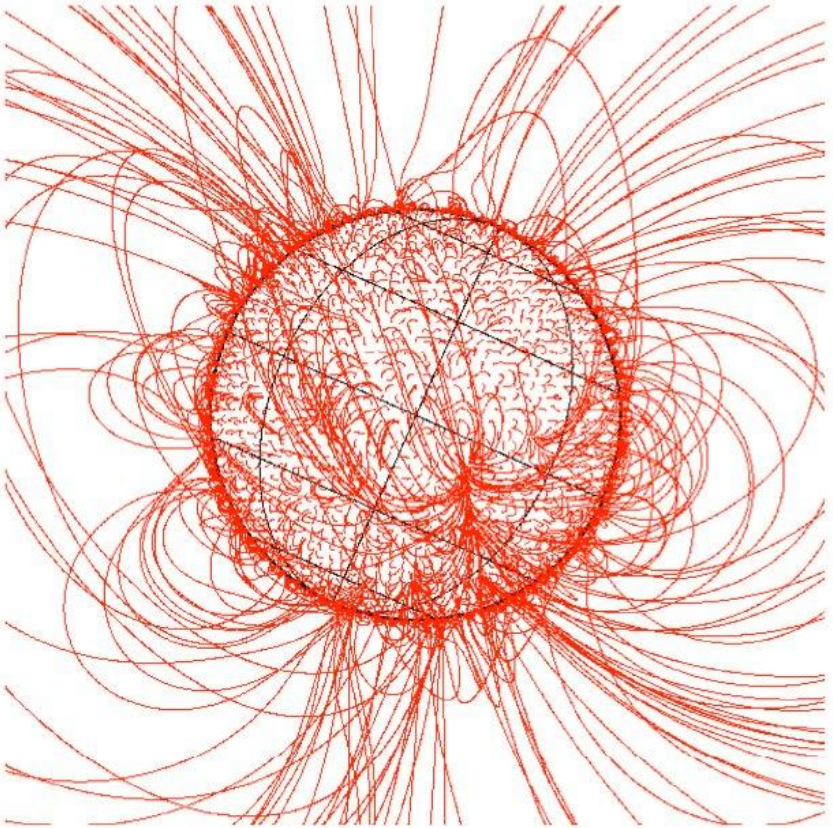
Mars is magnetically crazy

Earth magnetic field



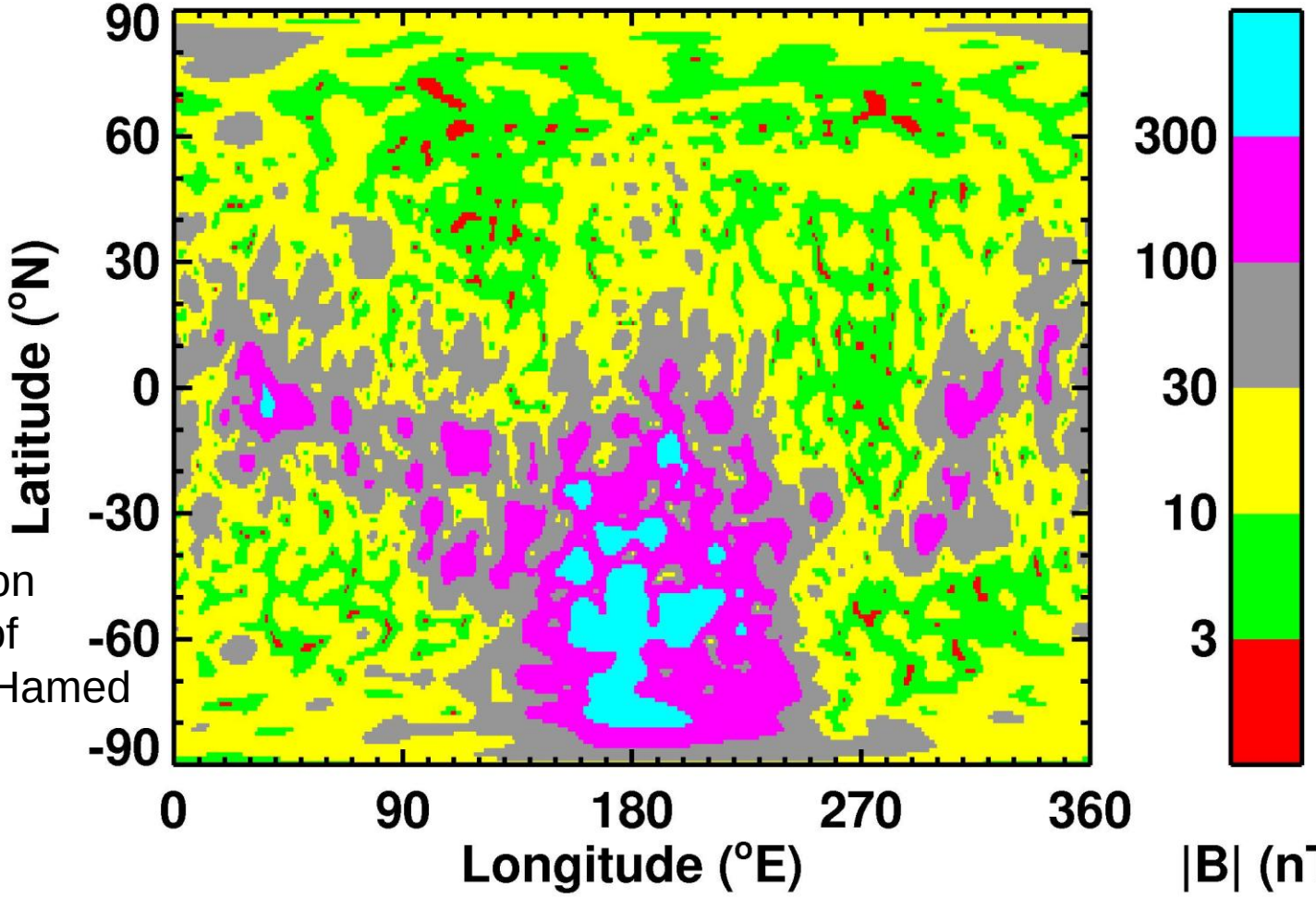
www.windows2universe.org

Mars magnetic field



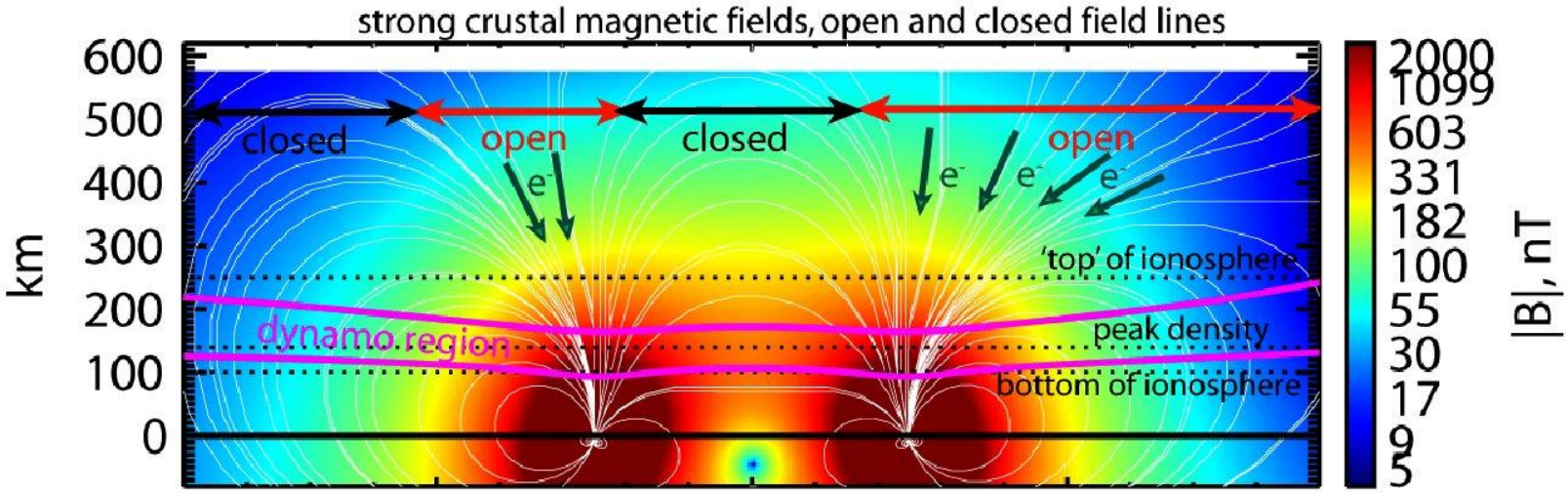
Brain (2002)

Magnetic field at Mars



Based on model of Arkani-Hamed (2004)

“Shield and sword”

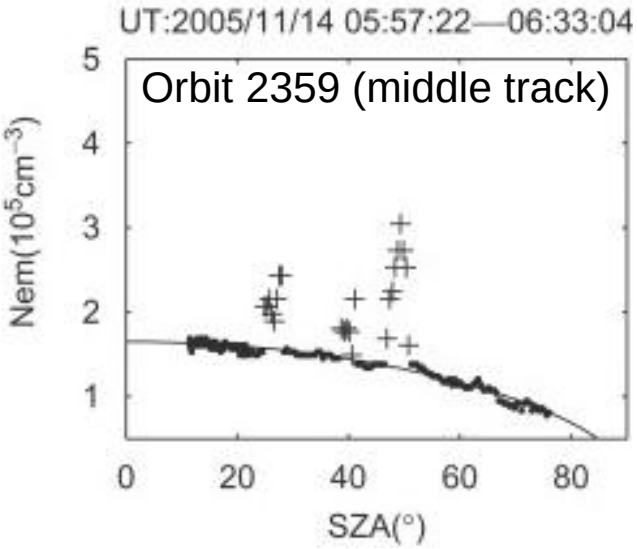


Lillis et al. (2011)

Closed field lines – Both ends anchored on planet

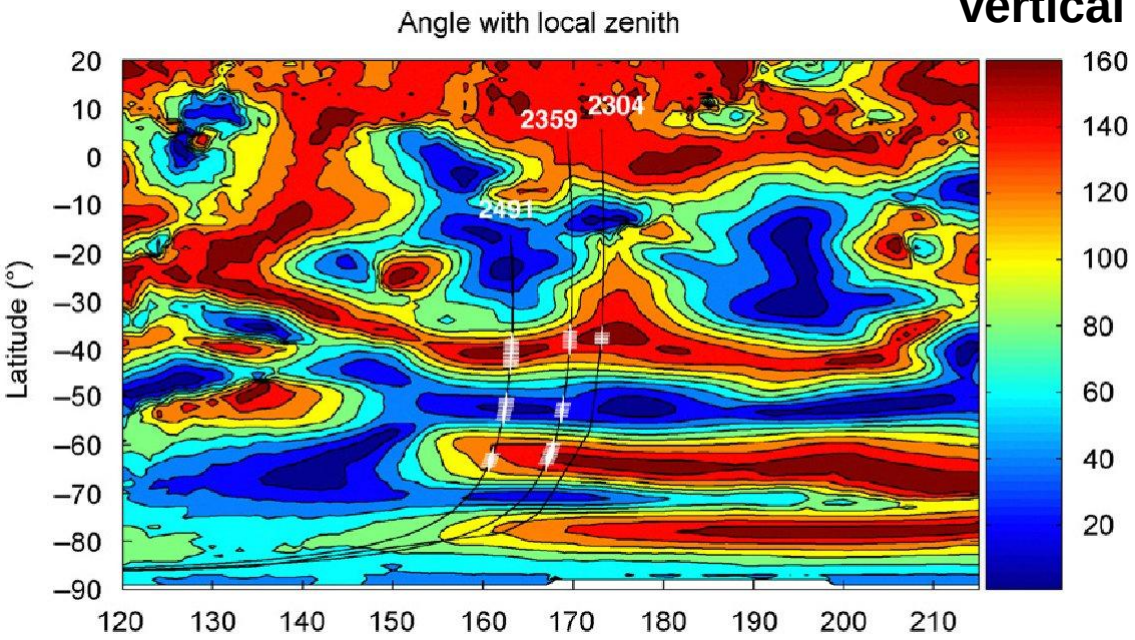
Open field lines – One end anchored on planet, other end connects with solar wind

Enhanced peak electron densities



Nielsen et al. (2007)

Angle between field and vertical

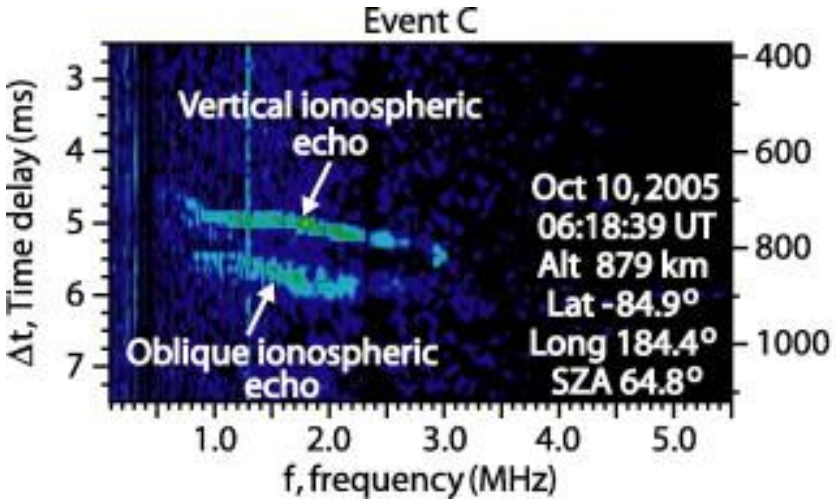


Nielsen et al. (2007)

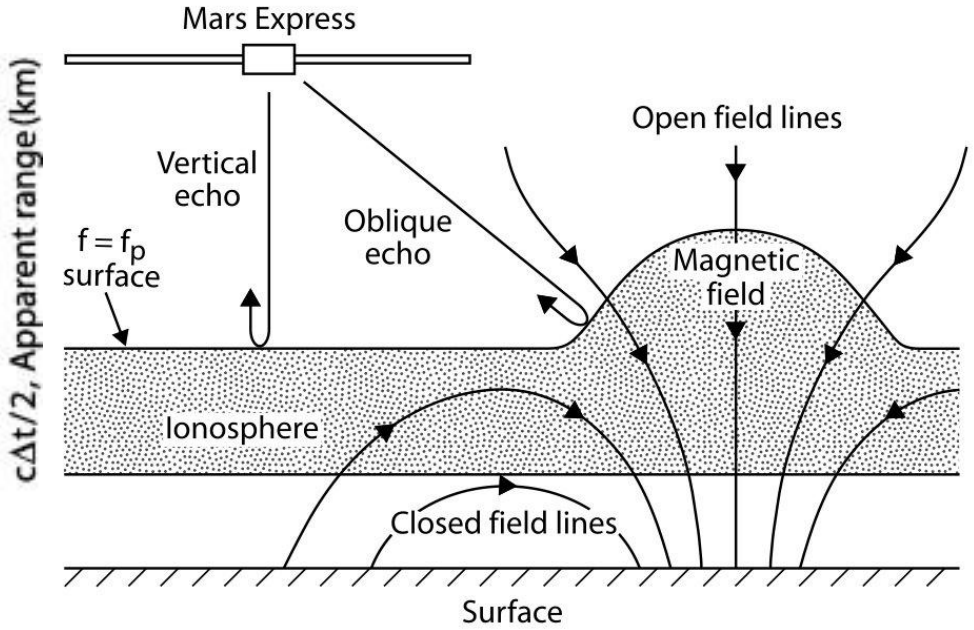
Peak electron densities MARSIS radar instrument

Enhancements seen over strong and vertical crustal magnetic fields

Higher densities at all altitudes above strong and vertical fields



Gurnett et al. (2008)



Duru et al. (2006)

N = 1E4 cm^{-3} x (f/MHz)^2
Specular echo at frequency f gives range to regions of corresponding plasma density

Extra echo must come from "iso-electron density surface" somewhere off to the side

Internal effects of **B** as well

$$m_j \frac{\partial \underline{v_j}}{\partial t} + m_j \left(\underline{v_j} \cdot \underline{\nabla} \right) \underline{v_j} = m_j \underline{g} - \frac{1}{N_j} \underline{\nabla} \left(N_j k T_j \right)$$

Gravity and pressure gradients

$$+ q_j \underline{E} + q_j \underline{v_j} \times \underline{B}$$

Electric and magnetic fields

$$- m_j \nu_{jn} \left(\underline{v_j} - \underline{u} \right)$$

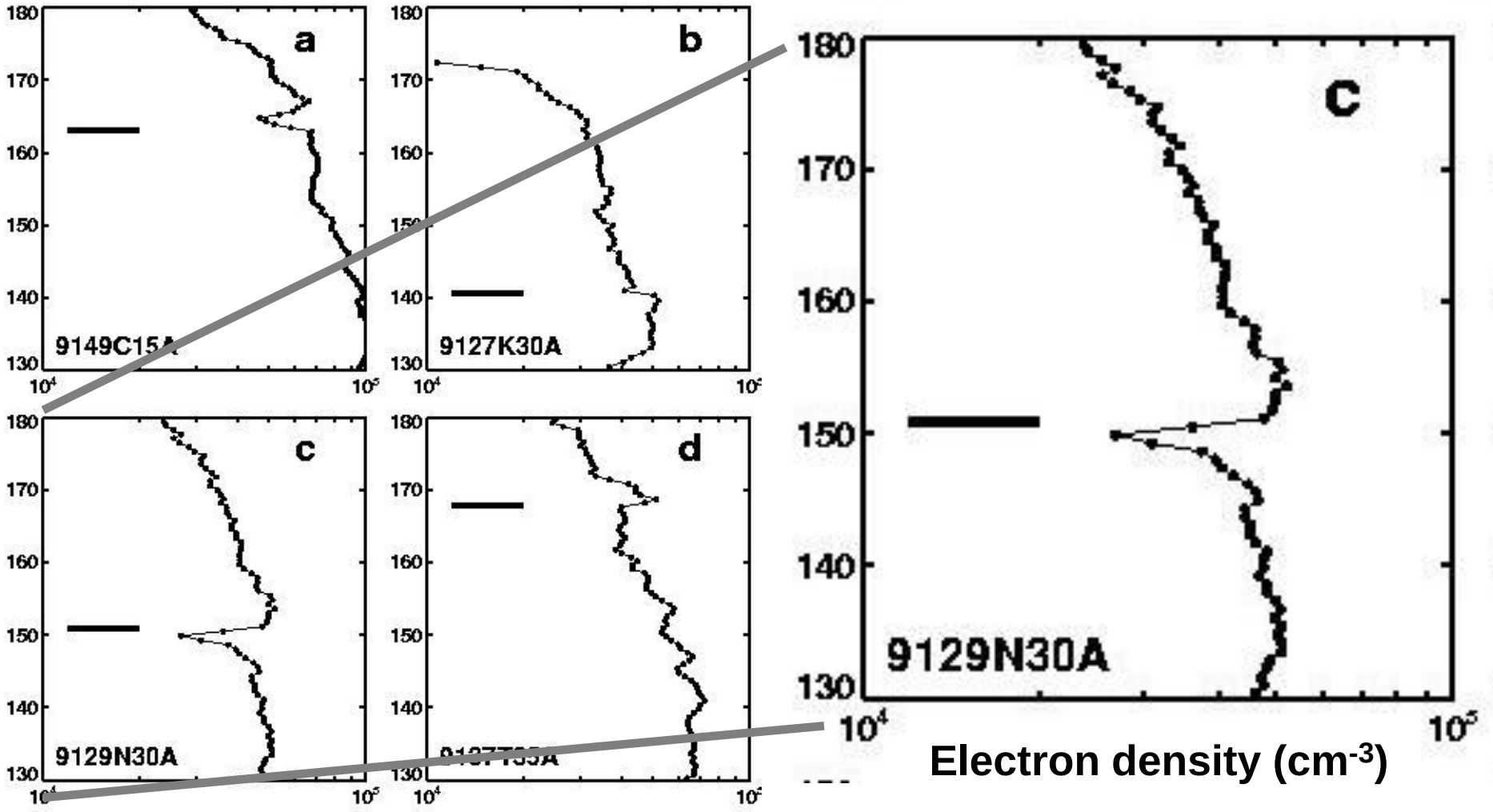
Ion-neutral collisions

$$\kappa_j = \frac{q_j B}{m_j \nu_{jn}}$$

This is a critical ratio – defines “strong” or “weak” field

Ion gyrofrequency to ion-neutral collision frequency

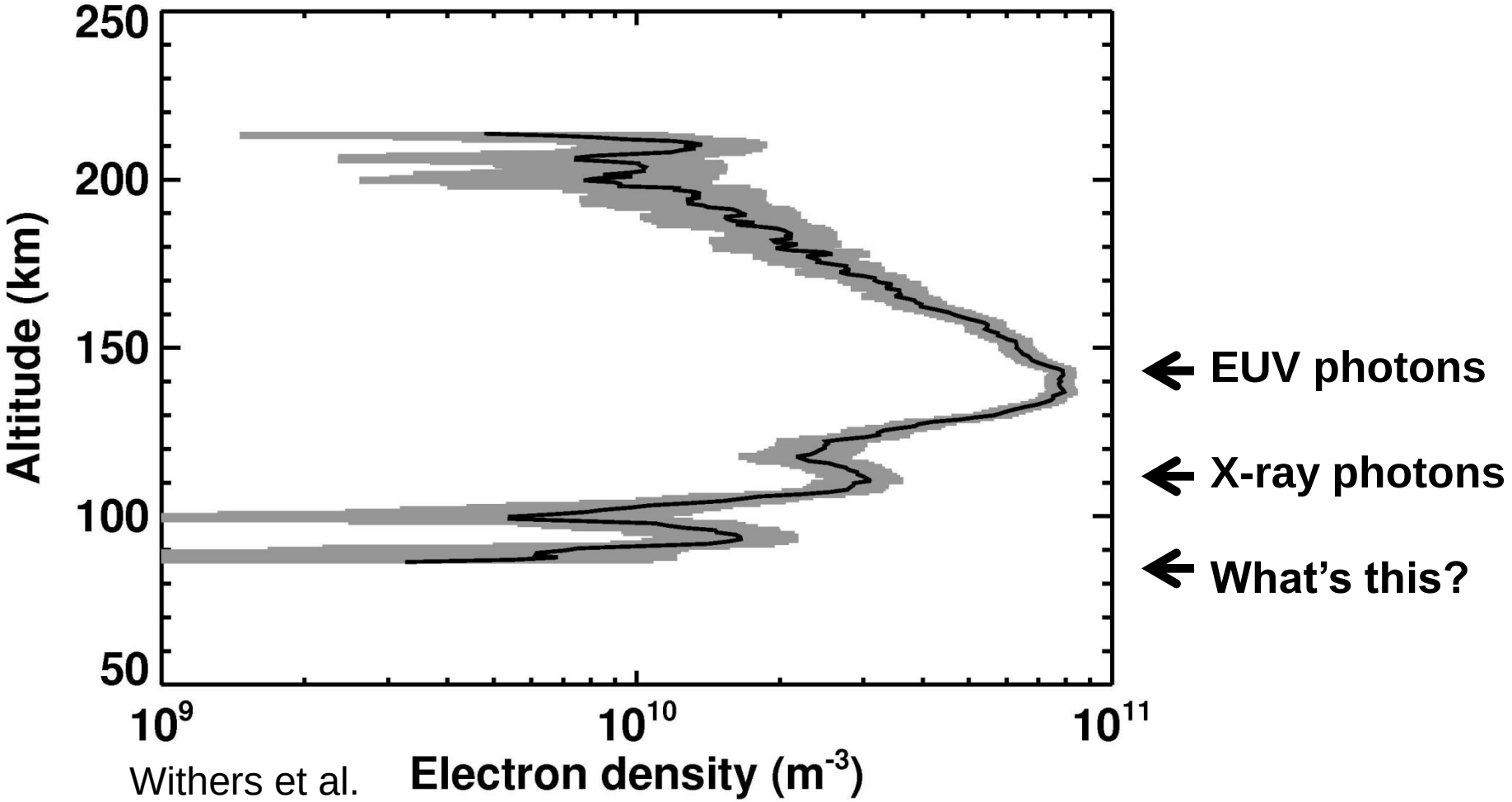
Localized variations as well



Withers et al. (2005)

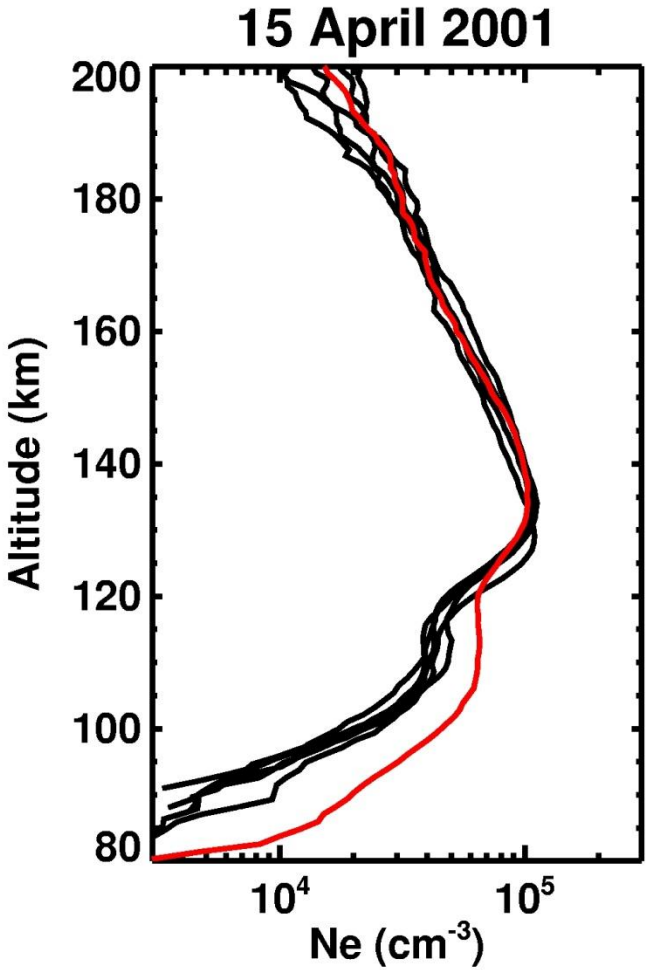
Menagerie of oddities not connected with magnetic fields

At the bottom



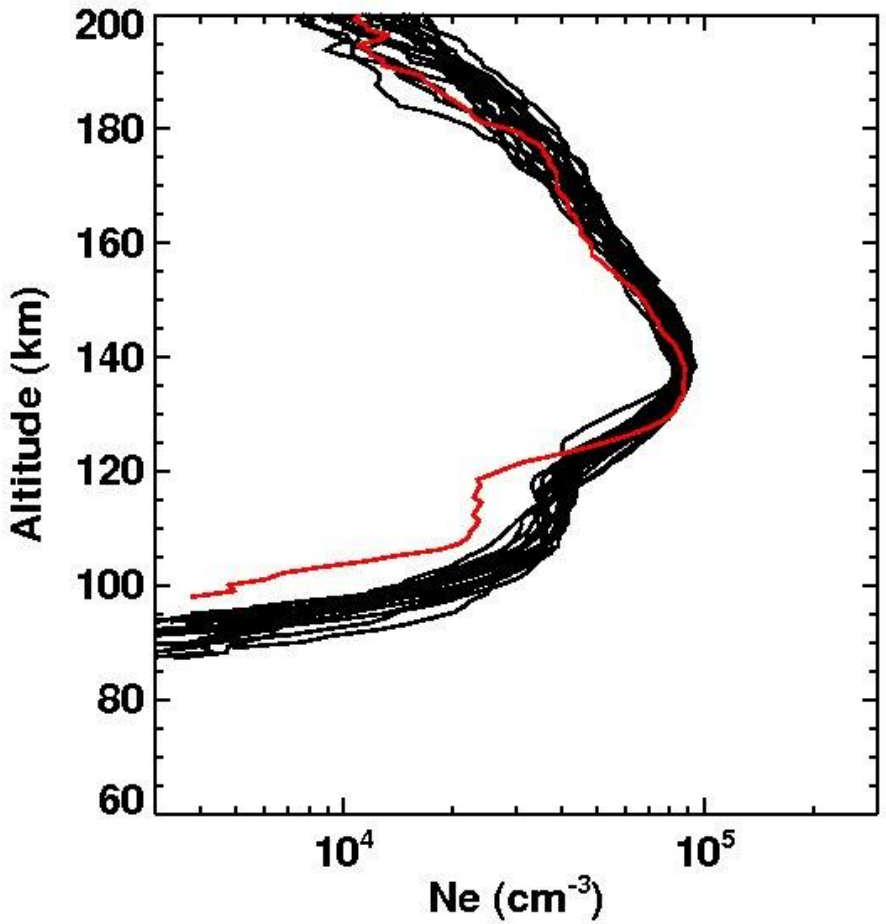
Withers et al. (2008)

At the X-ray-produced layer



Mendillo et al. (2006)

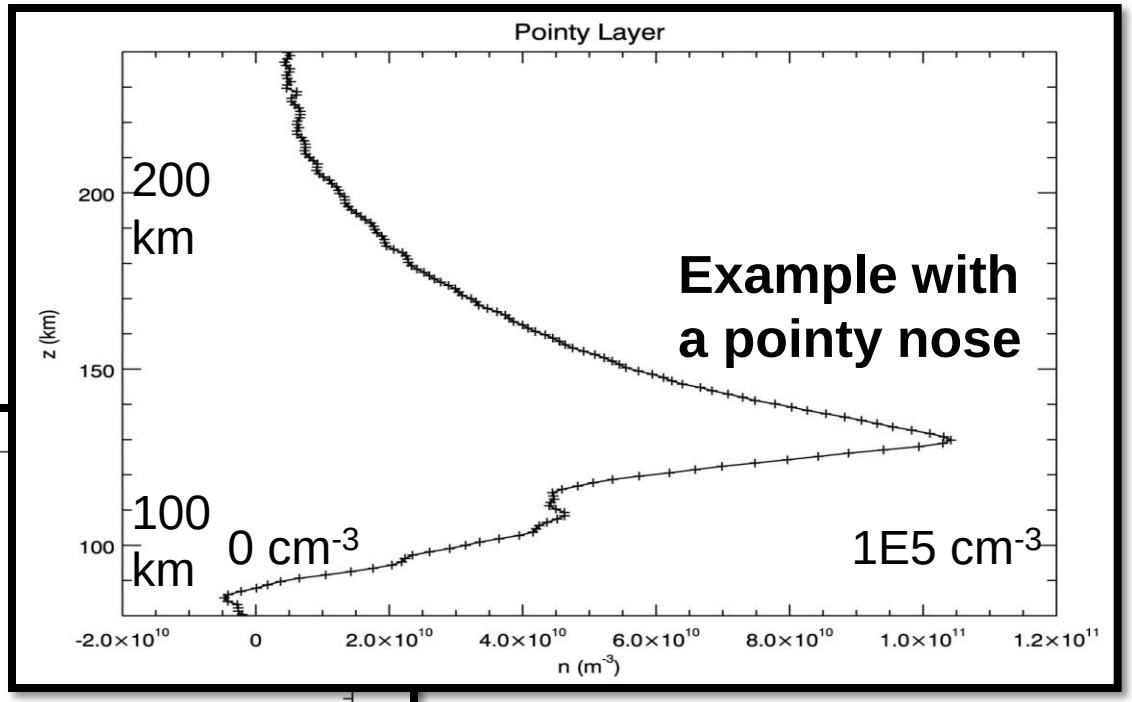
One case of large electron densities



Withers (2009)

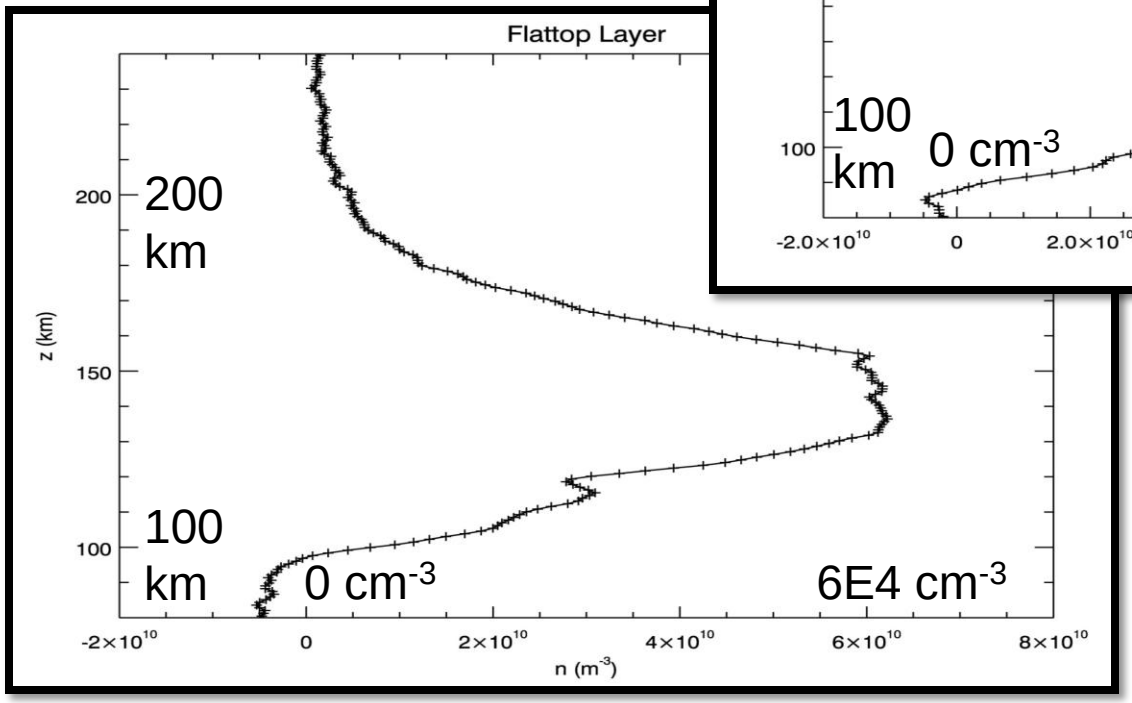
One case of small electron densities

At the EUV-produced layer



Example with a pointy nose

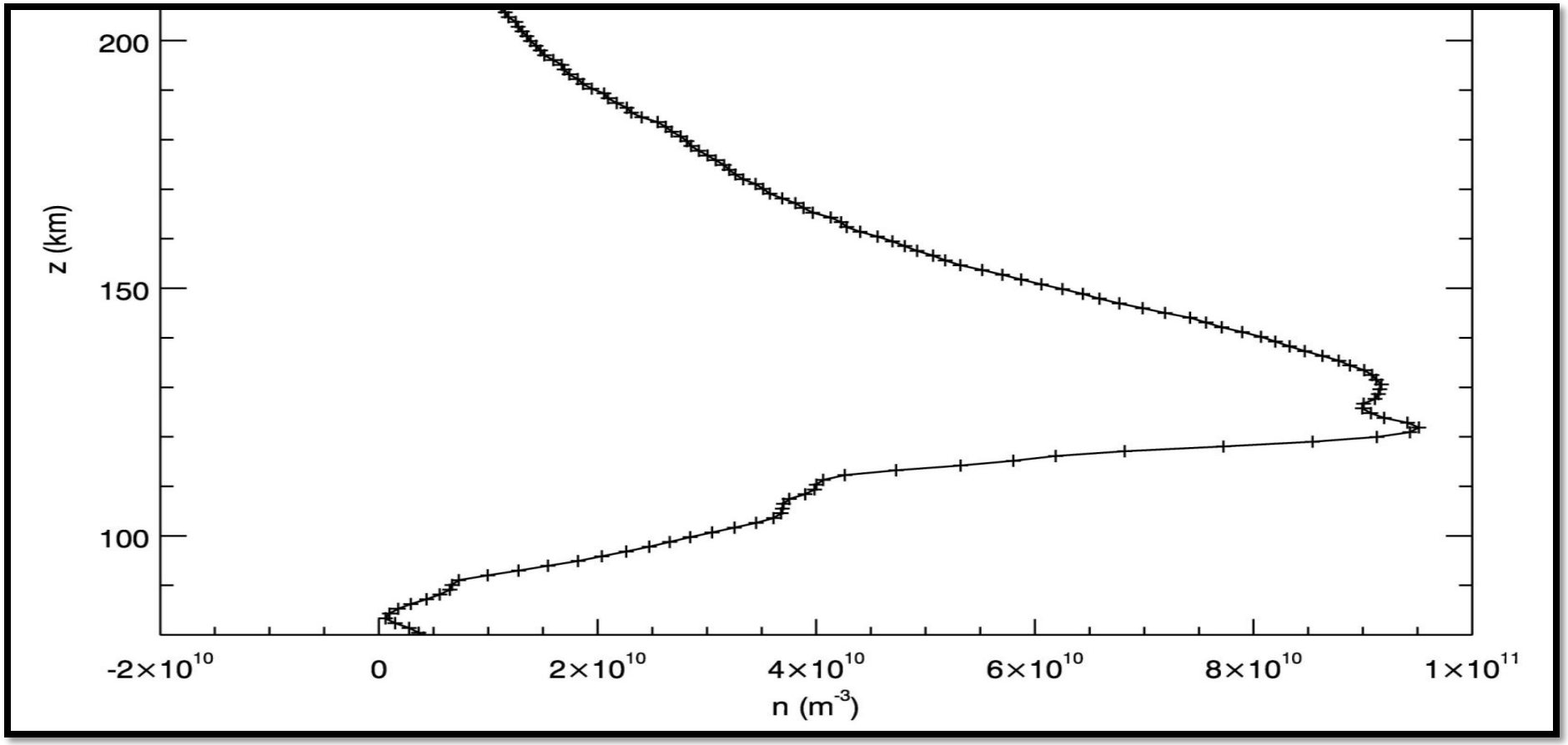
Example with a flat nose



Noses are usually smooth curves

Shape and width are meaningful

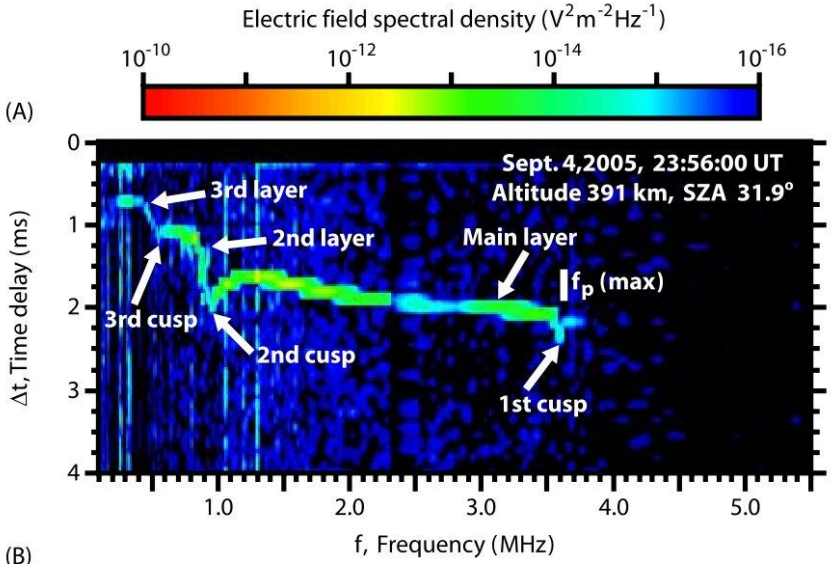
Wiggles as well



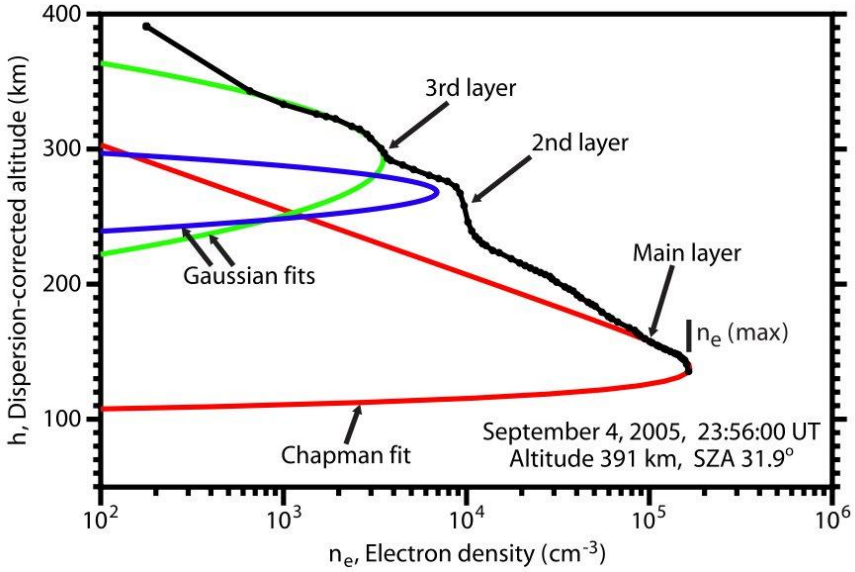
Wiggles are suggestive of plasma motion

But transport should be negligible at these low altitudes

Higher altitude layers



Kopf et al. (2008)



Kopf et al. (2008)

Each observed cusp (dip) means a local maximum in plasma density

Other observations also show deviations from "typical" shape of upper ionosphere

This derived profile has some inherent flaws, is forced to assume a smooth shape

How does the ionosphere of Mars work?

- Mars used to have a nice, simple ionosphere
- Unique magnetic fields have two effects
  - Exclude and enhance impact of the solar wind
  - Influence bulk motion and small-scale instabilities
- Many recent observations show limitations of current understanding
- MAVEN mission (2013) will reveal chemistry, dynamics, and energetics