COMPARATIVE AERONOMY
--- Thermospheres + Ionospheres in the Solar System ---

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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."

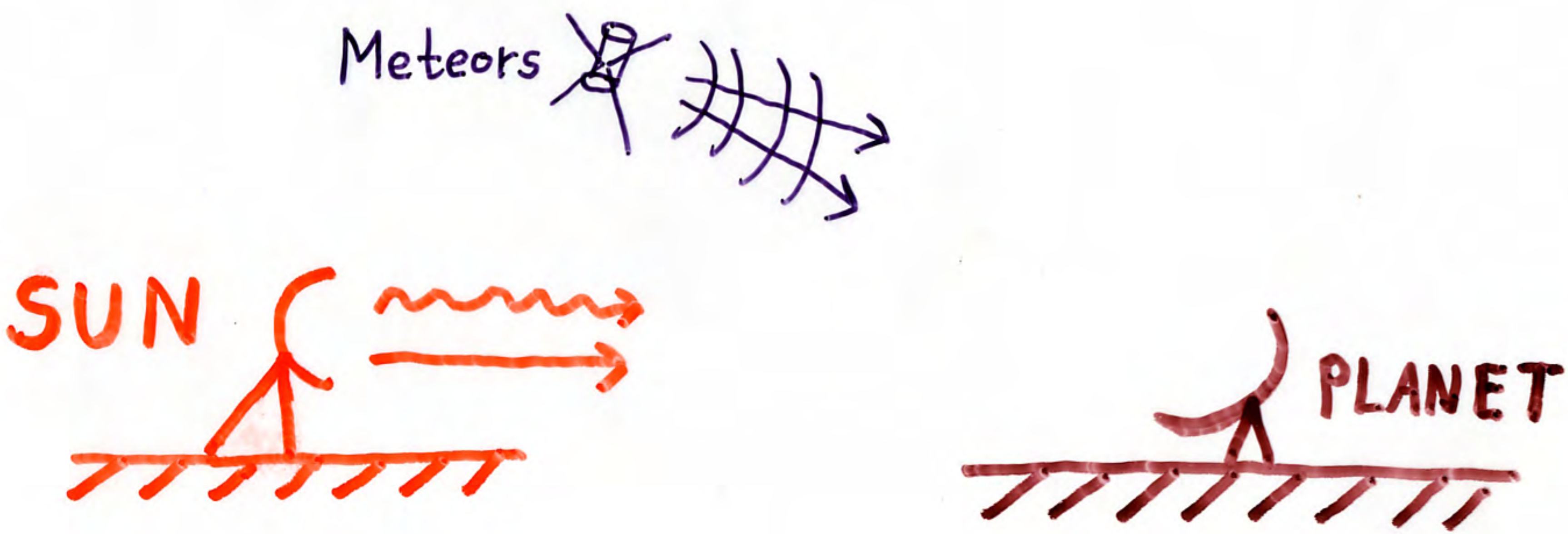
Thermospheres + Ionospheres in the Solar System

- 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

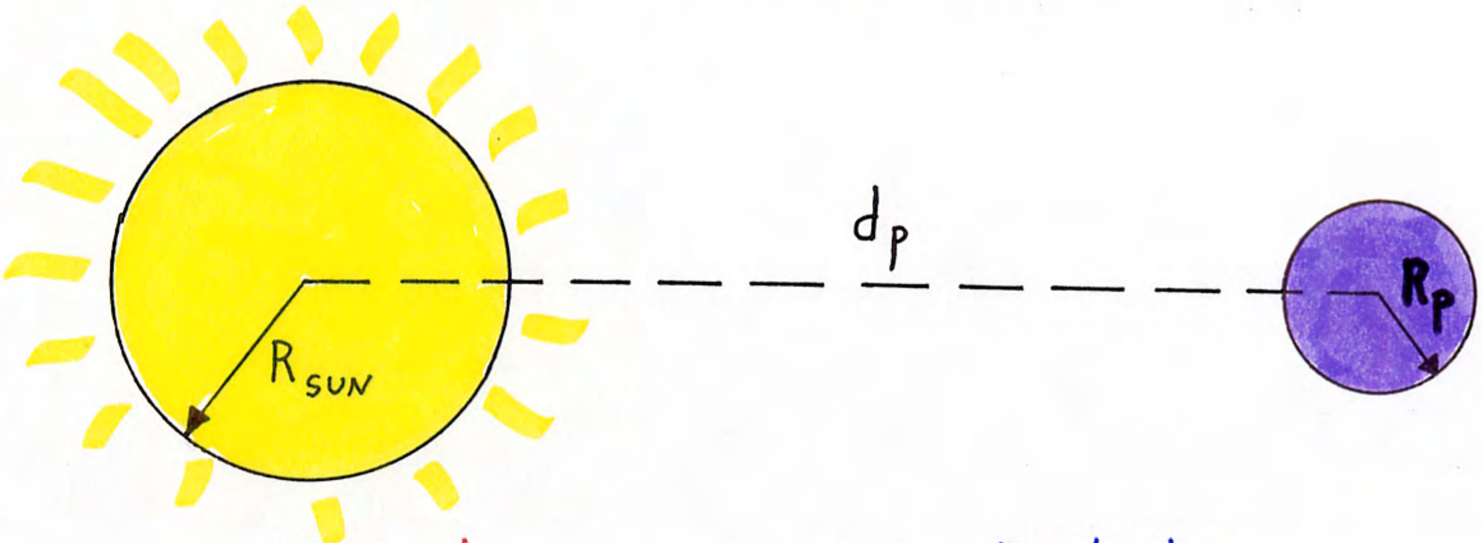
- UN-Common Receivers
  - → Atmospheric Compositions [H, H_2, O, O_2, N, N_2, He, Ar, Hydrocarbons]
  - → Magnetic Fields
    - None [Venus]
    - Crustal [Mars]
    - Global [Mercury, Earth, Jovians]
  - → Rotation Rates



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



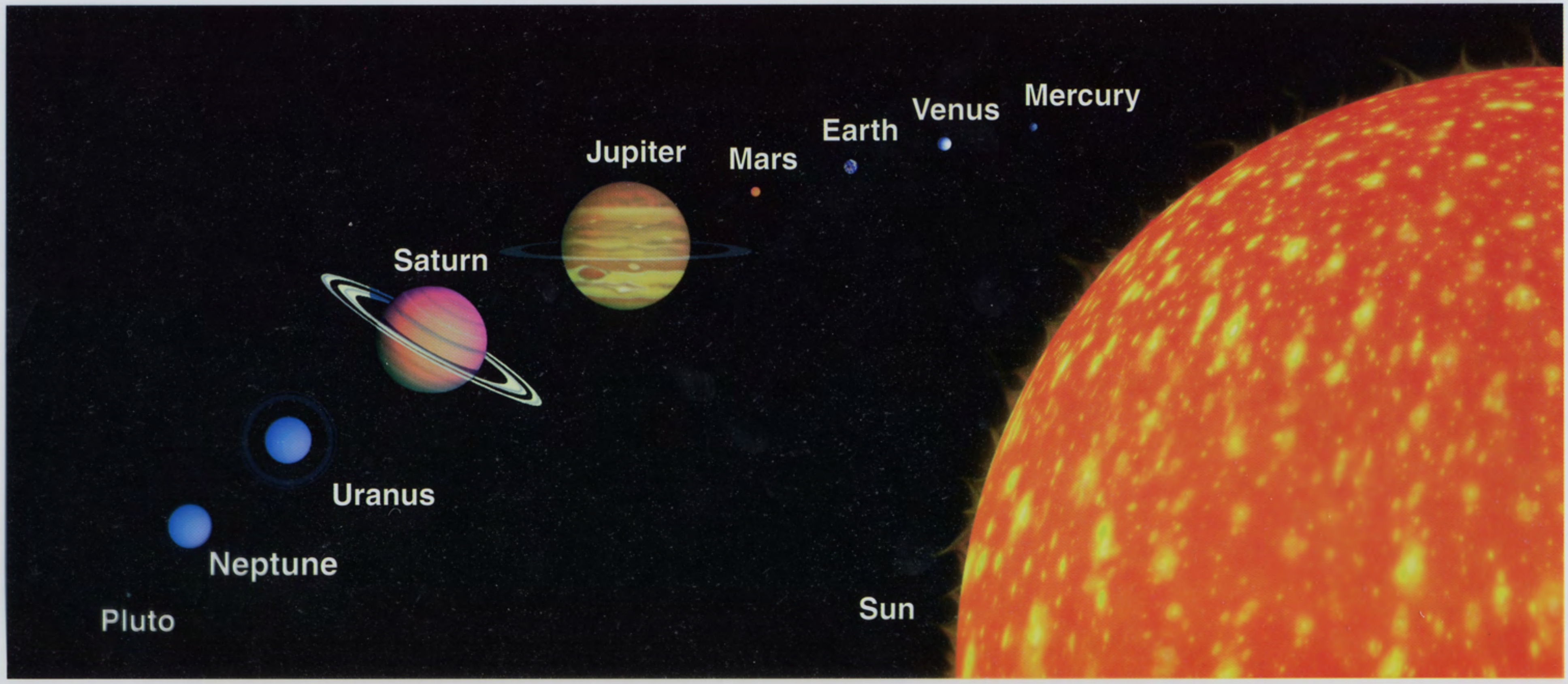
Absorption = Radiation

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

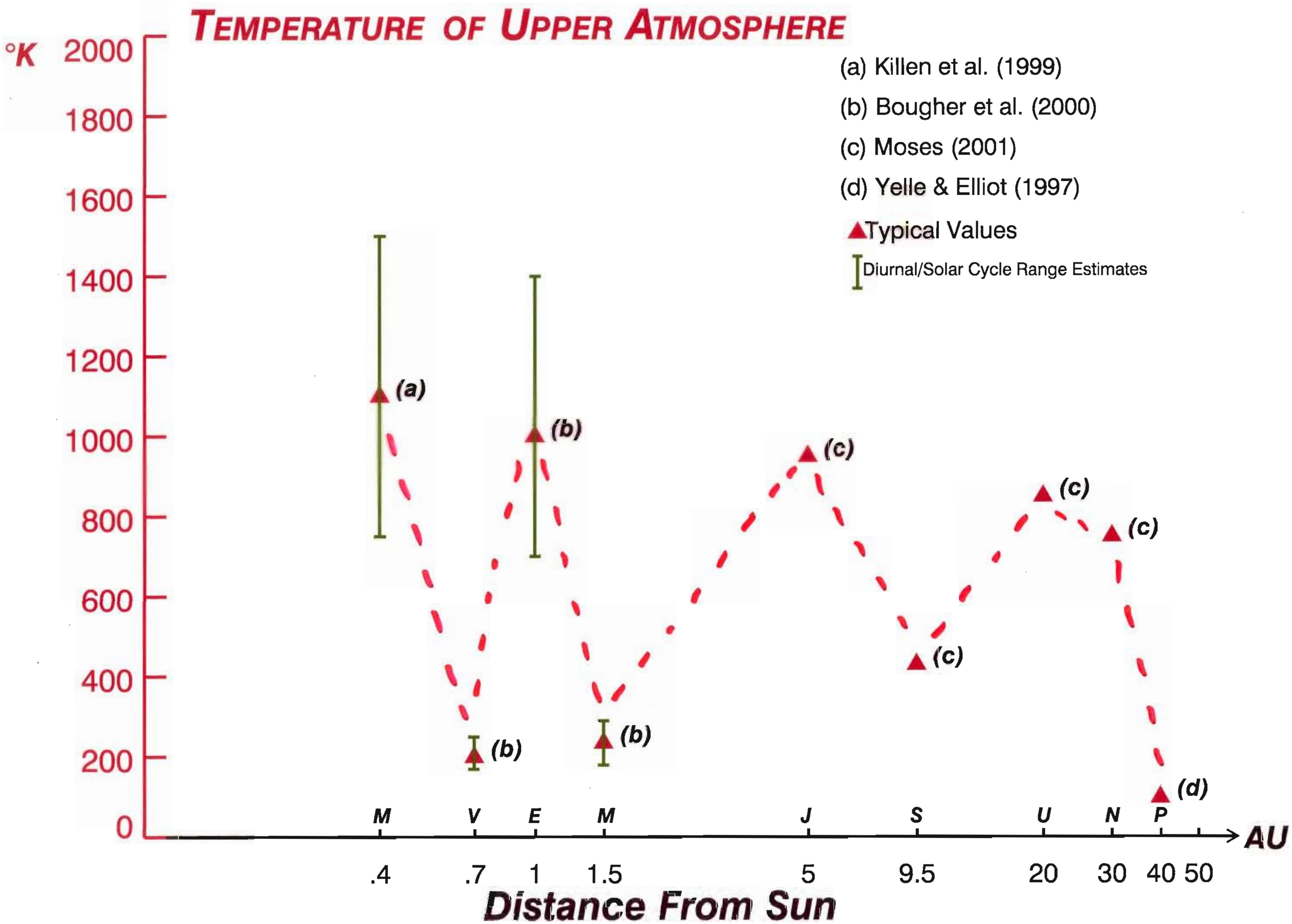
$$T_p \approx \frac{250°K}{\sqrt{d_p(AU)}}$$

(for constant Albedo, A)

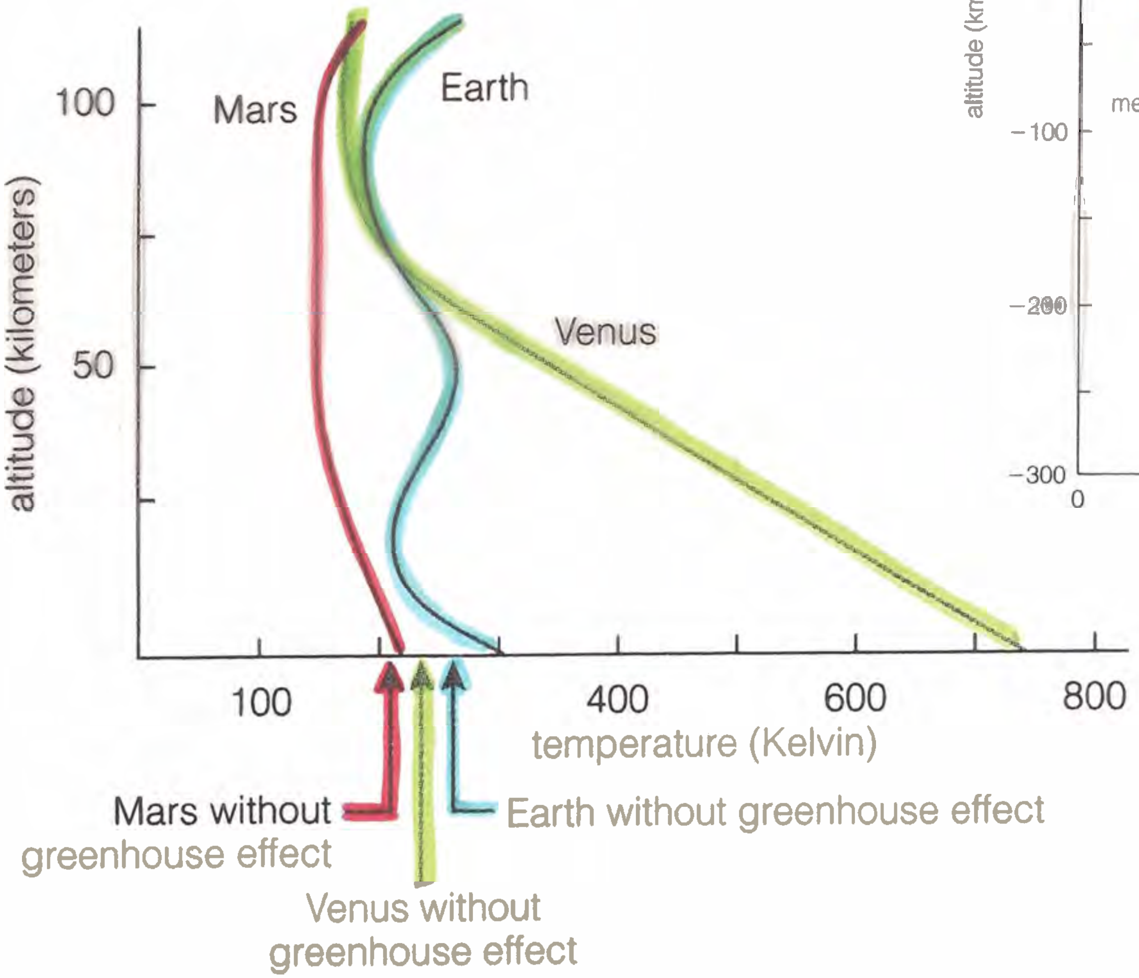
Fig. 1.6 The sizes of the Sun and planets on a 10-billion-to-one scale.

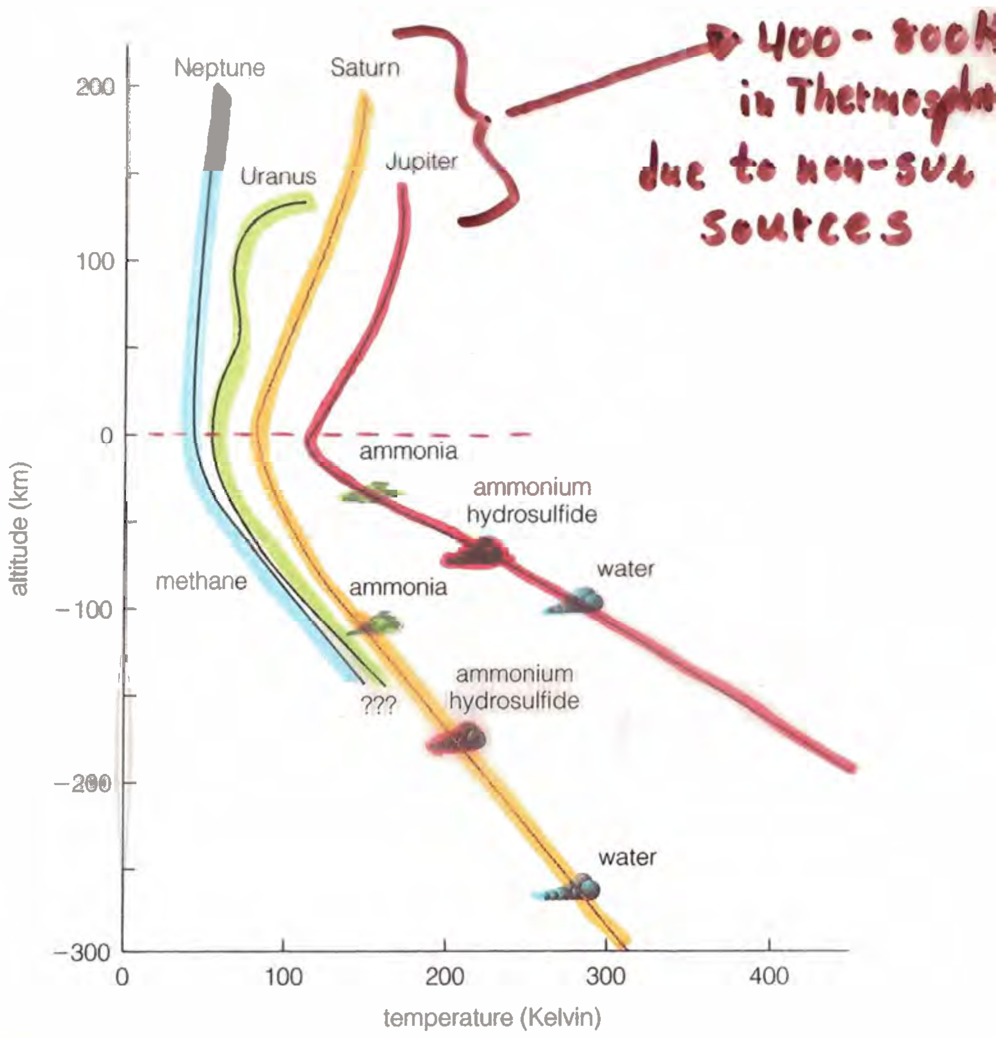


Neutral Atmosphere Characteristics in the Solar System



GREENHOUSE EFFECTS ON TERRESTRIAL PLANETS

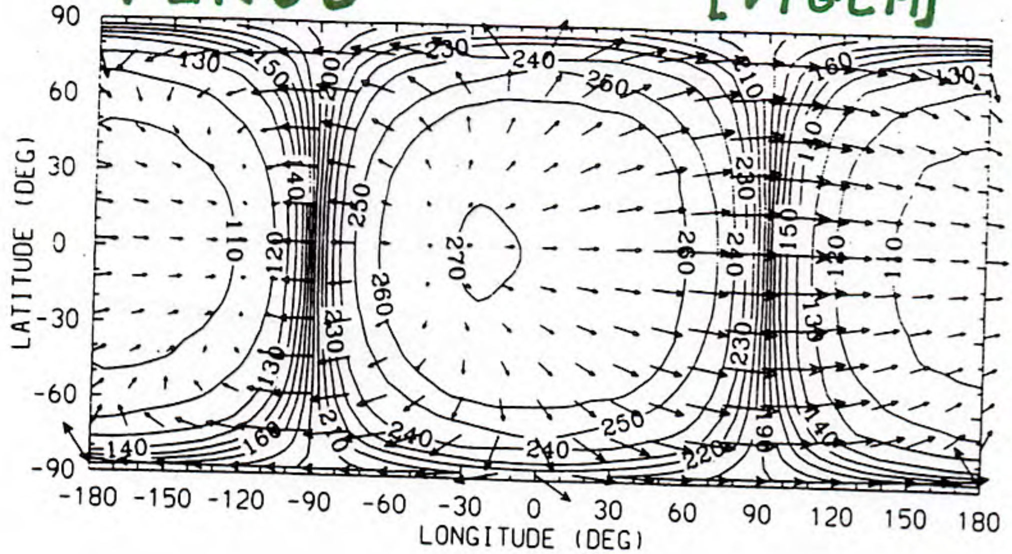




JOVIAN PLANETS

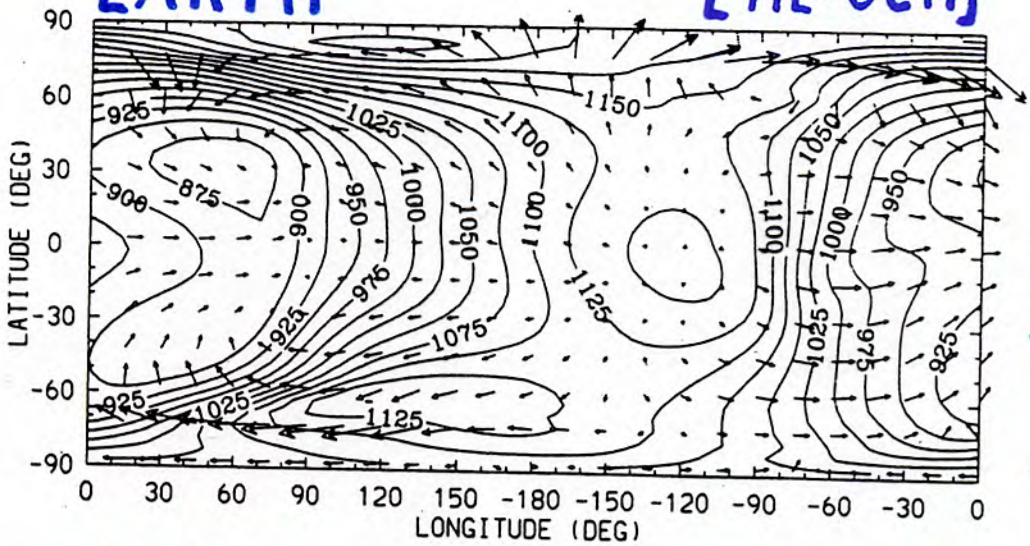
Exobase Parameters for Solar Median Conditions

VENUS [VTGCM]



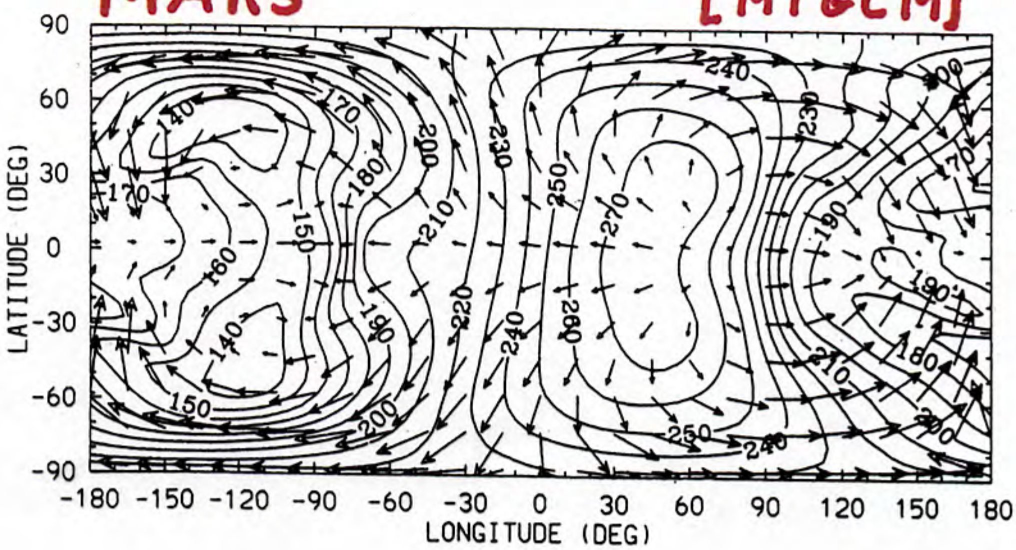
Z = 7
($\bar{h} \simeq 170$ Km)
$T_{min} \simeq 110$ °K
$T_{max} \simeq 270$ °K
→ = 240 m/s

EARTH [TIE-GCM]



Z = 7
($\bar{h} \simeq 550$ Km)
$T_{min} \simeq 865$ °K
$T_{max} \simeq 1150$ °K
→ = 460 m/s

MARS [MTGCM]

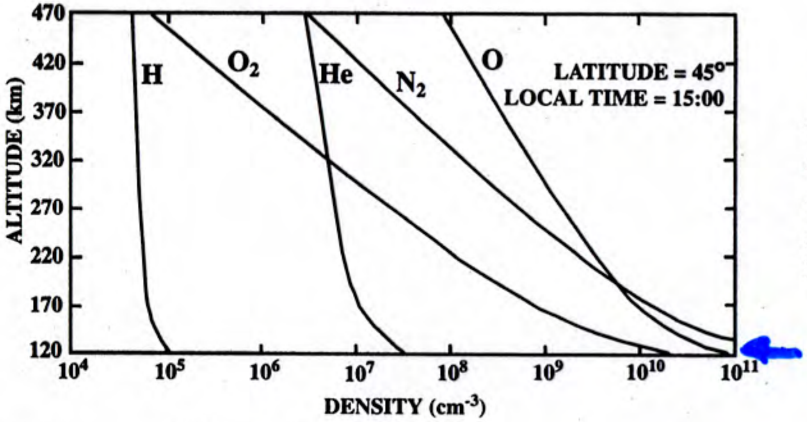


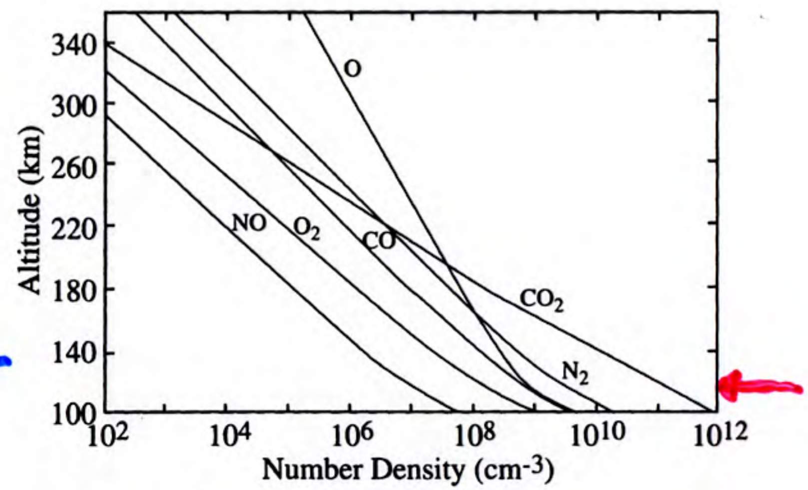
Z = 6
($\bar{h} \simeq 195$ Km)
$T_{min} \simeq 135$ °K
$T_{max} \simeq 275$ °K
→ = 260 m/s

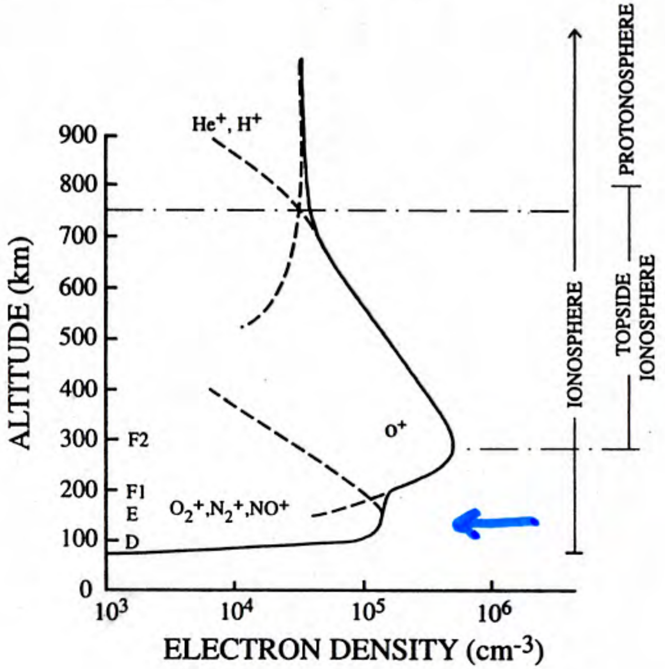
COMPARATIVE ATMOSPHERES/IONOSPHERES*

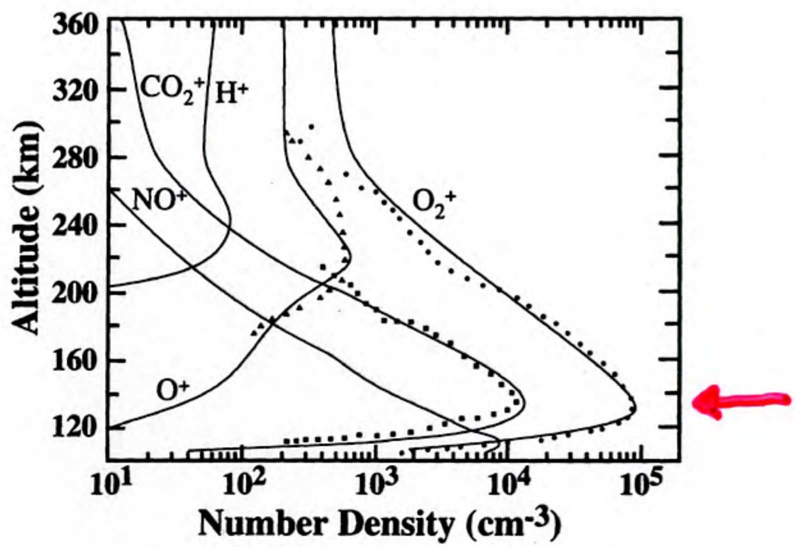
EARTH

MARS









E-Region

$h_mE \approx 110$ km

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

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

Maximum

$h_m \approx 135$ km

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

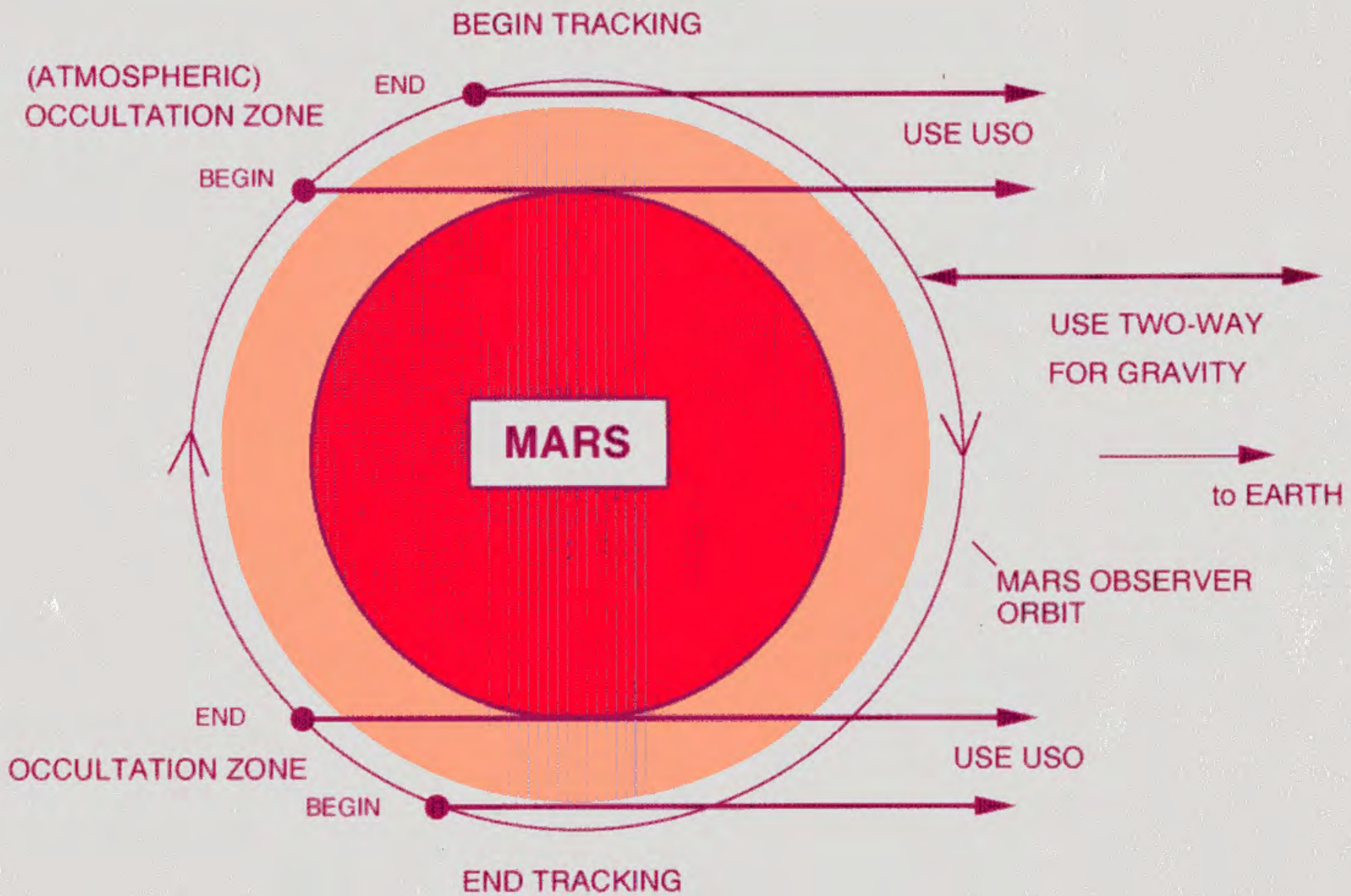
$[e^-] \approx 10^5$ cm^{-3}

* Schunk and Nagy (2000): IONOSPHERES, Physics, Plasma Physics, and Chemistry; Camb. Univ. Press

MARS Global Surveyor Radio Occultations

MGS Radio Science

Observational Strategy



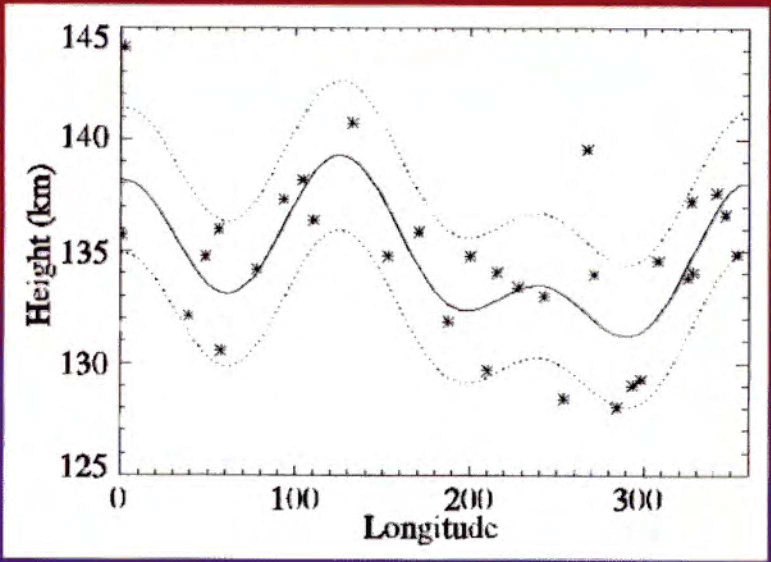
– from D. Hinson (Stanford U.)

Imaging science

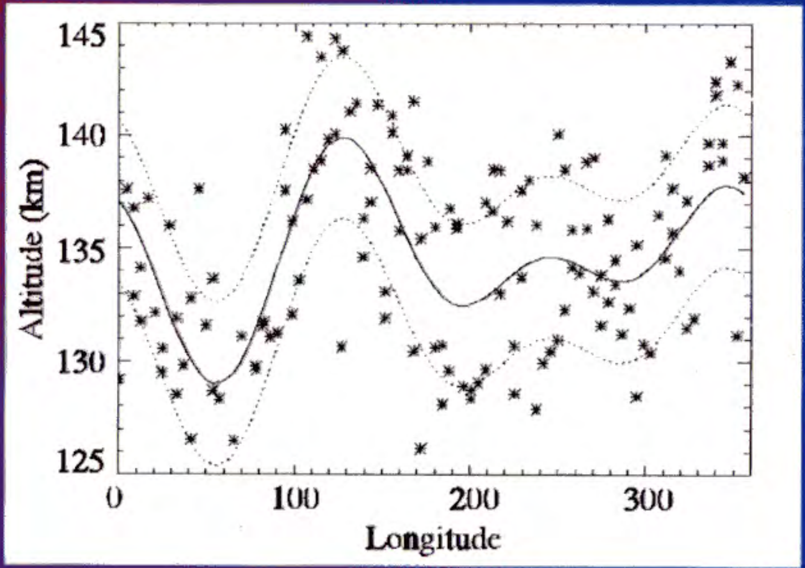
BOSTON UNIVERSITY

MARS IONOSPHERE: COUPLING FROM BELOW

--Systematic variations between the height of maximum electron density (h_mM2) 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 ➡ longitudinally dependent thermospheric motions ➡ ionospheric photochemistry at unit optical depth ➡ longitude-dependent h_mM2 (and not N_mM2).

–See J. Forbes' Nicolet Lecture: AGU Website

— Molecular Ion Plasmas —

Photo-Chemical Equilibrium

	EARTH	MARS
Production (P_o) :	$N_2 + h\nu \xrightarrow{k_1} N_2^+ + e^-$	$CO_2 + h\nu \xrightarrow{k_3} CO_2^+ + e^-$
Transformation :	$N_2^+ + O \xrightarrow{k_2} NO^+ + N$	$CO_2^+ + O \xrightarrow{k_4} O_2^+ + CO$
Loss (L):	$NO^+ + e^- \xrightarrow{\alpha_1} N + O$	$O_2^+ + e^- \xrightarrow{\alpha_2} O + O$

For $P_o = L$: $\mathbf{P_o = \alpha N_e^2}$

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

active regions (27-day) +
solar cycle dependence

In general, with $\chi \equiv$ $\underbrace{\text{Solar zenith}}$ 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: $Q = \Phi_{sun}(\lambda) \cdot \sigma_{ion}(\lambda)\, n(X_2)$

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

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

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

[for same/similar molecules, $N_{max}(h_{max})$ occurs at Q_{max}, where $\tau \simeq 1$, effectively where $n(X_2) \simeq 10^{11}/cm^3$]

Two Chapman "Scaling Laws":

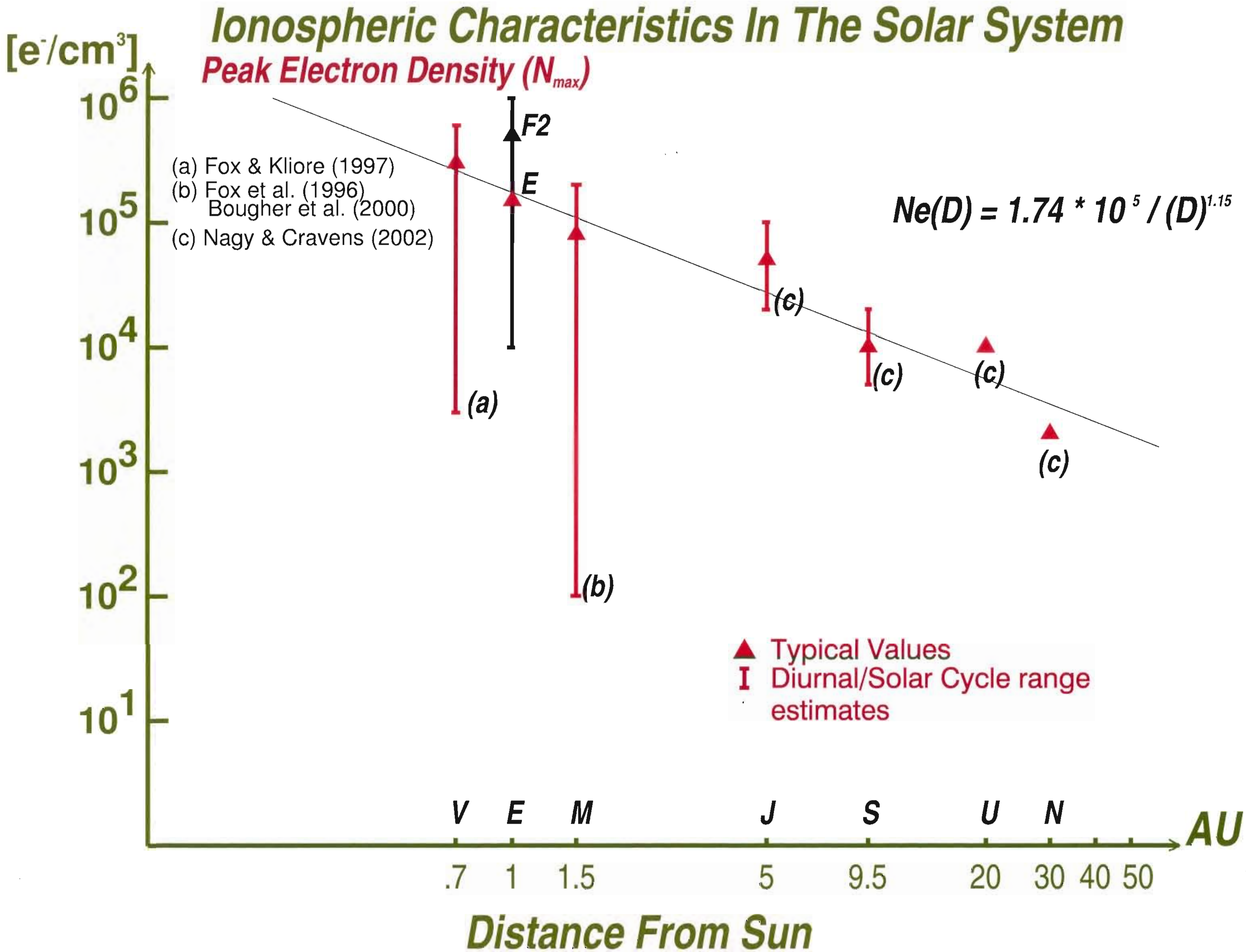
(a) For planets at distances (d_p), only solar flux varies with d_p,

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

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

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

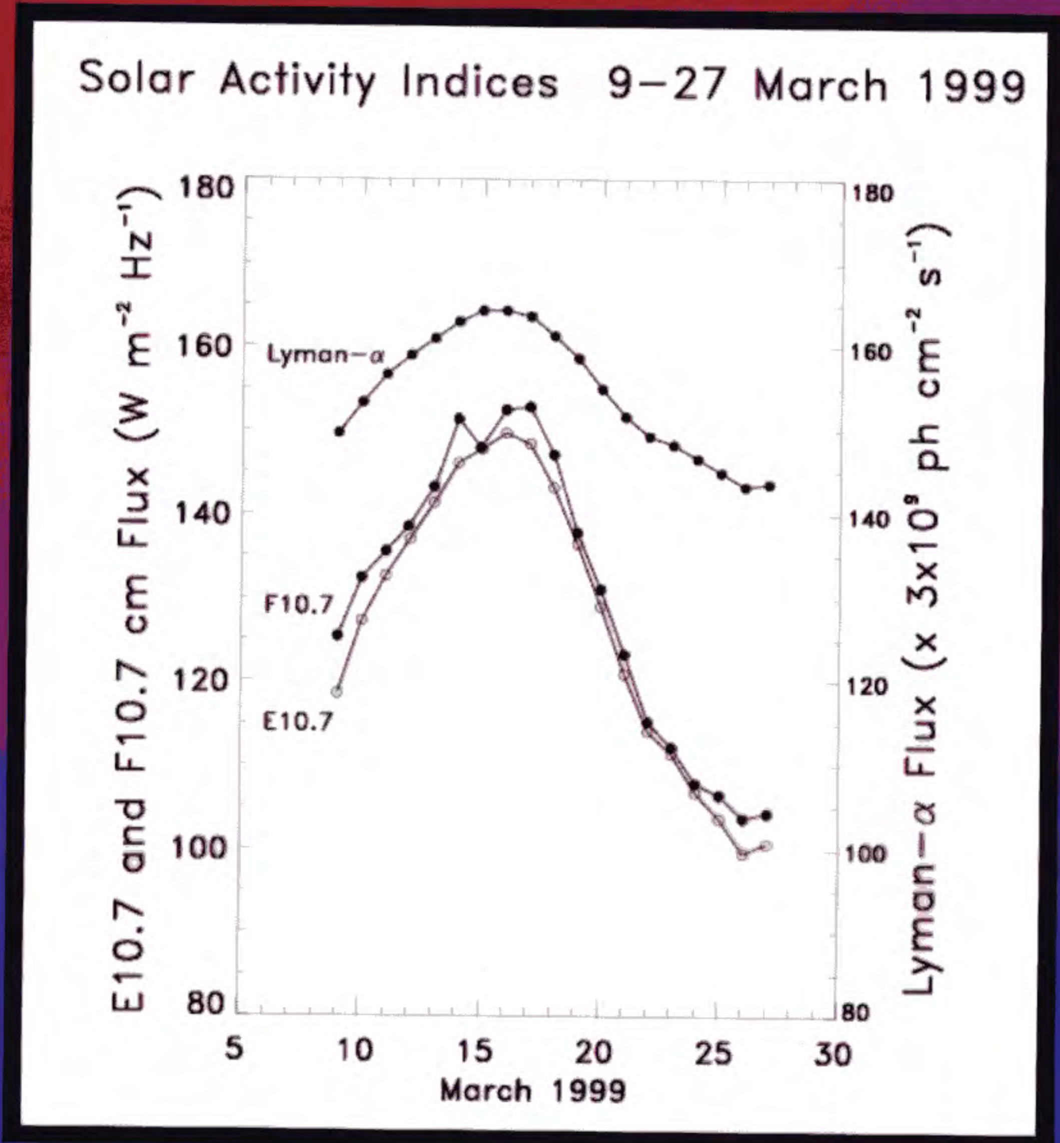
--- **Implication:** Ionospheric Variability $\propto$ Solar Variability

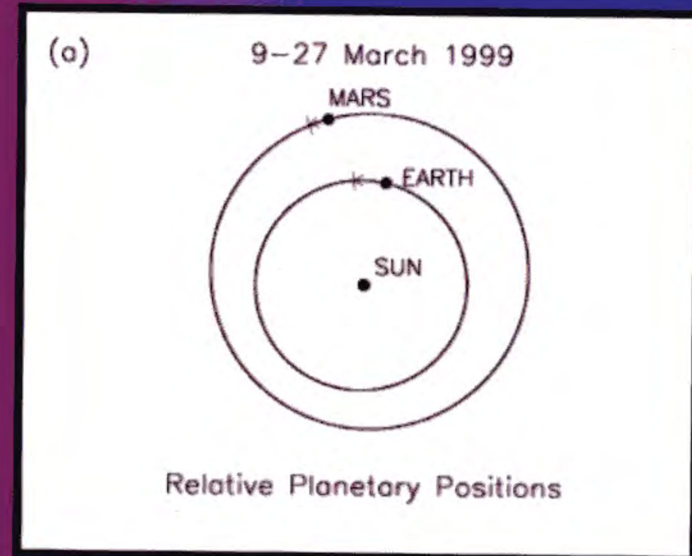


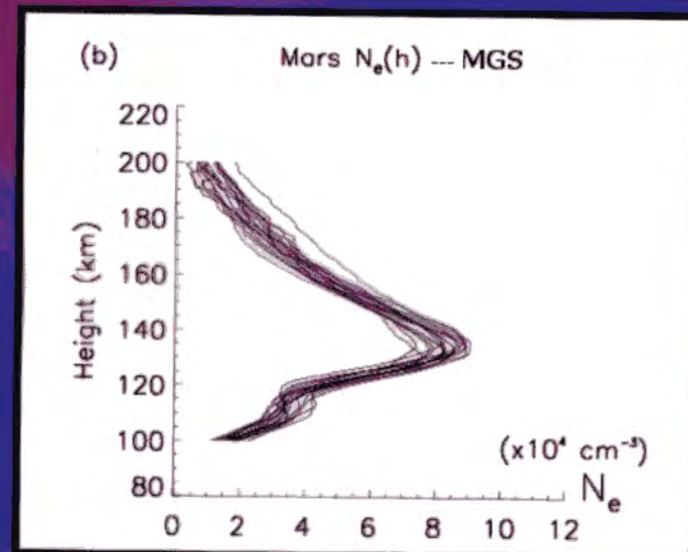
Ionospheric Characteristics In The Solar System
[e-/cm3]
Peak Electron Density (N max)
10^6
10^5
10^4
10^3
10^2
10^1
F2
E
(a) Fox & Kliore (1997)
(b) Fox et al. (1996)
Bougher et al. (2000)
(c) Nagy & Cravens (2002)
Ne(D) = 1.74 * 10^5 / (D)^1.15
(a)
(b)
(c)
(c)
(c)
(c)
Typical Values
Diurnal/Solar Cycle range estimates
V
E
M
J
S
U
N
AU
.7
1
1.5
5
9.5
20
30
40
50
Distance From Sun

Response to Solar Activity: Example - Active Regions

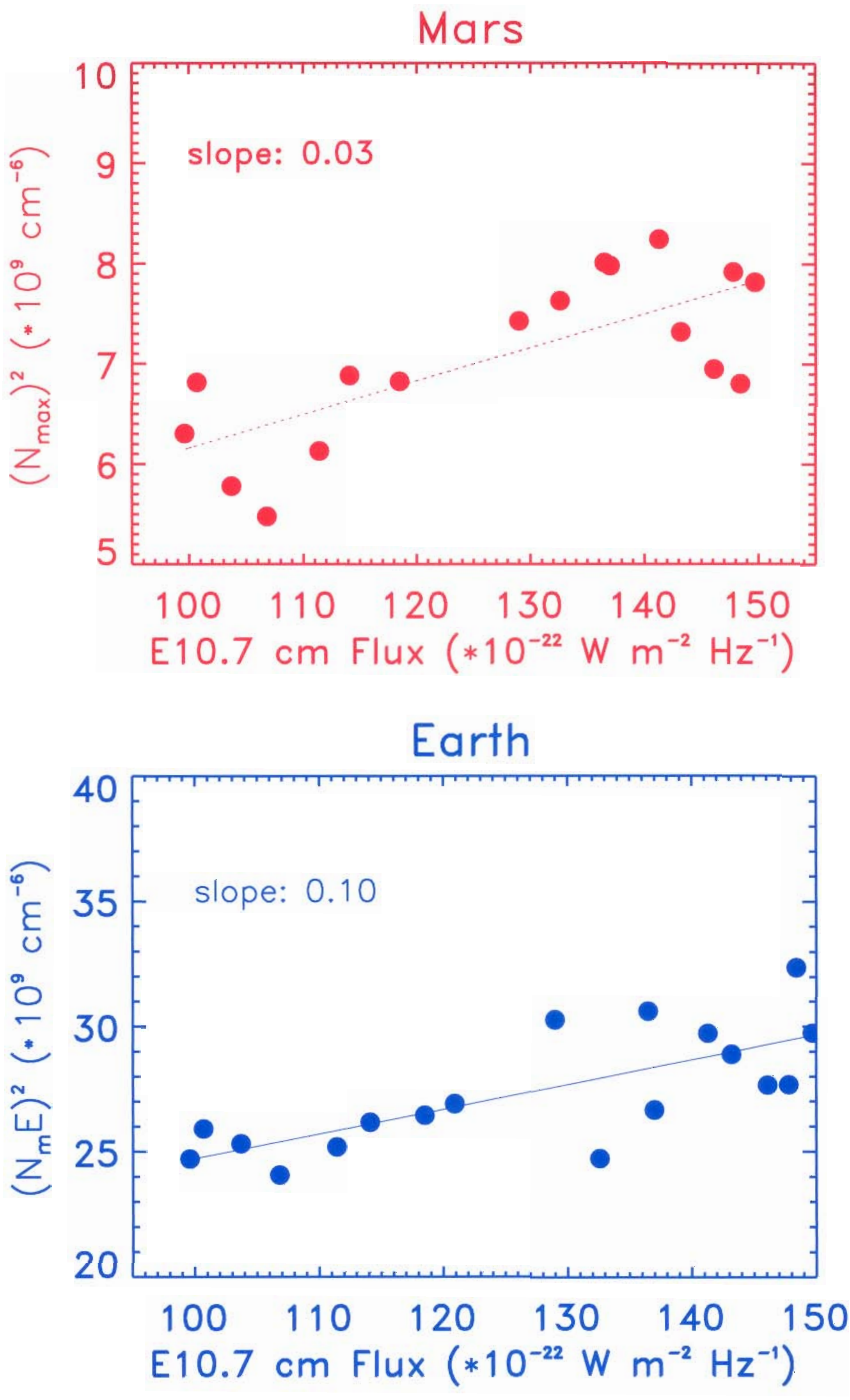
Case Study Period --- Mars near Opposition during a month of pronounced Solar Activity







COMPARATIVE IONOSPHERES: 9-27 MARCH 1999



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)

(Jupiter and Saturn:) 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
  - ΔNmax by MEX (Gurnett et al., 2005) --- 15 September 2005

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

Solar Flare Effect Upon Terrestrial Ionosphere

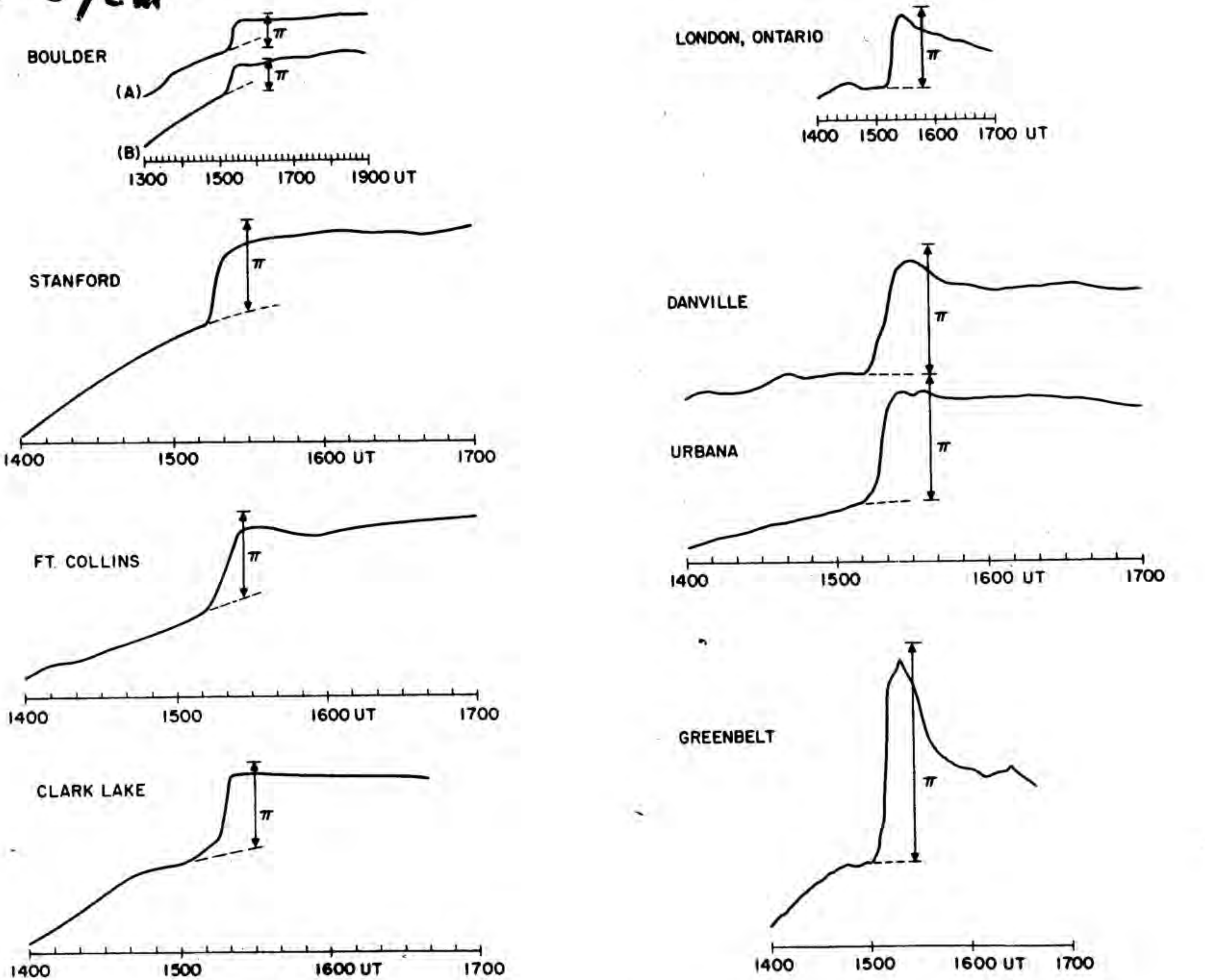
- X-rays → ΔN_e at low altitudes
  - → Sudden Frequency Deviations (SFDs)
    - ↓ Used to infer temporal patterns of flare hard X-rays prior to satellite era
  - → Prevent Ionosondes from observing effects of soft X-rays ($\Delta f_o E$) and EUV ($\Delta f_o F2$)

- EUV → $\Delta N_e(h)$ in F-layer
  - → ΔTEC (SITEC)
  - → ΔT_e and $\Delta \vec{V}_{plasma}$

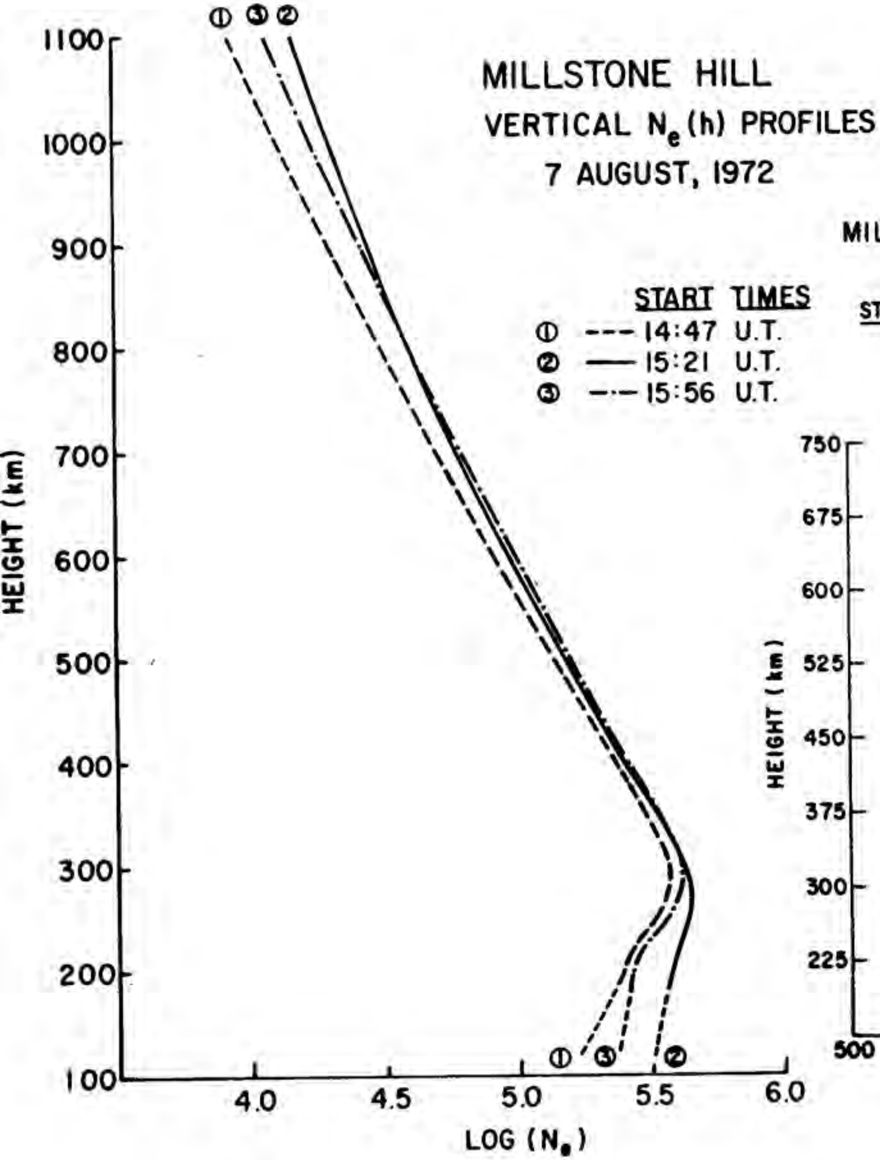
- Solar Flares as "Active Experiments" in Solar-Planetary Relations

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

$\pi \approx 4 \times 10^{16}\ e^-/cm^2$



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



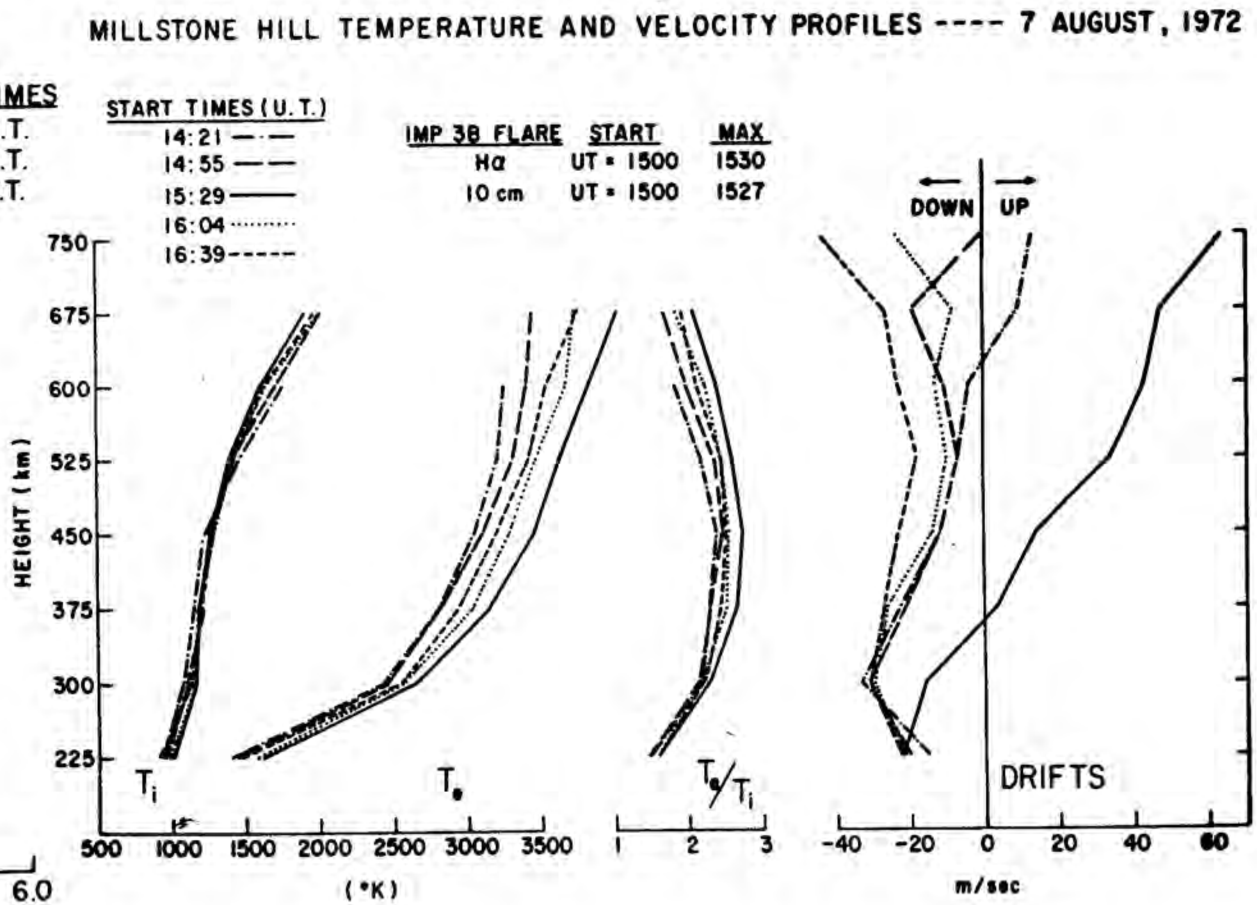
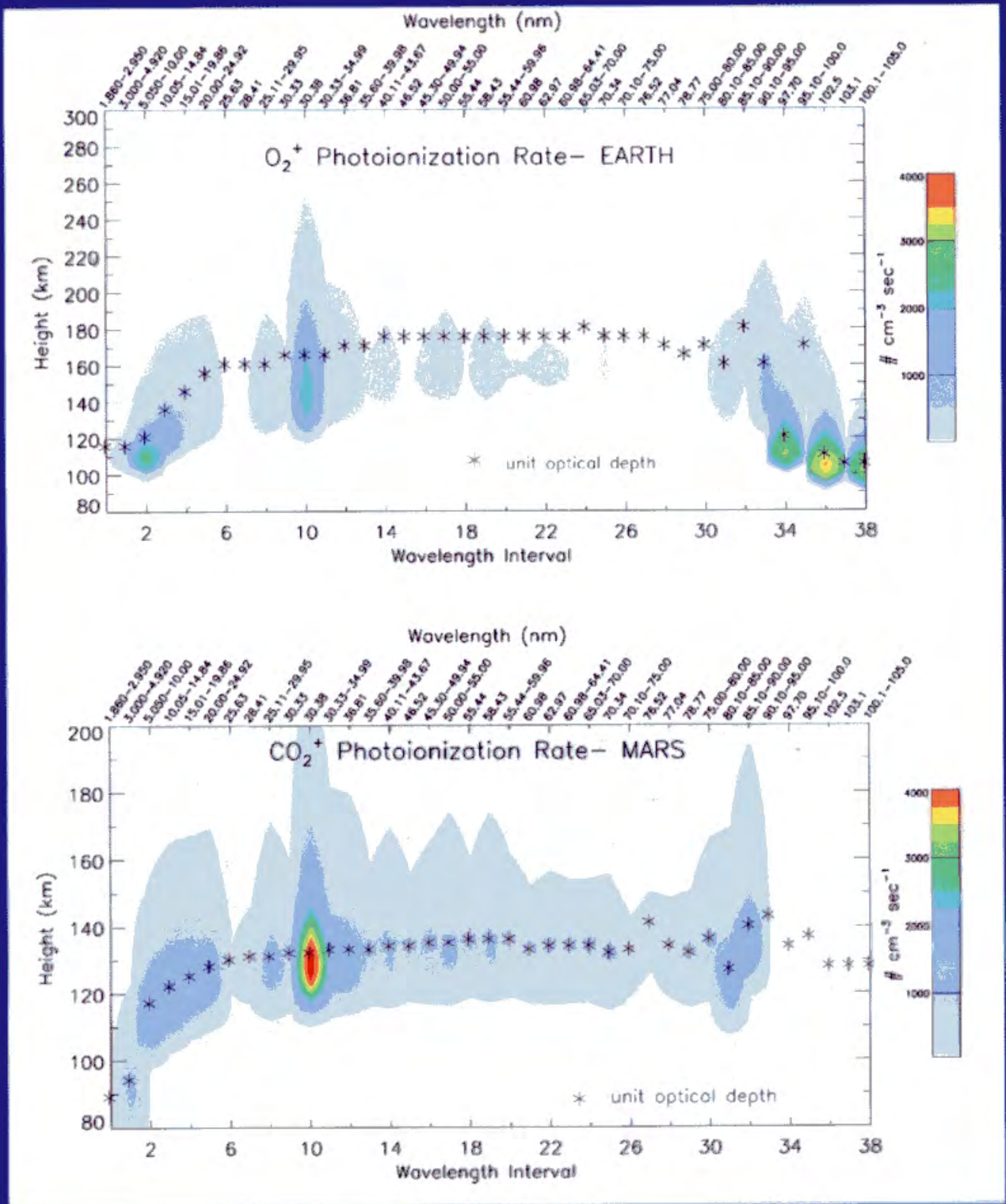
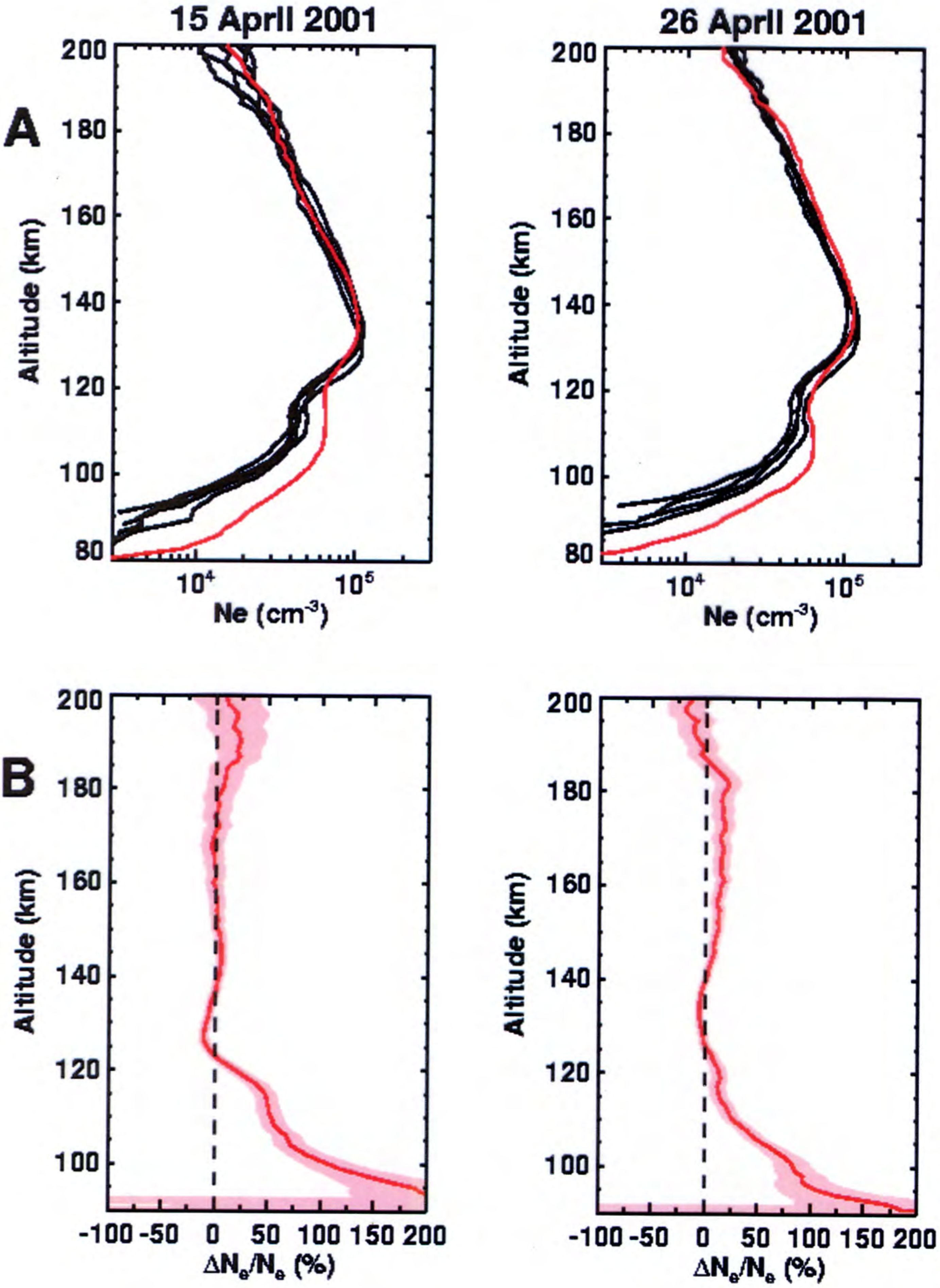


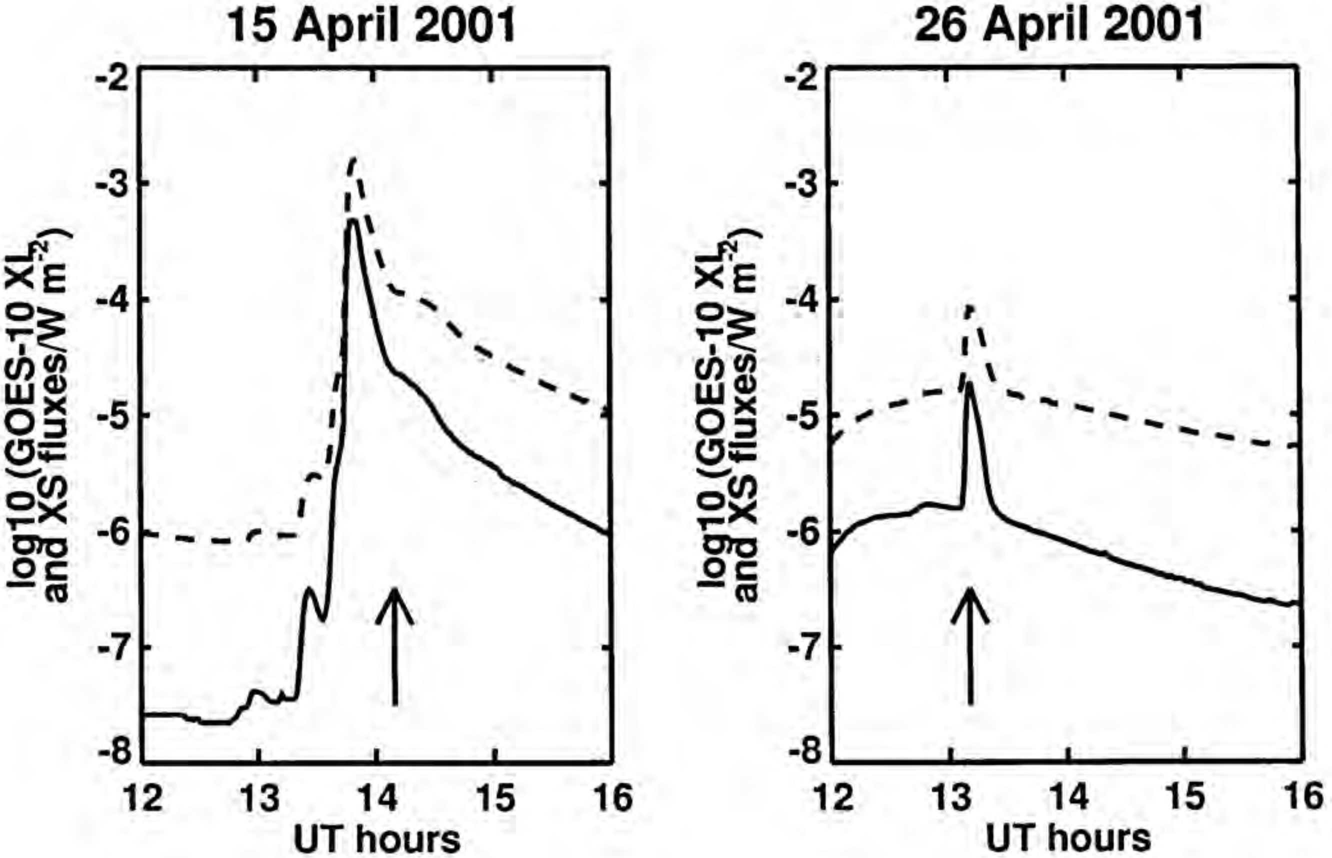
Photo-production vs. λ

EARTH

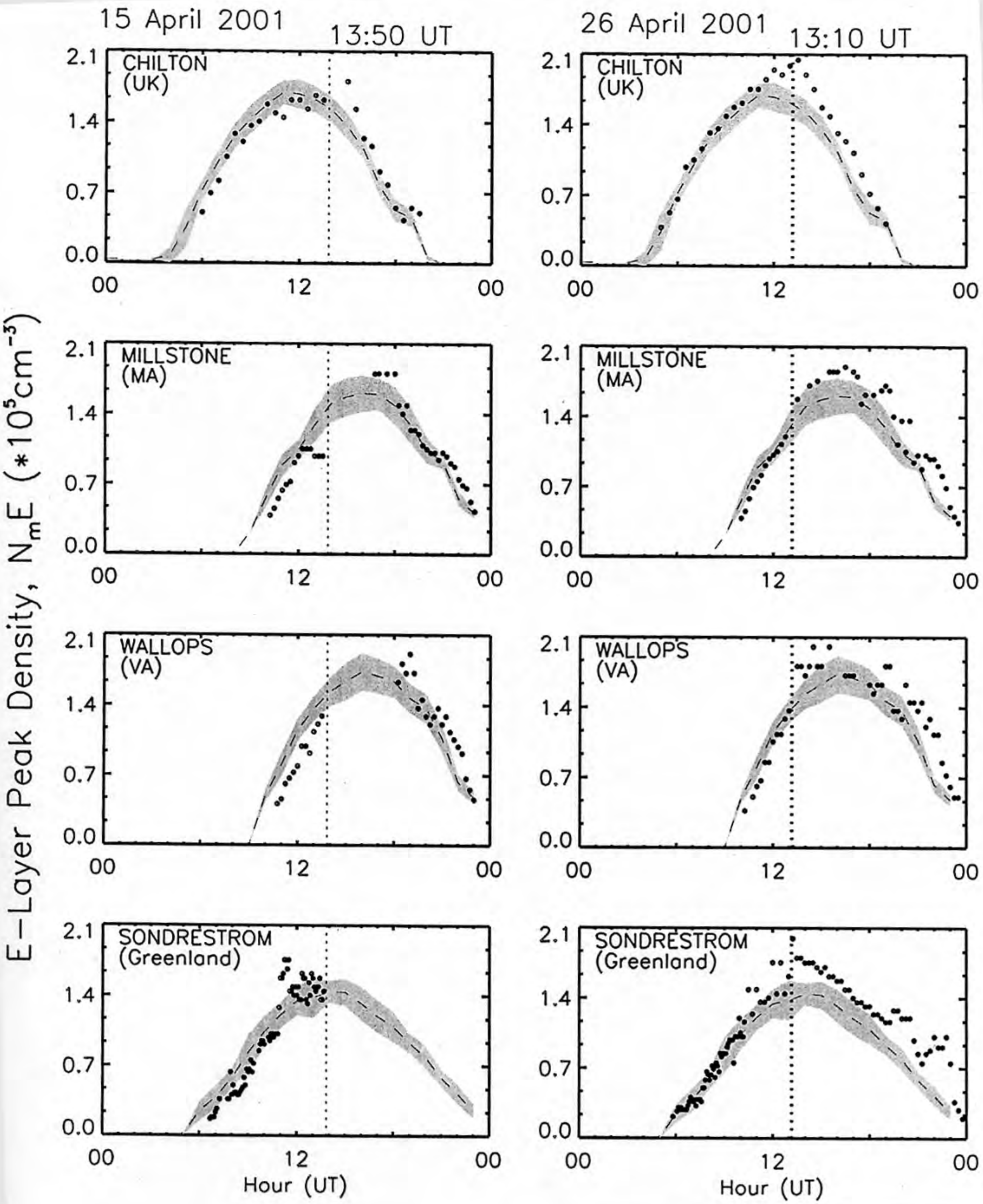
MARS




15 April 2001
26 April 2001
A
B
Altitude (km)
Ne (cm^{-3})
10^4
10^5
80
100
120
140
160
180
200
-100 -50 0 50 100 150 200
$\Delta N_e/N_e$ (%)



15 April 2001
26 April 2001
log10 (GOES-10 XL and XS fluxes/W m^{-2})
-2
-3
-4
-5
-6
-7
-8
12
13
14
15
16
UT hours


15 April 2001
13:50 UT
26 April 2001
13:10 UT
CHILTON (UK)
MILLSTONE (MA)
WALLOPS (VA)
SONDRESTROM (Greenland)
E-Layer Peak Density, N_mE ($*10^5 cm^{-3}$)
Hour (UT)
2.1
1.4
0.7
0.0
00
12
00

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)

  → O, O_2, N_2 (EARTH, MARS + VENUS)

- CONSTRAIN DYNAMO PROCESS
  - — SFE $\overrightarrow{\Delta B} = f\left(|B| \text{ and } \vec{u}_{neutrals}\right)$

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

--- Effects of Eclipses + Shadows of Rings

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

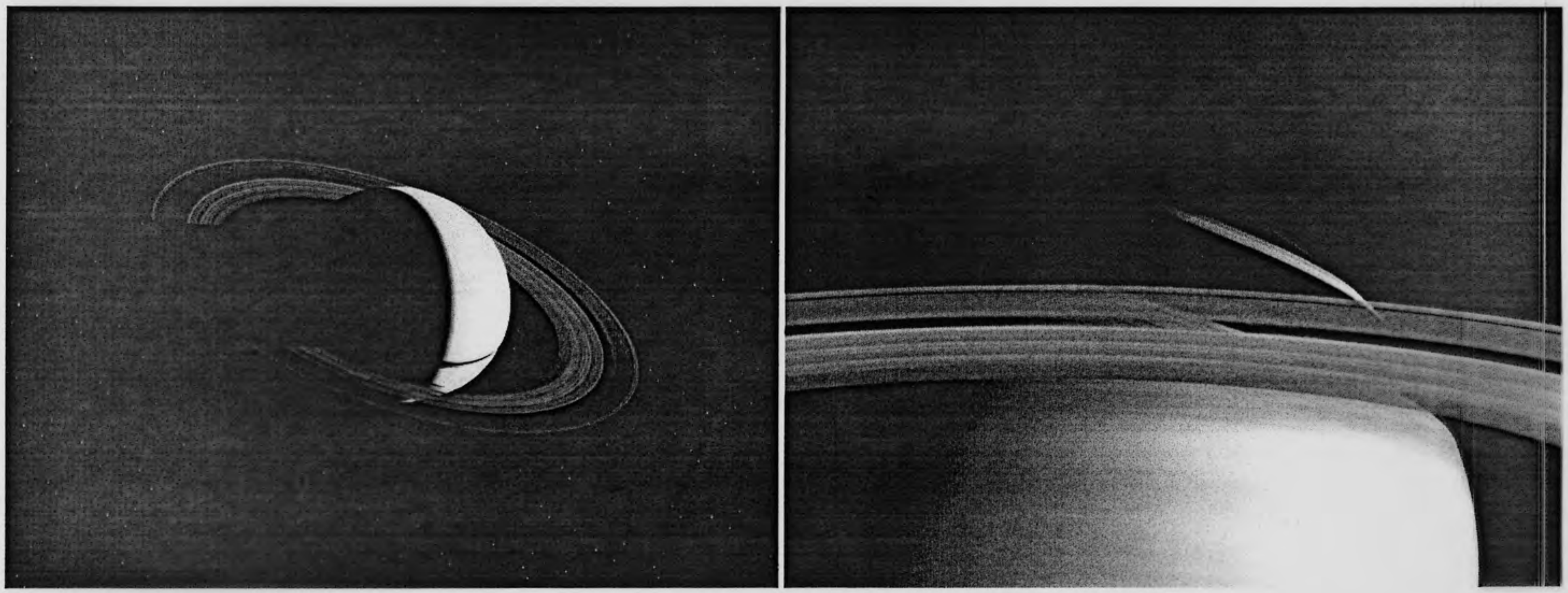
for Saturn ($\Delta t \simeq$ years)

Spectacular Personal Experience

Shortlived Ionosphere Effects

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

Ring Shadowing: Then and Now



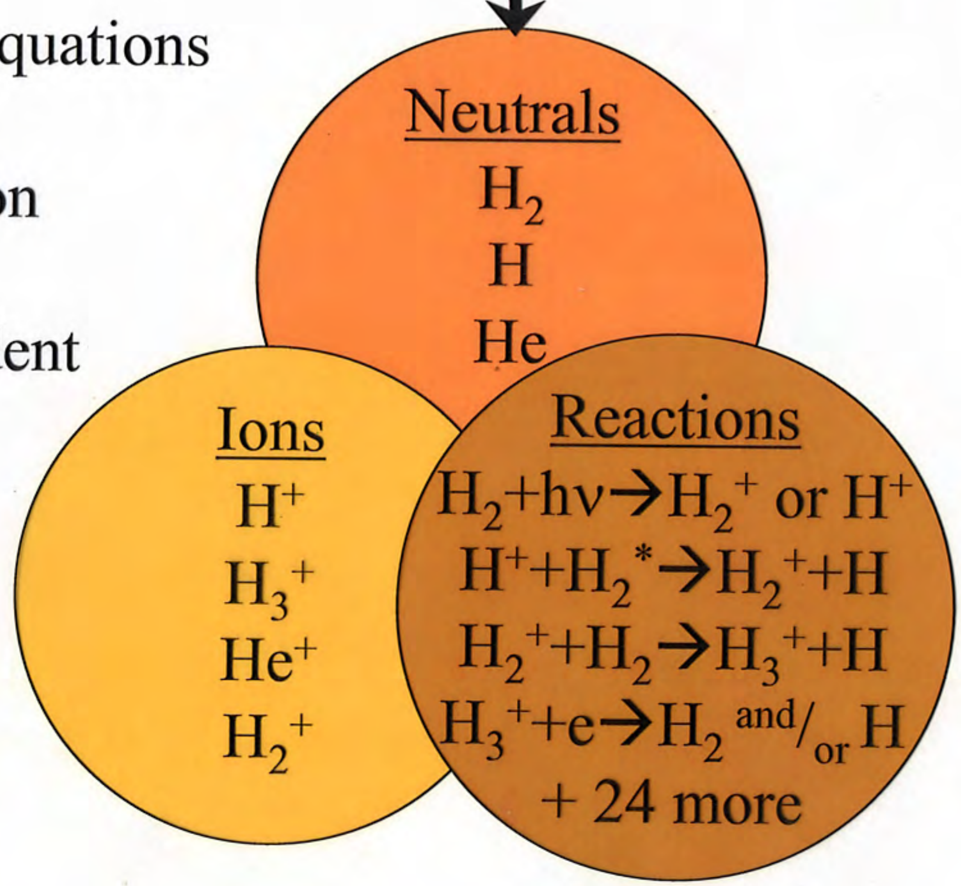
- (left) 1980, Voyager 1, Solar declination = -1.6°
- (right) 2004, Cassini, Solar declination = -26°

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

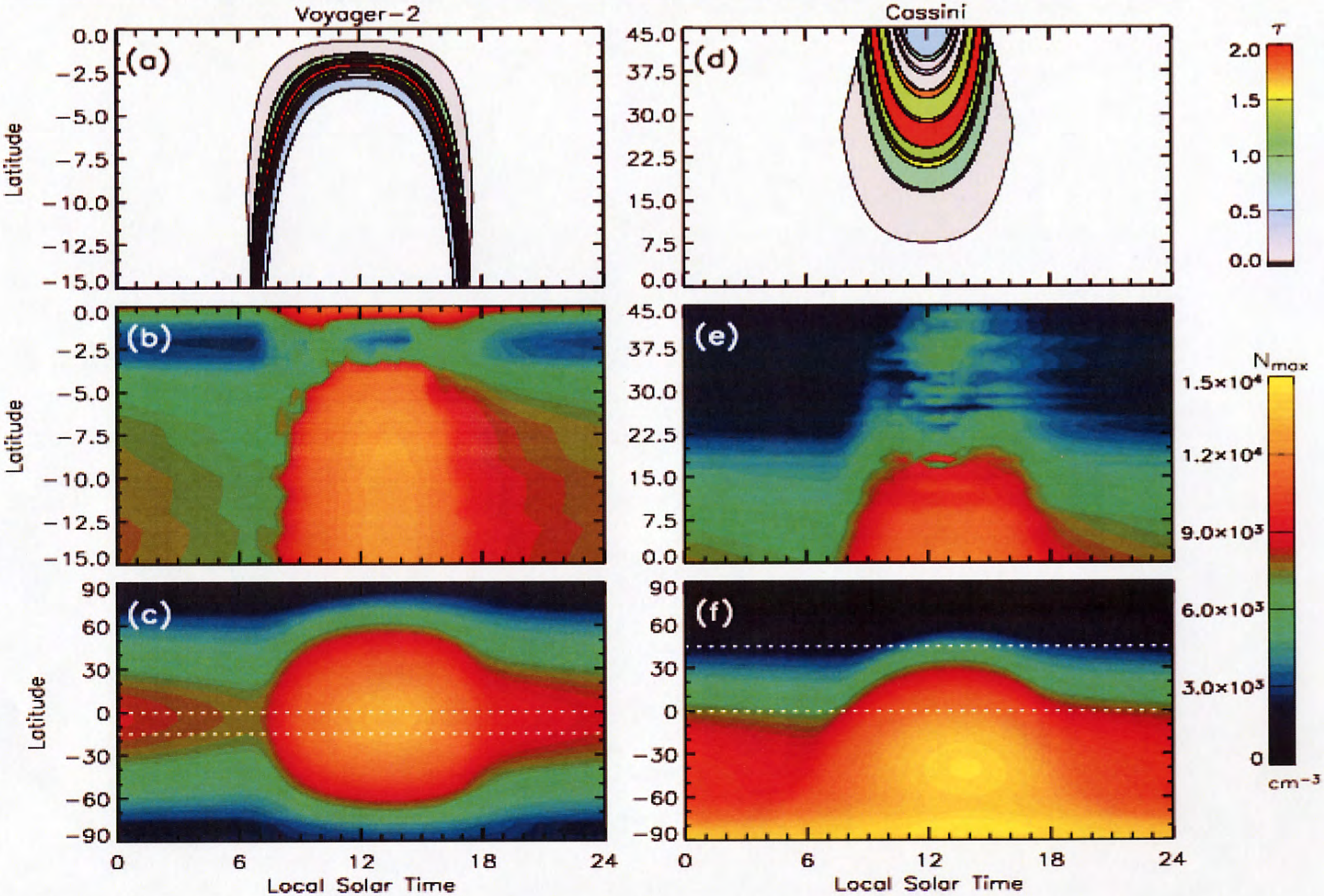
The Ionosphere

- 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

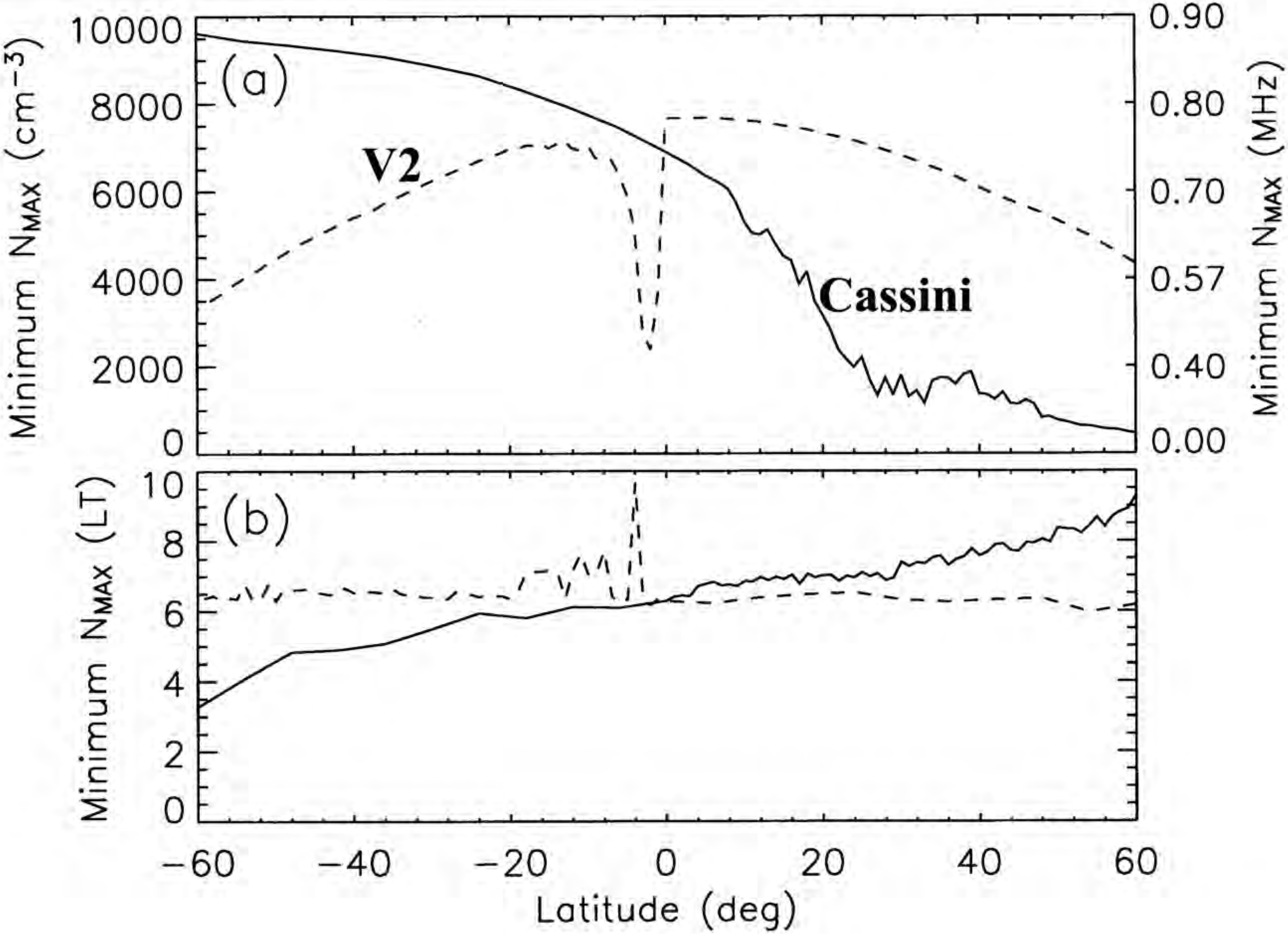
---Auroral + Wave Heating representations added---



Global Ring Shadowing Effects



Minimum N_{MAX} Values



ATOMIC ION IONOSPHERES ARE LONG-LIVED

--- Contrast Two Cases ---

Earth (24 hr day)

$O^+ + e^- \rightarrow O$ (slow)

but, $O^+ + N_2 \rightarrow NO^+ + N$ (fast)

$NO^+ + e^- \rightarrow N + O$ (faster)

∴ a diurnal pattern due to neutral molecules

Saturn (10 hr day)

$H^+ + e^- \rightarrow H$ (slow)

$H_2^+ + e^- \rightarrow H + H$ (fast)

∴ No diurnal pattern <u>if</u> H^+ persists

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

- Sub-Auroral Trough

$$O^+ + N_2^*(vib) \xrightarrow{\text{faster}} NO^+ + N$$

$$[N_2^*(vib)] = f(T_e),\ T_e \gtrsim 3000°K$$

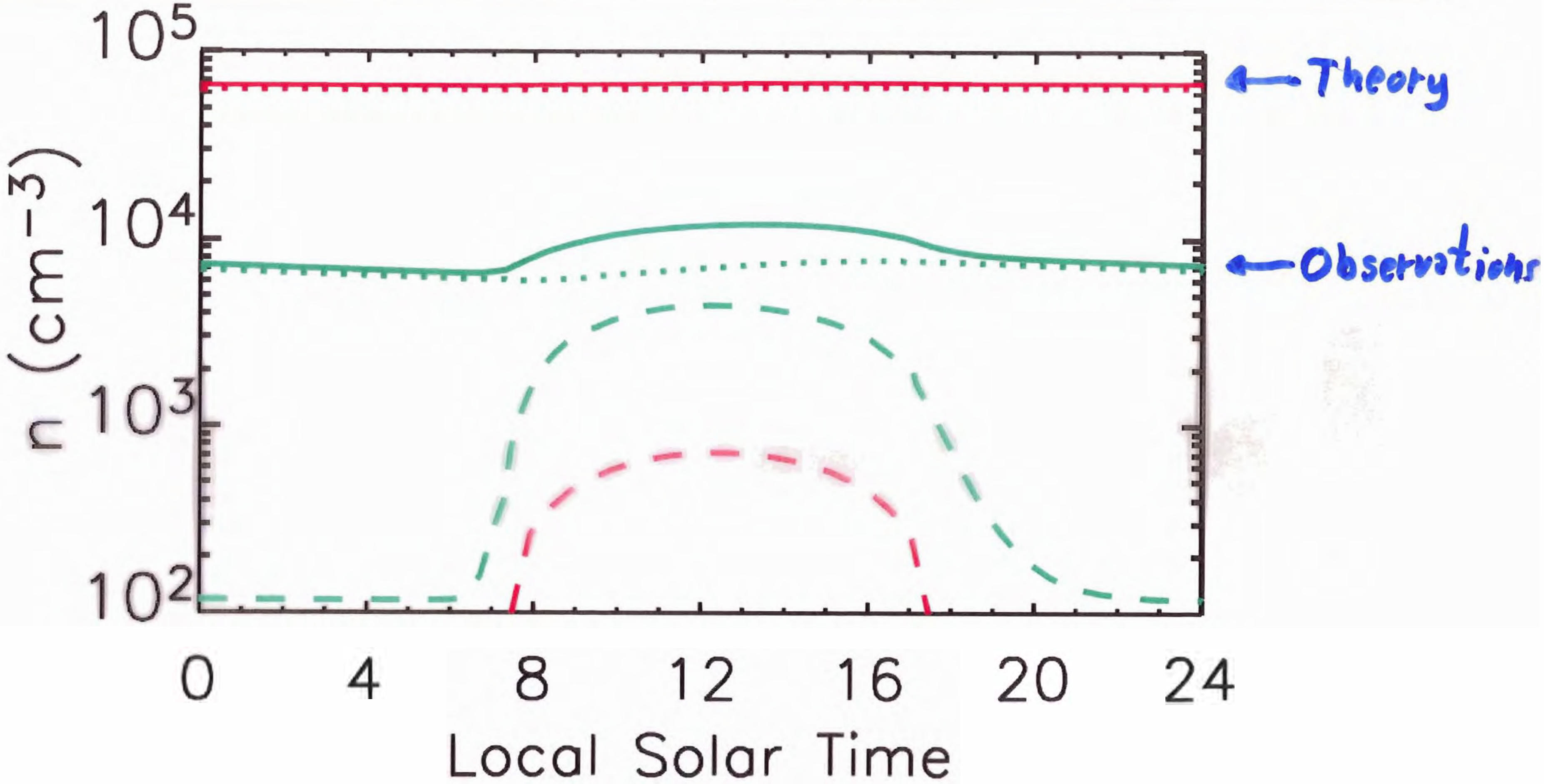
- Ionospheric "Holes" from Rocket Exhaust

$$O^+ + H_2O \xrightarrow{\text{fast}} H_2O^+ + O$$

$$H_2O^+ + e^- \xrightarrow{\text{fast}} H_2 + O$$

--- 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)?

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

BUT

$$H^+ + H_2\,(\text{vib} \geq 4) \xrightarrow{k_1} H_2^+ + H \qquad (1)$$

Then, H_2^+ produced directly and H_2^+ produced by above,

$$H_2^+ + H_2 \xrightarrow{\text{fast}} H_3^+ + H$$
$$H_3^+ + e^- \xrightarrow{\text{faster}} H_2 + H$$

} Diurnal Variation!

BUT

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

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

∴ Try "Water Dump" Solution

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

$$O^+ + H_2O \xrightarrow{k} H_2O^+ + O$$
$$H^+ + H_2O \xrightarrow{k'} H_2O^+ + H$$

} ~ 1000 × faster than by ambient molecules }

$$H_2O^+ + e^- \xrightarrow{\alpha} H_2 + O$$

"Ionospheric Holes"

EARTH

— Water Release "Active Experiments"

— Daytime → F-layer recovers in ~ hour(s)

— Nighttime → F-layer stays depleted until sunrise.

SATURN

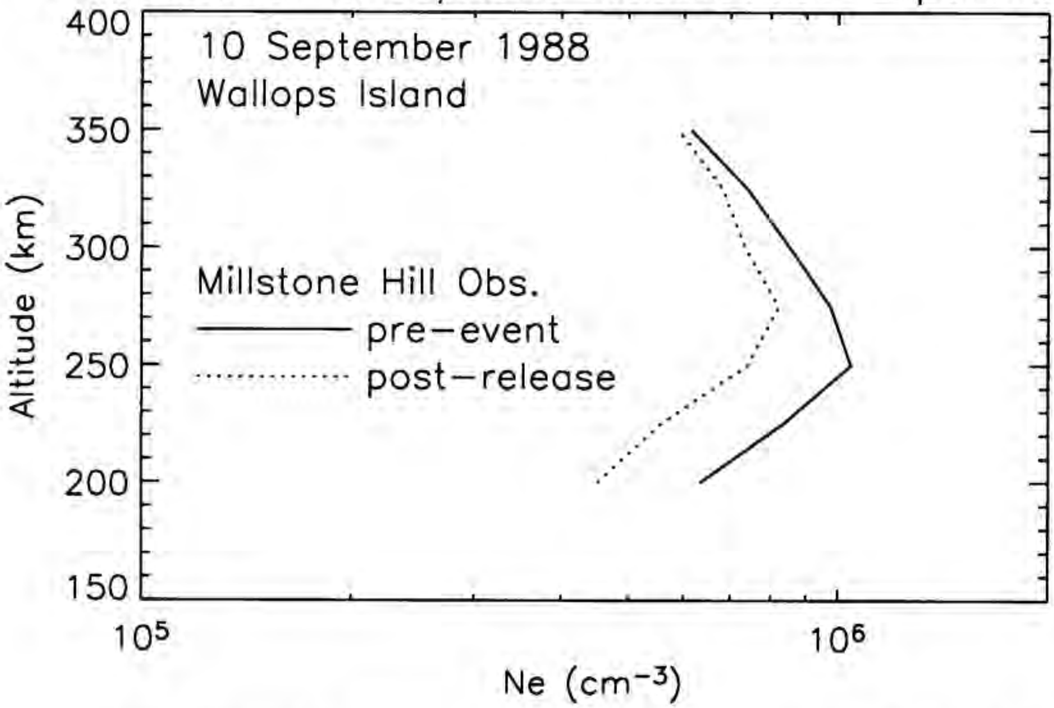
Constant H_2O sources:

— Ring sputtering

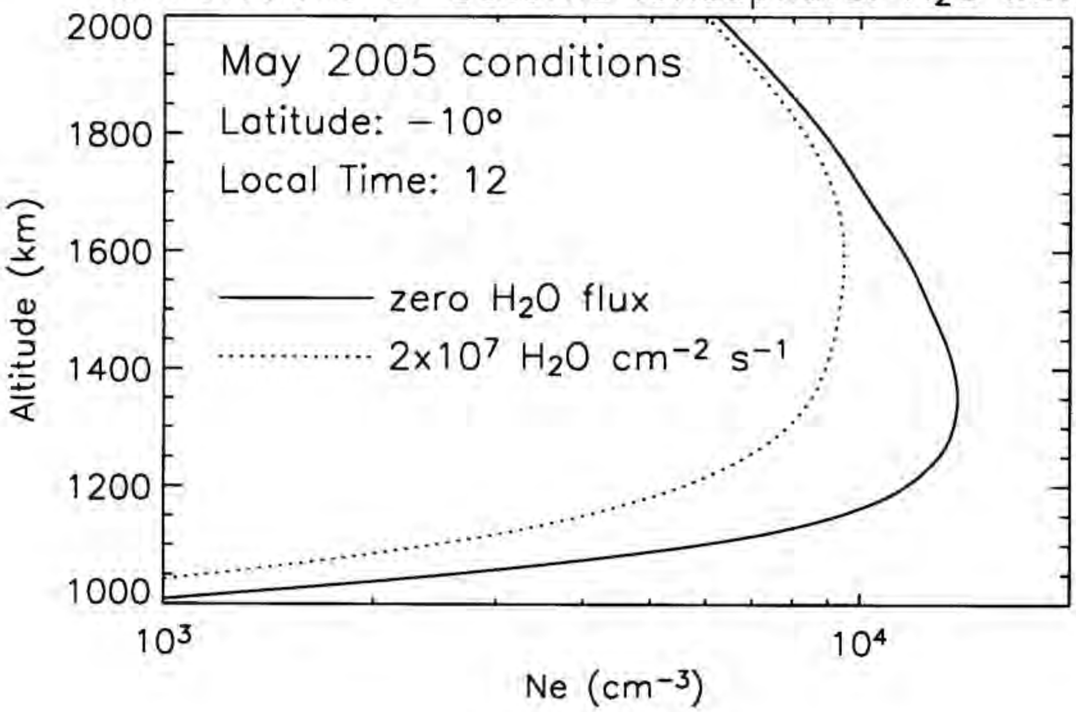
— Ejections from the moon Encylades

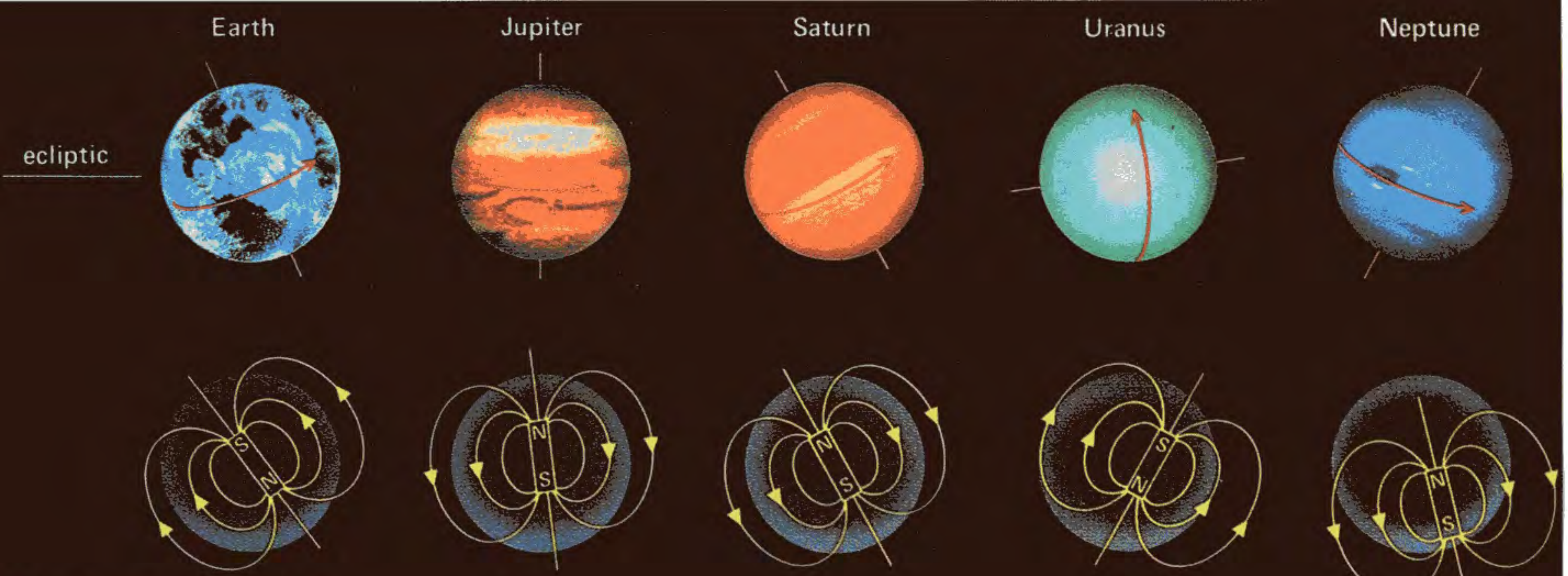
∴ Ionosphere continuously in a "depleted" state?

Observed "water dump" (5×10^{27} H_2O molecules)
Terrestrial Ionospheric Modification Experiment



Simulations of Saturns Ionosphere: H_2O Influx

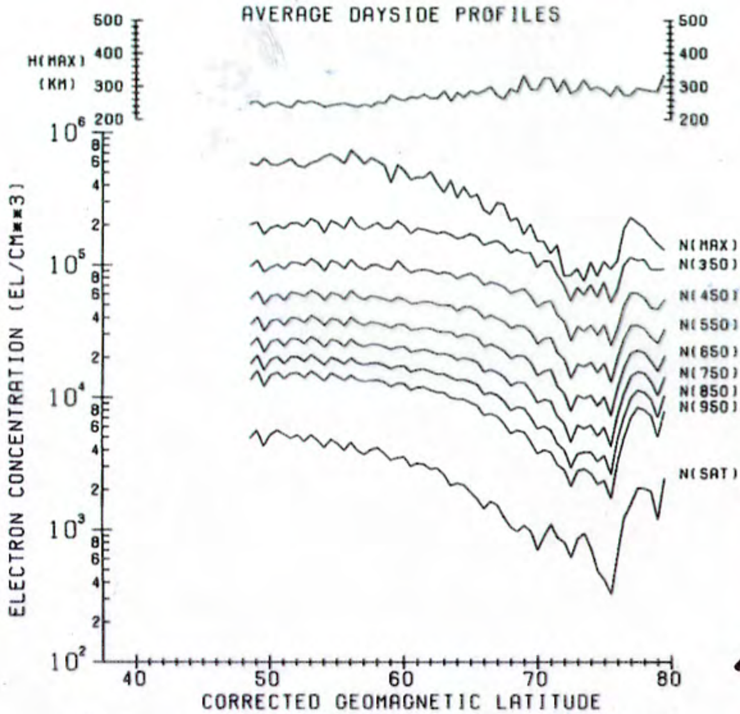




	Earth	Jupiter	Saturn	Uranus	Neptune
Tilt of rotation axis	23°	3°	27°	98°	30°
Tilt of magnetic axis	12°	–10°	–0°	–59°	–47°
Offset of magnetic axis	8%	10%	5%	31%	55%
Field at equator	31,000 nT	428,000 nT	22,000 nT	23,000 nT	13,000 nT
Magnetosphere	10 R_{Earth}	65 $R_{Jupiter}$	20 R_{Saturn}	18 R_{Uranus}	25 $R_{Neptune}$

Terrestrial Ionosphere Structures vs. Mag. Lat

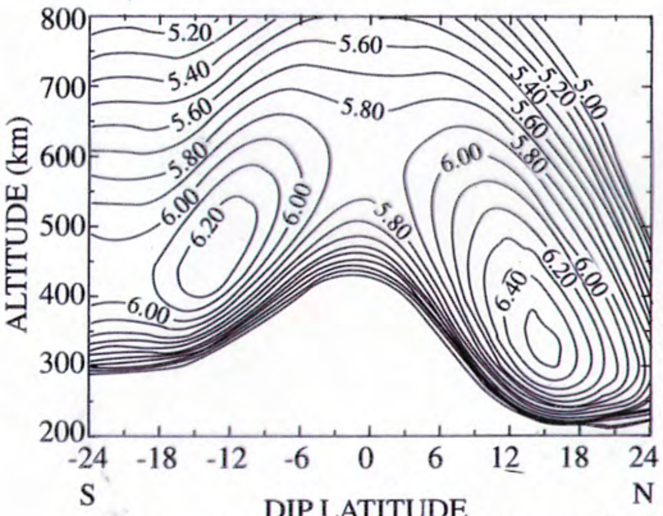
ISIS 2 Topside Sounder



(from Chacko and Mendillo, 1977)

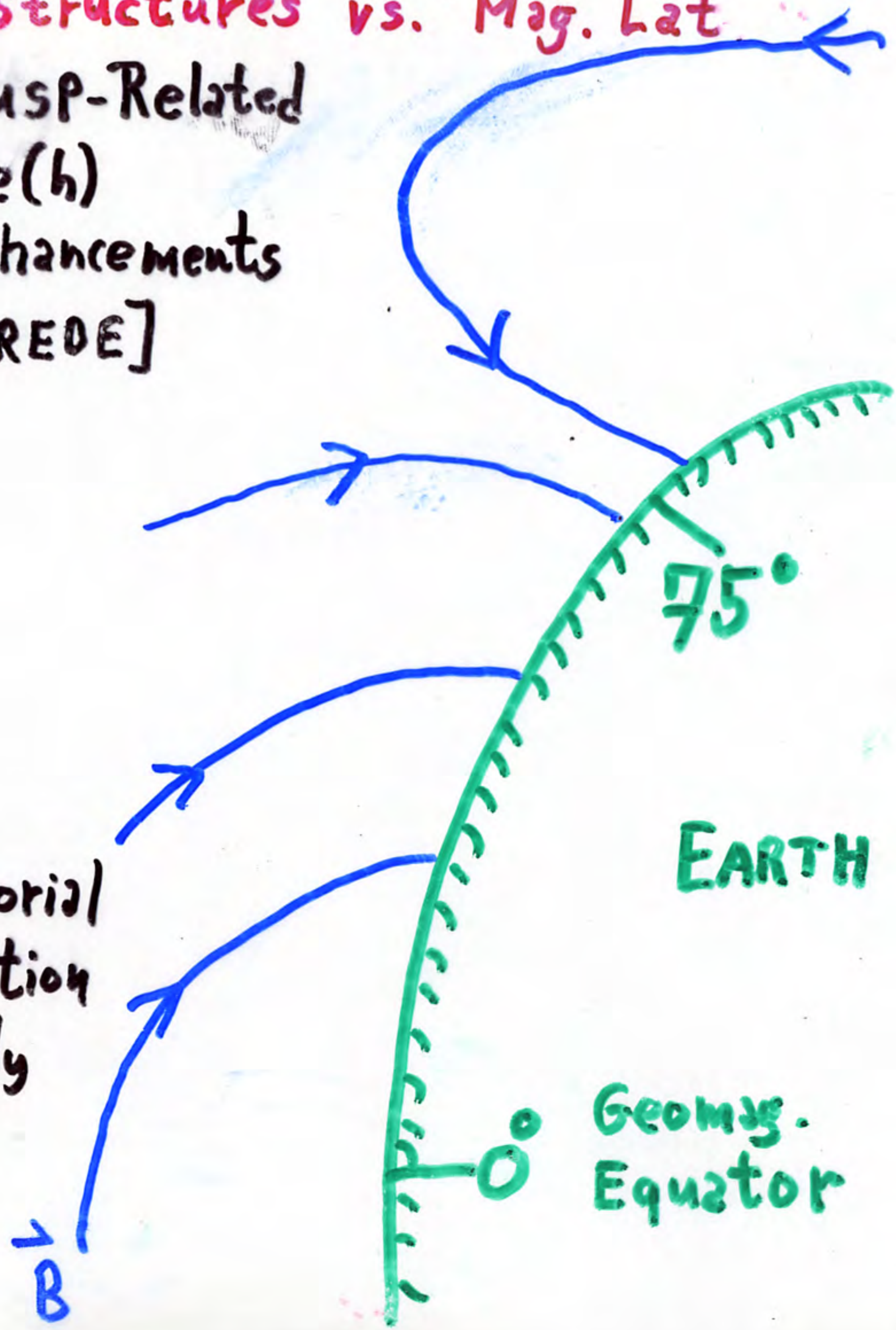
Cusp-Related Ne(h) Enhancements [CREDE]

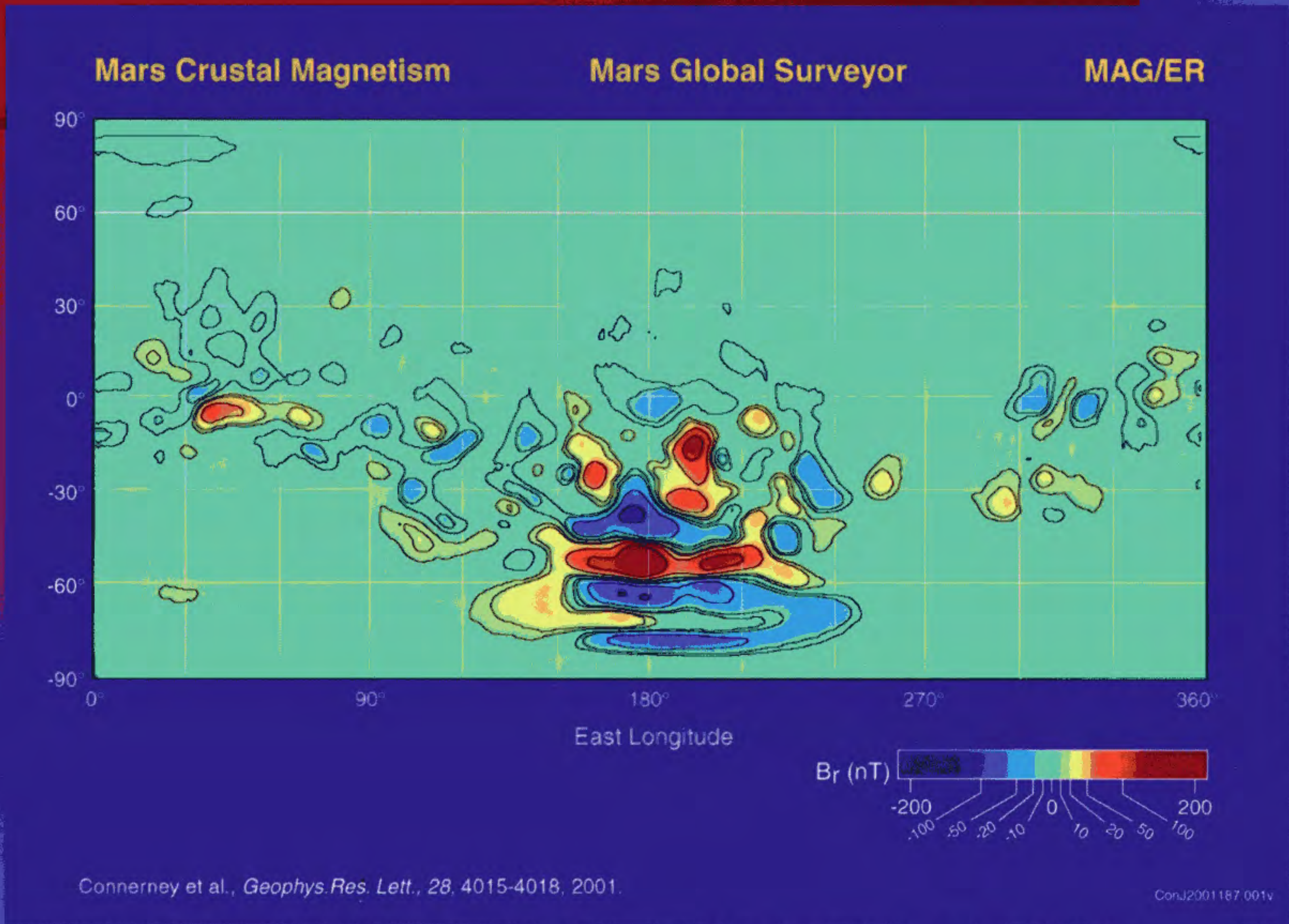
Ne(h) vs. Latitude



(from Anderson and Roble, 1981)

Equatorial Ionization Anomaly [EIA]

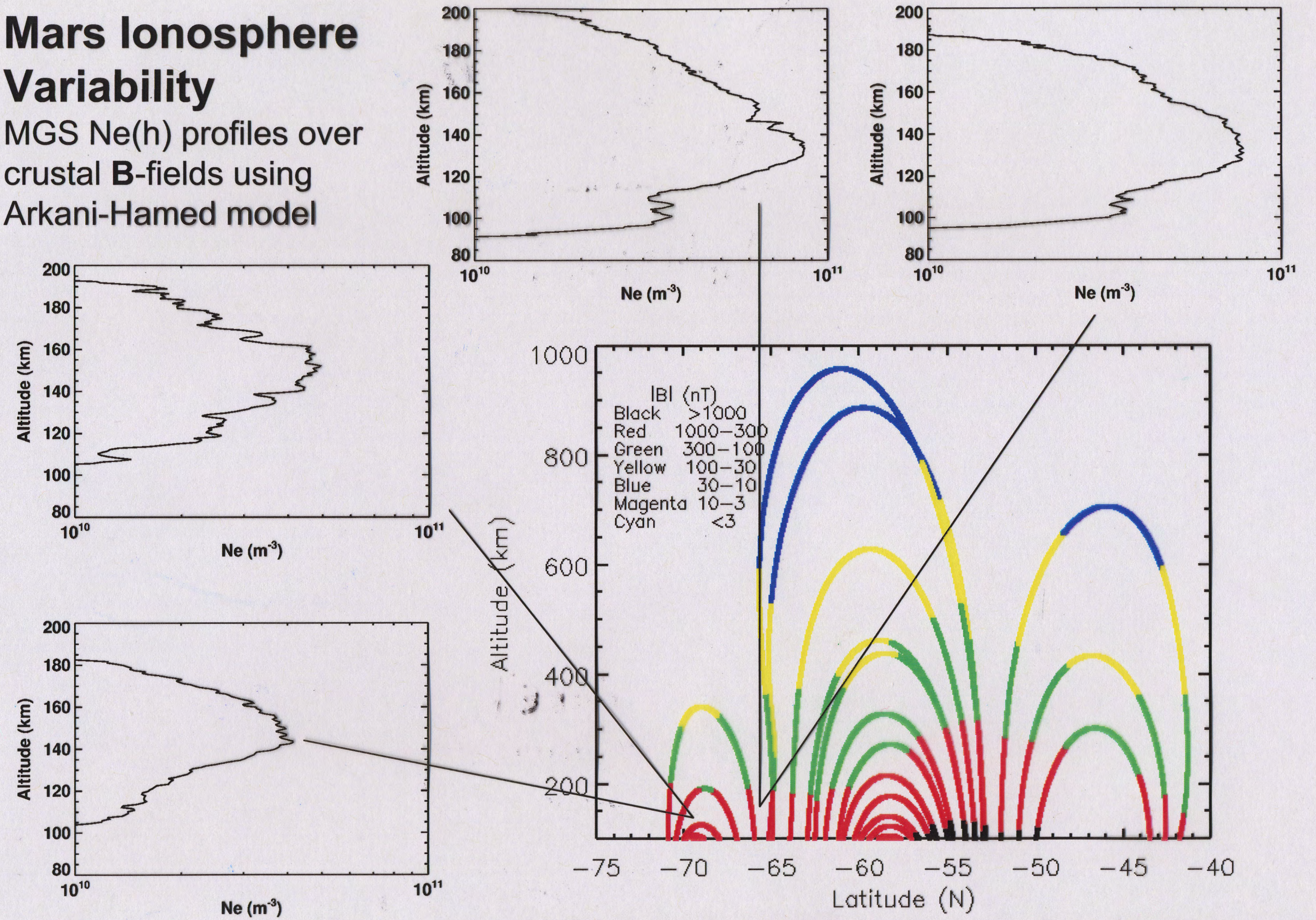




Mars Crustal Magnetism
Mars Global Surveyor
MAG/ER
90°
60°
30°
0°
-30°
-60°
-90°
0°
90°
180°
270°
360°
East Longitude
Br (nT)
-200
-100
-50
-20
-10
0
10
20
50
100
200
Connerney et al., Geophys.Res. Lett., 28, 4015-4018, 2001.
ConJ2001187.001v

Mars Ionosphere Variability

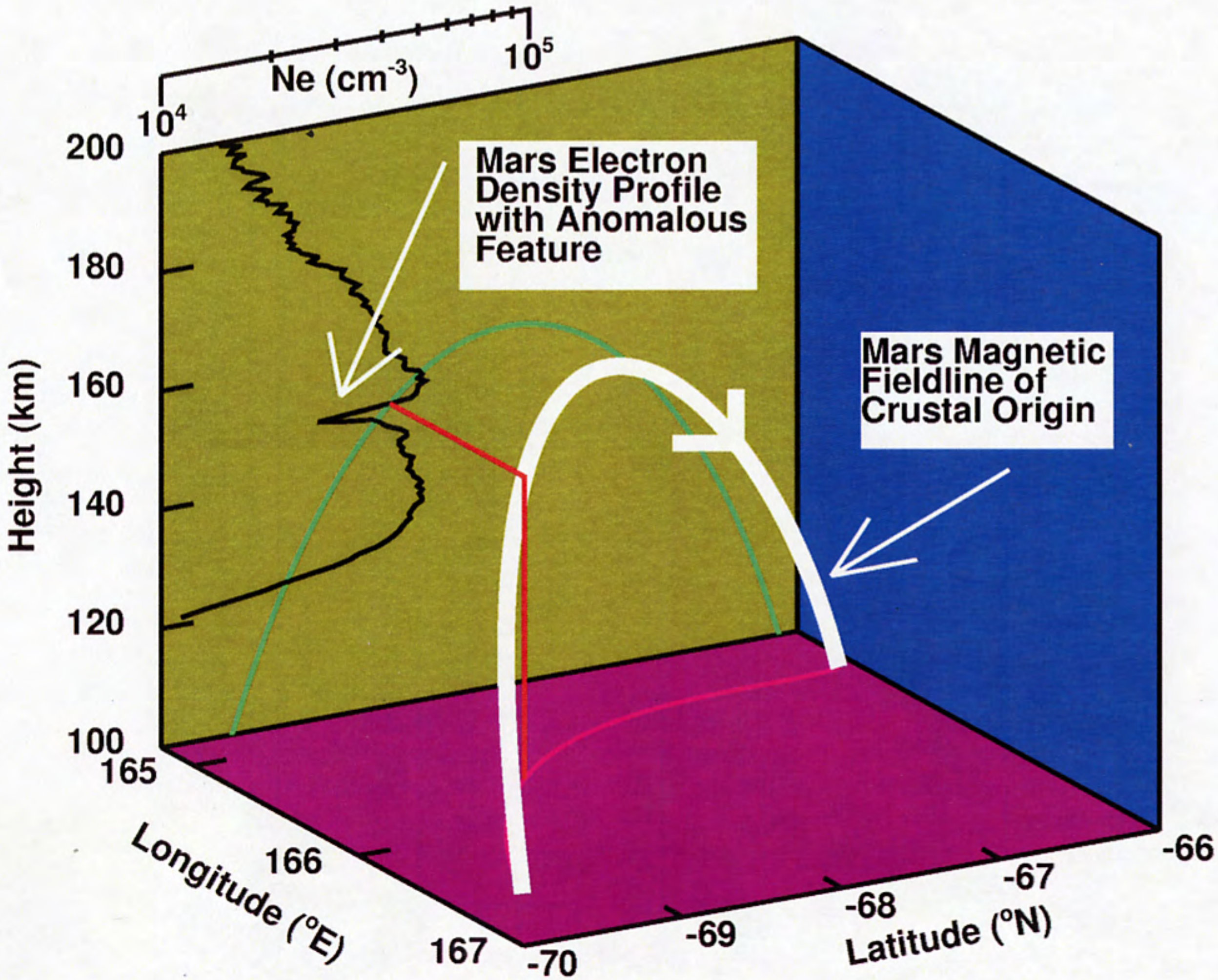
MGS Ne(h) profiles over crustal **B**-fields using Arkani-Hamed model



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

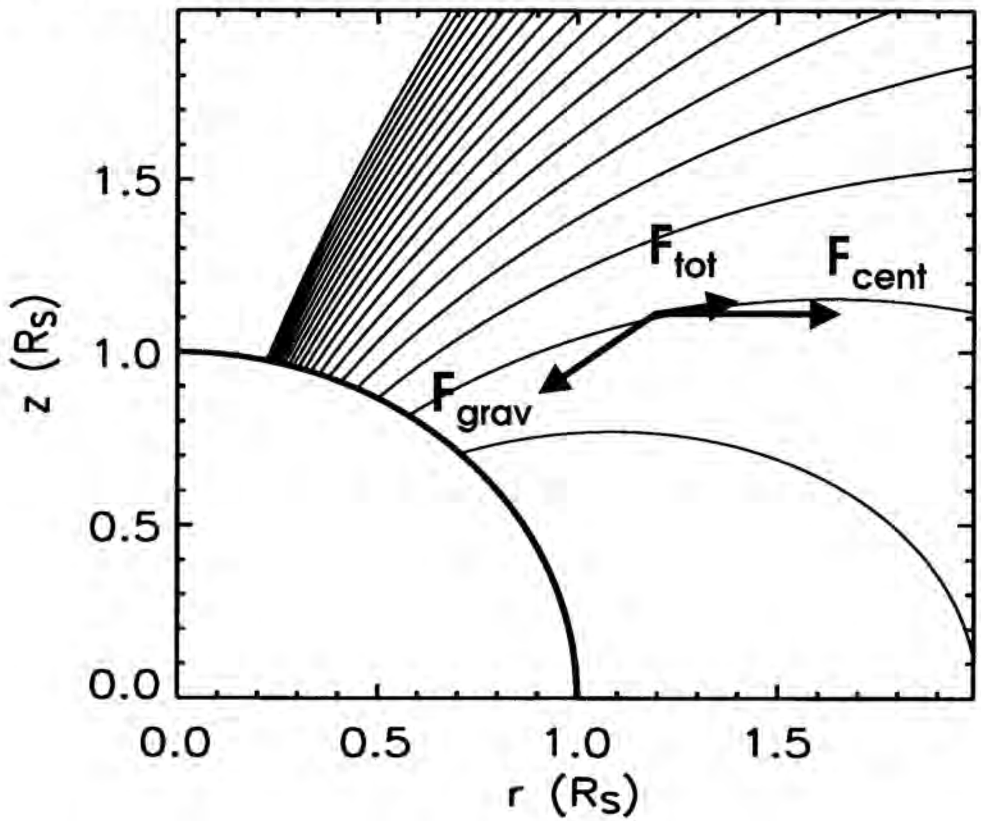


Saturn's Plasmasphere: Ionospheric Contribution

(1) Define plasma exobase parameters (z, T, VDF)

(2) Use Liouville's Theorem → solve for moments of VDF

(3) Evaluate in terms of exospheric classes of particles:



ballistic

incoming

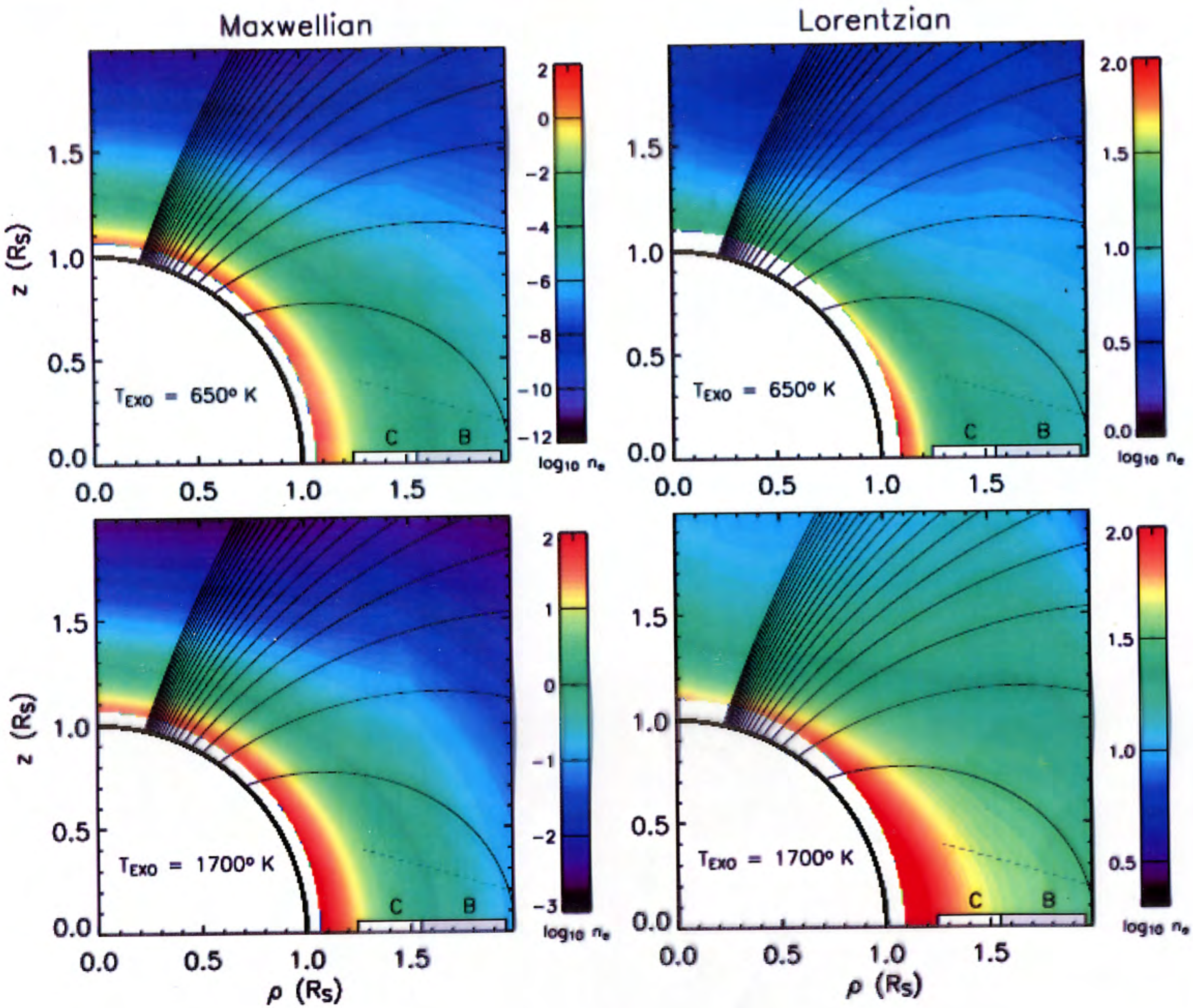
escaping

trapped

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

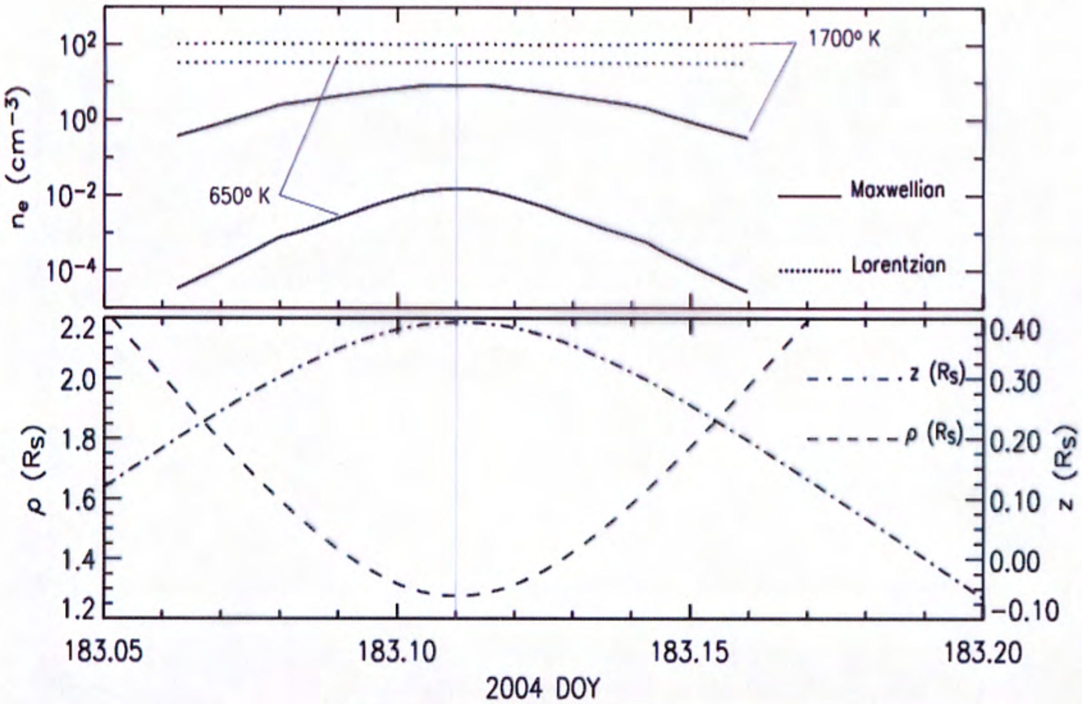
Use derivations of Lemaire (1976) and Pierrard and Lemaire (1996)

Inner Plasmasphere e^- Distributions

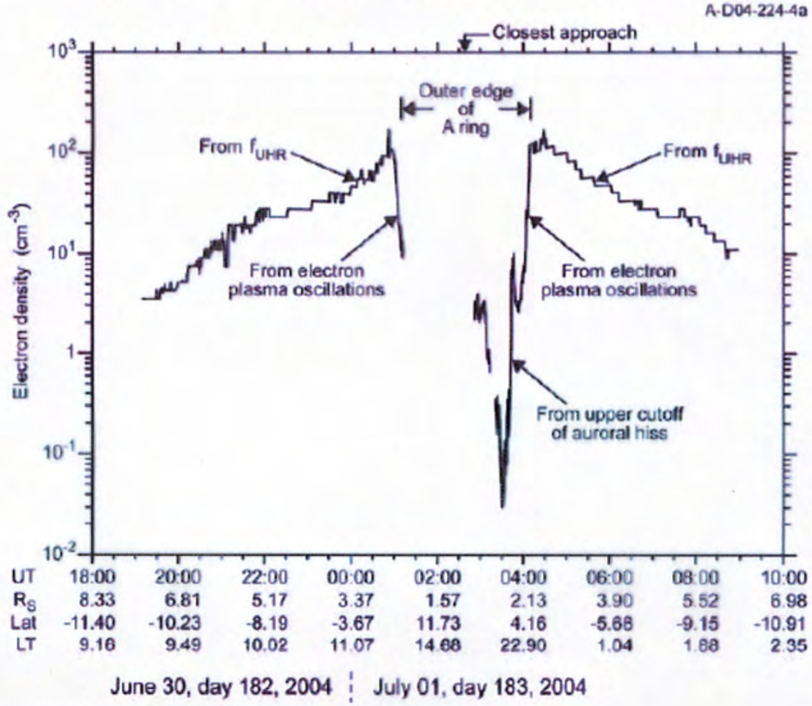


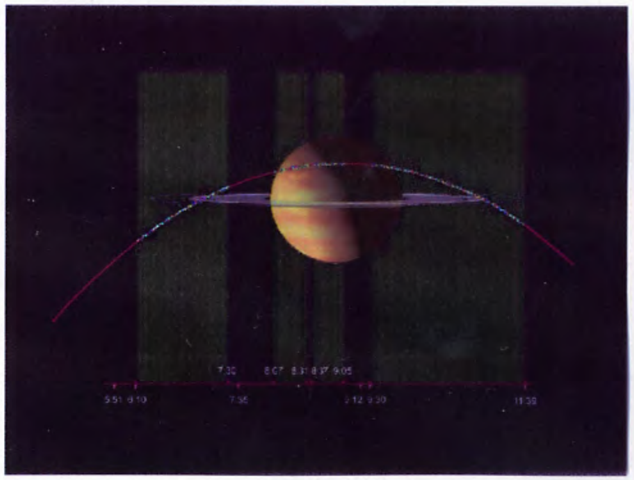
Model Predictions vs Observations

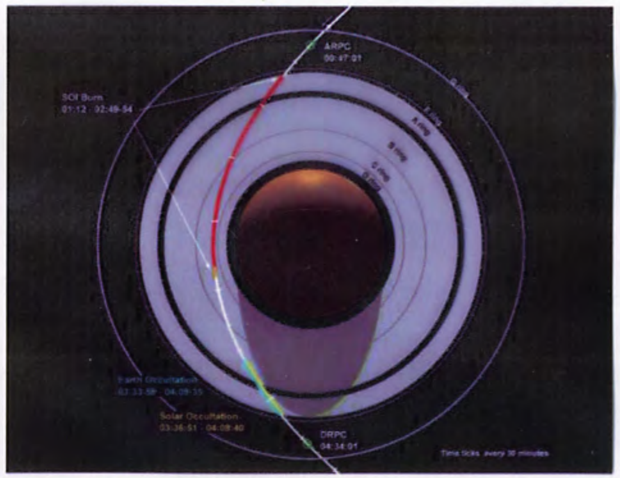
Modeled Closest Approach



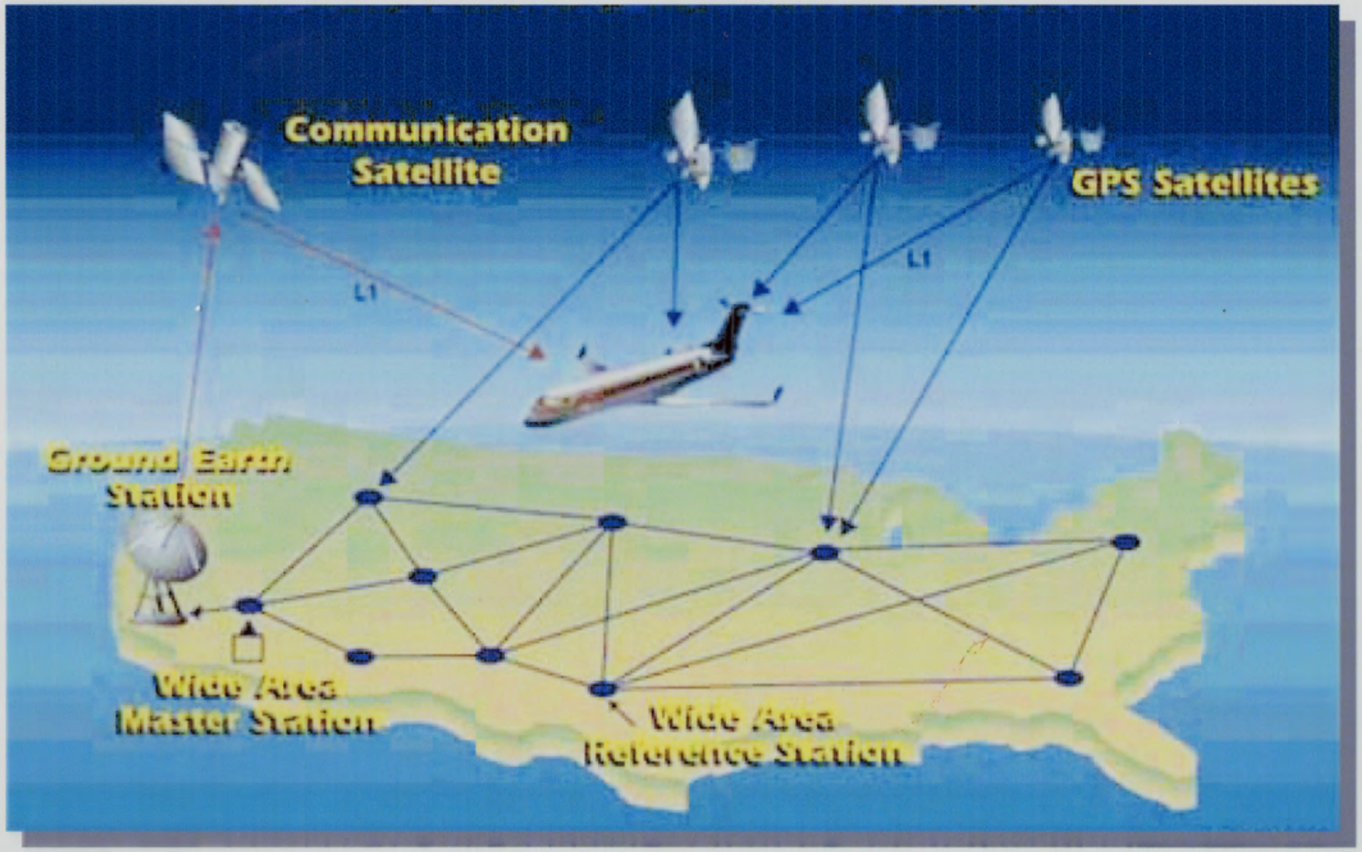
RPWS - Gurnett et al. 2005



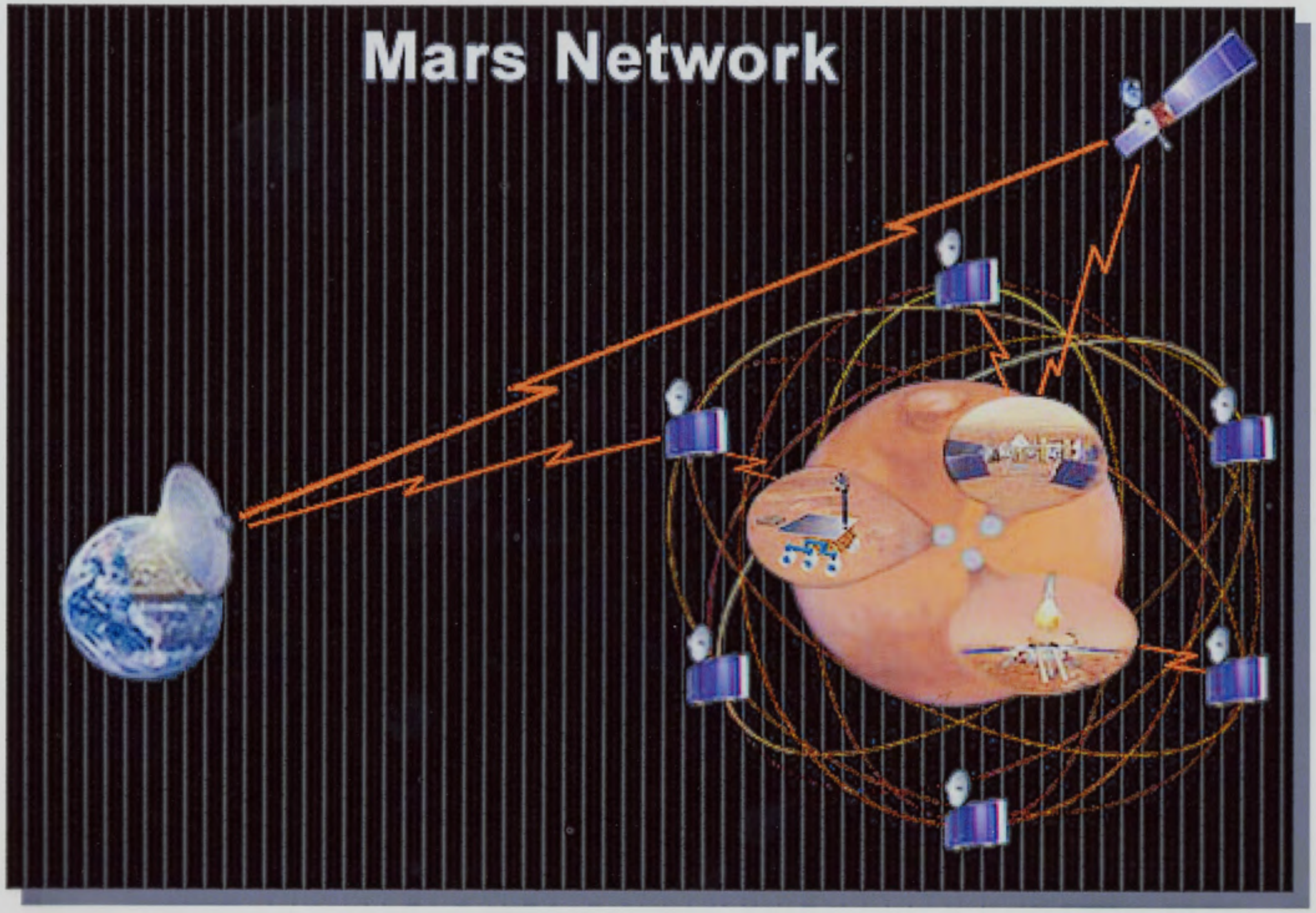




GPS Applications

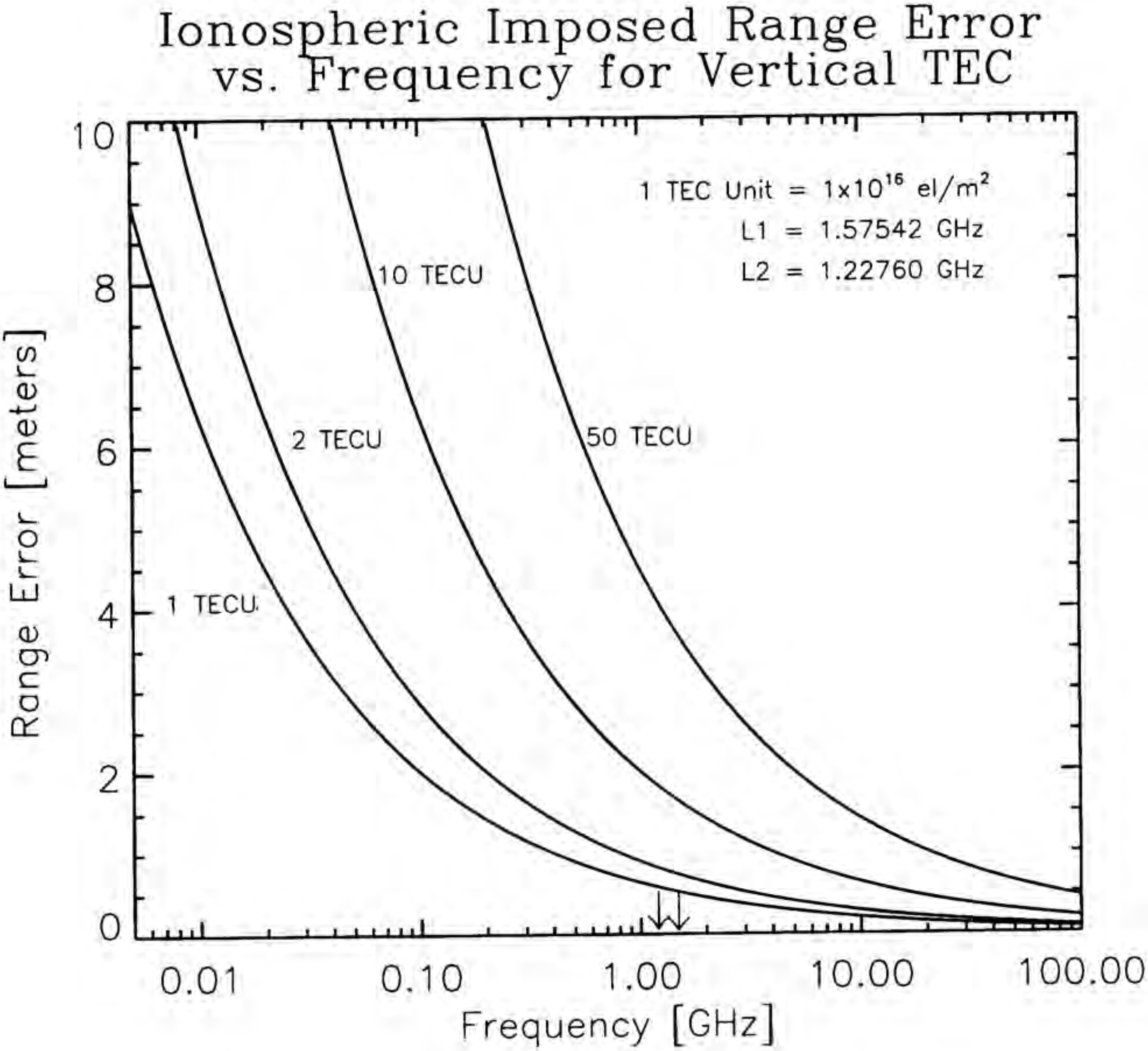


Courtesy to the Federal Aviation Administration.



"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
1 TEC Unit = 1x10^16 el/m^2
L1 = 1.57542 GHz
L2 = 1.22760 GHz
10 TECU
2 TECU
50 TECU
1 TECU
Range Error [meters]
0
2
4
6
8
10
0.01
0.10
1.00
10.00
100.00
Frequency [GHz]

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."