The Response of an Ionosphere to changes in the solar $F_{10.7}$ flux: Comparison of Venus, Earth and Mars

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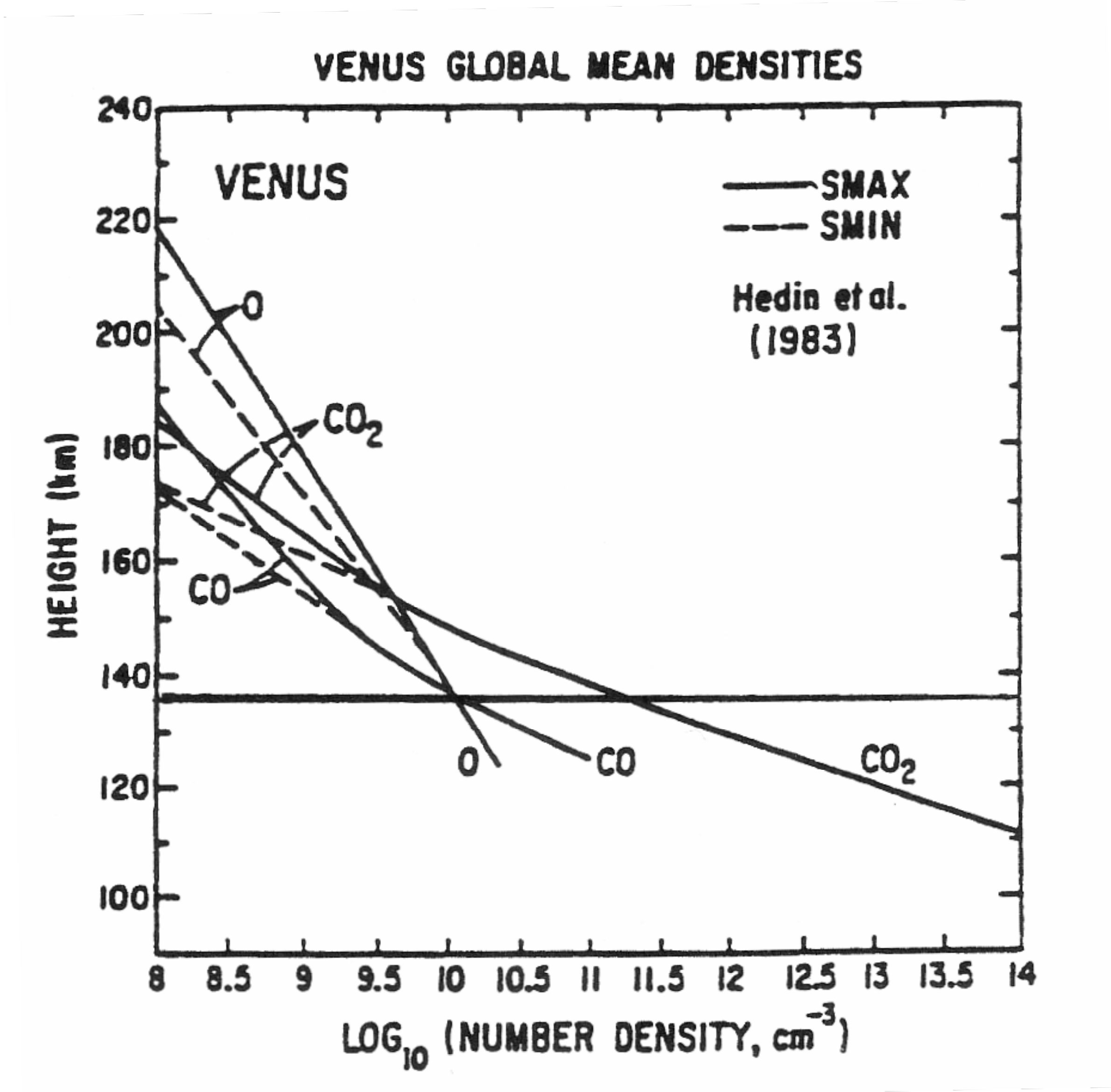
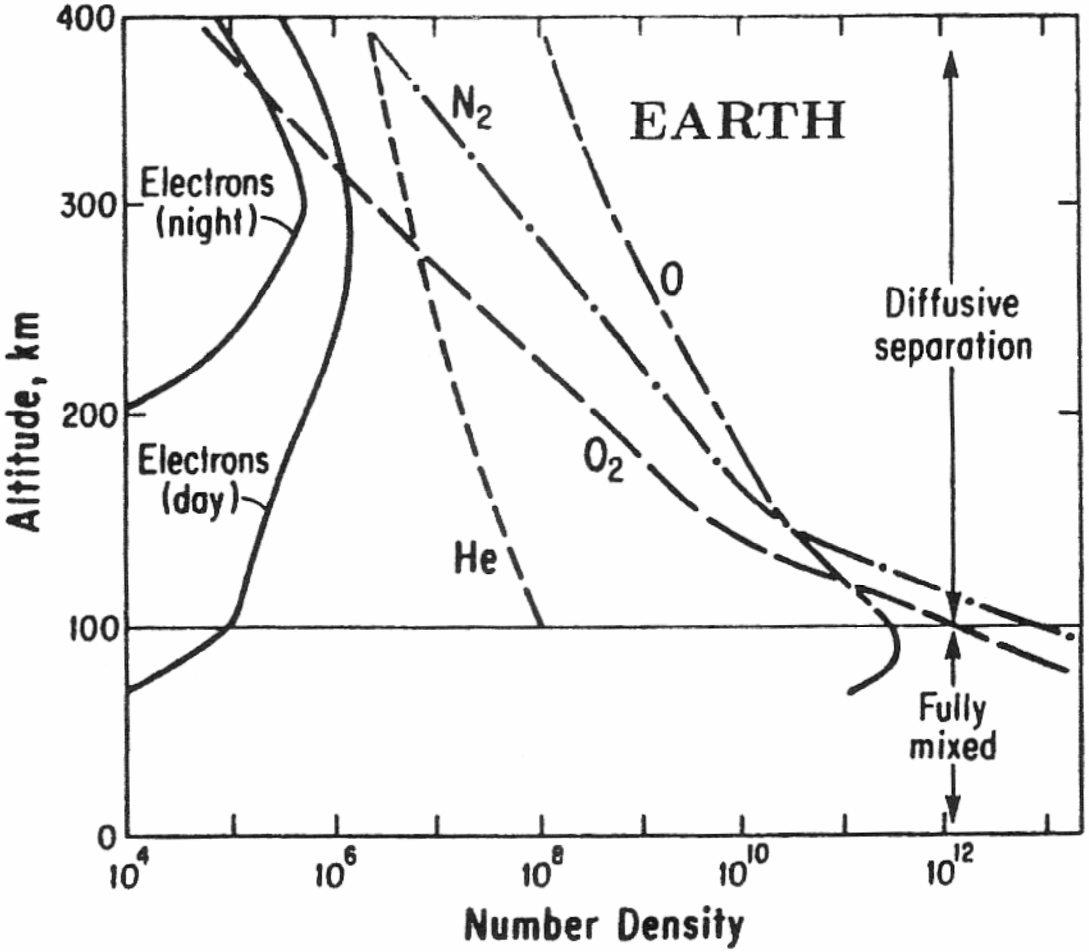
Abstract

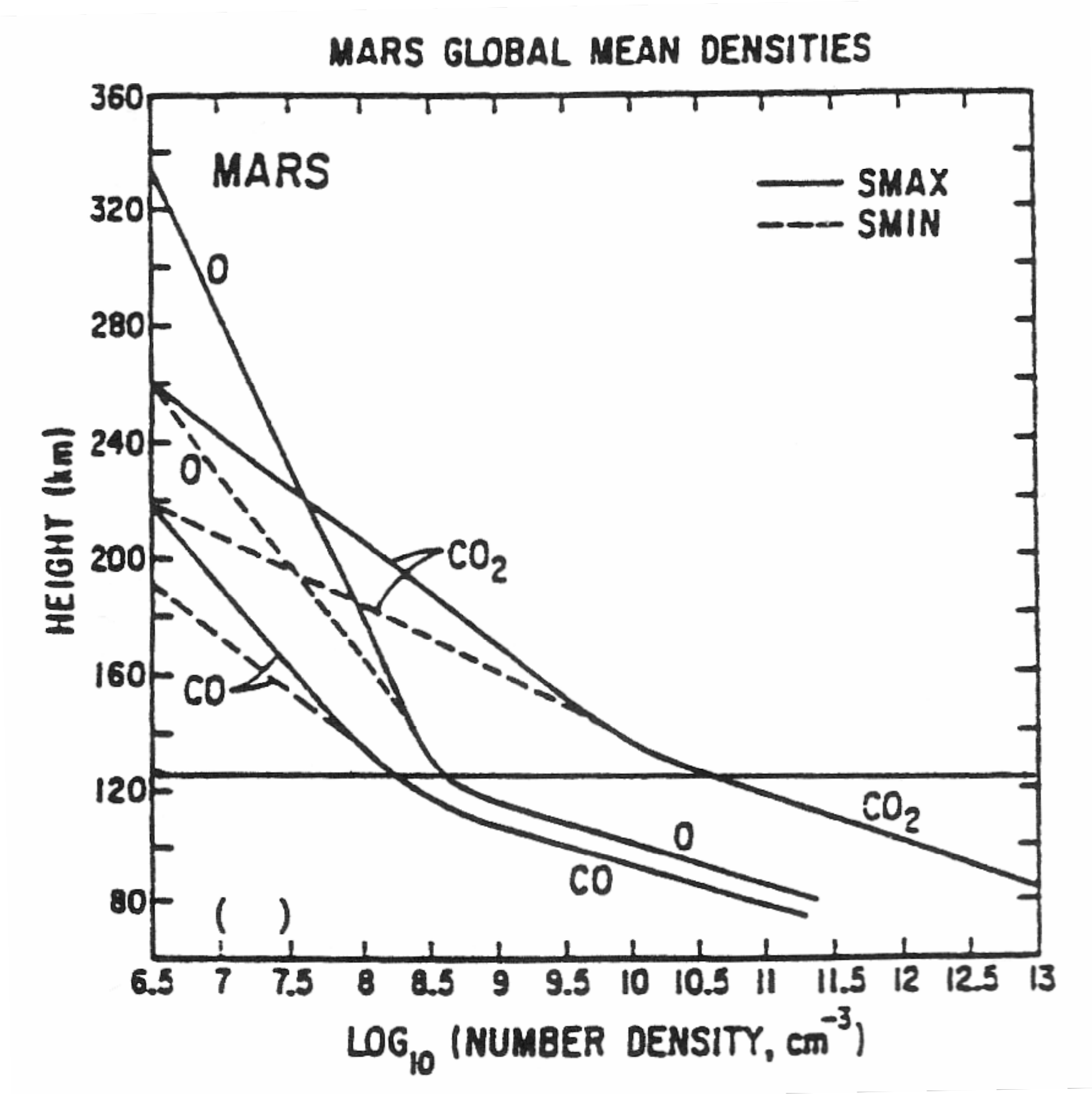
There are many similarities between the terrestrial E region and the ionospheres of Venus and Mars. All are dominated by photochemical, not transport, processes. The dissociative recombination of molecular oxygen ions is an important loss mechanism for all three regions. Various workers have studied how ionospheric properties, such as the peak electron density, in these regions respond to changes in solar flux, especially as represented by the F10.7 index. Timescales of interest include the solar cycle, the solar rotation period, and shorter periods, such as one day. We shall discuss the many parameterizations of such responses that have been published and examine their consistencies with known photochemical processes.



Neutral Atmosphere
Venus
Bougher et al. (2002)



Neutral Atmosphere
Earth
Bougher et al. (2002)



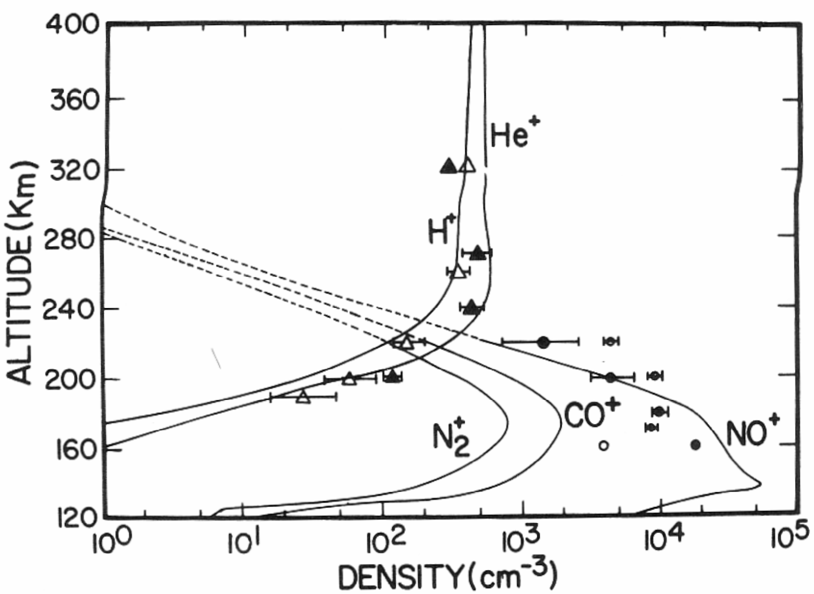
Neutral Atmosphere
Mars
Bougher et al. (2002)

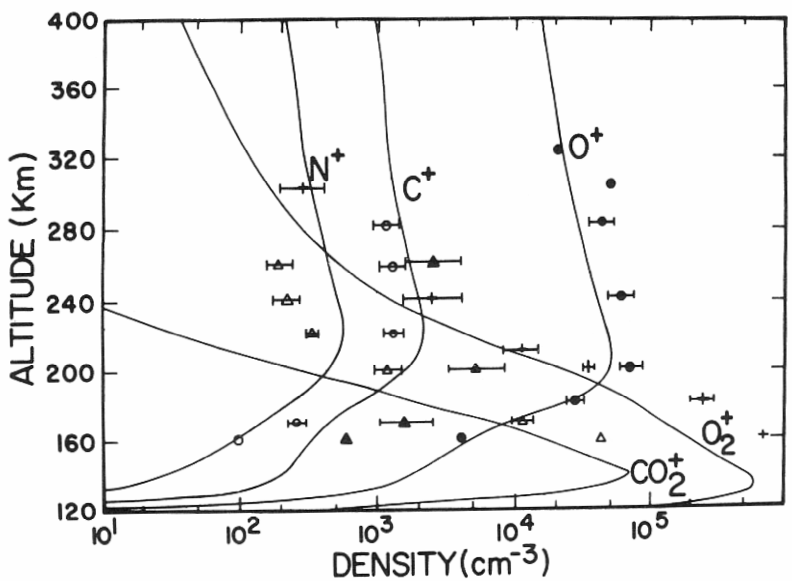
Planetary Properties at Ionospheric Peak

	Venus	Earth E-region	Mars
g (m s^{-2})	8.9 (p263, purple)	9.8 (p263, purple)	3.7 (p263, purple)
Solar distance (AU)	0.7 (p263, purple)	1.0 (p263, purple)	1.4 – 1.7 (p263, purple)
z_{peak} (km)	140 (p781 and 830, V1)	110 (p 228, C+H)	120 (p540, Hantsch)
Neutrals	CO_2 (p263, purple)	N_2, O_2 (p263, purple)	CO_2 (p263, purple)
Ions	O_2^+ (p780, V1)	O_2^+, NO^+ (p232, C+H)	O_2^+ (p1070, Mars)
Production process	CO_2+hv -> CO_2^+ + e CO_2^++O -> CO + O_2^+ (p855, V1)	N_2+hv -> N_2^+ + e N_2^+ + O -> N + NO^+ O_2+hv -> O_2^+ + e (p232, C+H)	CO_2+hv -> CO_2^+ + e CO_2^++O -> CO + O_2^+ (p1069, Mars)
Loss process	Dissociative Recombination (p855, V1)	DR (p232, C+H)	DR (p263, C+H)
N_n (cm^{-3})	1 E 11 (p265, purple)	1 E 13 (p265, purple)	1 E 11 (p204, Fox)
N_e (cm^{-3})	7 E 5 (p856, V1)	1 E 4 (p229, C+H)	2 E 5 (p541, Hantsch)
T_n (K)	200 (p264, purple)	300 (p264, purple)	200 (p264, purple)
T_e (K)	1000 K (p791, V1)	300 (p264, purple) But ~1000 at 150 km, Ch 23, B+K	200 K (p1074, Mars)

Planetary Properties at Ionospheric Peak

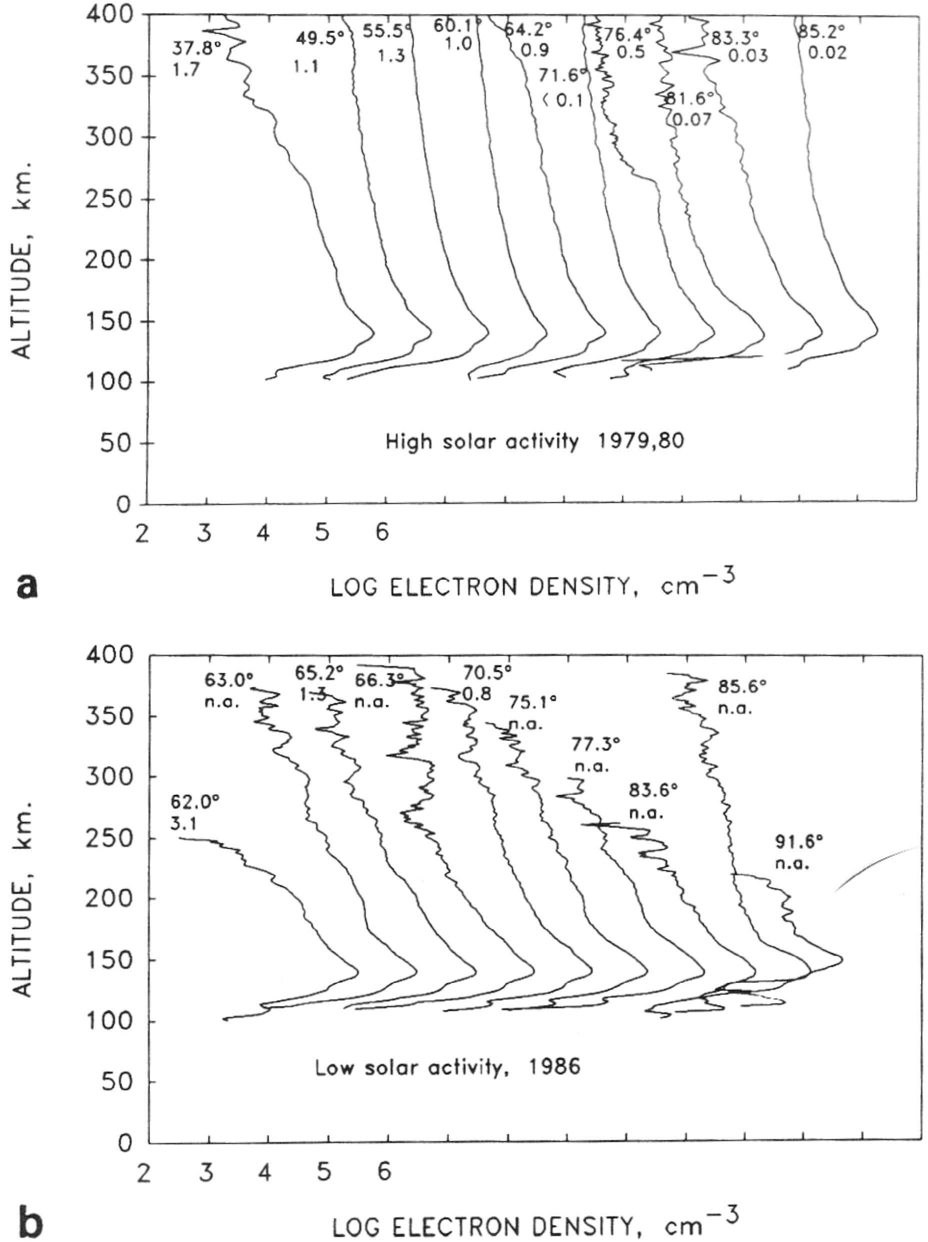
	Venus	Earth E-region	Mars
g (m s^{-2})	8.9	9.8	3.7
Solar distance (AU)	0.7	1.0	1.4 – 1.7
z_{peak} (km)	140	110	120
Neutrals	CO_2	N_2, O_2	CO_2
Ions	O_2^+	O_2^+, NO^+	O_2^+
Production process	CO_2+hv -> CO_2^+ + e CO_2^++O -> CO + O_2^+	N_2+hv -> N_2^+ + e N_2^+ + O -> N + NO^+ O_2+hv -> O_2^+ + e	CO_2+hv -> CO_2^+ + e CO_2^++O -> CO + O_2^+
Loss process	Dissociative Recombination	DR	DR
N_n (cm^{-3})	1 E 11	1 E 13	1 E 11
N_e (cm^{-3})	7 E 5	1 E 4	2 E 5
T_n (K)	200	300	200
T_e (K)	1000	300 – but ~1000 at 150 km	200





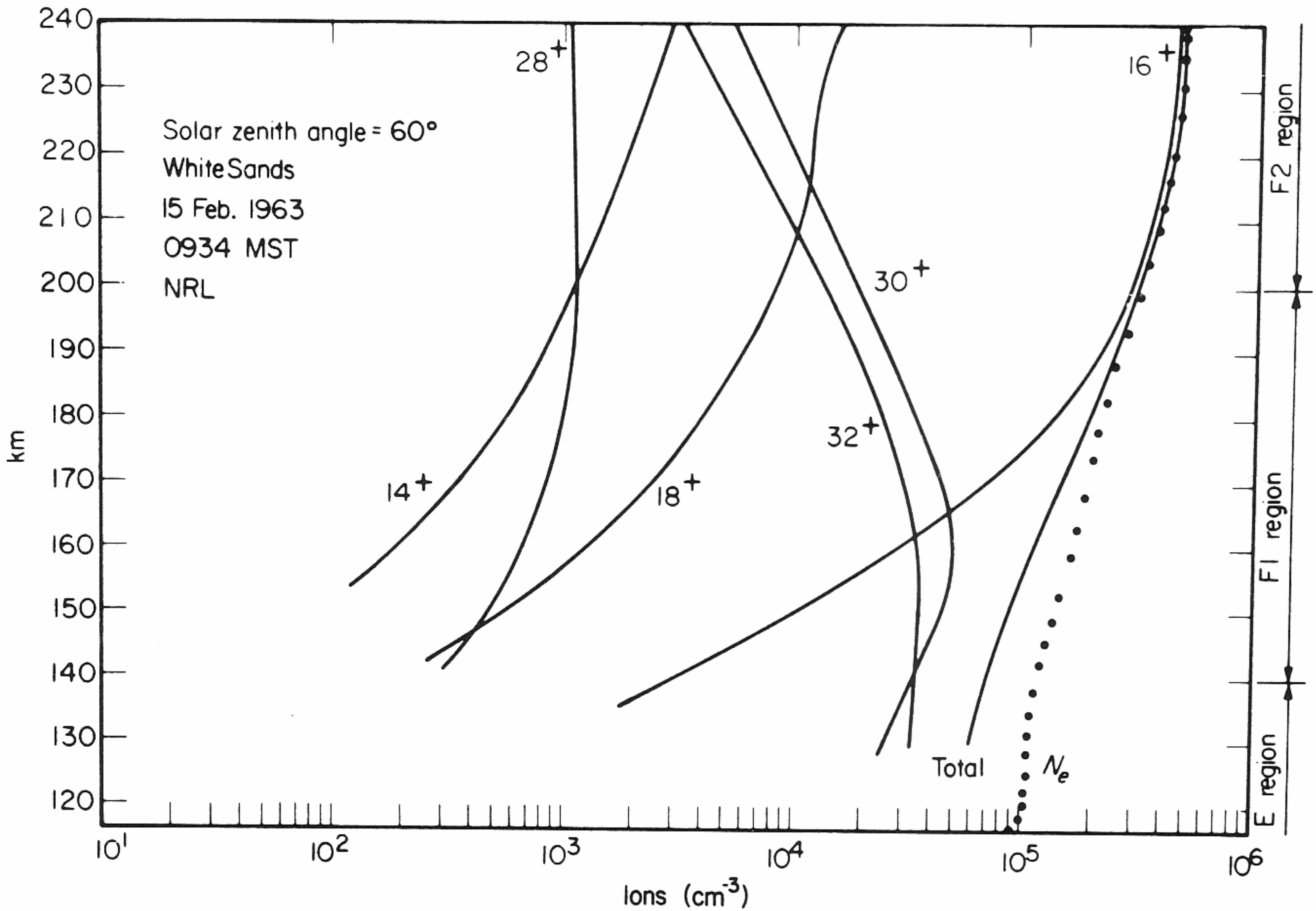
Ionospheric composition
Venus
PVO data (symbols) and
Nagy model (lines)
Chamberlain and Hunten (1987)

Ionospheric structure
Venus
PVO radio occultations
Kliore (1992)

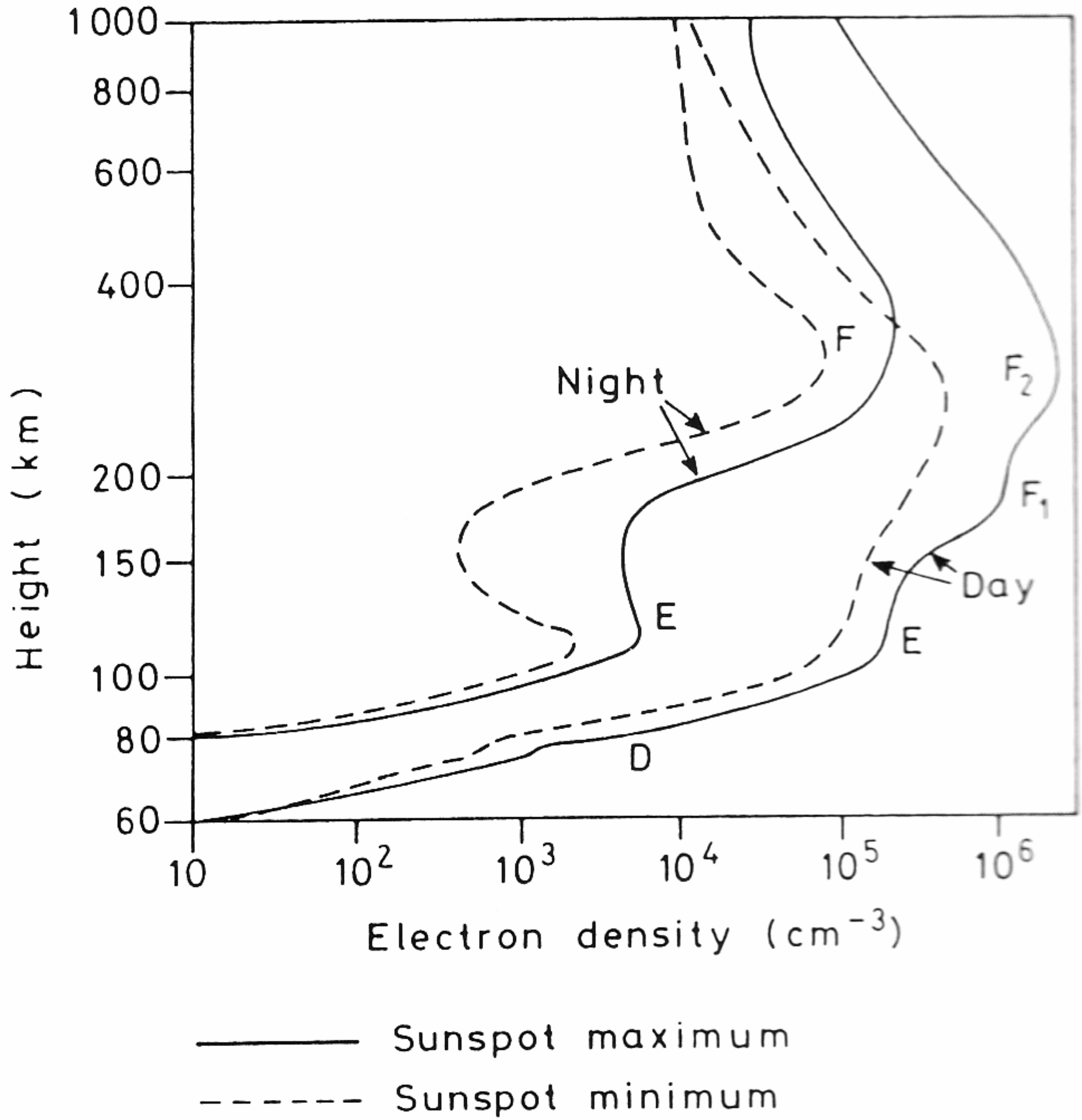


Ionospheric composition
Earth
Chamberlain and Hunten (1987)

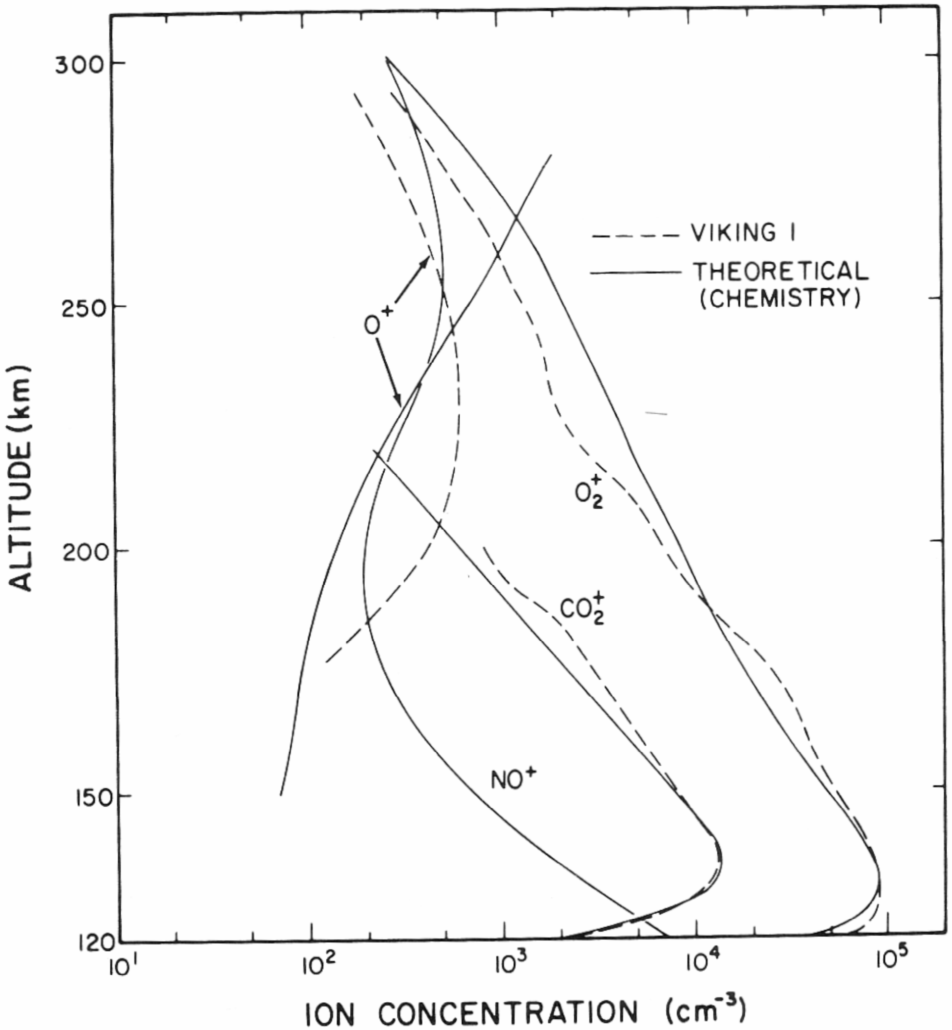
$14^+ = N^+$, $16^+ = O^+$, $18^+ = H_2O^+$
$28^+ = N_2^+$, $30^+ = NO^+$, $32+ = O_2^+$



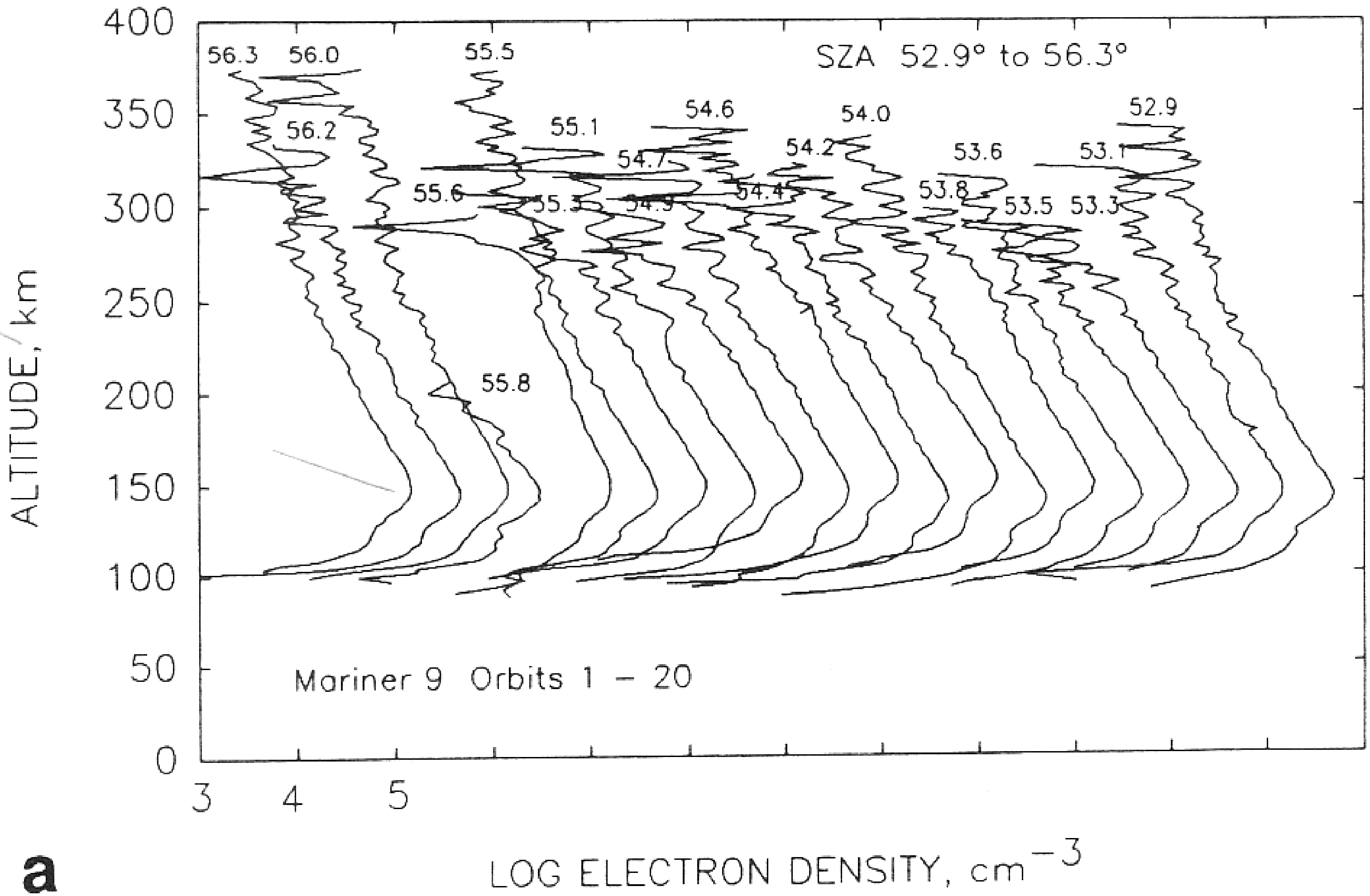
Ionospheric structure
Earth
Hargreaves (1992)



Ionospheric composition
Mars
Viking Lander 1 RPA data
and Hanson model
Chamberlain and Hunten (1987)



Ionospheric structure
Mars – Mariner 9
radio occultations
Kliore (1992)



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Chapman Theory for a Simple Ionospheric Layer

$$\alpha(T_e) \times N^2(z) = \frac{F_{1AU}}{(D/1AU)^2} \frac{1}{Ch(\chi)} \frac{1}{He} \times f(z)$$

$$f(z) = \exp(1 - \frac{z - z_m}{H} - \exp(-\frac{z - z_m}{H}))$$

$$z_m = z_0 + H \ln Ch$$

α = Dissociative recombination coefficient
T_e = Electron temperature
N = Number density of electrons
F_{1AU} = Ionizing flux at 1 AU
D = Distance from Sun
Ch(χ) = Geometrical correction function, secant(χ) for small χ

χ = Solar zenith angle
H = Scale height of neutral atmosphere
e = exp(1)
z = Altitude
z_m = Altitude at which N(z) is maximum
z_0 = Altitude at which N(z) is maximum for χ=0

Chapman Theory for a Simple Ionospheric Peak

$N_m = N_{max}$
$N_0 = N_m$ at $\chi=0$

$$N_m^2 \times (D/1AU)^2 H = \frac{1}{Ch(\chi)} \frac{F_{1AU}}{\alpha(T_e)e}$$

α_{NO+} = 4.0E-7 $cm^3\ s^{-1}$ $(300K/Te)^{0.5}$
α_{O2+} = 1.95E-7 $cm^{-3}\ s^{-1}$ $(300K/Te)^{0.5}$ for Te < 1200 K
α_{O2+} = 7.38E-8 $cm^{-3}\ s^{-1}$ $(1200K/Te)^{0.56}$ for Te > 1200 K

If H and T_e are independent of F_{1AU}, then:

$$\frac{\partial \ln N_m}{\partial \ln F_{1AU}} = 0.5$$

But H and Te are not independent of F_{1AU} …

- So dln(Nm) / dln(F) will not equal 0.5
- Response of H and Te to changes in F_{1AU} may vary with (a) planet (thermal structure, composition, etc) and (b) timescale (diurnal, solar rotational, solar cycle)
- Plus, H and Te may vary with χ as well
- Does dln(Nm) / dln(F) = m accurately represent the response of all three planets and all timescales for any single value of m?

Published studies of dln(Nm) / dln(F) = m

Reference	Planet	Equation for m	Result for m	Timescale	Correction for changing solar phase and distance?	Spacecraft	Solar Flux Proxy, F
Elphic et al. (1984)	Venus	$\frac{\partial \ln(N_m \sqrt{\sec \chi})}{\partial \ln F}$	m=0.33	Few months?	Yes	PVO	PVO/LP derived proxy
Kliore and Mullen (1989)	Venus	$\frac{\partial \ln(N_m (\sec \chi)^{0.511})}{\partial \ln F}$	m=0.376+/-0.011	7 years	Yes	PVO	AE-E/F10.7 derived proxy
Rishbeth and Garriott (1969)	Earth	$\frac{\partial \ln(N_m \sqrt{\sec \chi})}{\partial \ln F}$	m=0.35-0.50	Years	N/A	"Ground-based"	F10.7
Titheridge (1997)	Earth	$\frac{\partial \ln N_0}{\partial \ln F}$	m=0.32-0.40	Years	N/A	"IRI-90"	F10.7
Stewart and Hanson (1982)	Mars	$\frac{\partial \ln(N_m D \sqrt{\sec \chi})}{\partial \ln F}$	m=0.5	1 year	Yes	Mariner 9	F10.7
Hantsch and Bauer (1990)	Mars	$\frac{\partial \ln(N_m \sqrt{\sec \chi})}{\partial \ln F}$	m=0.36	>10 years	No	Mars 2,4,6, Mariner 4,6,7,9 VO1,2, VL1,2	F10.7
Breus et al. (2004)	Mars	$\frac{\partial \ln(N_m \sqrt{H \sec \chi})}{\partial \ln F}$	m=0.37+/-0.06	3 months?	Yes?	MGS	E10.7
Withers et al. (2005)	Mars	$\frac{\partial \ln\left(N_m D \sqrt{HCh}\right)}{\partial \ln F}$	m=0.243+/- 0.031	3 weeks	Yes	MGS	E10.7

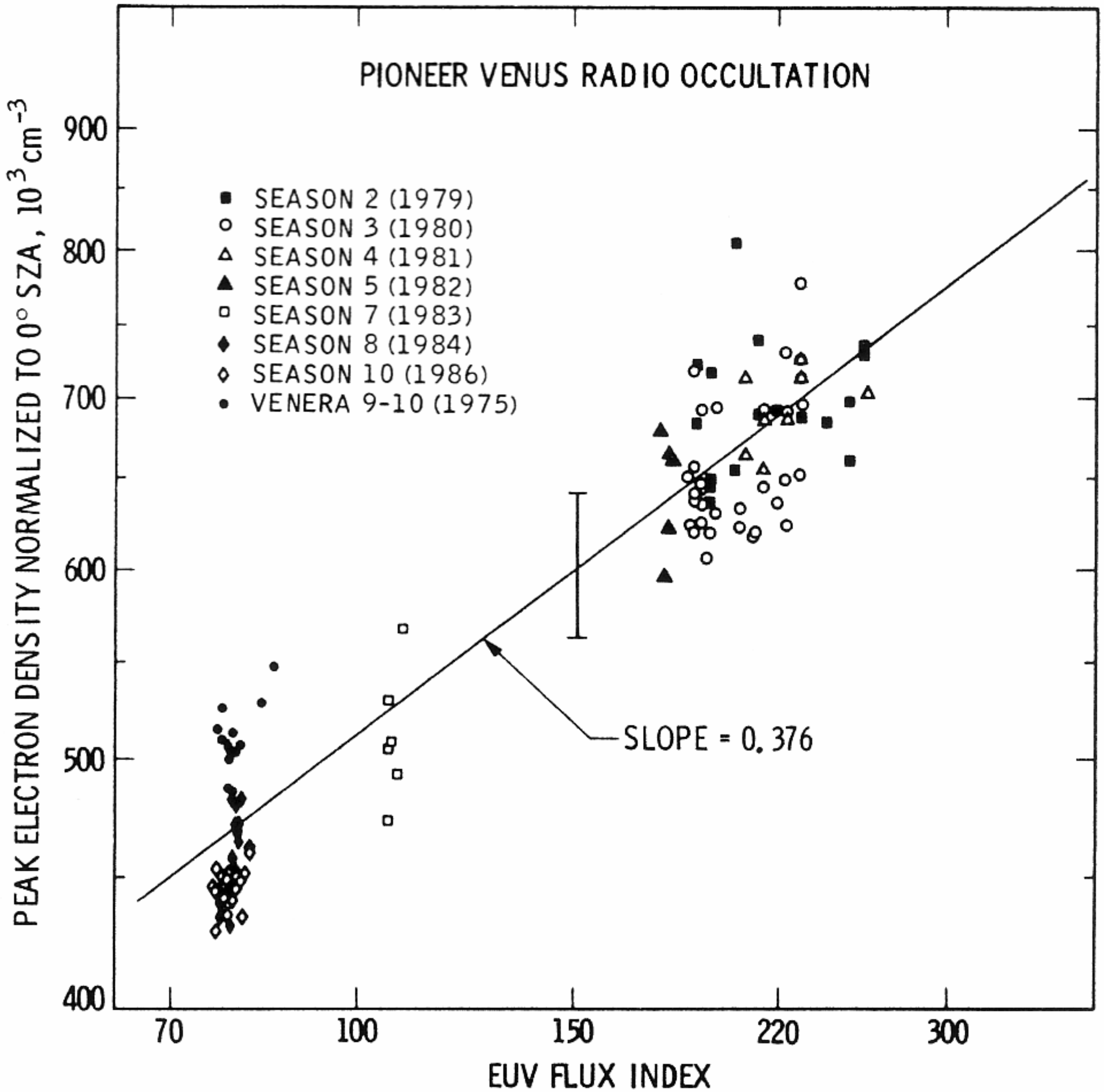
Comments on Published Studies – Venus and Earth

- Kliore and Mullen's (1989) work on Venus used a large dataset with an extensive range of solar zenith angles and solar fluxes. Their quantitative analysis included the effects of errors. Elphic et al.'s (1984) work is less suitable for our purposes.
- There are surprisingly few relationships between N_m and F for the Earth, probably because terrestrial workers are rarely interested in such simple analyses. We adapted the two relationships that we could find in order to determine dln(Nm) / dln(F). However, the relationships that do exist benefit from large datasets, so they should be reliable.

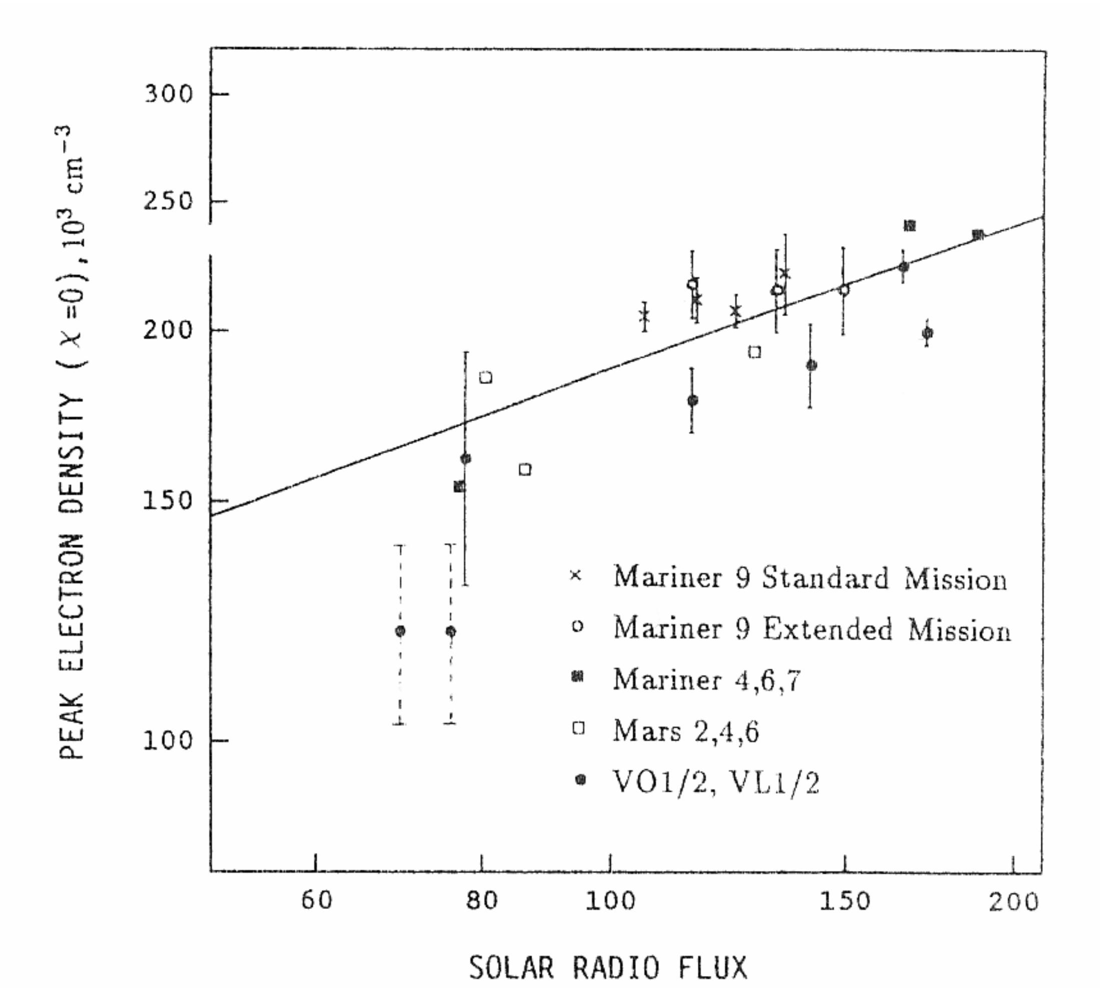
Comments on Published Studies - Mars

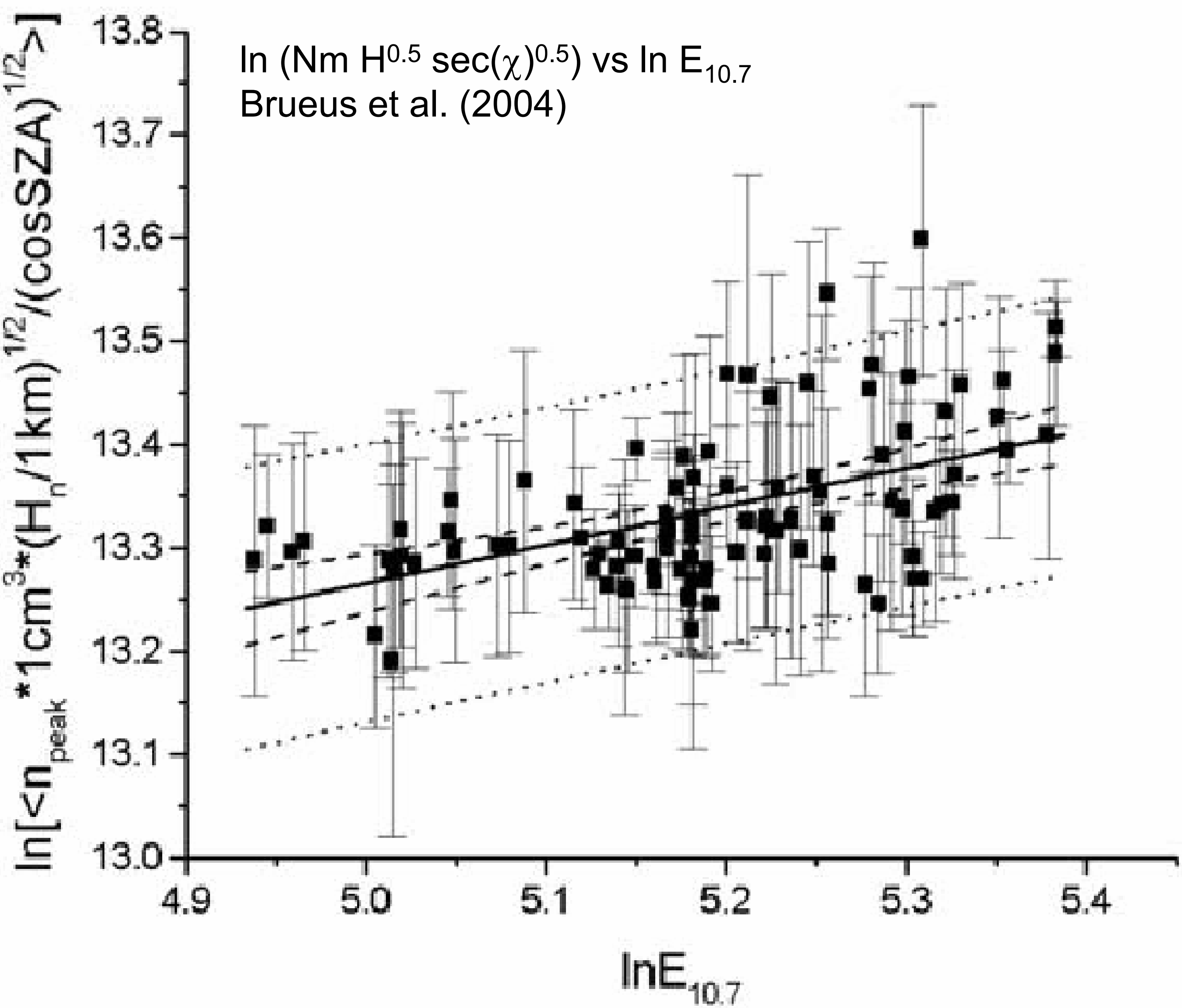
- Stewart and Hanson (1982) assumed that dln(Nm) / dln(F) = 0.5 and then fitted other model parameters to data
- Hantsch and Bauer (1990) did not consider the effects of solar rotation, nor of changes in the Mars-Sun distance. They appear to have treated results from individual flybys on equal terms with averages from many measurements by Mariner 9. They did not correct sec(χ) at high solar zenith angles and did not consider the effects of errors.
- Breus et al. (2004) did not correct sec(χ) at high solar zenith angles despite half their data being at $\chi > 80^o$. It is unclear whether they have corrected for solar rotation and, if so, how.
- Withers et al. (2005) included an explicit H dependence and used Tobiska's $E_{10.7}$ proxy for solar flux, which changes with each new release of Solar2000, but their result only changes from 0.243 +/- 0.031 to 0.241 +/- 0.012 if $F_{10.7}$ and a constant scale height are used instead. Their timescale of a few weeks is much shorter than those of the Venus and Earth studies, but has values of $E_{10.7}$ that range from 126 to 291.

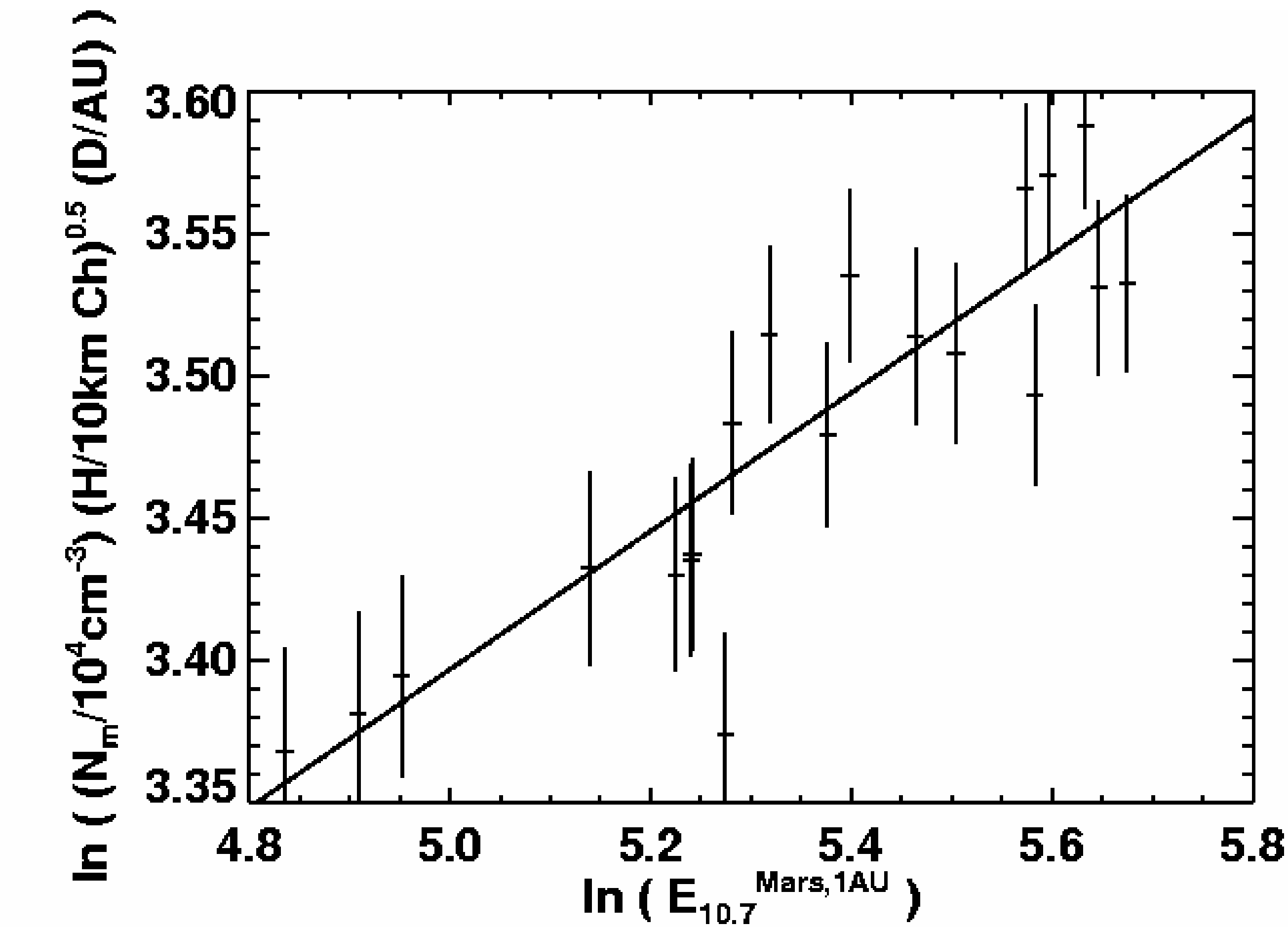
N_0 vs Flux for Venus
Logarithmic axes
Kliore and Mullen (1989)



N_0 vs $F_{10.7}$ for Mars
Logarithmic axes
Hantsch and Bauer (1990)




ln (Nm H^0.5 sec(χ)^0.5) vs ln E_10.7
Brueus et al. (2004)
ln[<n_peak*1cm^3*(H_n/1km)^1/2/(cosSZA)^1/2>]
lnE_10.7
13.0
13.1
13.2
13.3
13.4
13.5
13.6
13.7
13.8
4.9
5.0
5.1
5.2
5.3
5.4



$$\ln\left(\left(N_m / 10^4\, cm^{-3}\right)\sqrt{ChH / 10km}\left(D / AU\right)\right) =$$
$$\left(0.243 \pm 0.031\right)\ln\left(E_{10.7}^{Mars,1AU}\right) + \left(2.181 \pm 0.165\right)$$

Withers et al. (2005)

Results for Venus, Earth, and Mars

- dln(Nm) / dln(F) = 0.35-0.40 is a reasonable approximation for Earth and Venus on timescales of years.
- It is not clear if it is valid at Mars. There are problems with published work studying long timescales. Withers et al. (2005), studying timescales of a few weeks, found that dln(Nm) / dln(F) = 0.24 +/- 0.03.

Electron Temperatures and Scale Heights

$$N_m^2 = \frac{1}{H \times \alpha(T_e)} \frac{F_{1AU}}{(D/1AU)^2 Ch(\chi)e}$$

- H x α(Te) responds similarly to changes in F on Venus and Earth, but seems to respond differently on Mars.
- If true, this could be due to the relatively low Te on Mars (~200 K) compared to Venus and Earth (~1000 K)

Conclusions

- Despite similarities between their photochemistry, peak electron density in the terrestrial planet ionospheres does not respond in the same way to changes in ionizing solar flux
- dln(Nm) / dln(F) = 0.35-0.40 for Venus and Earth on timescales of years, but 0.24 for Mars on timescales of weeks.
- dln(Nm) / dln(F) differs from 0.5 on Venus, Earth, and Mars due to the dependence of H and Te on solar flux. The response of H and Te to changes in F might be different from planet to planet,
- Is this response function different when solar flux changes on very short timescales, e.g. due to flares, when ion production rates increase instantly but H and Te have a longer response time?
- Properly calibrated, this response function can be used to determine the ionizing solar flux at Venus or Mars from routine ionospheric measurements.

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