

COMPARATIVE AERONOMY

--- Thermospheres & Ionospheres
in the Solar System ---

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Boston University

CEDAR Meeting --- 2006

CONCLUSION

IUGG REPORT: (Nagy et al., 1995):

“The very basic processes such as ionization, chemical transformations and diffusive as well as convective transport are analogous in all ionospheres;

The major differences are the result of factors such as different neutral atmospheres, intrinsic magnetic field strength, distance from Sun, etc.

Improving our understanding of any of the ionospheres in our solar system helps in elucidating the controlling physical and chemical processes in all of them.”

Thermospheres + Ionospheres in the Solar System

● Common Transmitter = **SUNLIGHT**

Impulsive
- Flares

Regular

Diurnal
- LT effects

Solar-Rotational
- Monthly effects

Long Term
- Solar-Cycle effects

● Other Common Transmitters = **PARTICLES**

Meteors
- Episodic

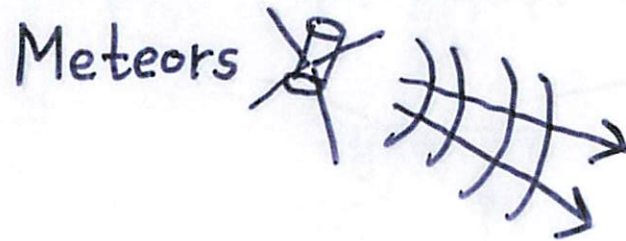
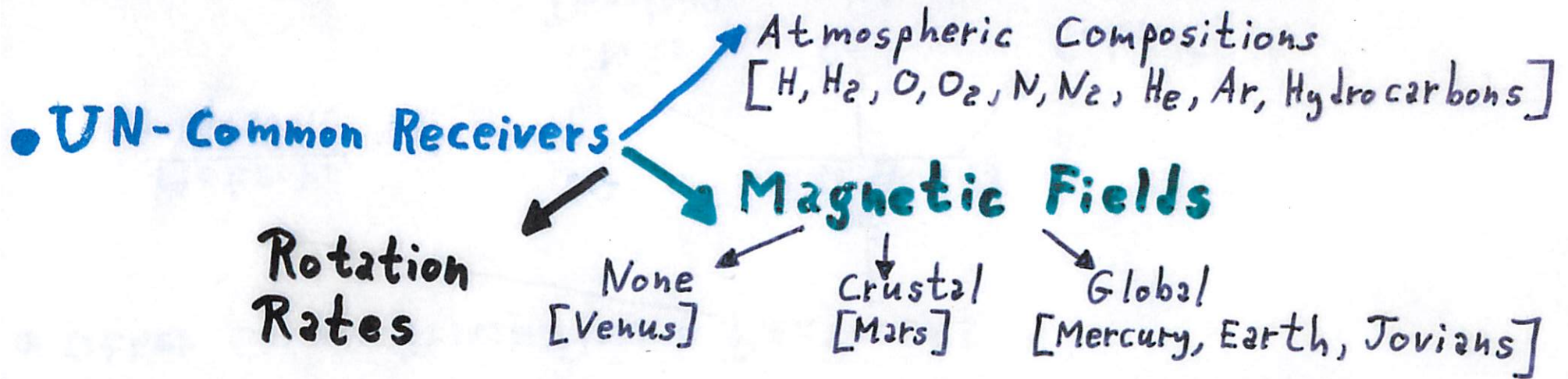
Solar Wind

CMEs
- Impulsive

Sectors
- Weekly
- Monthly

Solar Cycle
- Decadal

Thermospheres + Ionospheres in the Solar System

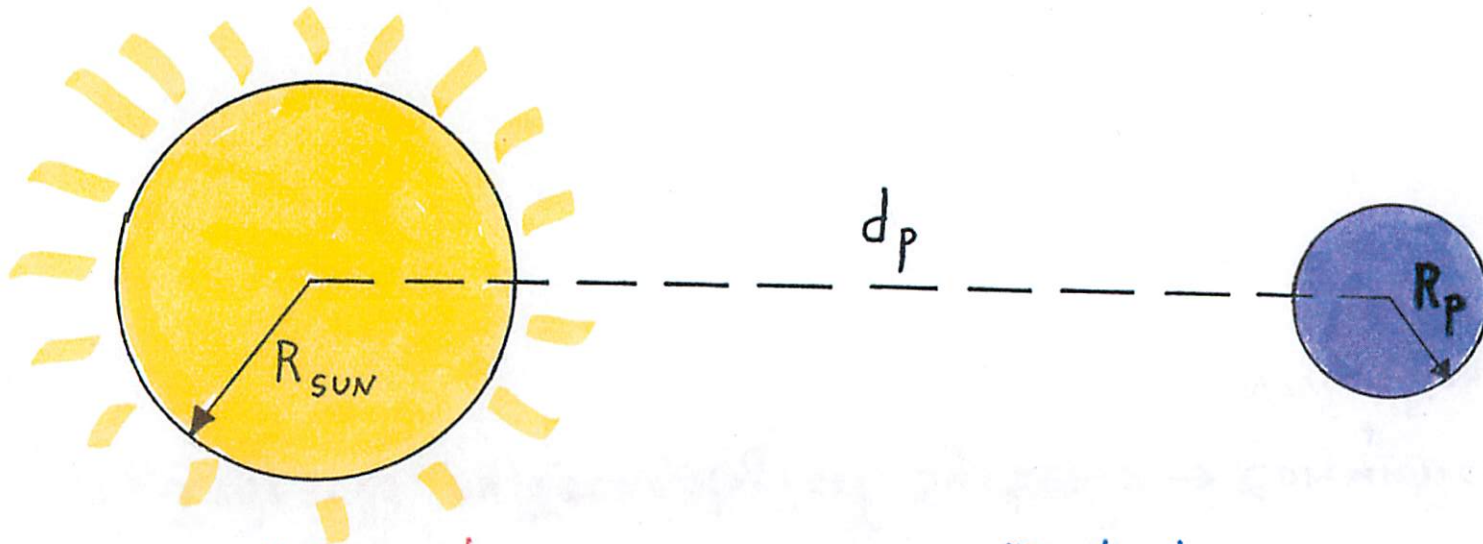


Thermospheres + Ionospheres in the Solar System

• COMMON PROCESSES

- Photochemistry
 - Neutral Atmosphere ✓
 - Ionosphere ✓
- Meteoritic Layers
- Magnetosphere - Ionosphere Coupling
 - Aurora
 - Joule + Partical Heating
 - Plasmasphere ✓
- Solar Wind - Ionosphere Coupling
- Coupling from Below
 - Tides
 - Waves
- Impacts on Technological Systems → Communications + Navigation ✓

TEMPERATURE OF A PLANET WITHOUT AN ATMOSPHERE



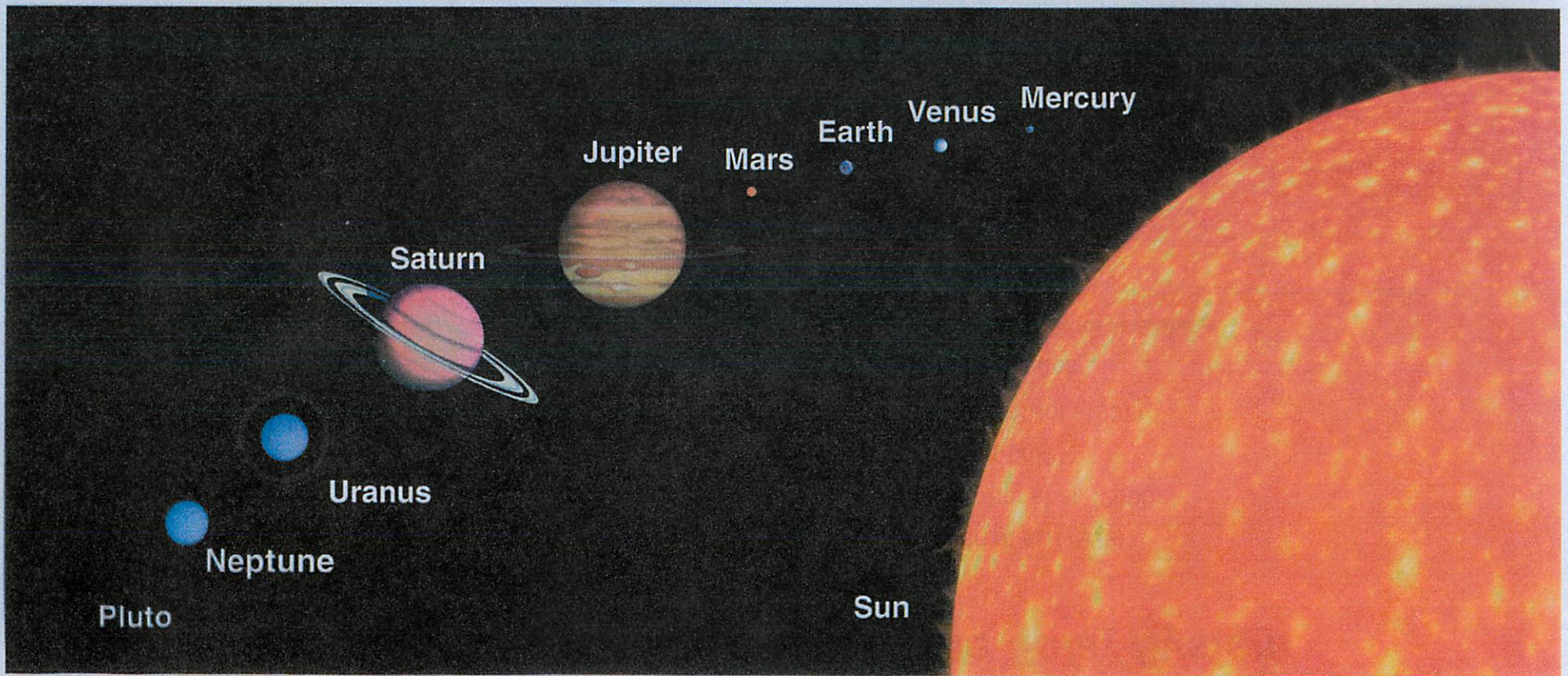
Absorption = Radiation

$$\sigma T_{\text{SUN}}^4 \left(\frac{R_{\text{SUN}}}{d_p} \right)^2 \pi R_p^2 [1-A] = 4\pi R_p^2 \sigma T_p^4$$

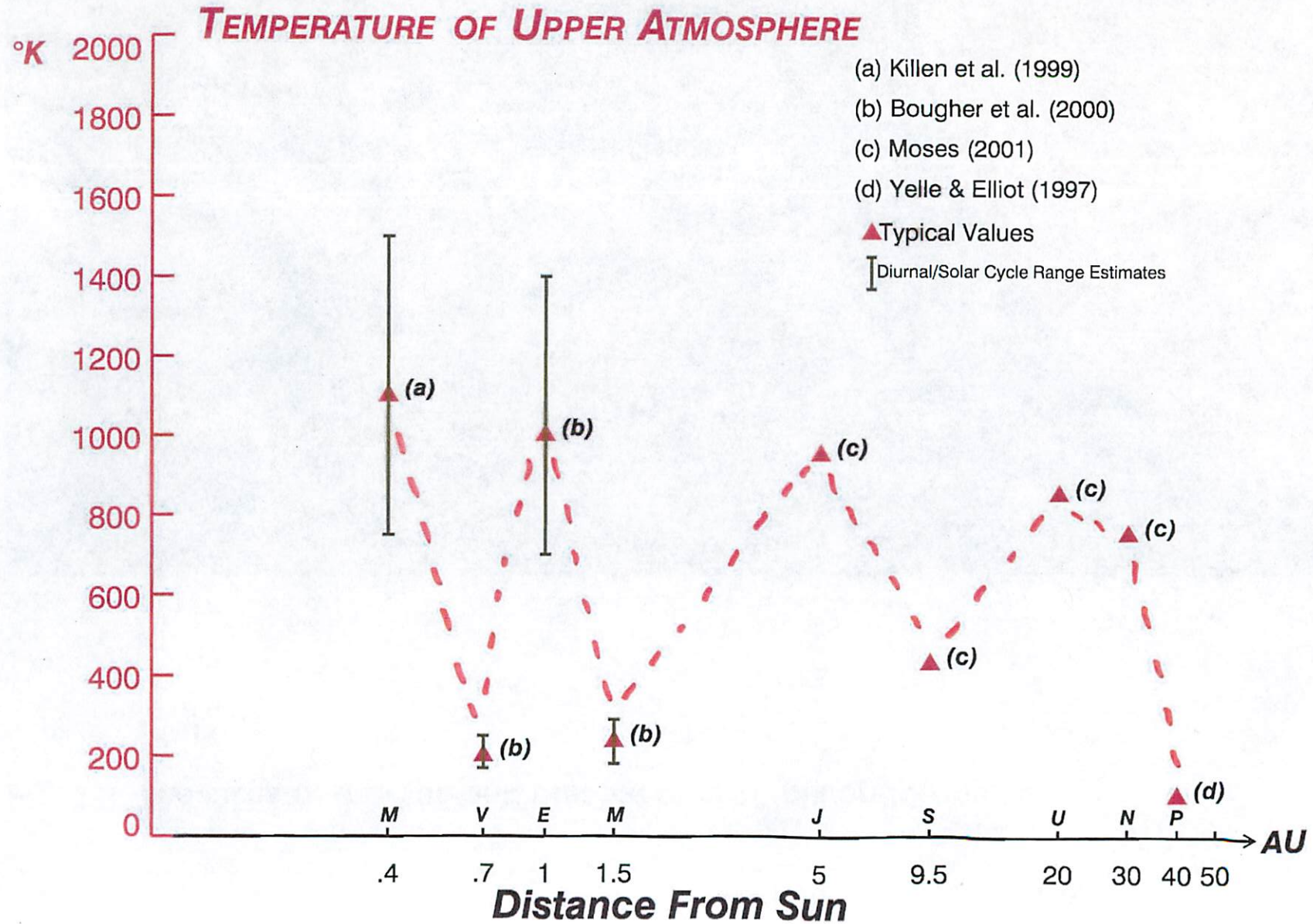
$$T_p \approx \frac{250^\circ\text{K}}{\sqrt{d_p (\text{AU})}}$$

(for constant Albedo, A)

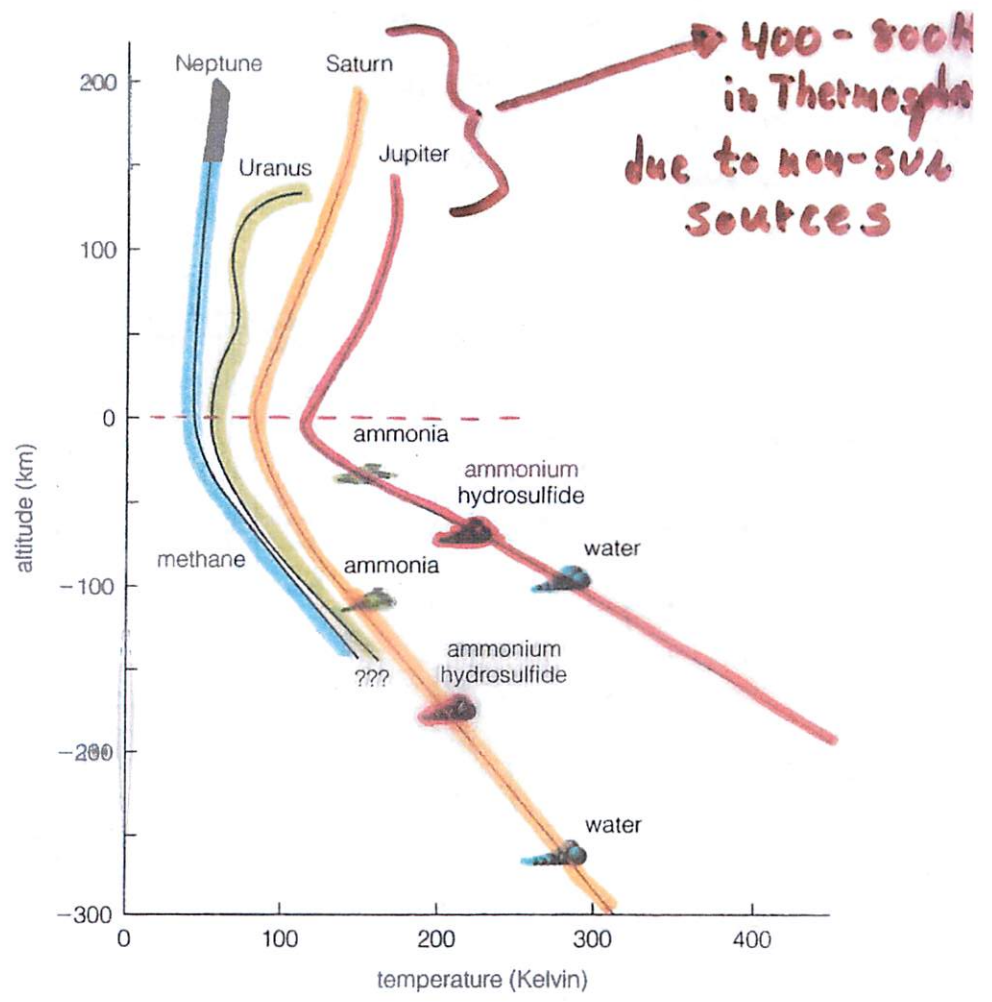
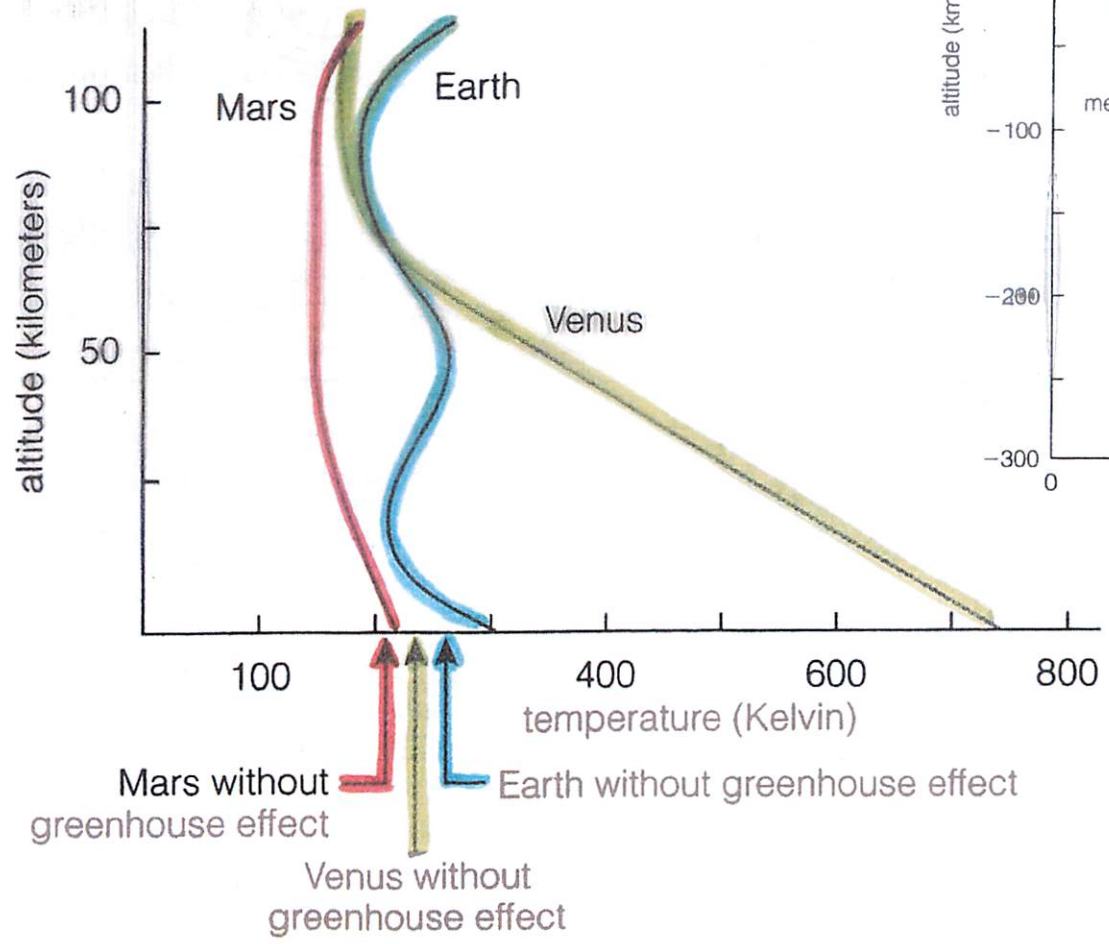
Fig. 1.6 The sizes of the Sun and planets on a 10-billion-to-one scale.



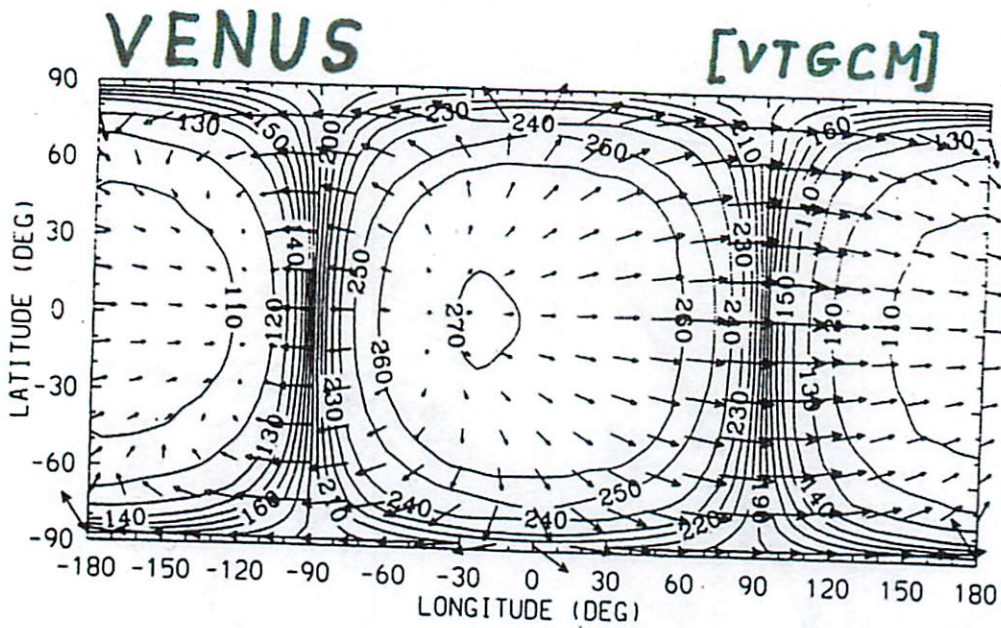
Neutral Atmosphere Characteristics in the Solar System



GREENHOUSE EFFECTS ON TERRESTRIAL PLANETS



JOVIAN PLANETS



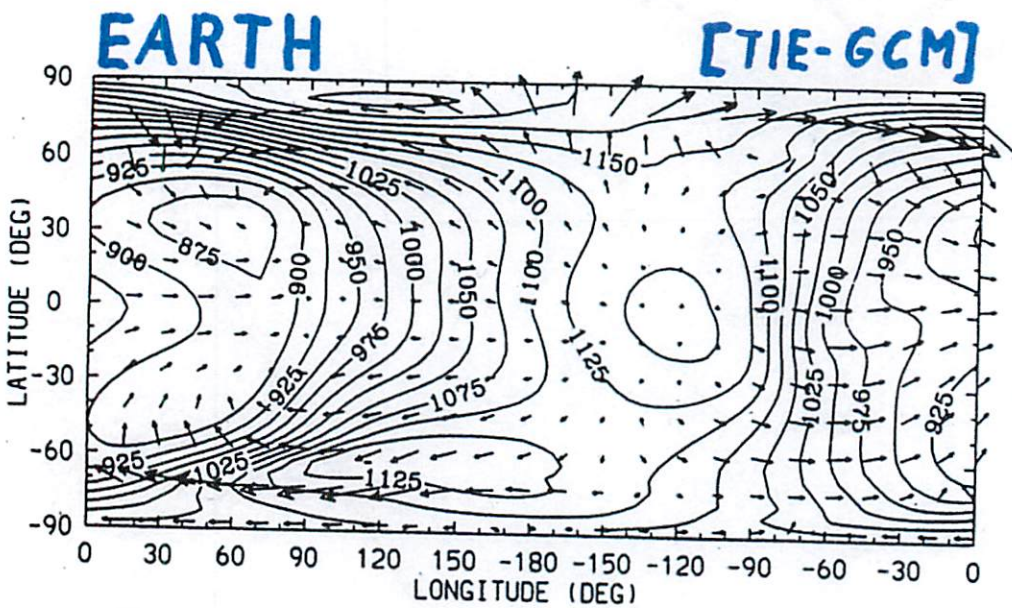
Exobase
Parameters for
Solar Median
Condition.

$Z = 7$
($\bar{h} \approx 170 \text{ km}$)

$T_{\min} \approx 110^\circ \text{K}$

$T_{\max} \approx 270^\circ \text{K}$

$\rightarrow = 240 \text{ m/s}$

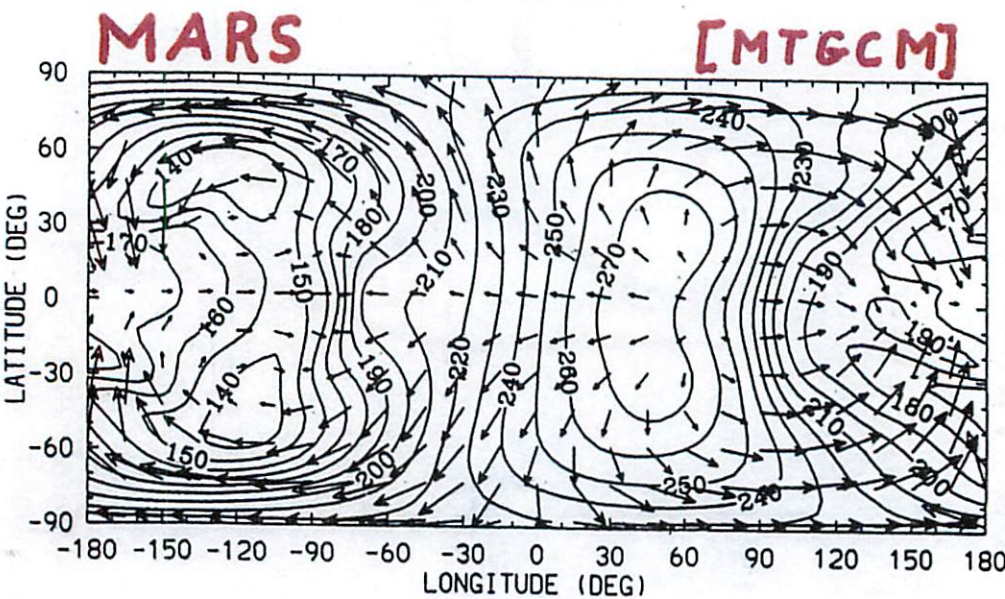


$Z = 7$
($\bar{h} \approx 550 \text{ km}$)

$T_{\min} \approx 865^\circ \text{K}$

$T_{\max} \approx 1150^\circ \text{K}$

$\rightarrow = 460 \text{ m/s}$



$Z = 6$
($\bar{h} \approx 195 \text{ km}$)

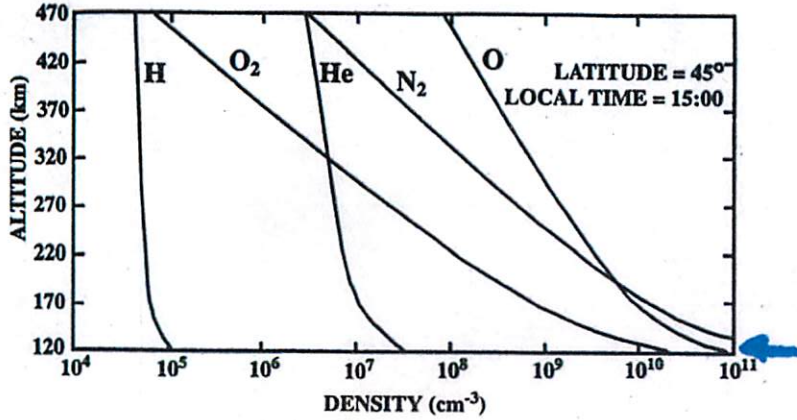
$T_{\min} \approx 135^\circ \text{K}$

$T_{\max} \approx 275^\circ \text{K}$

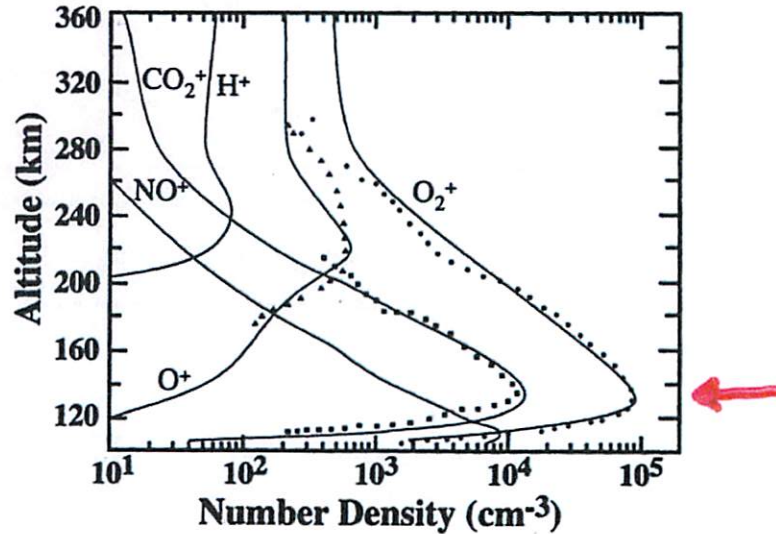
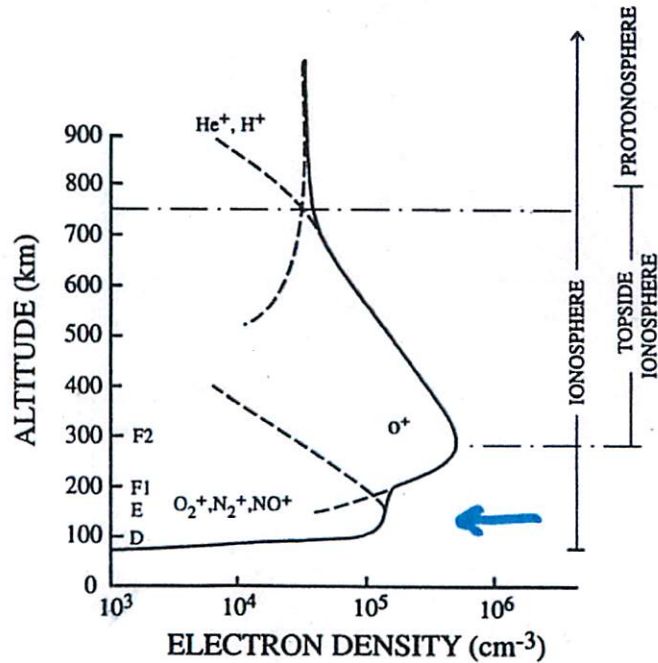
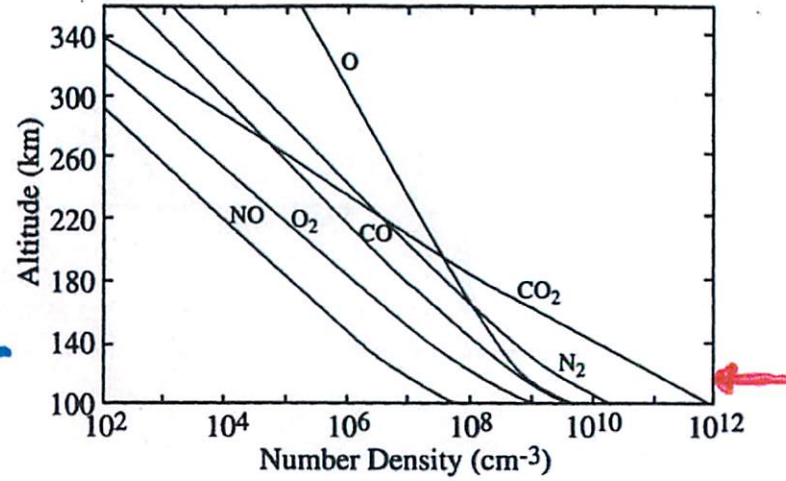
$\rightarrow = 260 \text{ m/s}$

COMPARATIVE ATMOSPHERES/IONOSPHERES

EARTH



MARS



E-Region

$h_m E \approx 110 \text{ km}$

$[N_2] \approx \text{few} \times 10^{11} \text{ cm}^{-3}$

$[e^-] \approx 10^5 \text{ cm}^{-3}$

Maximum

$h_m \approx 135 \text{ km}$

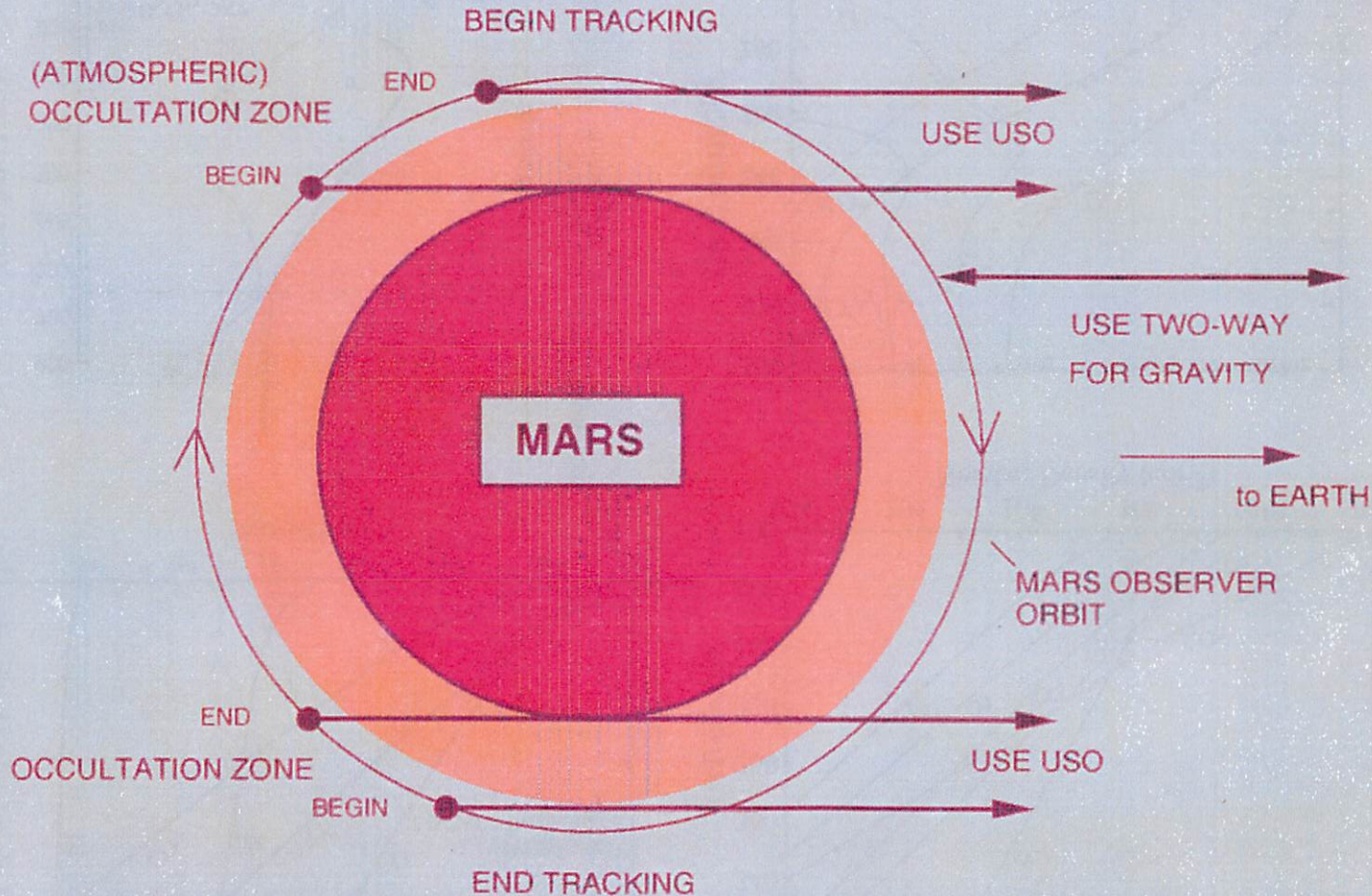
$[CO_2] \approx 10^{11} \text{ cm}^{-3}$

$[e^-] \approx 10^5 \text{ cm}^{-3}$

MARS Global Surveyor Radio Occultations

MGS Radio Science

Observational Strategy

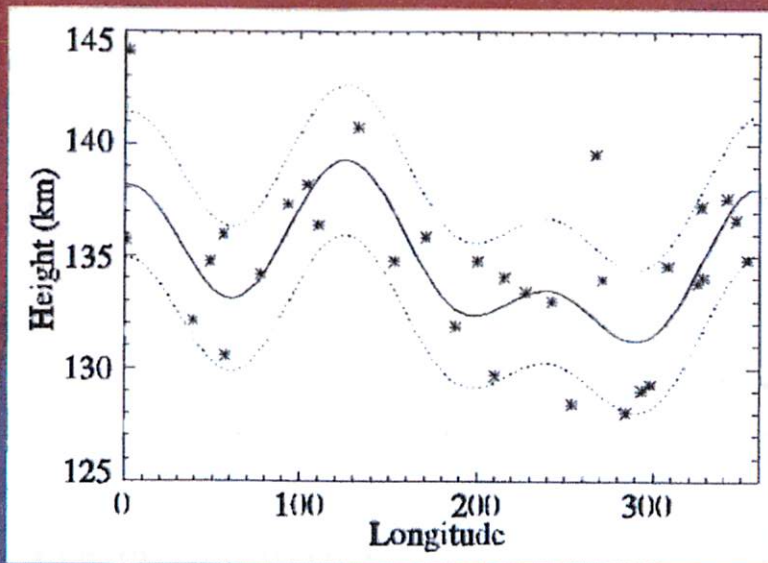


-from D. Hinson (Stanford U.)

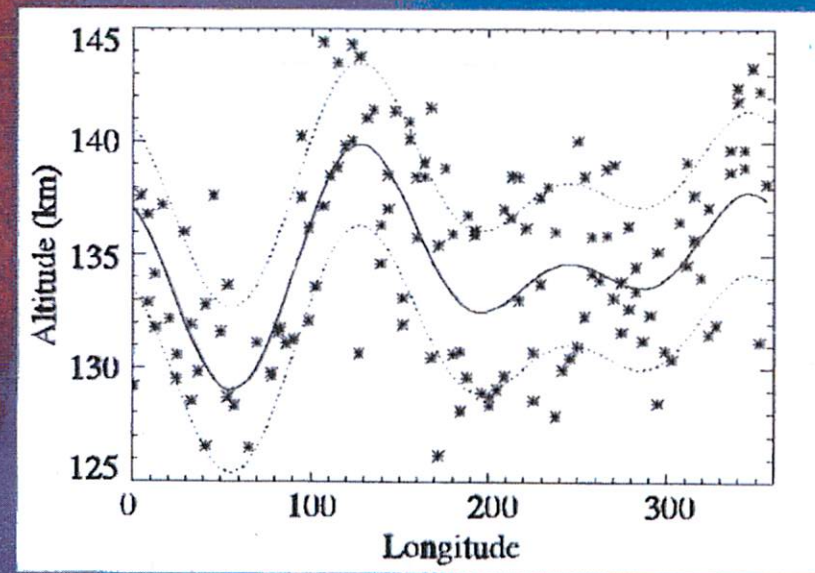
MARS IONOSPHERE: COUPLING FROM BELOW



--Systematic variations between the height of maximum electron density ($h_m M2$) with longitude



MGS: 24-31 December 1998
Bougher et al. (2001)



9-21 December 2000
Bougher et al. (2004)

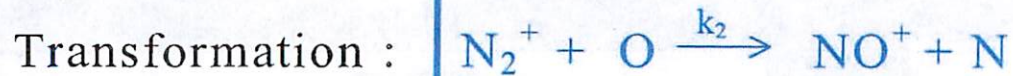
Interpretation: Tidal wave number components 2 and 3 related to Martian topography \longrightarrow longitudinally dependent thermospheric motions \longrightarrow ionospheric photochemistry at unit optical depth \longrightarrow longitude-dependent $h_m M2$ (and not $N_m M2$).

-See J. Forbes' Nicolet Lecture: AGU Website

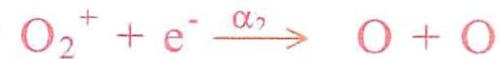
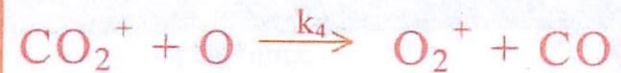
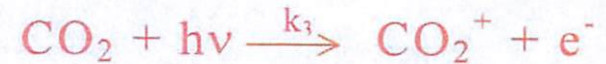
— Molecular Ion Plasmas —

Photo-Chemical Equilibrium

EARTH



MARS



For $P_o = L$:

$$P_o = \alpha N_e^2$$

With $P_o \equiv$ Production of overhead Sun = $f(\text{EUV/x-rays}) \approx f'(E10.7)$

active regions (27-day) +
solar cycle dependence

In general, with $\chi \equiv$ Solar zenith angle

Latitude + Local Time dependence
 $\cos \chi$ or $Ch^{-1}(R_p, H, \chi)$

$$N_e = \sqrt{\frac{P_o [f'(E10.7)] \cos \chi}{\alpha}}$$

IONOSPHERES WITH MOLECULAR IONS ARE Chapmanesque!

Production rate: $Q = \Phi_{\text{sun}}(\lambda) \cdot \sigma_{\text{ion}}(\lambda) m(X_2)$

Loss rate: $L = \alpha N_e^2$

--- For Photo-Chemical-Equilibrium, $Q \approx L$

$$N_e^2 = \frac{\Phi_{\text{sun}} \sigma_{\text{ion}} m(X_2)}{\alpha}$$

[for same/similar molecules, $N_{\text{max}}(h_{\text{max}})$ occurs at Q_{max} ,
where $\gamma \approx 1$, effectively where $m(X_2) \approx 10^{21}/\text{cm}^3$]

Two Chapman "Scaling Laws":

(a) For planets at distances (d_p),
only solar flux varies with d_p ,

$$\therefore N_{\text{max}}^2 \propto \frac{\text{constants}}{d_p^2}$$

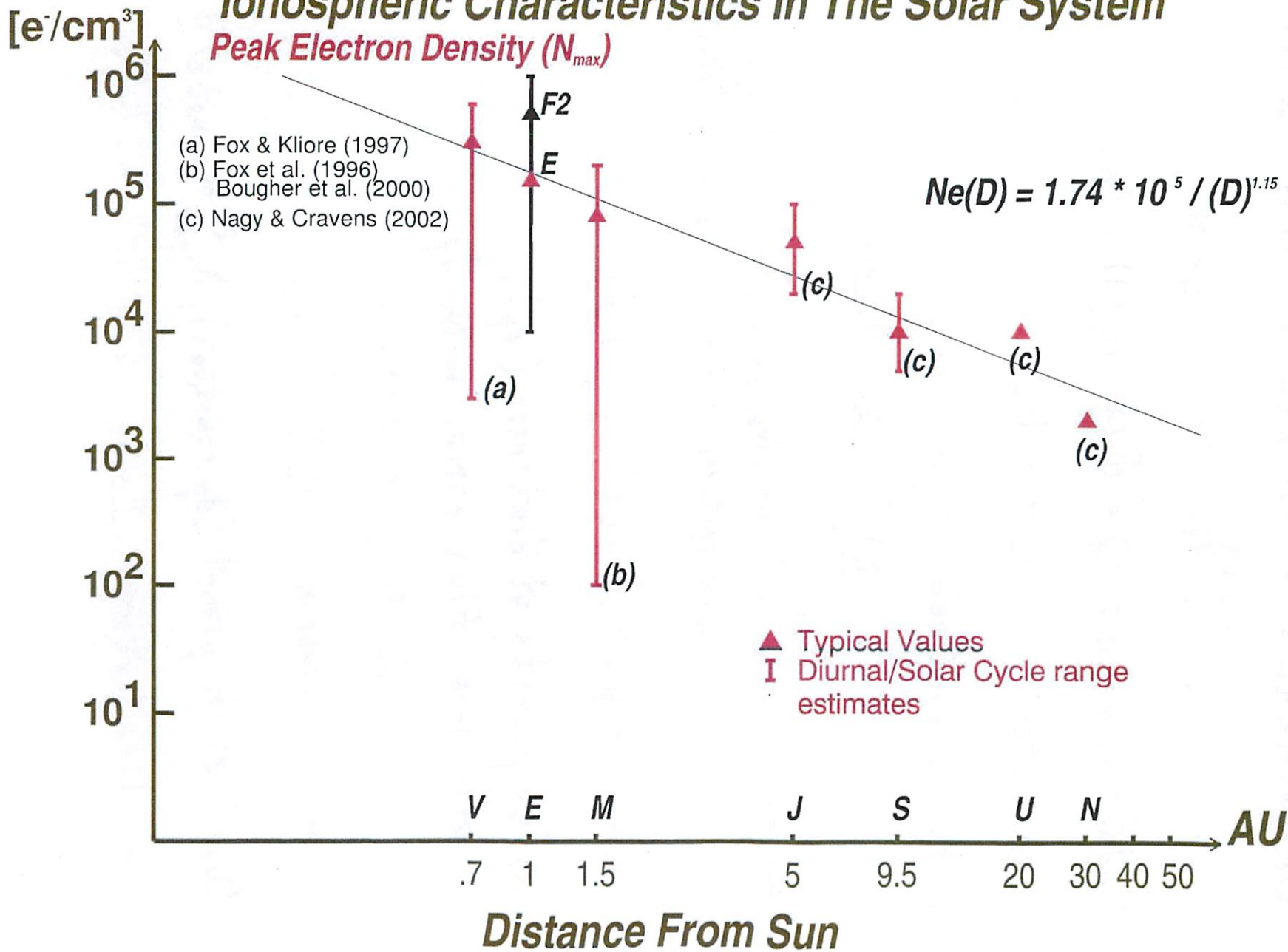
--- Implication: Peak Densities $\propto \frac{1}{\text{distance}}$

(b) At each planet (d_p constant), $N_{\text{max}}^2 \propto \text{Const} \odot \Phi_{\text{sun}}$

--- Implication: Ionospheric Variability \propto Solar Variability

Ionospheric Characteristics In The Solar System

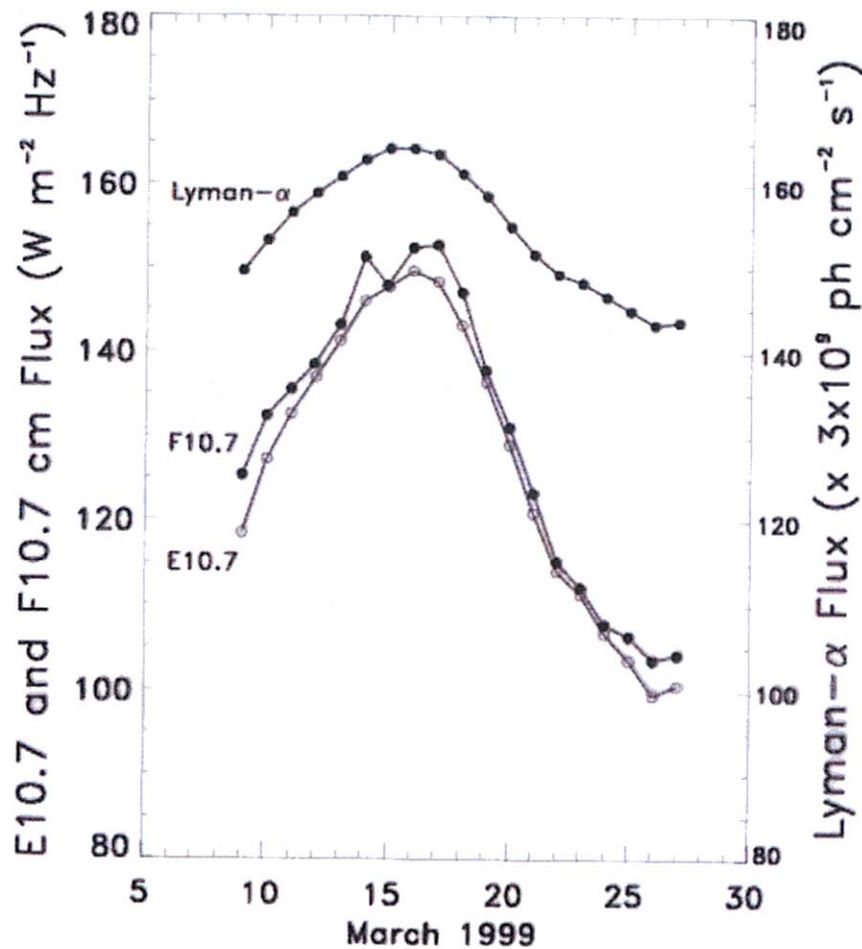
Peak Electron Density (N_{max})



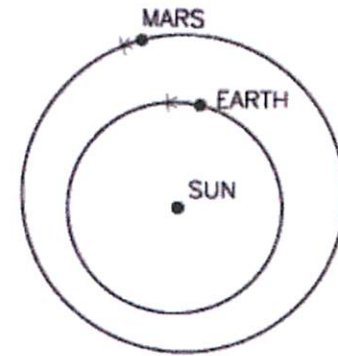
Response to Solar Activity : Example = Active Regions

Case Study Period --- Mars near Opposition during a month of pronounced Solar Activity

Solar Activity Indices 9-27 March 1999

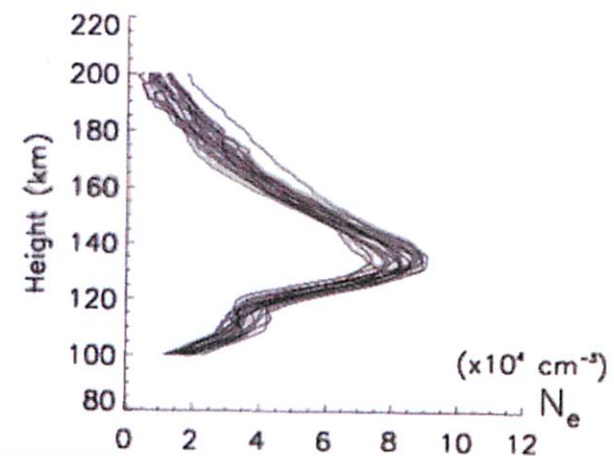


(a) 9-27 March 1999



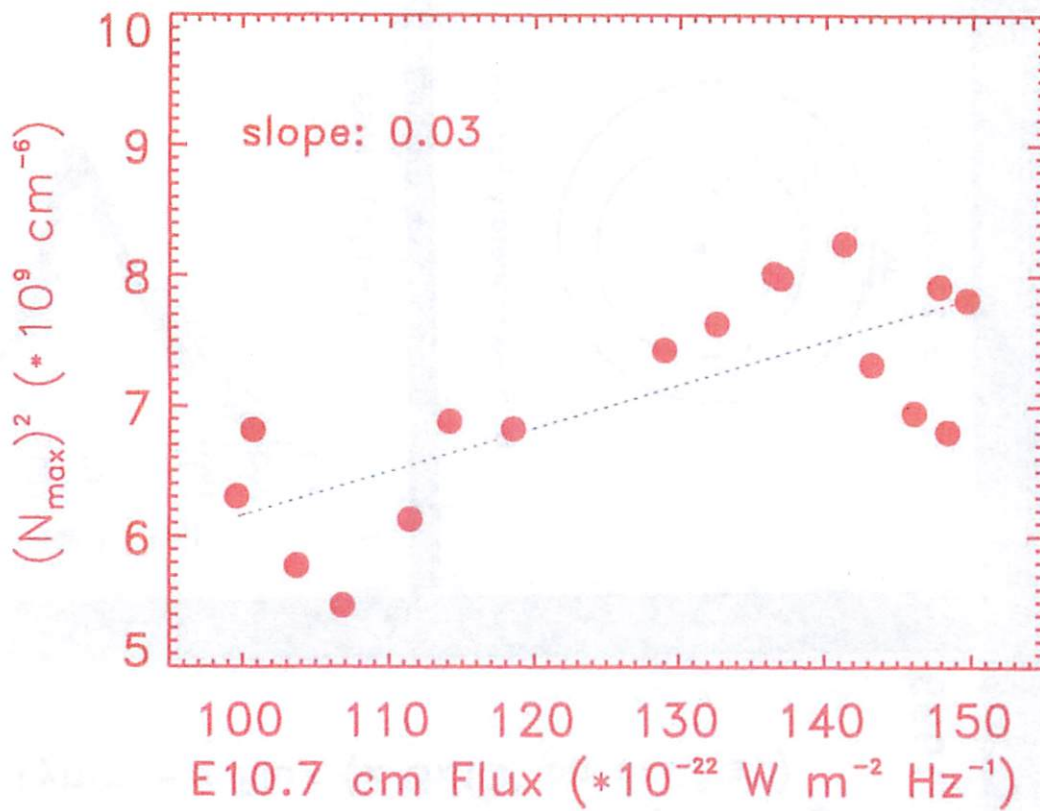
Relative Planetary Positions

(b) Mars $N_e(h)$ --- MGS

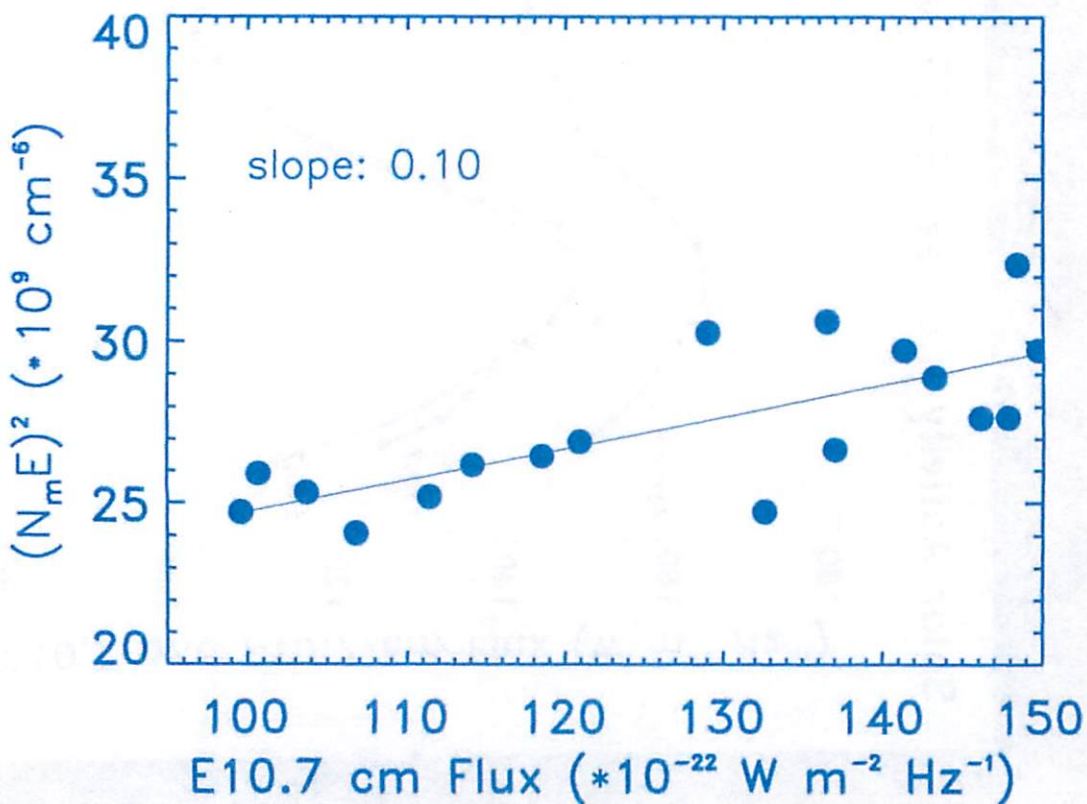


COMPARATIVE IONOSPHERES: 9-27 MARCH 1999

Mars



Earth



Effects of Solar Flares Upon the Planets

- EARTH --- Many Ionospheric D-E-F-Layer Studies and Effects Upon the Geomagnetic Field
 - JUPITER --- Bhardwaj et al. (2005a)
 - SATURN --- Bhardwaj et al. (2005b)
- } Solar flare X-rays reflected to Earth-orbiting satellites
- MARS --- Recent Mars Global Surveyor + Mars Express detections of ionospheric enhancements

ΔNe(h) by MGS
(Mendillo et al., 2006)
--- 15 + 26 April 2001

ΔN_{max} by MEX
(Gurnett et al., 2005)
--- 15 September 2005

--- CEDAR Post-doc Report: Dr. Paul Withers - This AM!

Solar Flare Effect Upon Terrestrial Ionosphere

- X-rays $\rightarrow \Delta N_e$ at low altitudes

Sudden Frequency Deviations (SFDs)

Used to infer temporal patterns of flare hard X-rays prior to satellite era

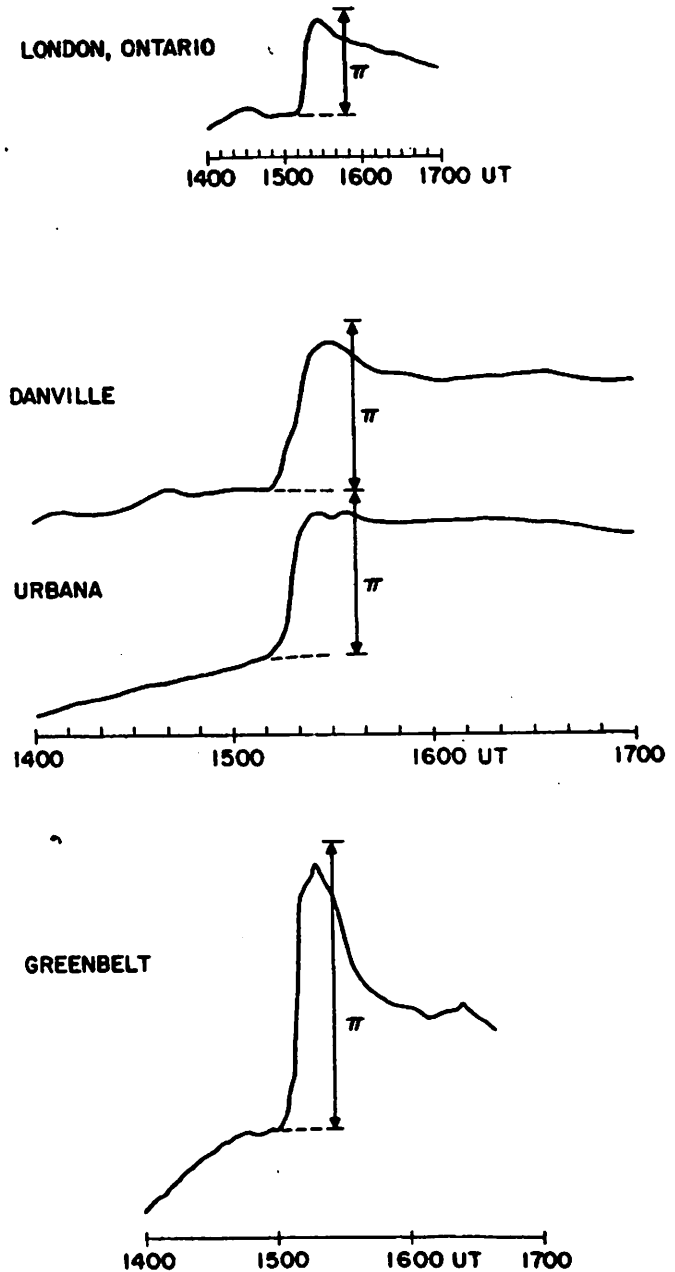
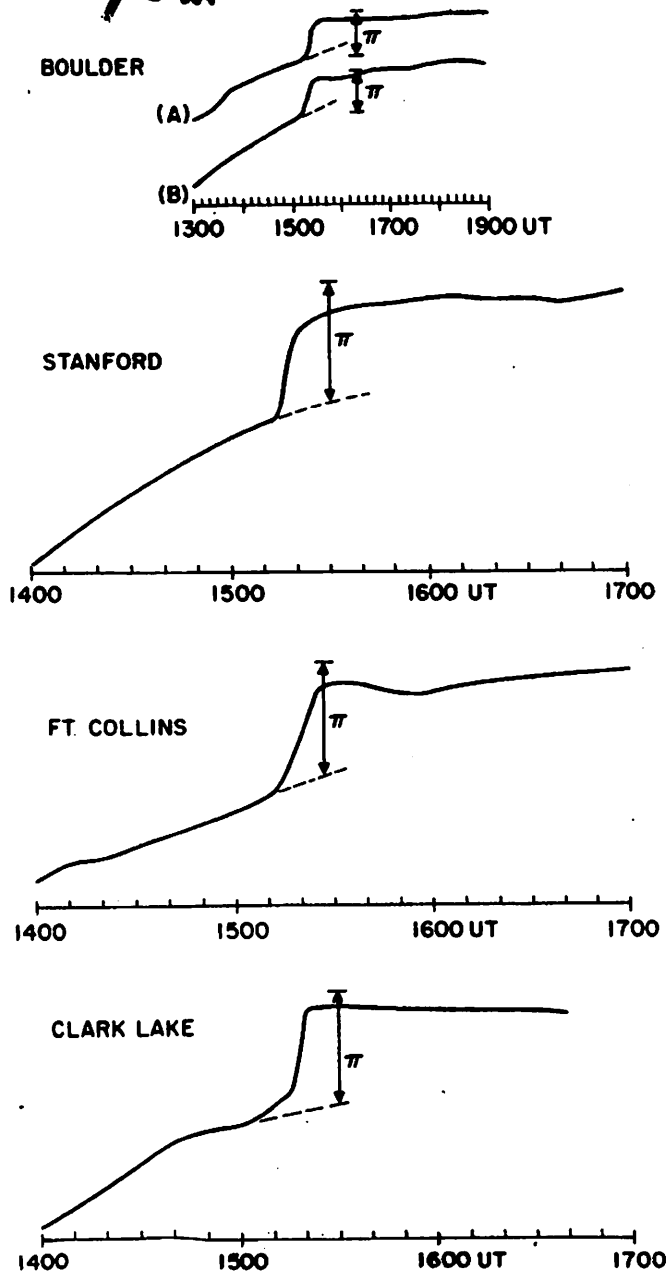
Prevent Ionosondes from observing effects of soft X-rays ($\Delta f_o E$) and EUV ($\Delta f_o F2$)

- EUV $\rightarrow \Delta N_e(h)$ in F-layer
 - $\rightarrow \Delta TEC$ (SITEC)
 - $\rightarrow \Delta T_e$ and $\Delta \vec{V}_{plasma}$

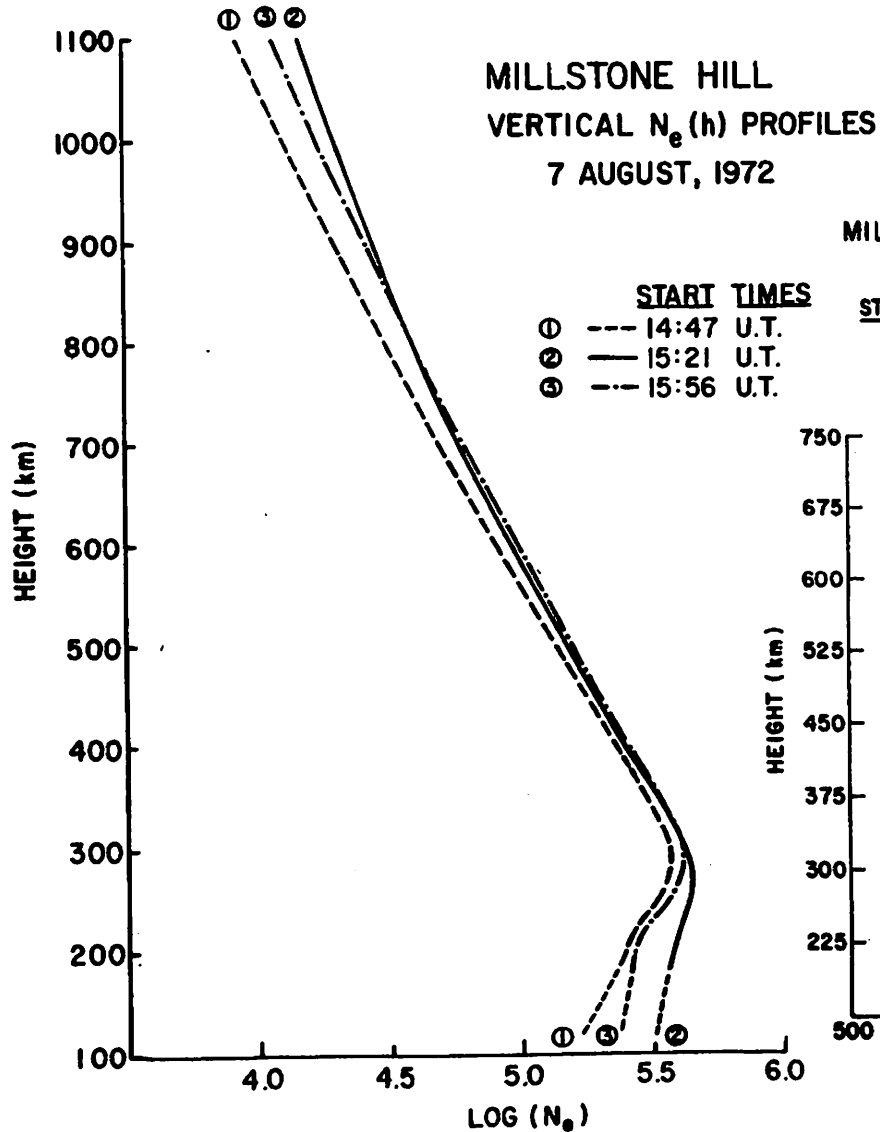
- Solar Flares as "Active Experiments" in Solar-Planetary Relations

The Great Solar Flare of 7 August 1972: Total Electron Content

$$\pi \approx 4 \times 10^{12} \text{ e}^-/\text{cm}^2$$



The Great Solar Flare of 7 August 1972 : Millstone Hill ISR



MILLSTONE HILL TEMPERATURE AND VELOCITY PROFILES ---- 7 AUGUST, 1972

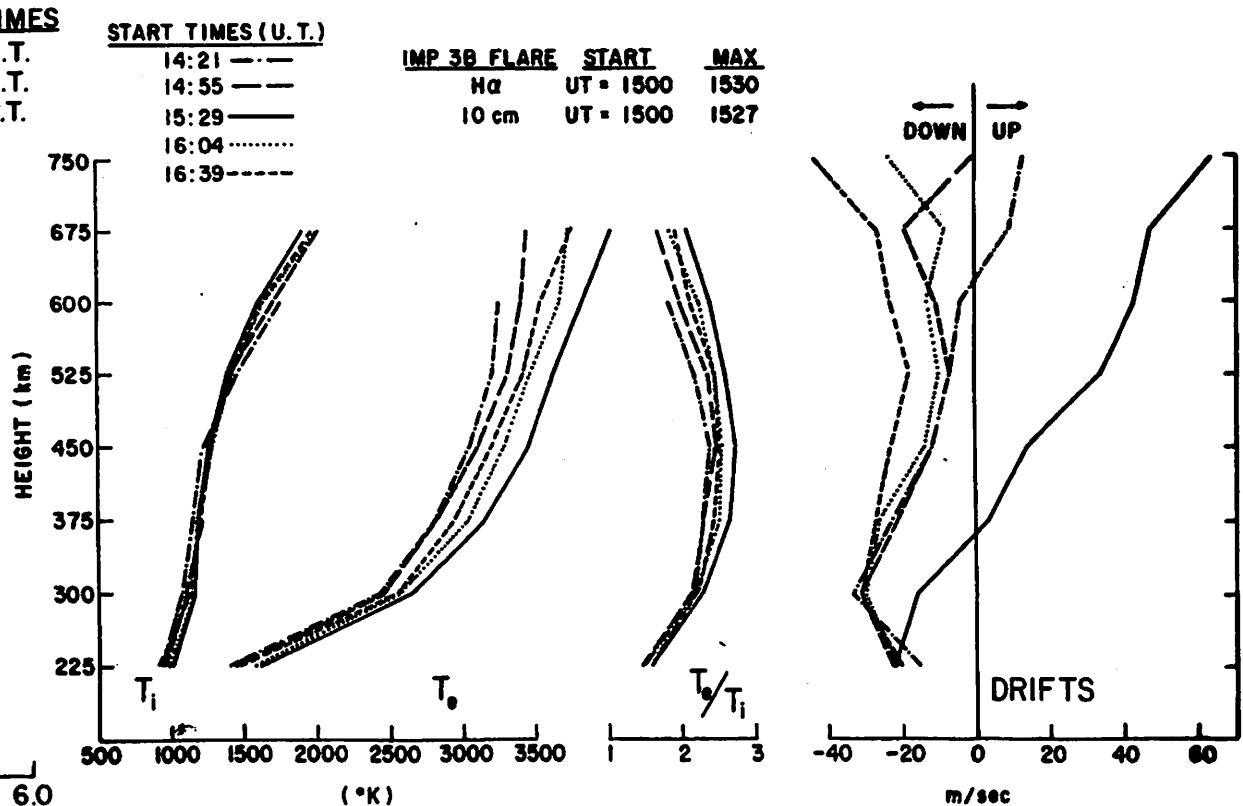
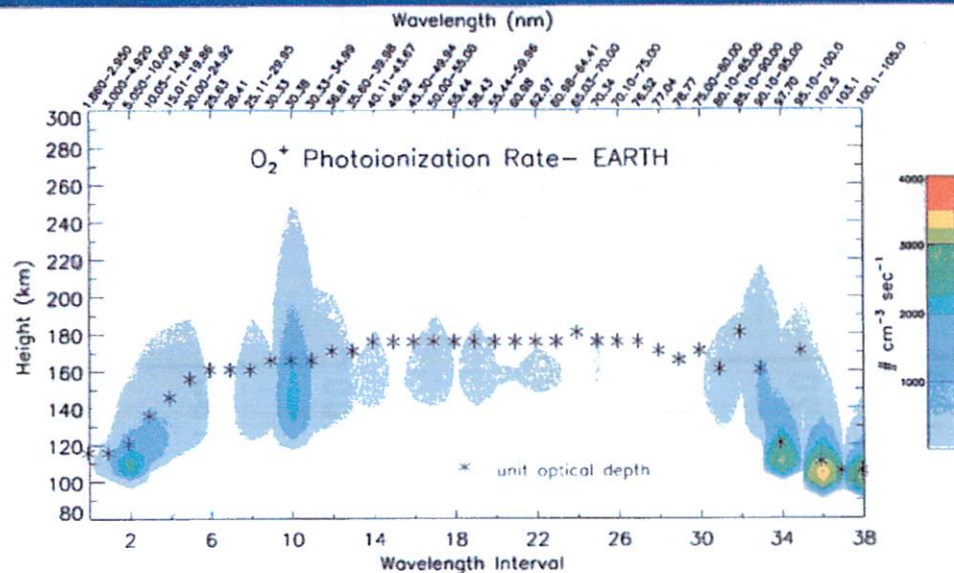
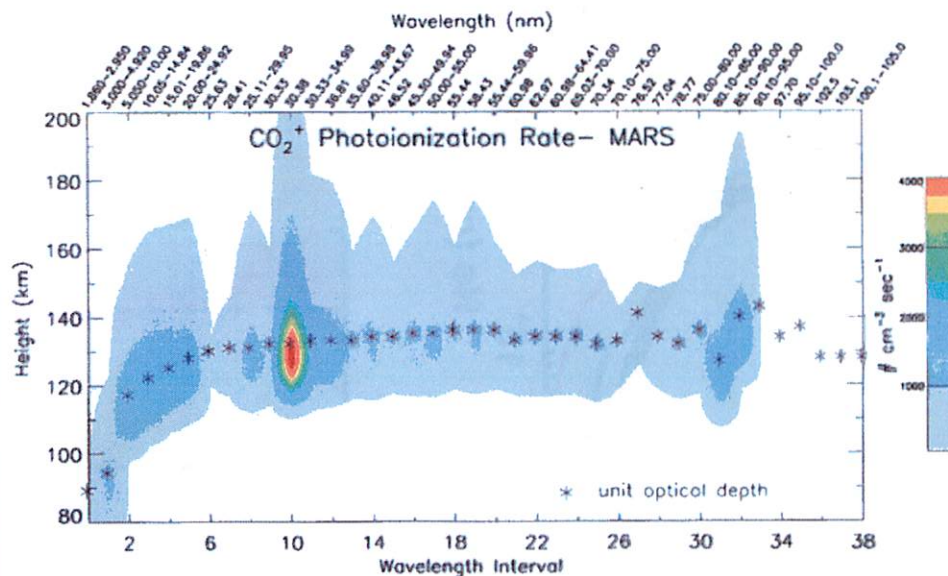


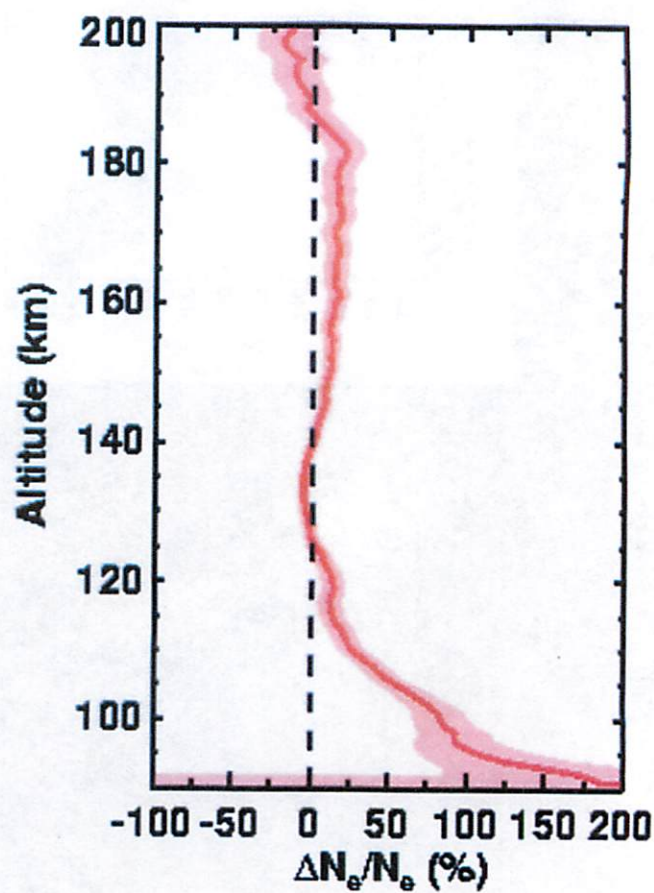
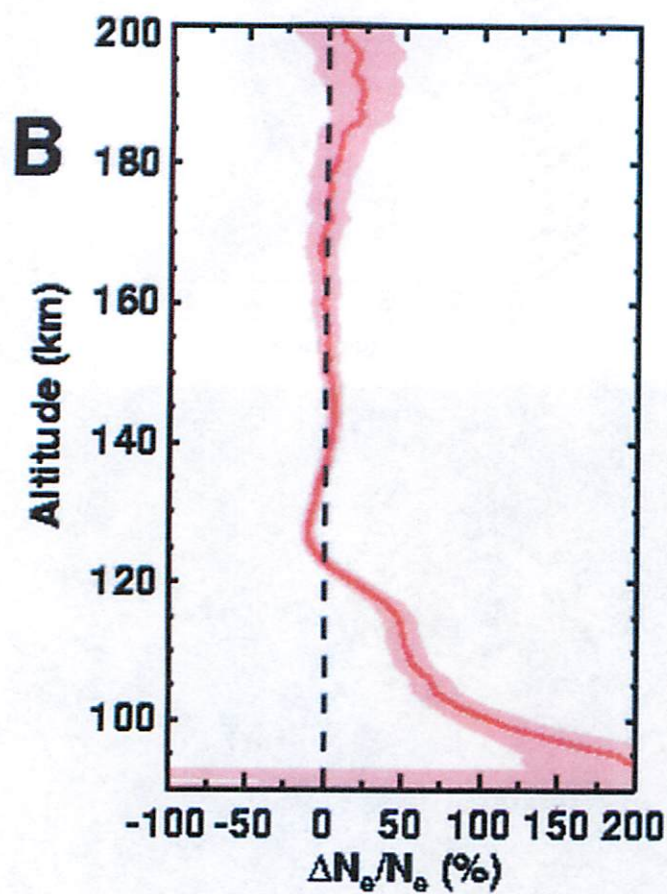
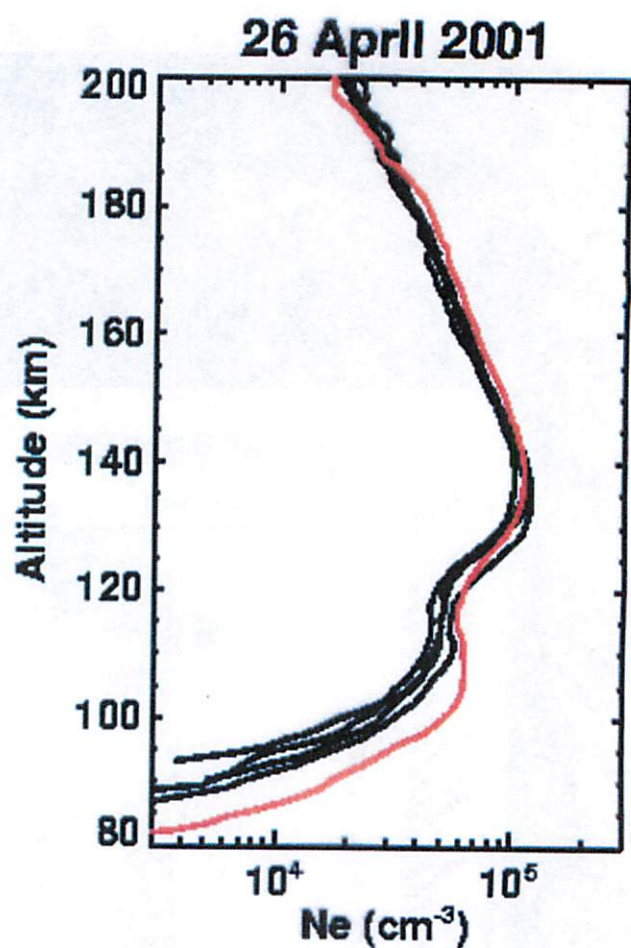
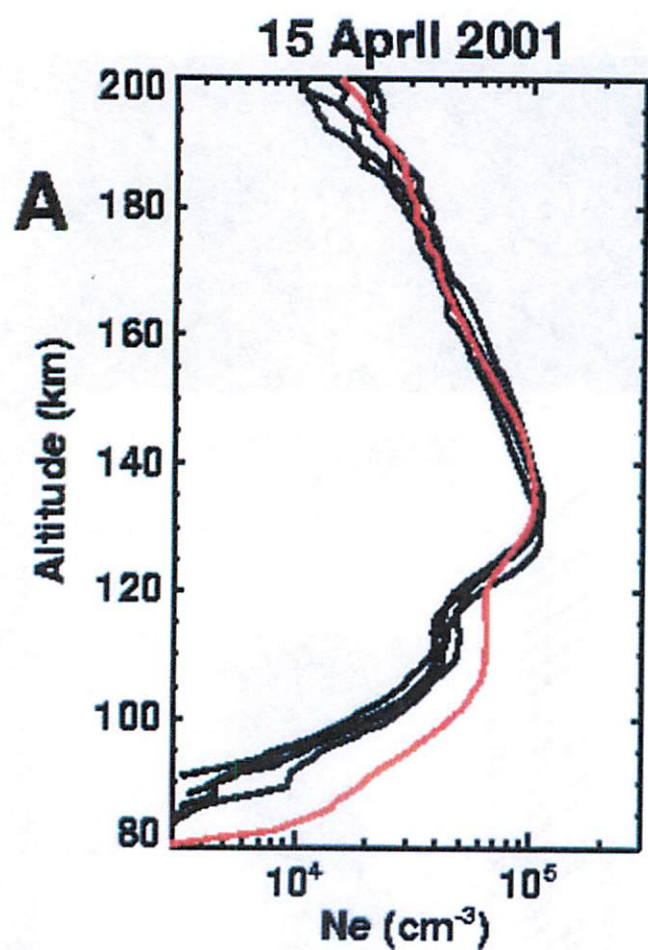
Photo-production vs. λ

EARTH

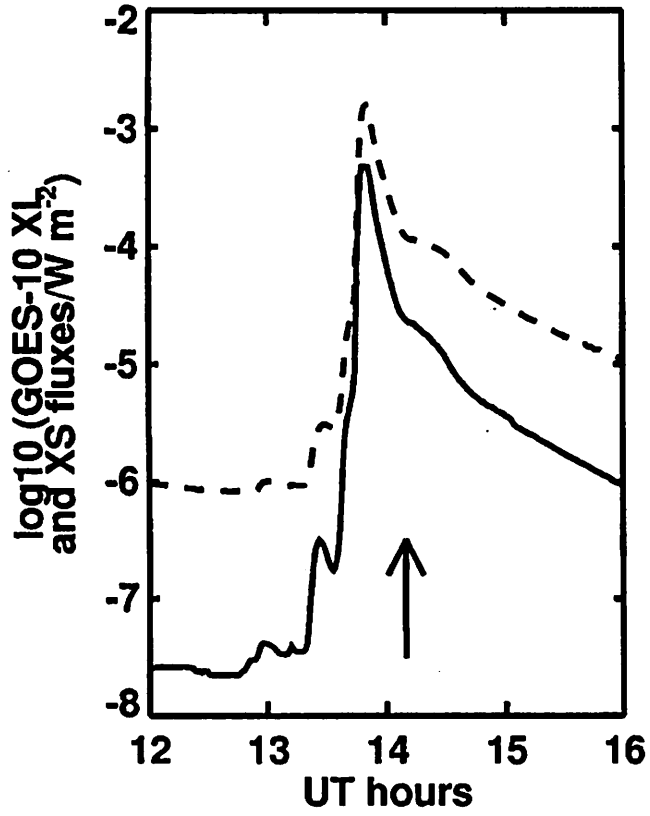


MARS

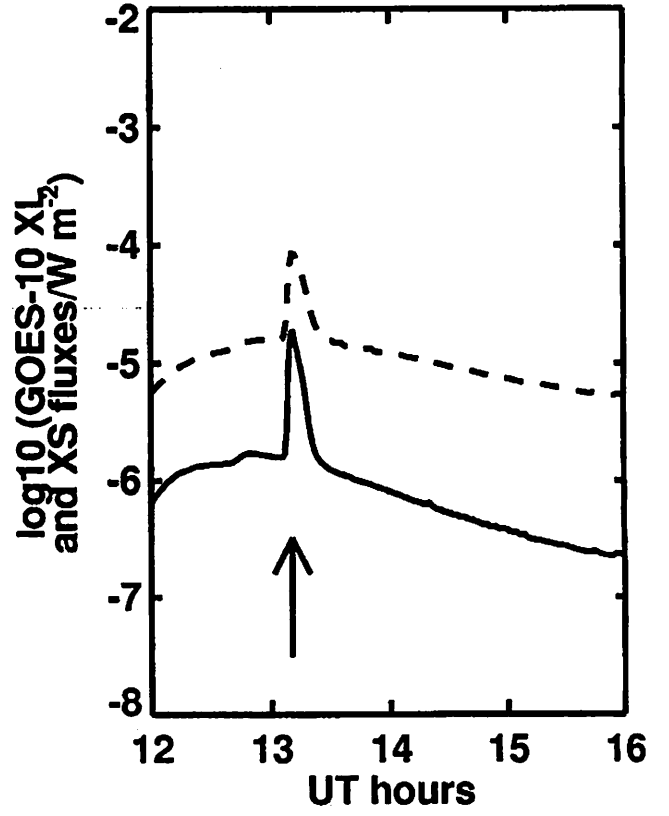




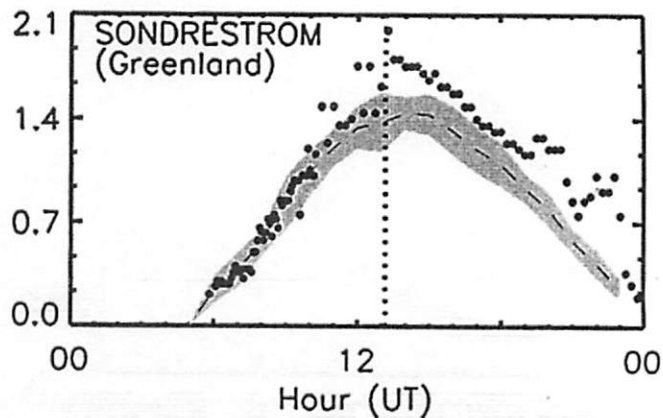
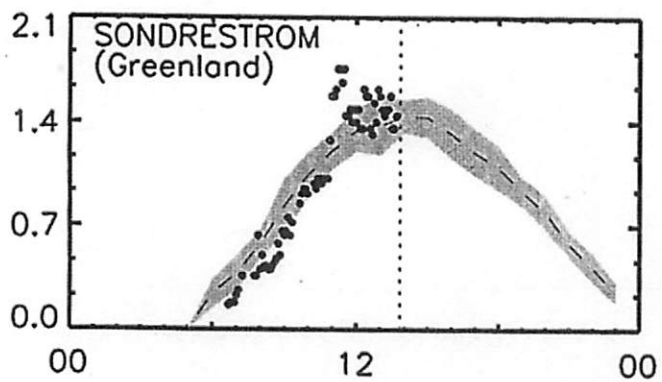
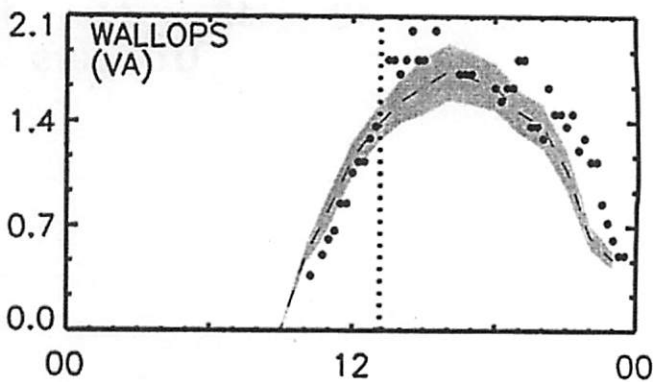
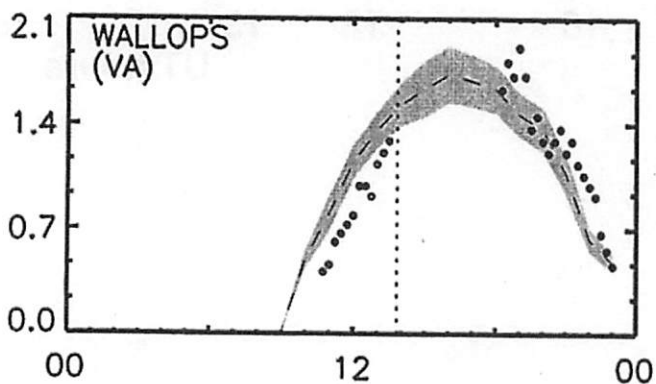
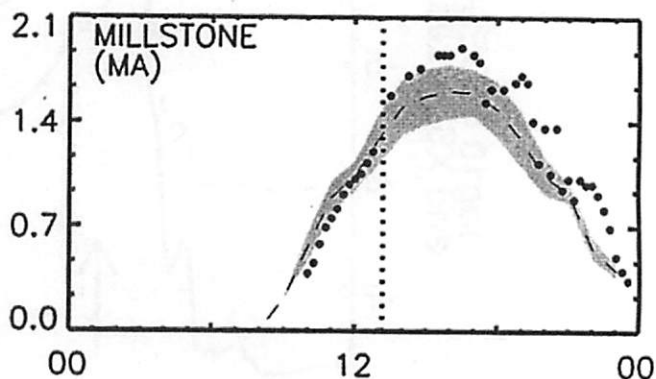
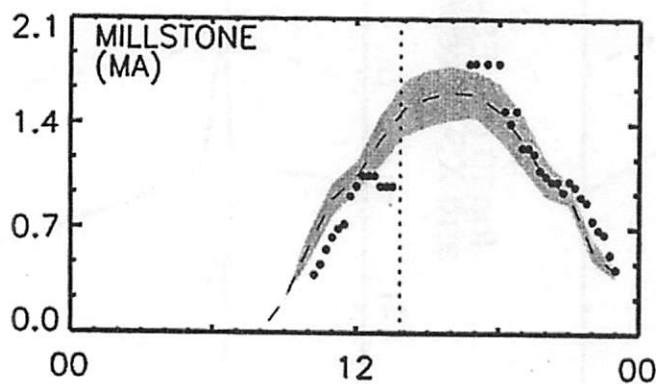
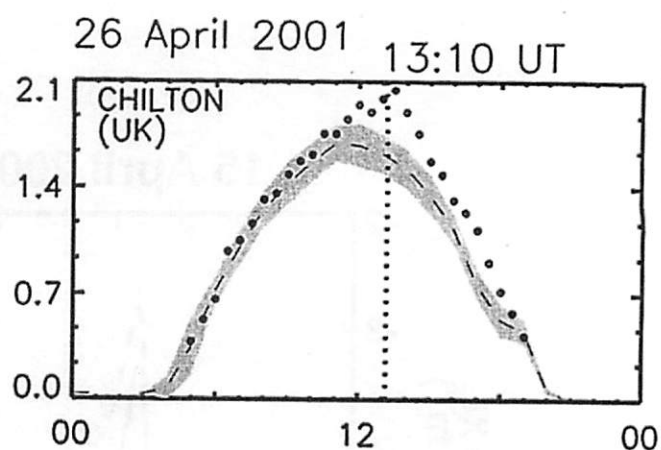
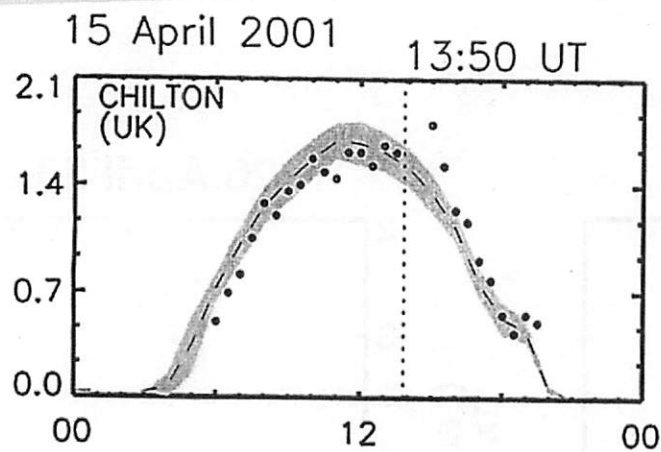
15 April 2001



26 April 2001



E-Layer Peak Density, $N_m E$ ($\times 10^5 \text{cm}^{-3}$)



POTENTIAL SCIENCE YIELD FROM COMPARATIVE STUDIES OF SOLAR FLARE-INDUCED "Active Experiments"

- CONstrain Secondary Ionization by Photoelectrons
 - X-RAYS
 - EUV
 - CO_2 (MARS + VENUS)
 - H, H_2 (JOVIAN PLANETS)
 - $\text{O}, \text{O}_2, \text{N}_2$ (EARTH, MARS + VENUS)

- CONstrain DYNAMO PROCESS

- SFE $\Delta \vec{B} = f(|\vec{B}| \text{ and } \vec{u}_{\text{neutrals}})$

The opposite of Flare Effects --- Turn Photochemistry OFF!

--- Effects of Eclipses + Shadows of Rings

for Earth ($\Delta t \leq 7^{\text{min}}$)

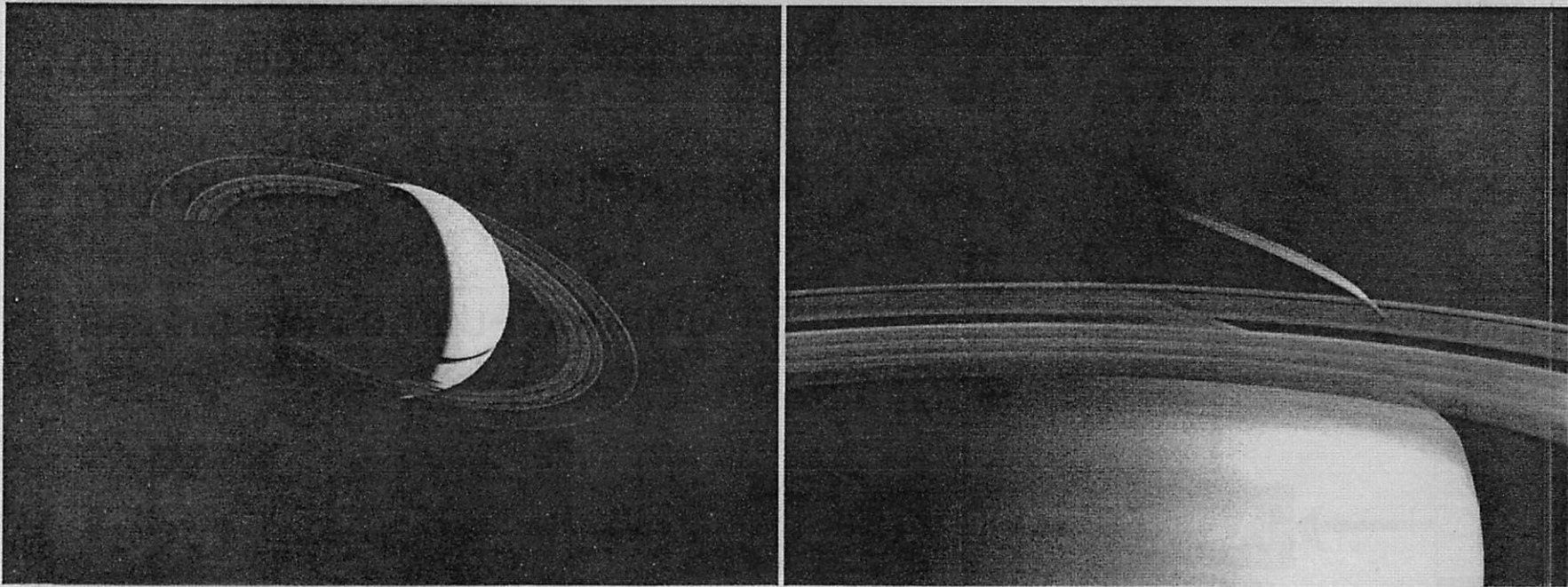
Spectacular
Personal Experience

Shortlived Ionosphere
Effects

for Saturn ($\Delta t \approx \text{years}$)

for Jovian Planets, eclipses
can be massive events
--- with mutual eclipses.

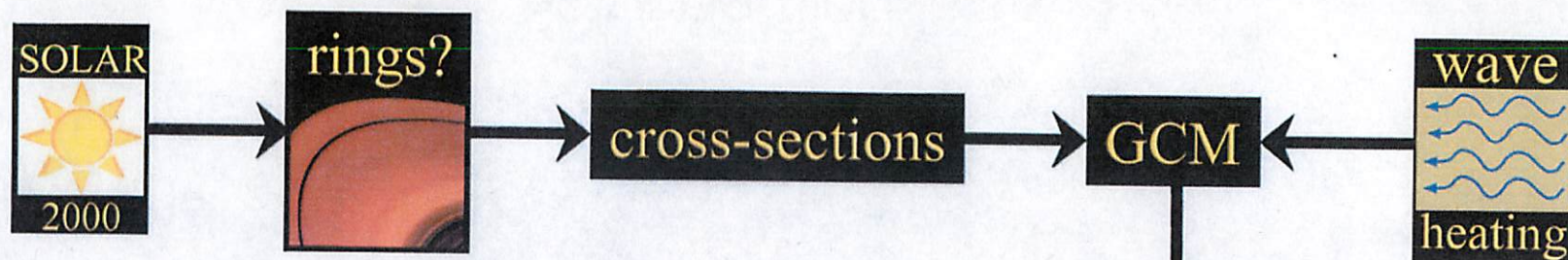
Ring Shadowing: Then and Now



- (left) 1980, Voyager 1, Solar declination = -1.6°
- (right) 2004, Cassini, Solar declination = -26°

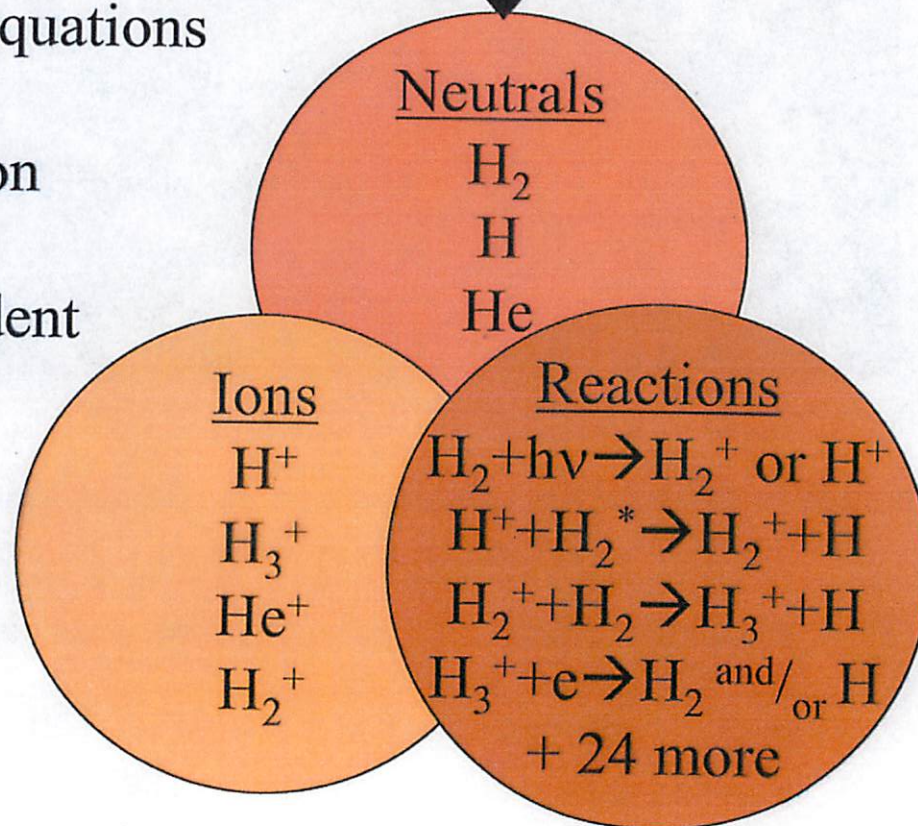
Saturn Thermosphere Ionosphere Model (STIM)--- See Moore poster

The Ionosphere

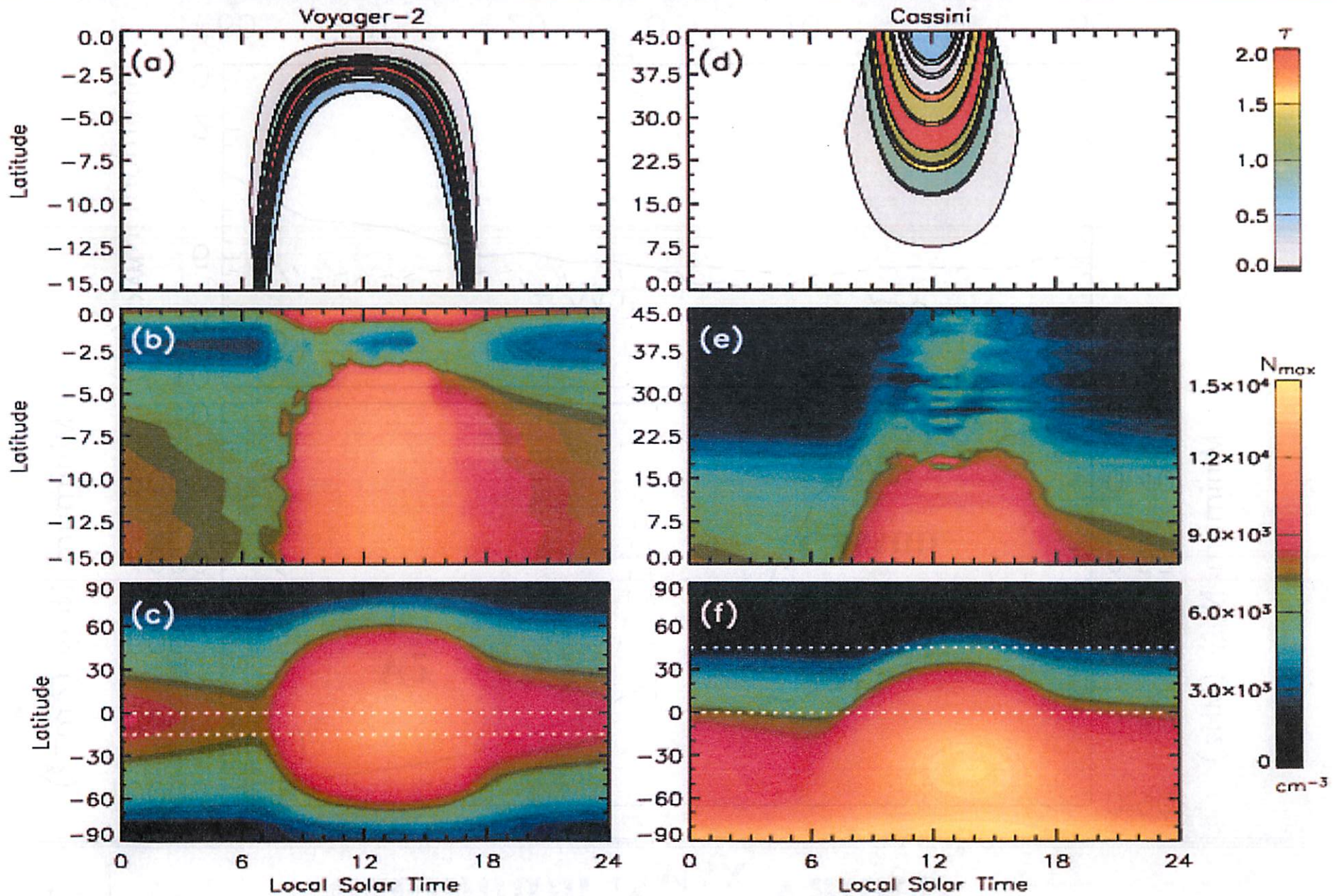


- 1-D solution of ion-continuity equations
- Photochemistry and ion-diffusion
- Global ionospheric time-dependent structure using GCM
- Solar flux is the only source of photoionization

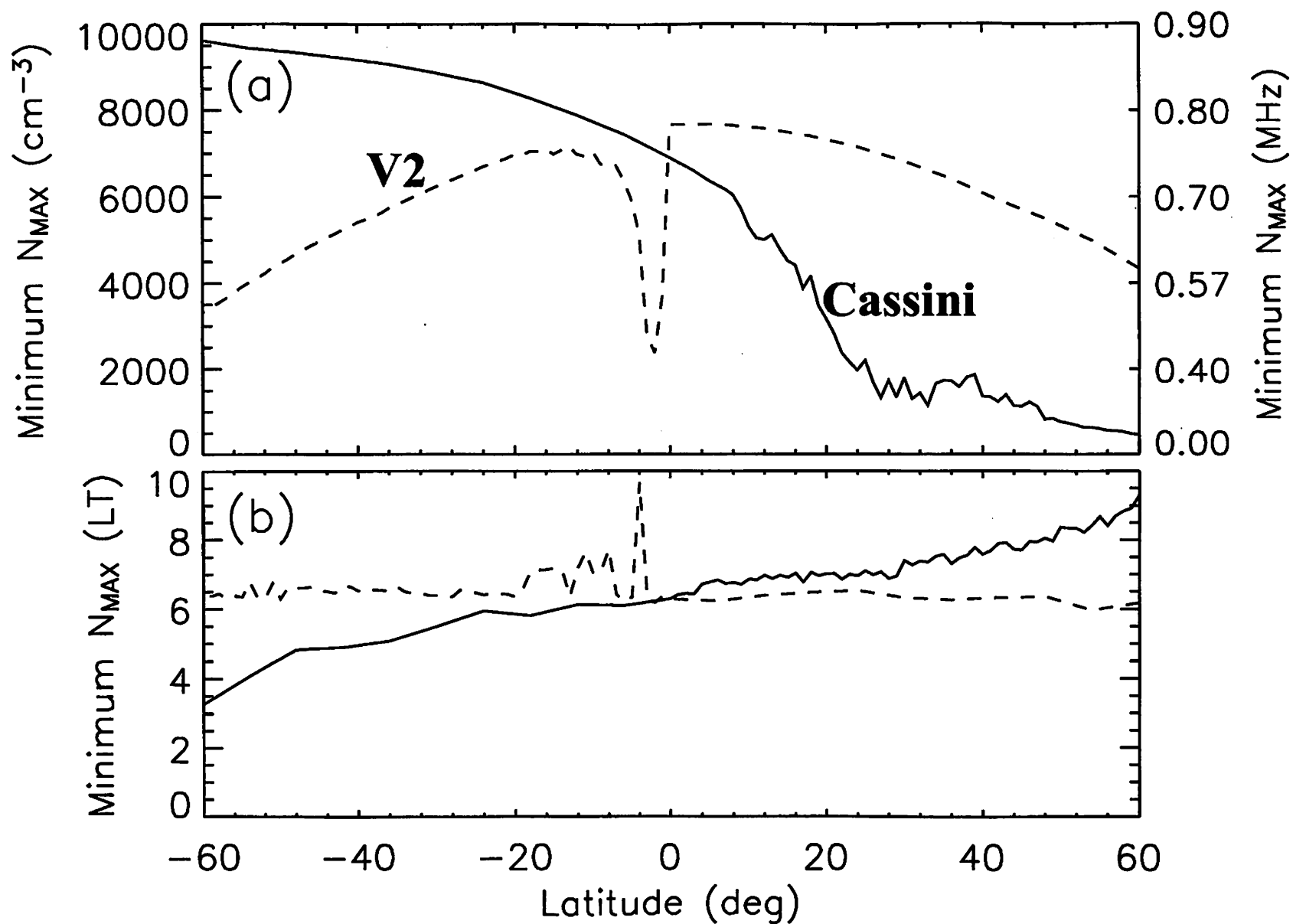
---Auroral + Wave Heating representations added---



Global Ring Shadowing Effects



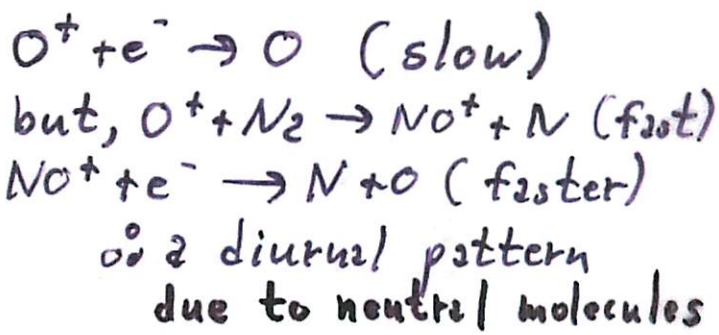
Minimum N_{MAX} Values



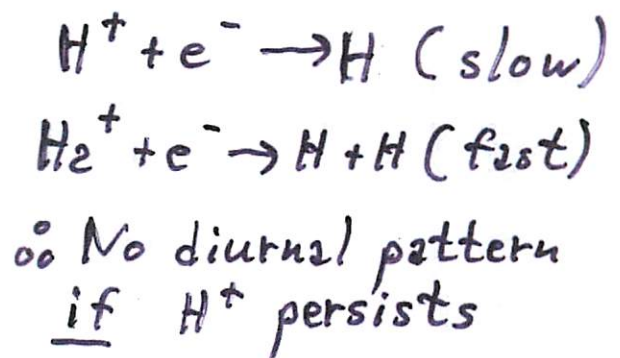
ATOMIC ION IONOSPHERES ARE LONG-LIVED

--- Contrast Two Cases ---

Earth (24 hr day)

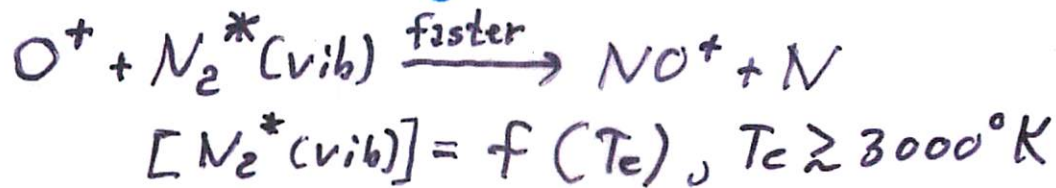


Saturn (10 hr day)



--- Ways to Enhance Loss?
Lessons from Earth?

• Sub-Auroral Trough

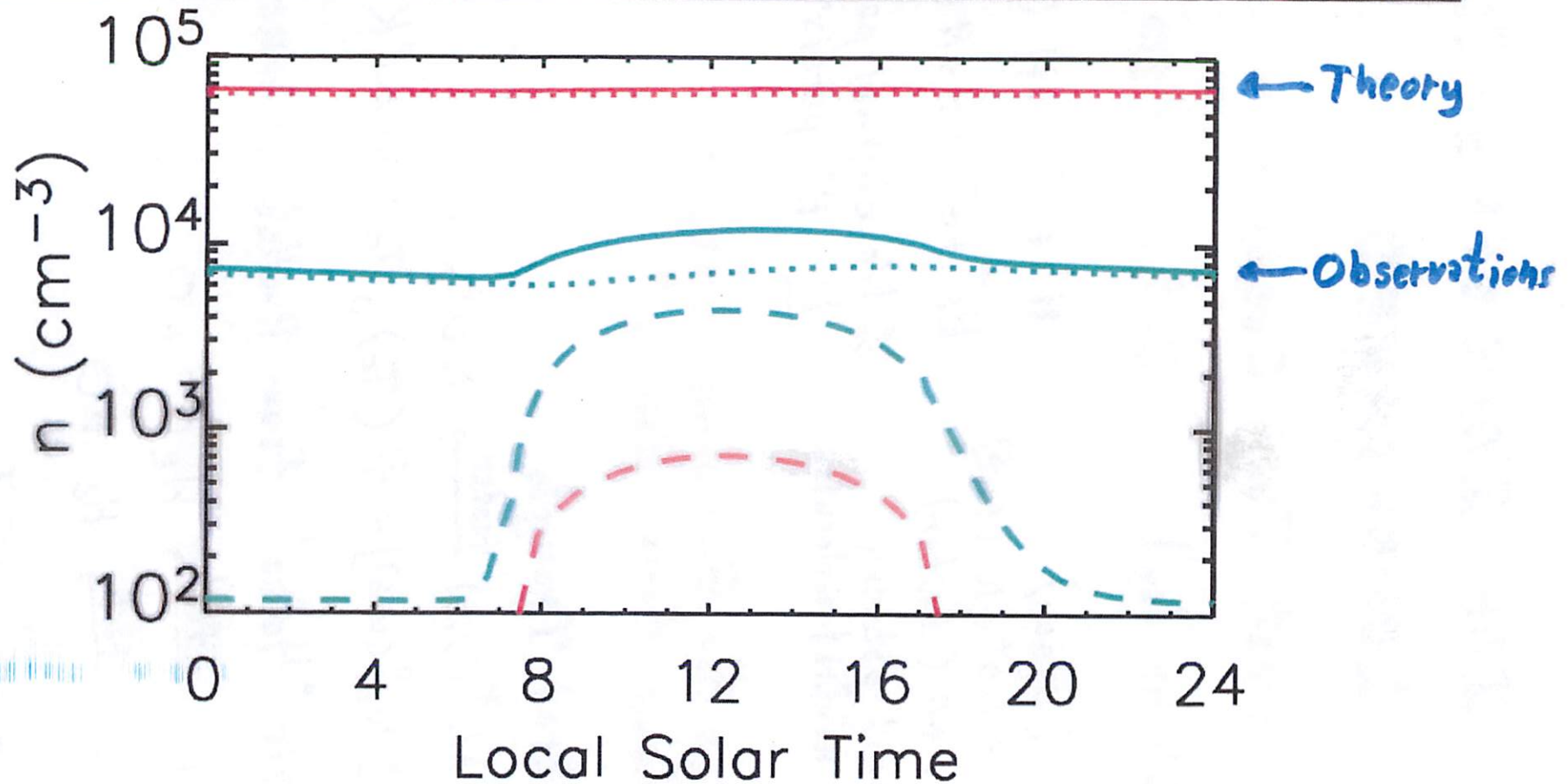


• Ionospheric "Holes" from Rocket Exhaust



--- Can similar processes
occur at SATURN?

Diurnal N_{MAX} Variation - SATURN



30° N, Equinox, Solar Max

30° N, Equinox, Solar Max, $k = 1 \times 10^{-4} k_1$

CAN H^+ be converted to a molecular ion (to enhance loss)?

$H^+ + H_2 \rightarrow$ Not possible (Q.M.)

BUT



Then, H_2^+ produced directly and

H_2^+ produced by above,



} Diurnal Variation!

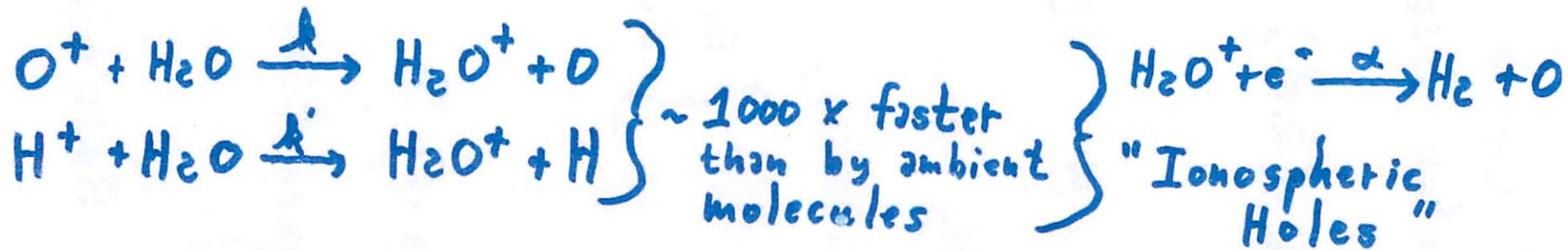
BUT

How to excite H_2 ($\text{vib} \geq 4$)?

And, if so, (1) may be slower than expected (D. Huostis).

oo Try "Water Dump" Solution

If an Ionosphere has atomic ions (O^+ , H^+), water can make them into molecular ions \rightarrow leading to rapid recombination.



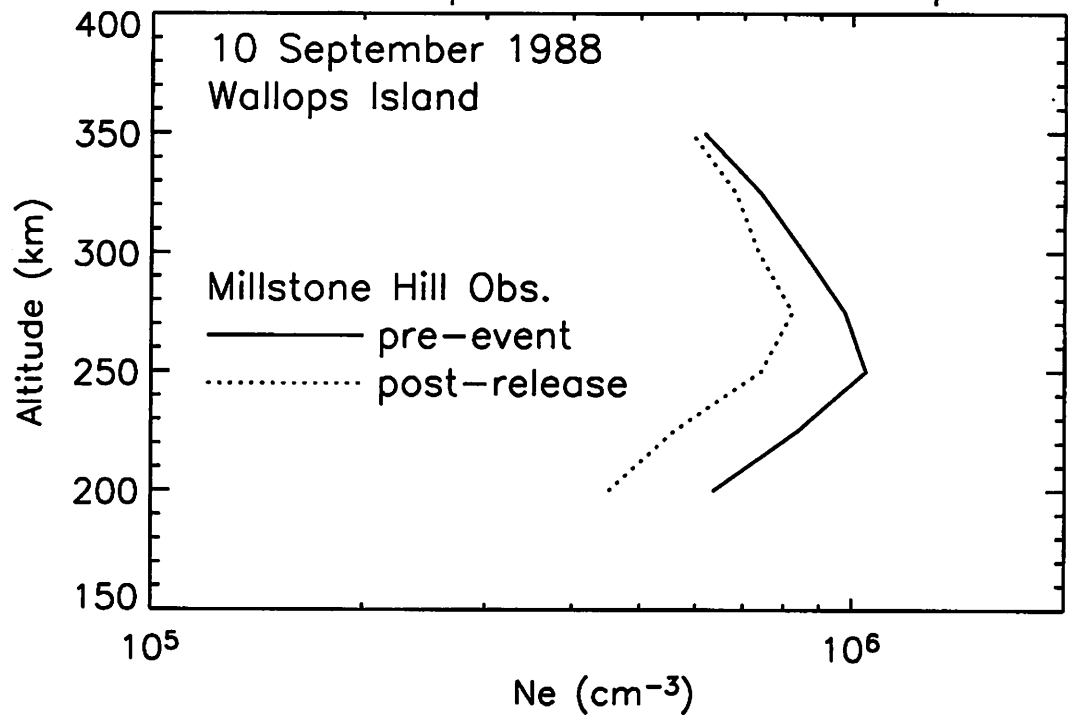
EARTH

- Water Release "Active Experiments"
 - Daytime \rightarrow F-layer recovers in \sim hour(s)
 - Nighttime \rightarrow F-layer stays depleted until sunrise.

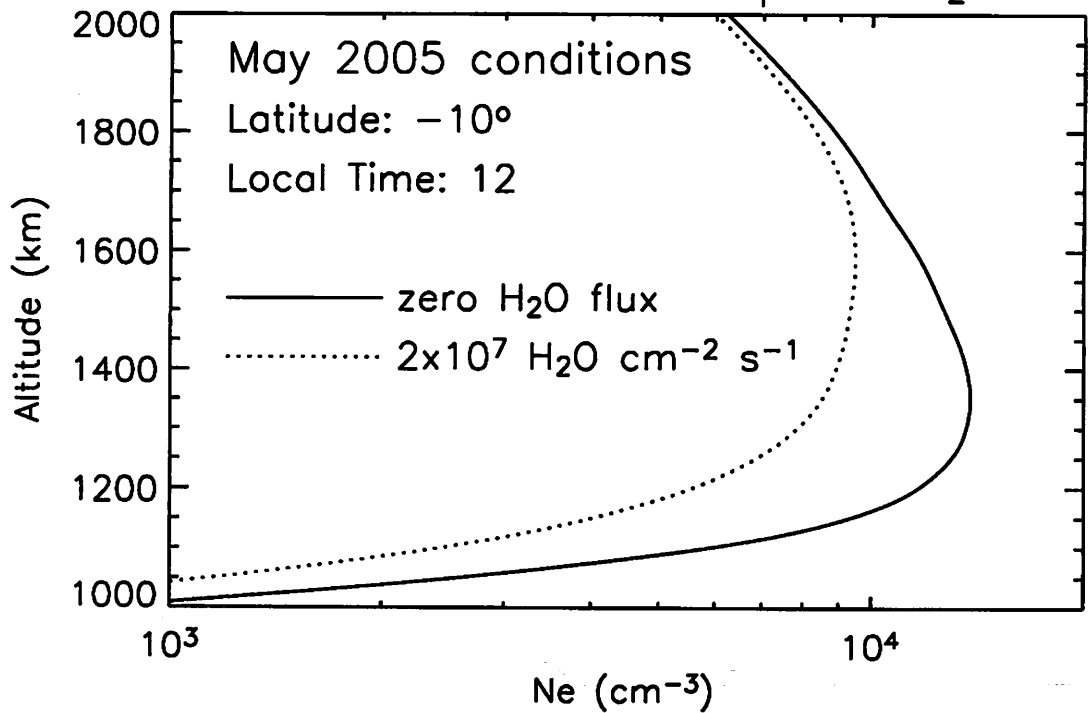
SATURN

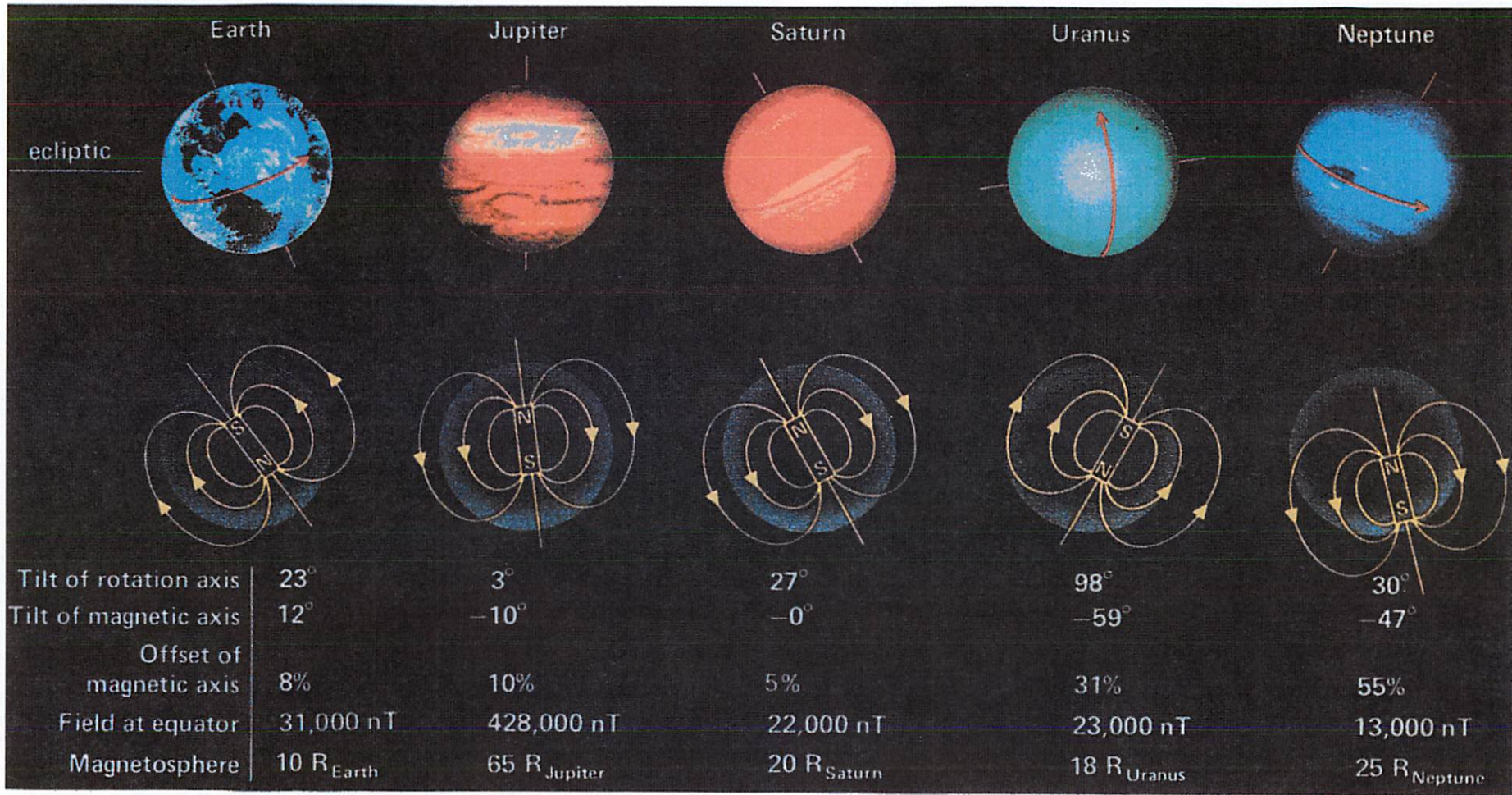
- Constant H_2O sources:
- Ring sputtering
 - Ejections from the moon Encelades
- o Ionosphere continuously in a "depleted" state?

Observed "water dump" (5×10^{27} H₂O molecules)
Terrestrial Ionospheric Modification Experiment

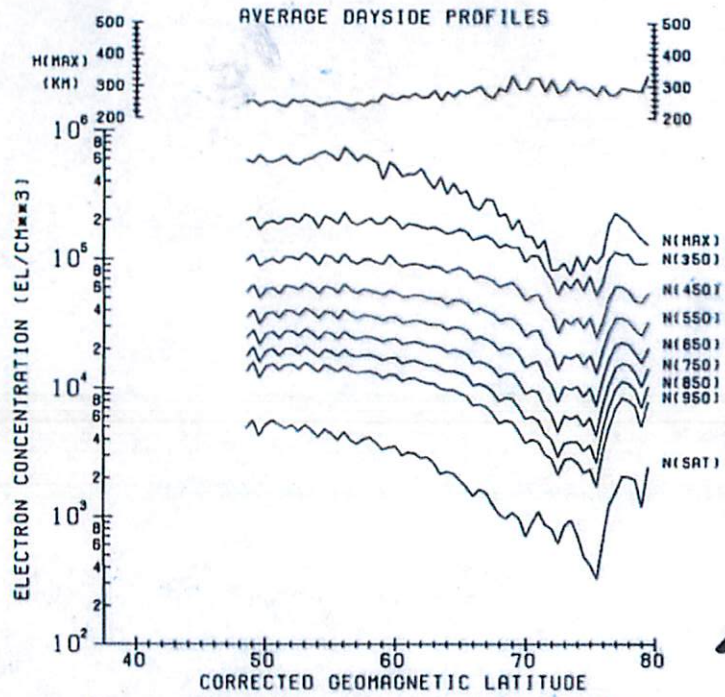


Simulations of Saturns Ionosphere: H₂O Influx



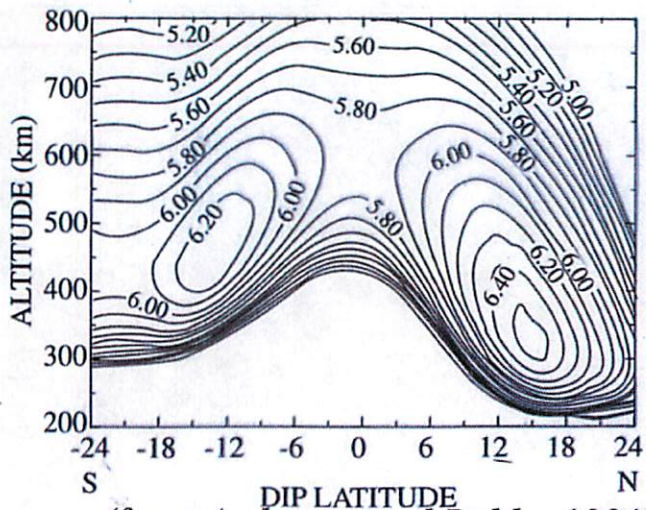


ISIS 2 Topside Sounder



(from Chacko and Mendillo, 1977)

Ne(h) vs. Latitude

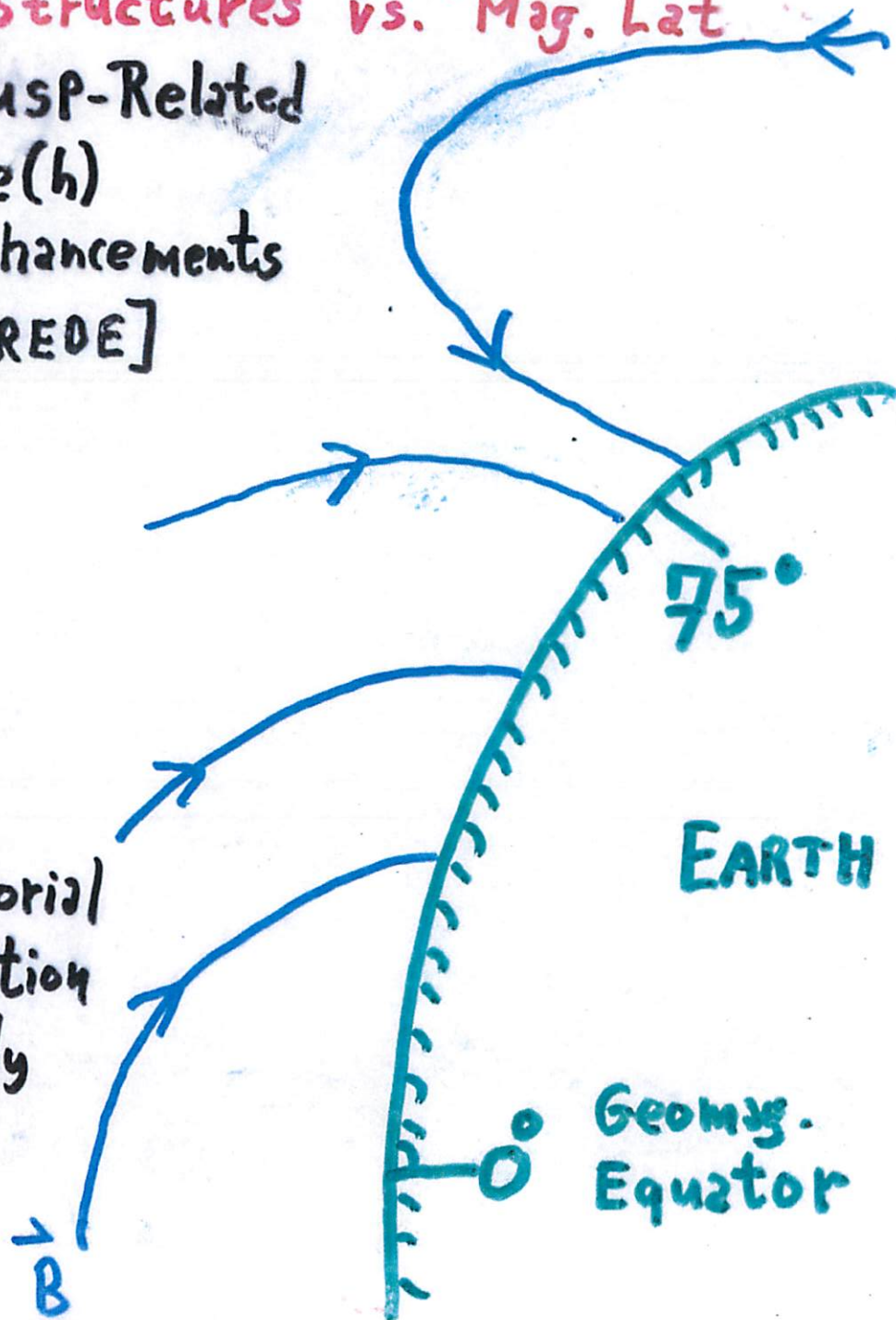


(from Anderson and Roble, 1981)

Terrestrial Ionosphere Structures vs. Mag. Lat

Cusp-Related
Ne(h)
Enhancements
[CREDE]

Equatorial
Ionization
Anomaly
[EIA]

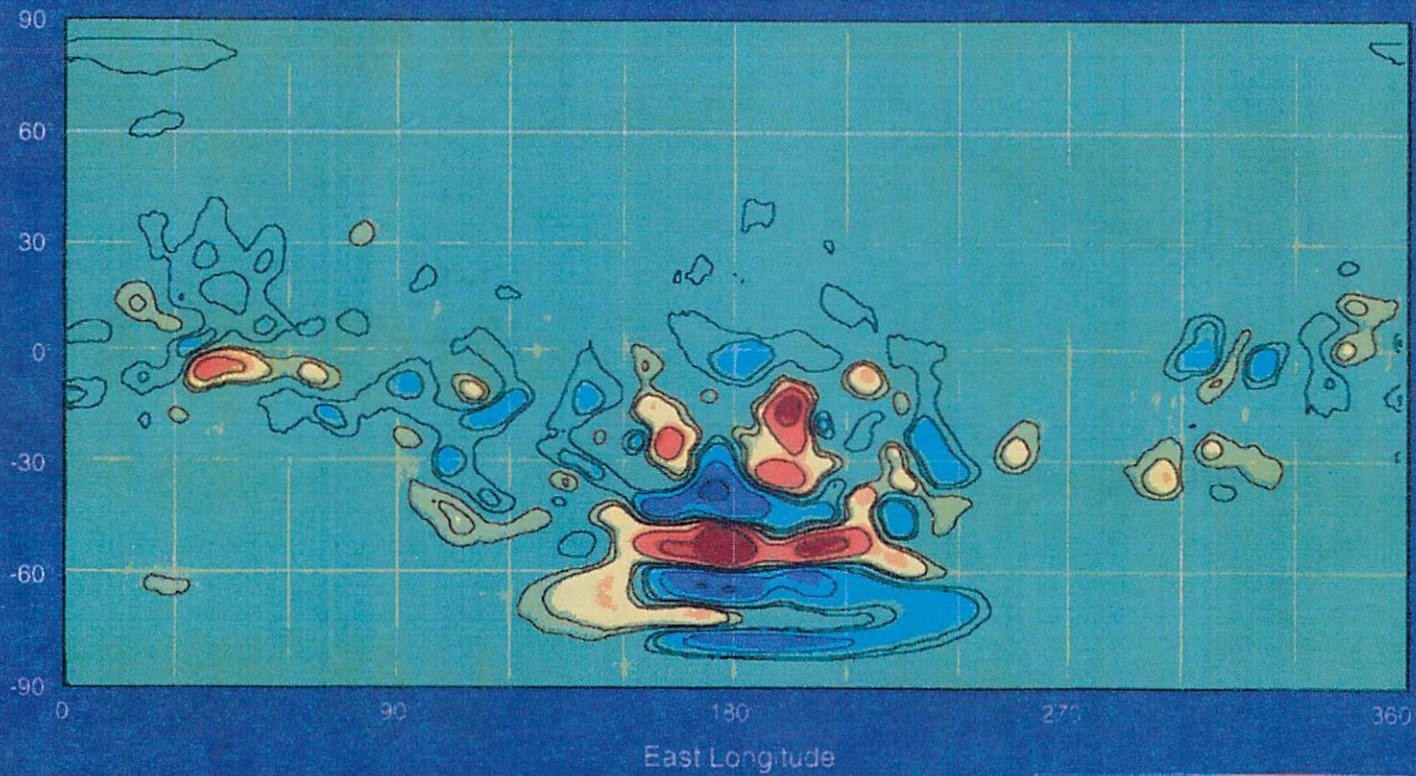




Mars Crustal Magnetism

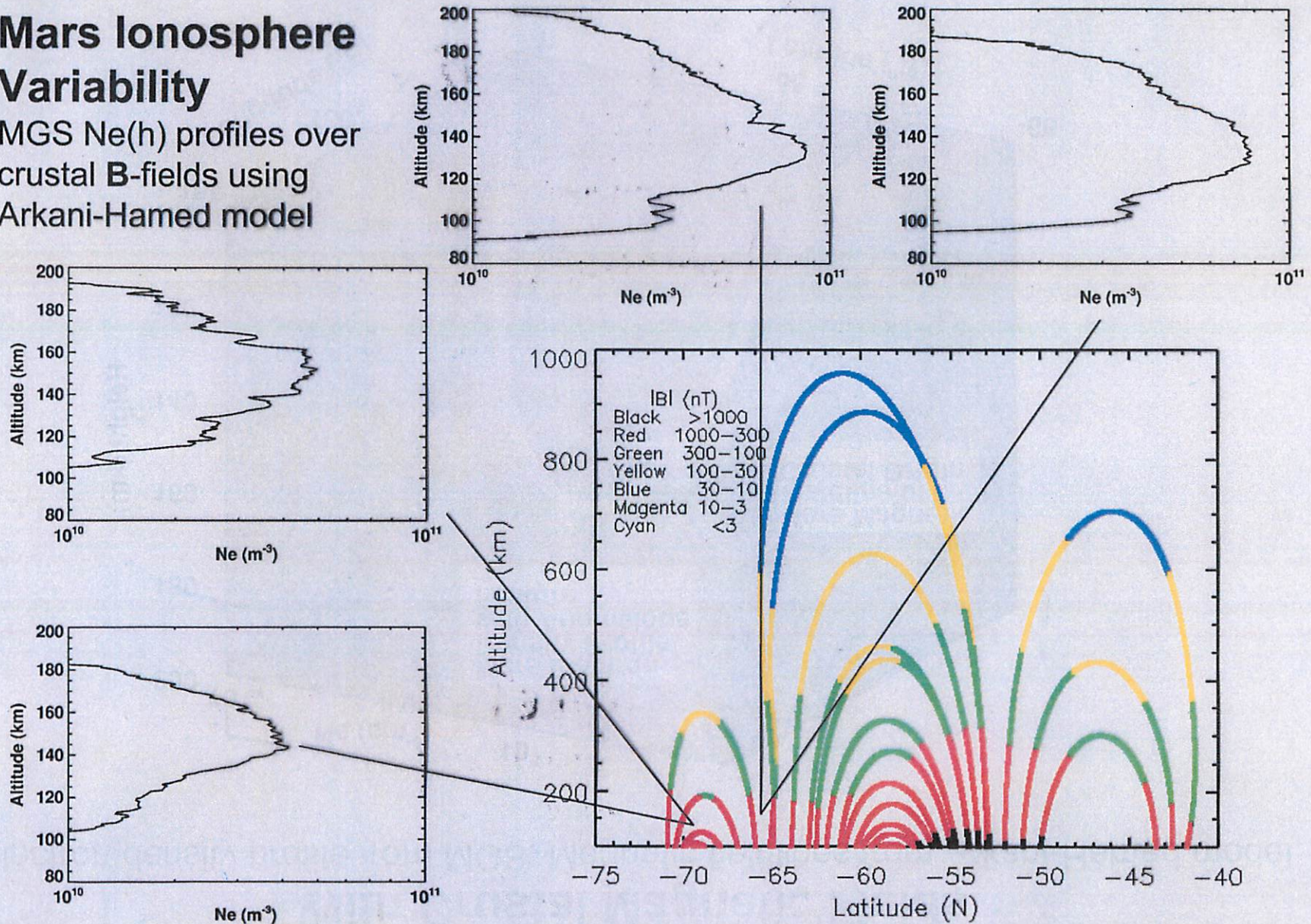
Mars Global Surveyor


MAG/ER



Mars Ionosphere Variability

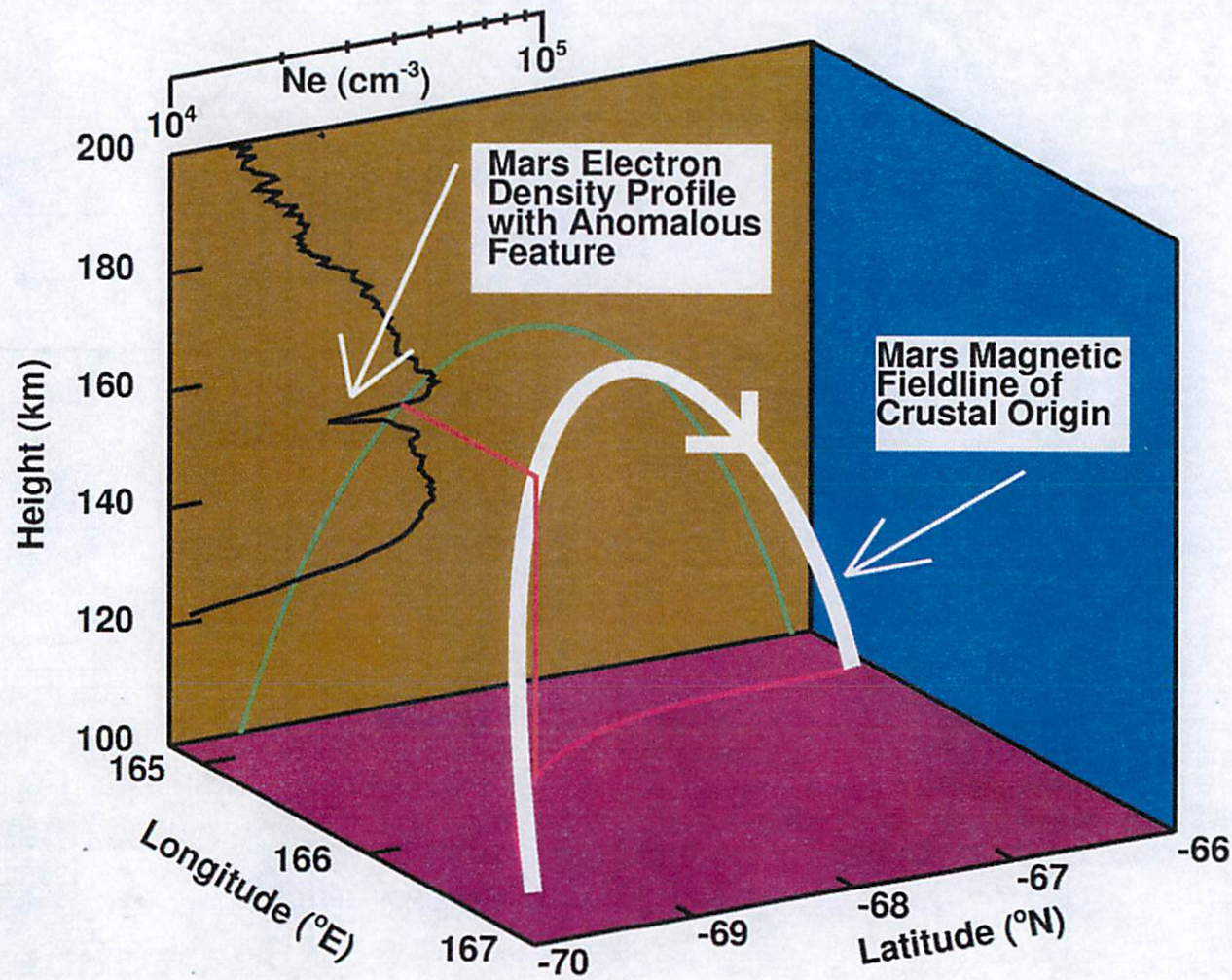
MGS Ne(h) profiles over crustal **B**-fields using Arkani-Hamed model



AMISR  Cusp + Equatorial AERONOMY from same site!

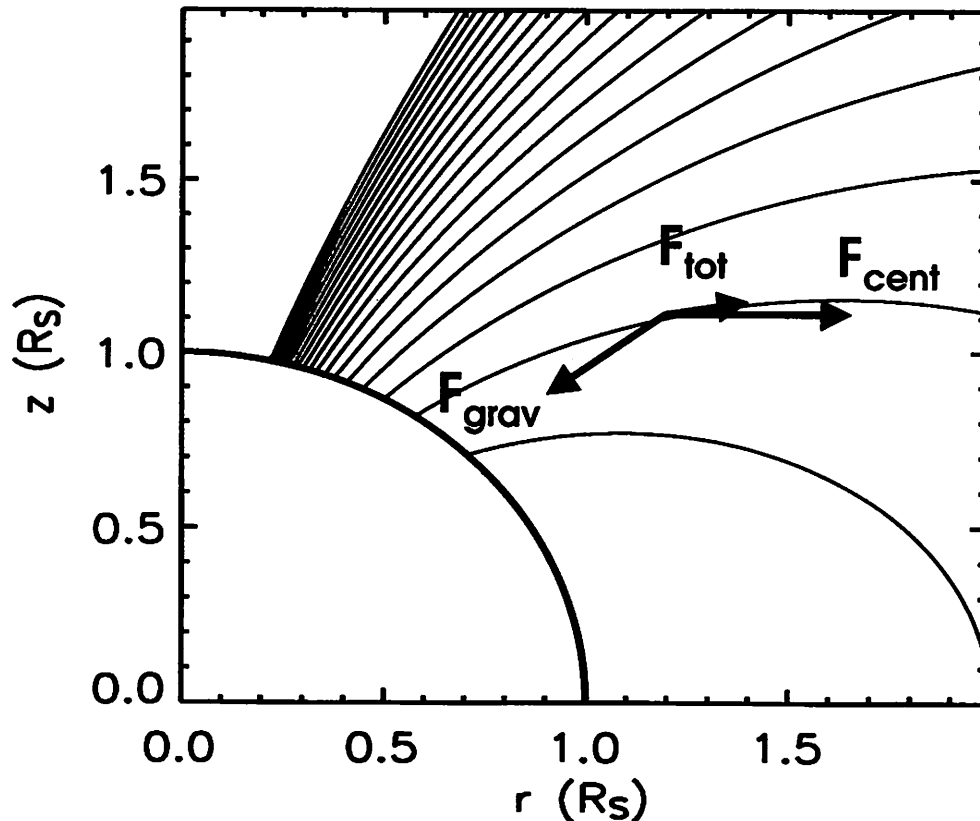
Mars Ionospheric Irregularities Associated With Crustal Magnetic Fields

Electron density profile from MGS, Magnetic fieldlines from Arkani-Hamed model



Saturn's Plasmasphere: Ionospheric Contribution

- (1) Define plasma exobase parameters (z , T , VDF)
- (2) Use Liouville's Theorem \rightarrow solve for moments of VDF
- (3) Evaluate in terms of exospheric classes of particles:

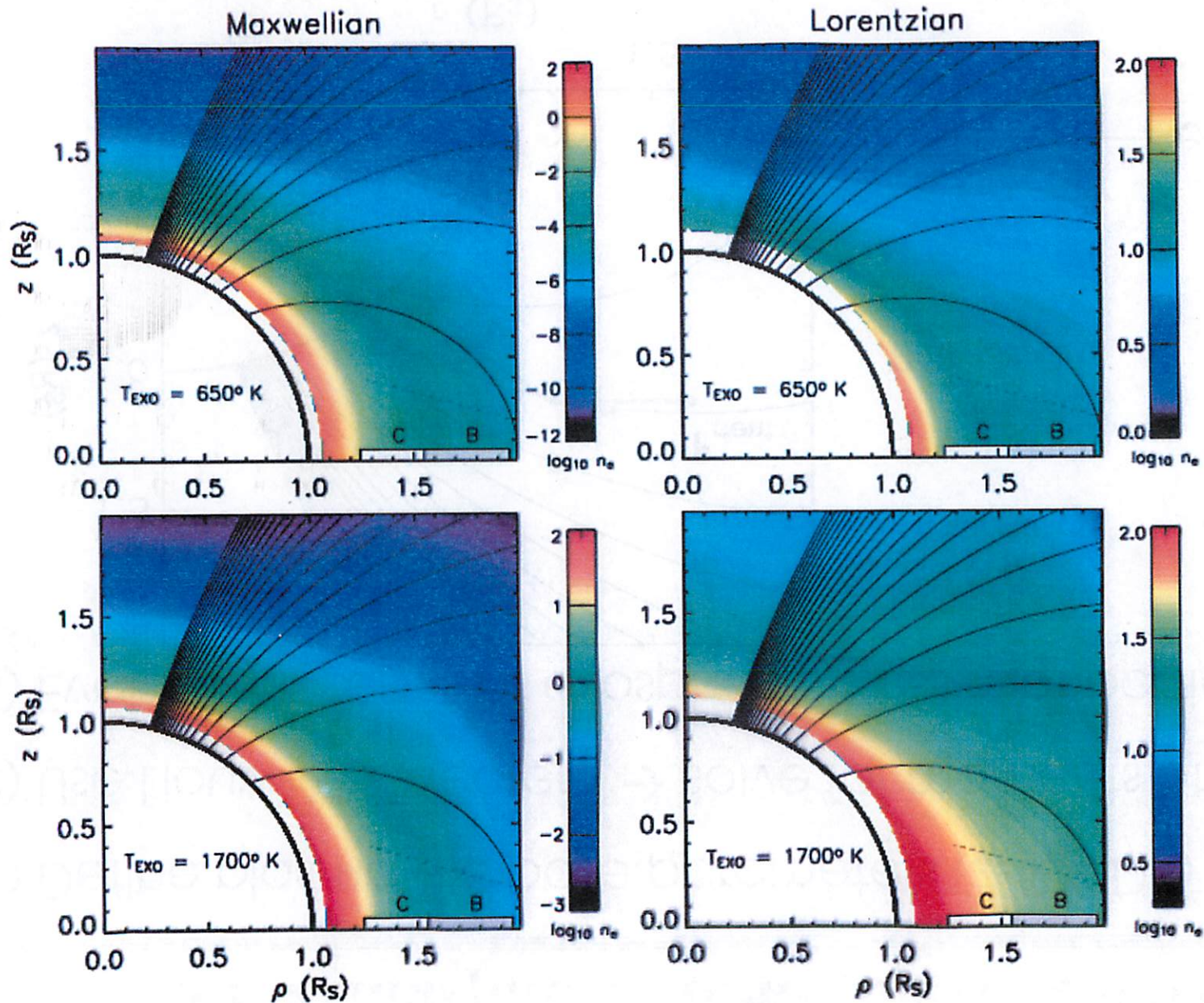


ballistic
incoming
escaping
trapped

$$r_c = \left(\frac{2GM_s}{3\Omega^2} \sec^2 \lambda \right)^{1/3}$$

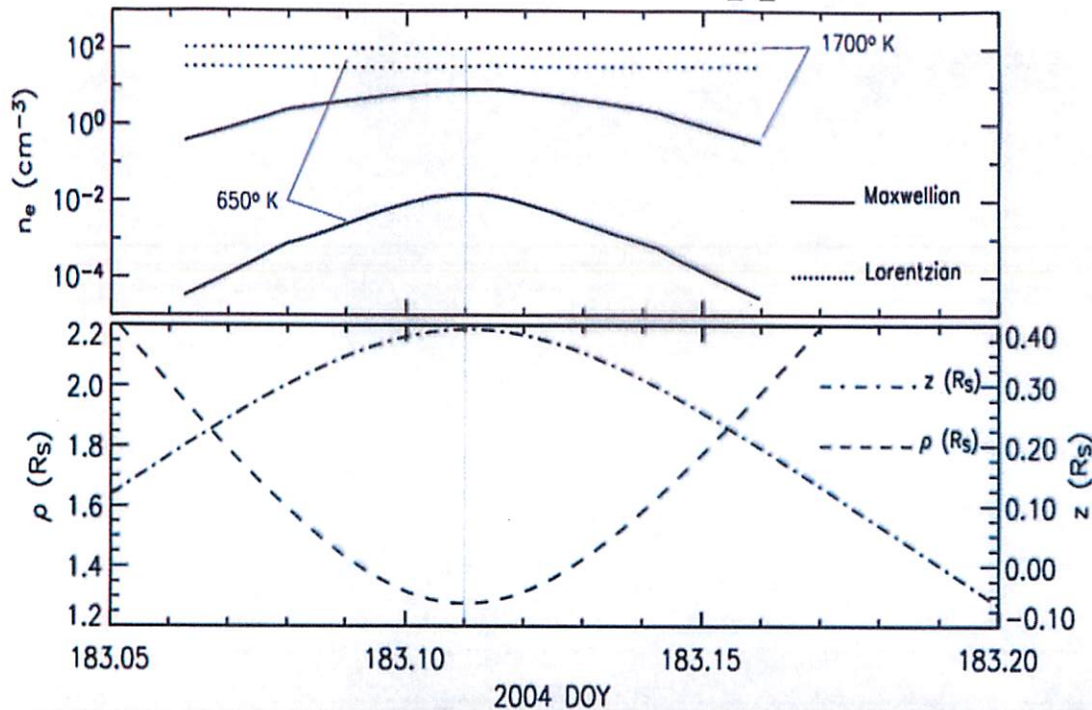
Use derivations of Lemaire (1976) and Pierrard and Lemaire (1996)

Inner Plasmasphere e^- Distributions

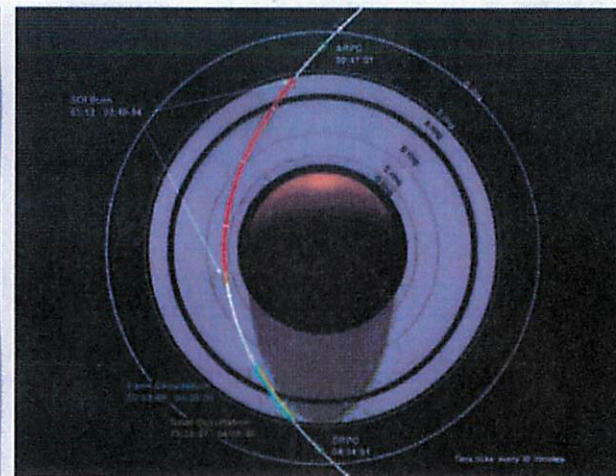
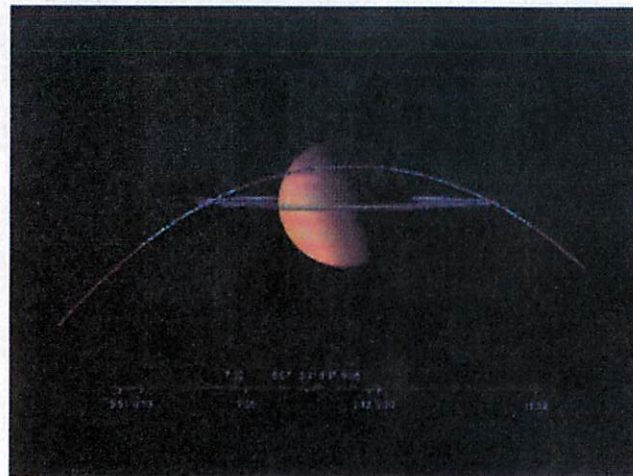
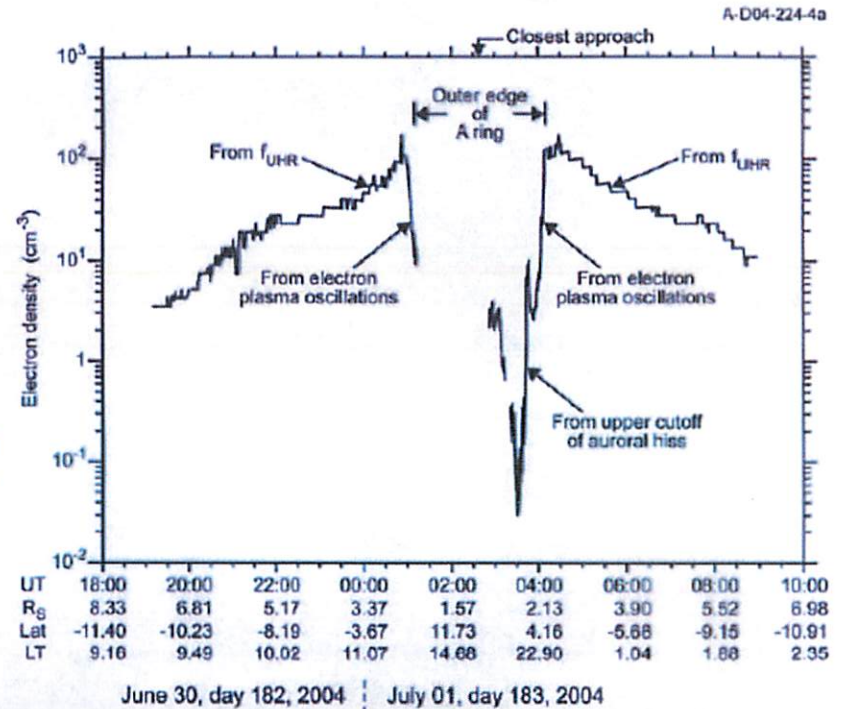


Model Predictions vs Observations

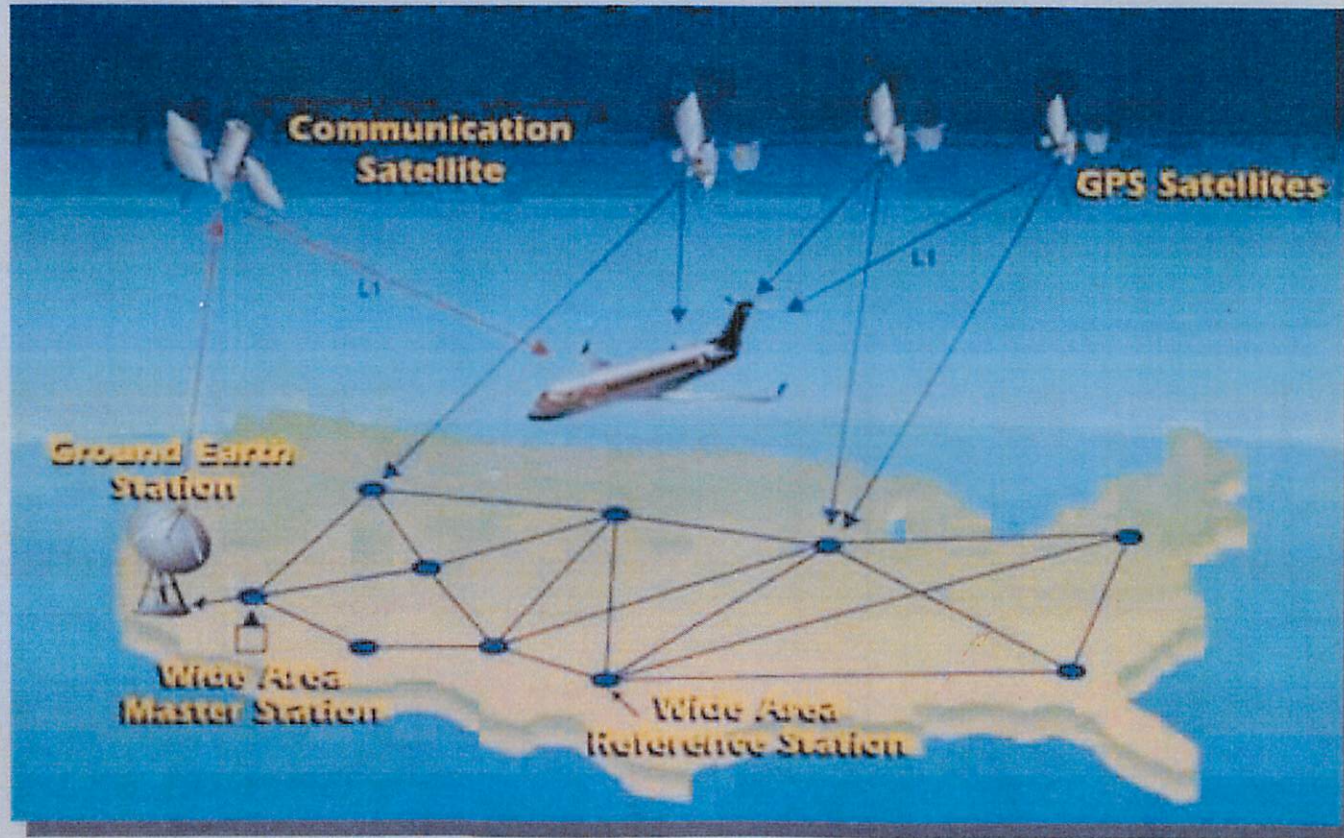
Modeled Closest Approach



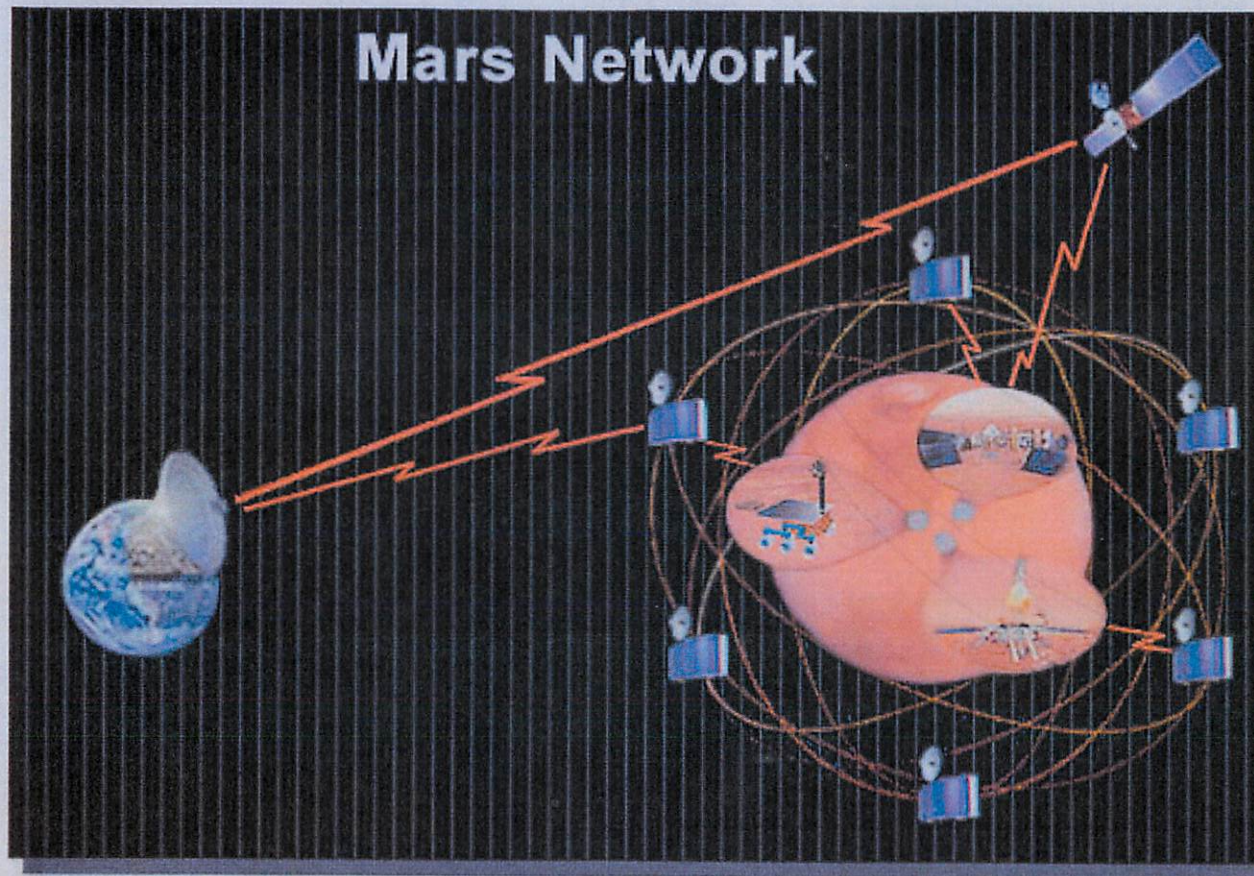
RPWS - Gurnett et al. 2005



GPS Applications



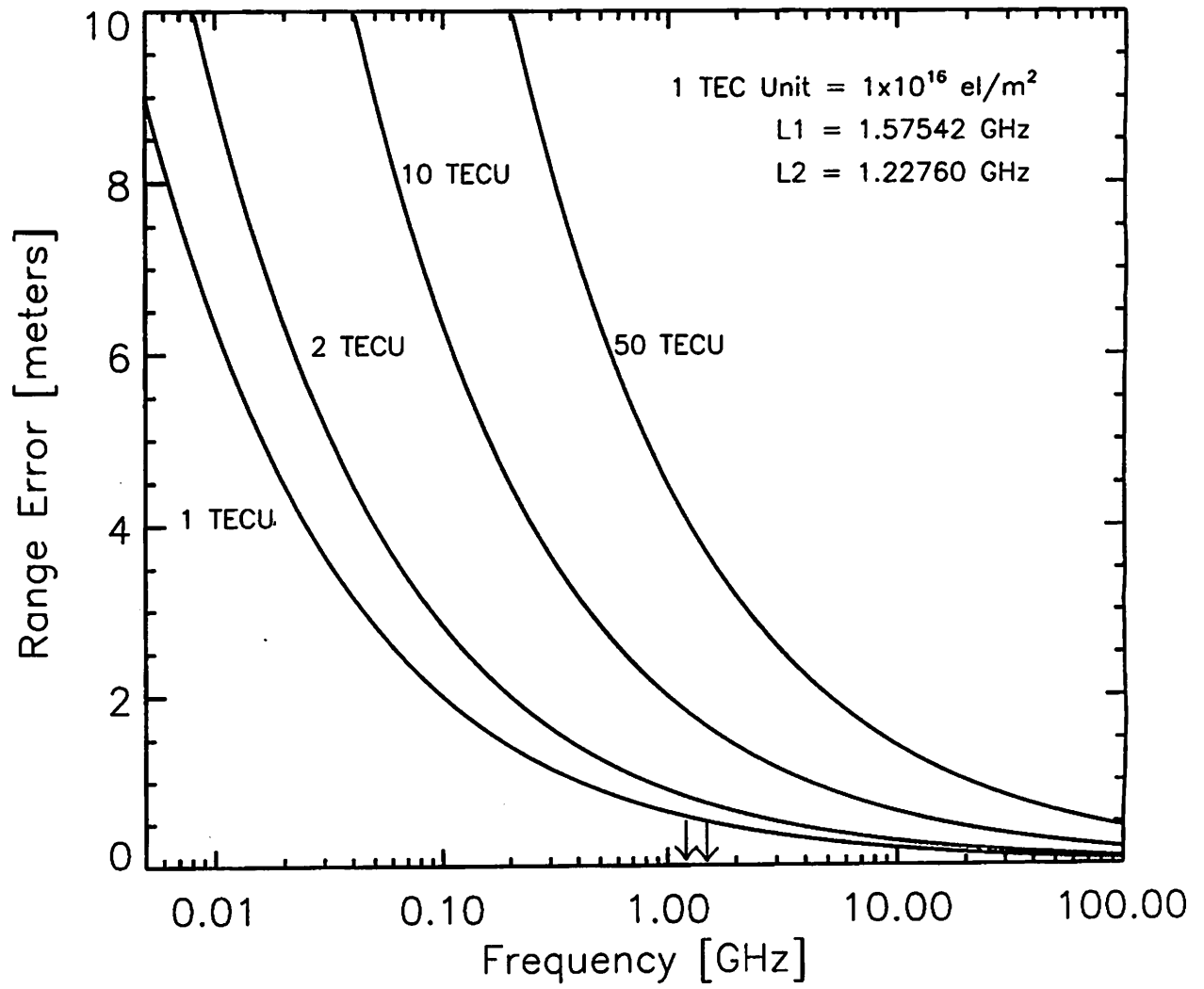
Courtesy to the Federal Aviation Administration.



“As our ability to explore Mars increases, we need to create a capable communications system that will support global reconnaissance of the planet. This infrastructure will also relay back to Earth the vast amounts of information gathered through surface exploration, sample return missions, robotic outposts and even eventual human exploration.”

Courtesy to the Jet Propulsion Laboratory.

Ionospheric Imposed Range Error vs. Frequency for Vertical TEC



Conclusion

IUGG REPORT (Nagy *et al.*, 1995):

"The very basic processes such as ionization, chemical transformations and diffusive as well as convective transport are analogous in all ionospheres;

The major differences are the result of factors such as different neutral atmospheres, intrinsic magnetic field strength, distance from the Sun, etc.

Improving our understanding of any of the ionospheres in our solar system helps in elucidating the controlling physical and chemical processes in all of them."