Exosphere of Mars: theory, model and observations.

Jean-Loup Bertaux

(1) LATMOS/IPSL/UVSQ: Université de Versailles Saint-Quentin/CNRS

Heavily based on the work of Jean-Yves Chaufray , post-doc at LMD.

Workshop Mars III : Les Houches, 29 March, 2 april, 2010

Atmospheric evolution

- Water content now: Earth, 2.8 km liquid
- Mars, ~20+20 m (polar caps +polar terrains) ice
- Venus, 30 mm (~30 ppmv) vapor
- Was Venus originally wet ? Or dry?
- Was Mars endowed with more H_2O ?
- Study the escape processes now
- Extrapolate back in time
- H and D atoms, O escape

Structure of the atmosphere

Collisionless medium: ballistic trajectory in gravity field

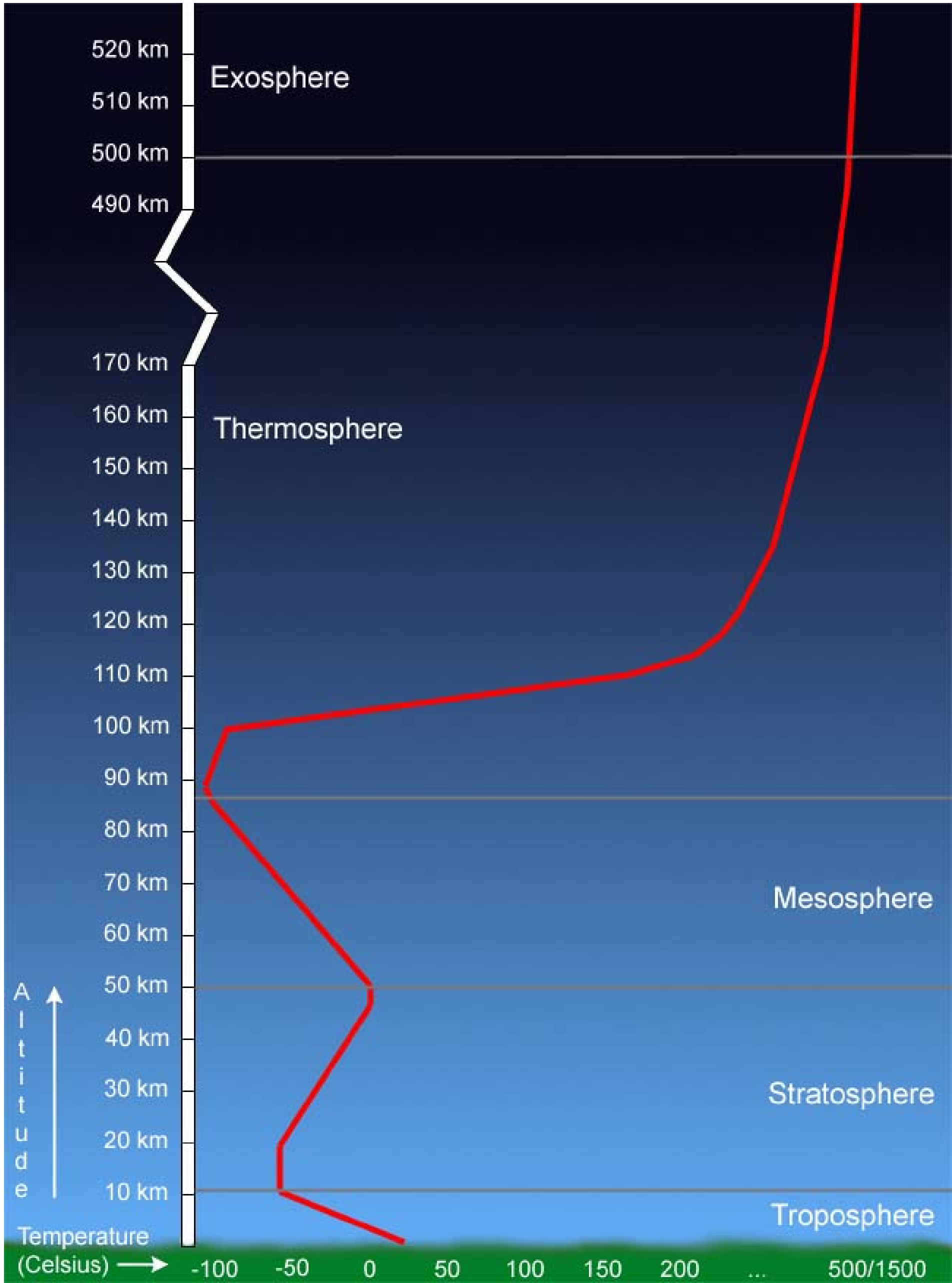
All gases follow their own scale height H_i :diffusive separation according to mass, $H_i = kT/m_i g$

$n(z) = n_0 \exp(-(z-z_0)/H_i)$

Hydrostatic equilibrium

All (inert)gases are well mixed by convection, turbulence,… vertical mixing

- homosphere heterosphere



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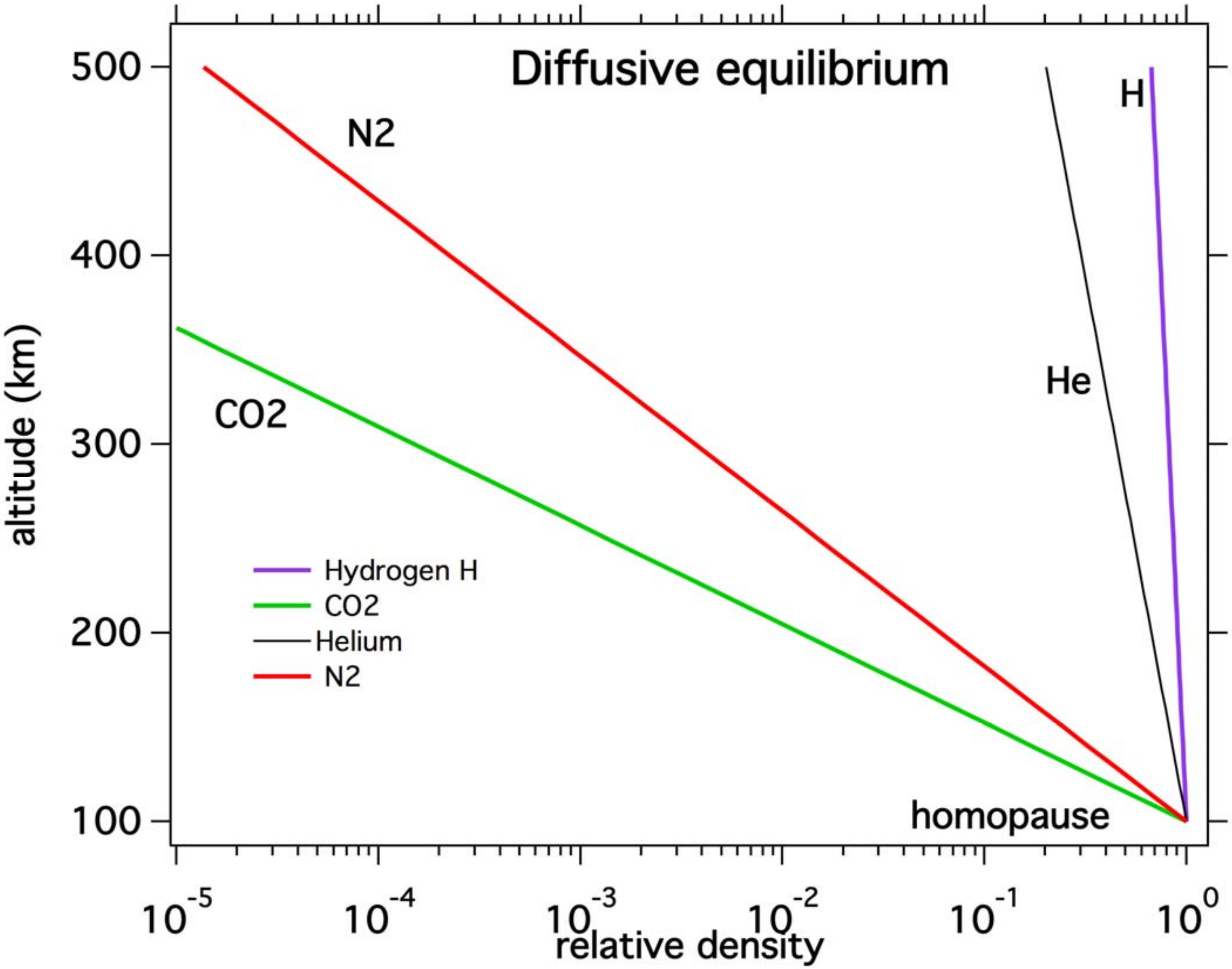
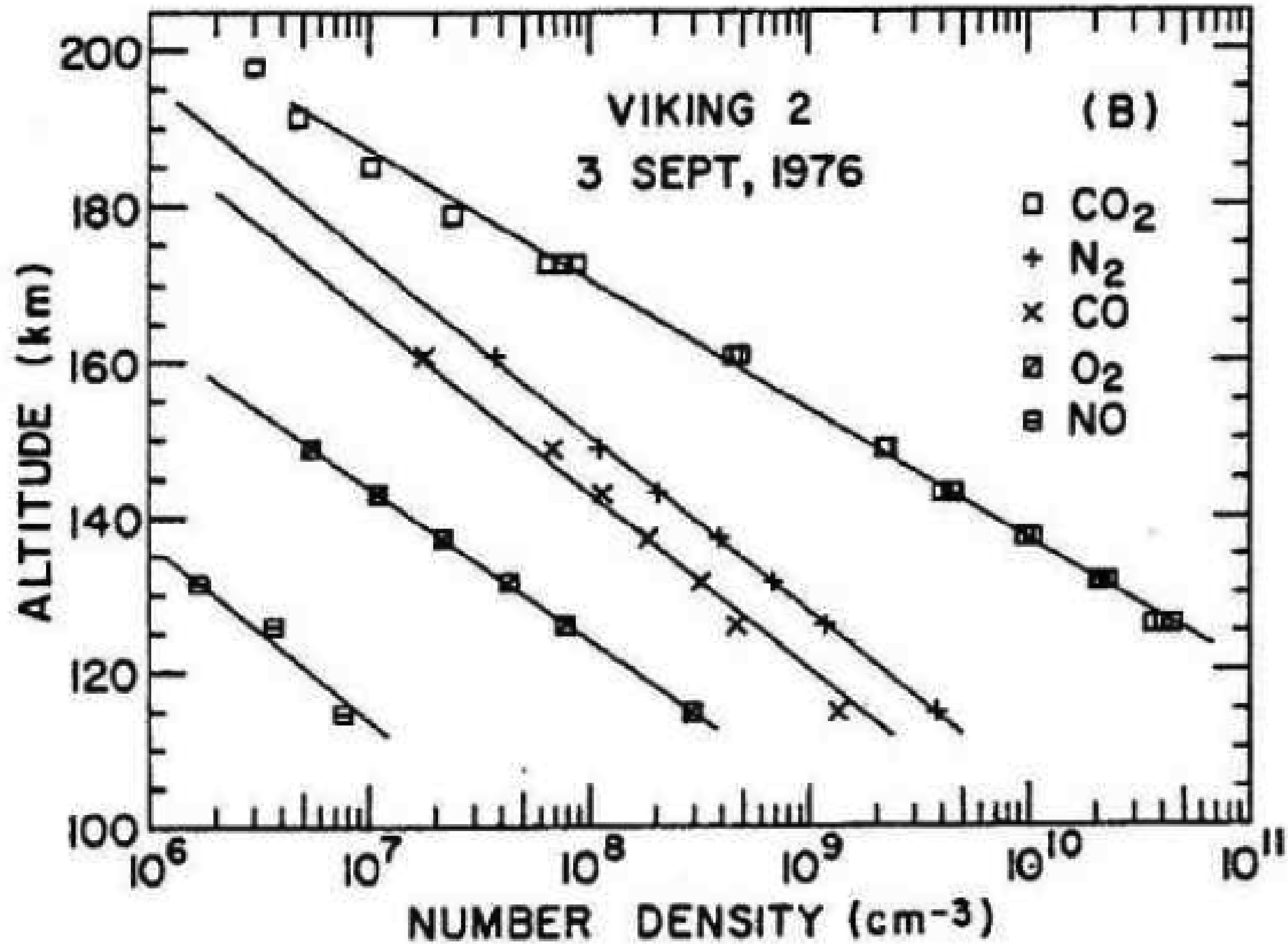


Earth thermosphere, isotherm, T=1000 K

There is no diffusion of gases in the diffusion equilibrium!

$n(z)=n_0 \exp(-(z-z_0)/H_i)$

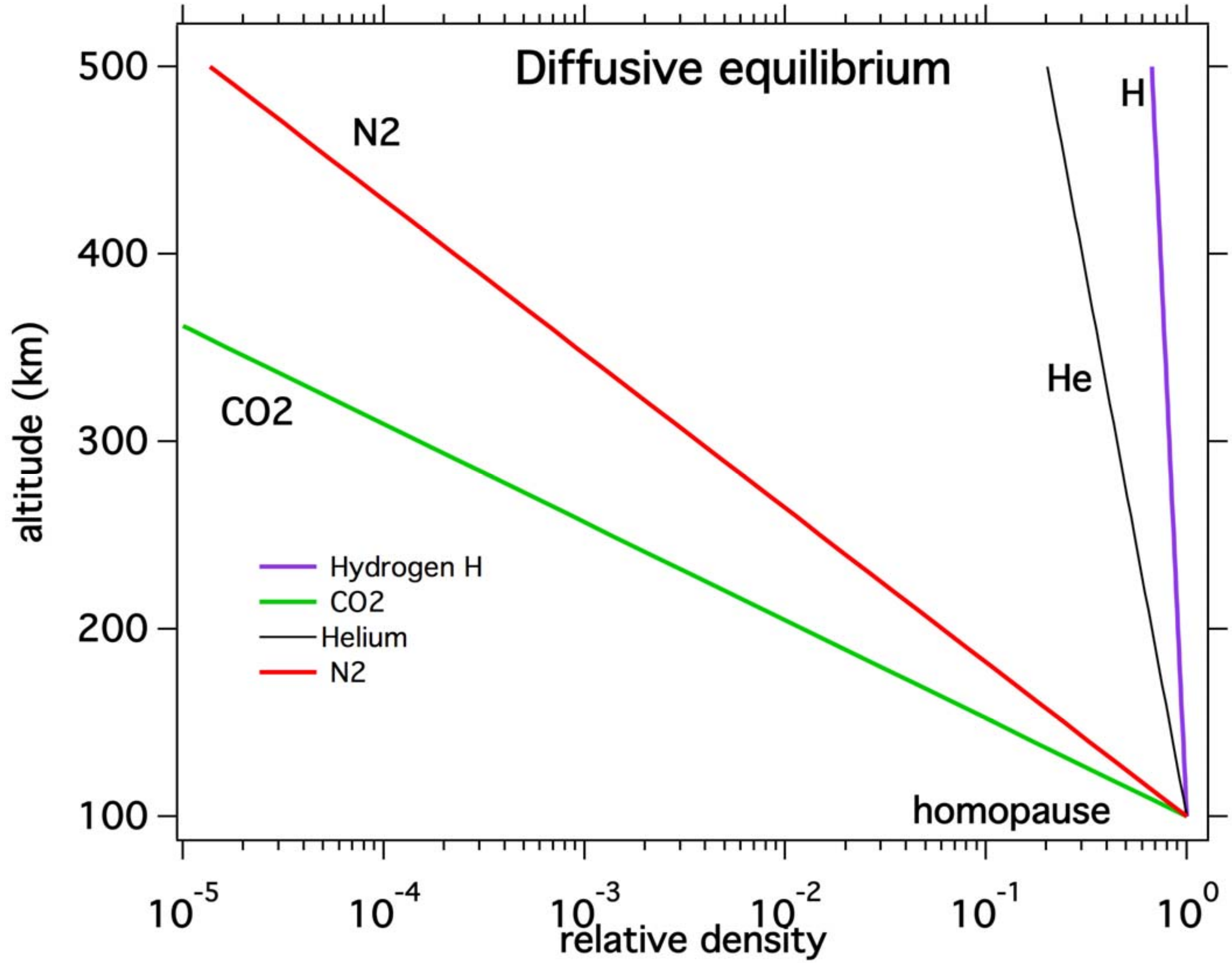
Mars thermosphere composition



What happens if there is some escape of H at top of atmosphere ?

Conservation of flux: pumping is done through the main atmospheric constituent : diffusion

H density decreases at top



Earth thermosphere, isotherm, T=1000 K

There is no diffusion of gases in the diffusion equilibrium!

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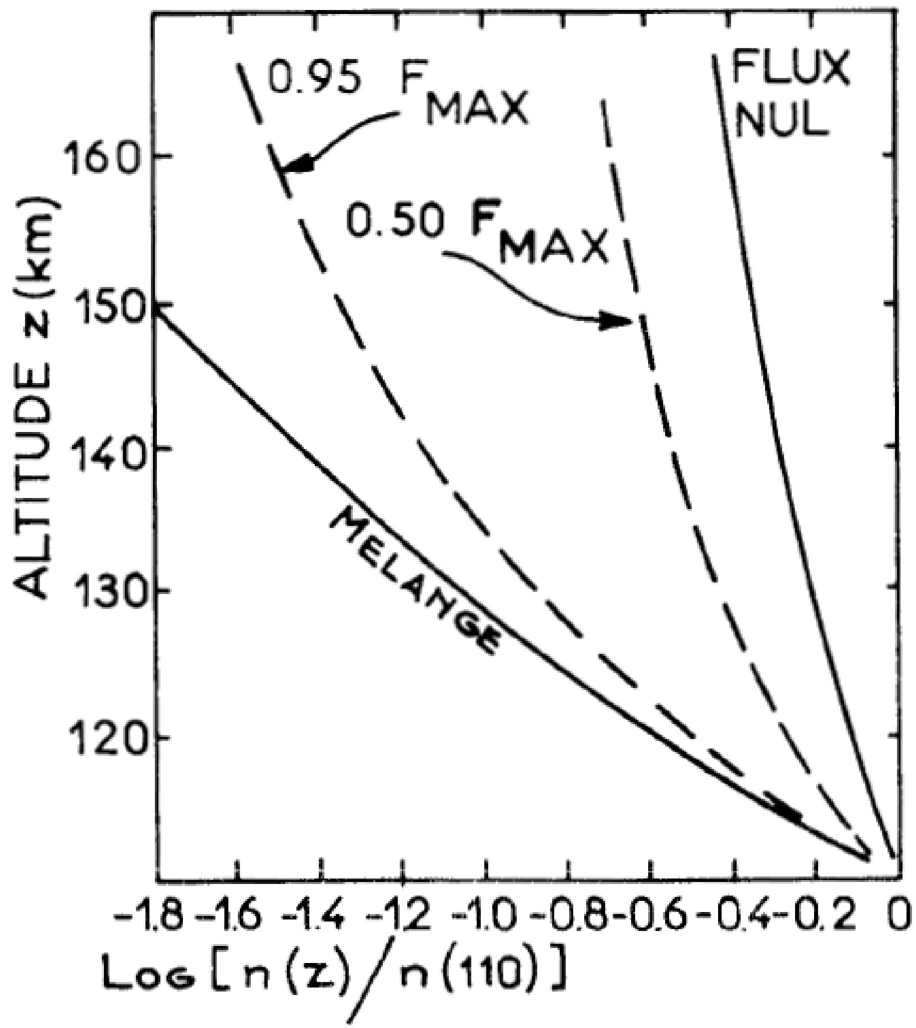
Diffusion and pumping

What happens if there is some escape of H at top of atmosphere ?

Conservation of flux: pumping is done through the main atmospheric constituent : diffusion

H density decreases at top

There is a maximum flux, determined by conditions at homopause level.



Reactions in thermosphere (Kranopolsky,2002)

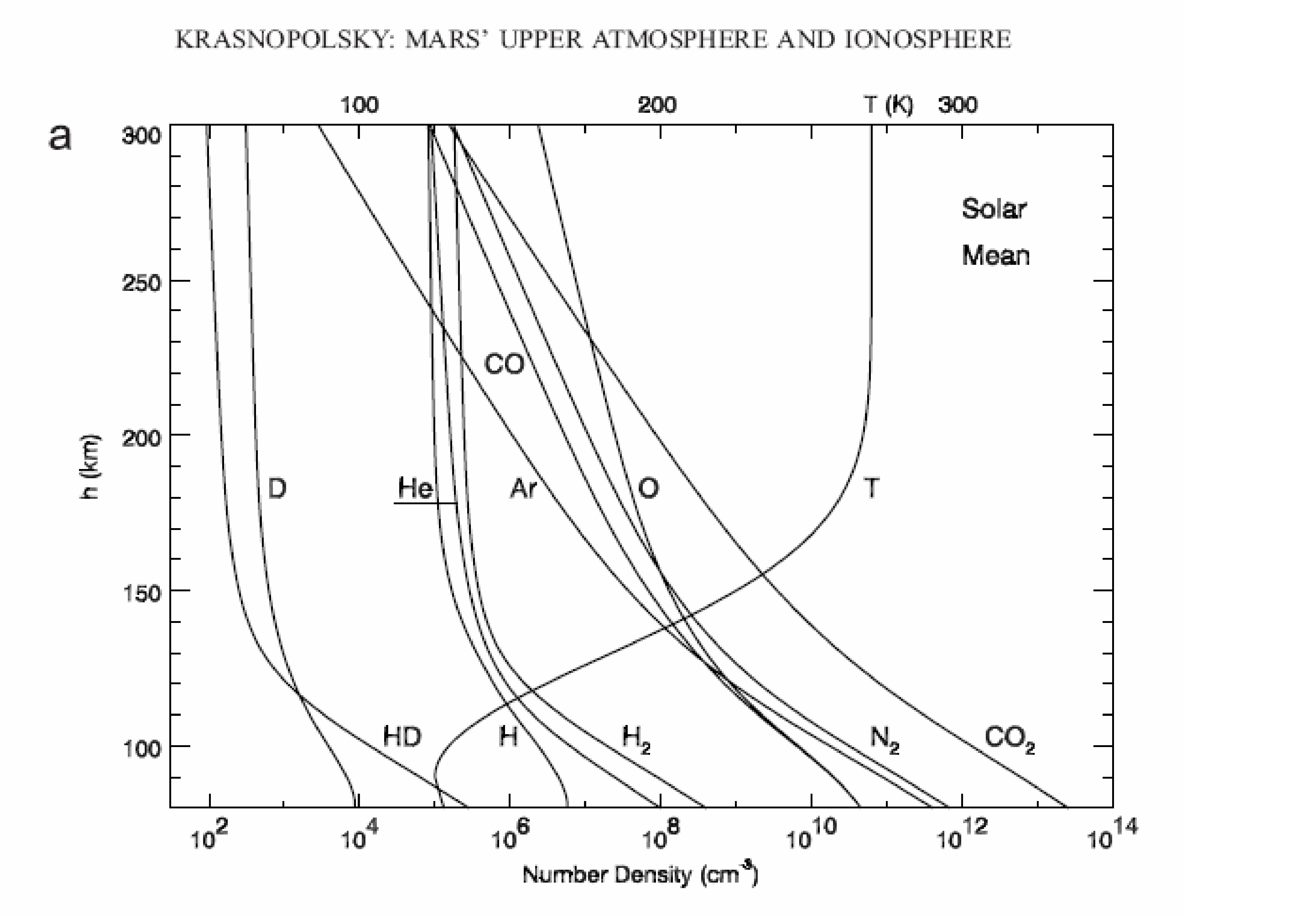
Table 2. (continued)

	Reaction	Rate Coefficients	Column Rate
74	$ArH^+ + CO_2 \rightarrow HCO_2^+ + Ar$	$1.1-9^f$	1.95 + 4
75	$HCO_2^+ + O \rightarrow HCO^+ + O_2$	1 − 9	6.45 + 7
76	$HCO_2^+ + CO \rightarrow HCO^+ + CO_2$	7.8 − 10	3.25 + 7
77	$CO_2^+ + e \rightarrow CO + O$	$3.8 \times 10^{-7}(300/T_e)^{0.5}$	7.52 + 9
78	$O_2^+ + e \rightarrow O + O$	$2 \times 10^{-7}(300/T_e)^{0.7}$	1.36 + 10
79	$NO^+ + e \rightarrow N + O$	$4.3 \times 10^{-7}(300/T_e)^{0.37}$	7.32 + 8
80	$HCO^+ + e \rightarrow CO + H$	$1.1 \times 10^{-7} \times 300/T_e$	1.17 + 8
81	$HCO_2^+ + e \rightarrow CO_2 + H$	$3.4 \times 10^{-7}(300/T_e)^{0.5}$	9.69 + 6
82	$O(^1D) + CO_2 \rightarrow O + CO_2$	$7.4 \times 10^{-11}e^{120/Te}$	2.72 + 11
83	$O(^1D) \rightarrow O + h\nu$	$\tau = 110$ s	9.07 + 8
84	$O(^1D) + H_2 \rightarrow OH + H$	$1.75-10^g$	9.93 + 6
85	$OH + O \rightarrow O_2 + H$	$2.2 \times 10^{-11}e^{120/Te}$	9.93 + 6
86	$H_2 + O \rightarrow OH + H$	$3.4 \times 10^{-13}(T/300)^{2.7}e^{-3165/Te}$	122

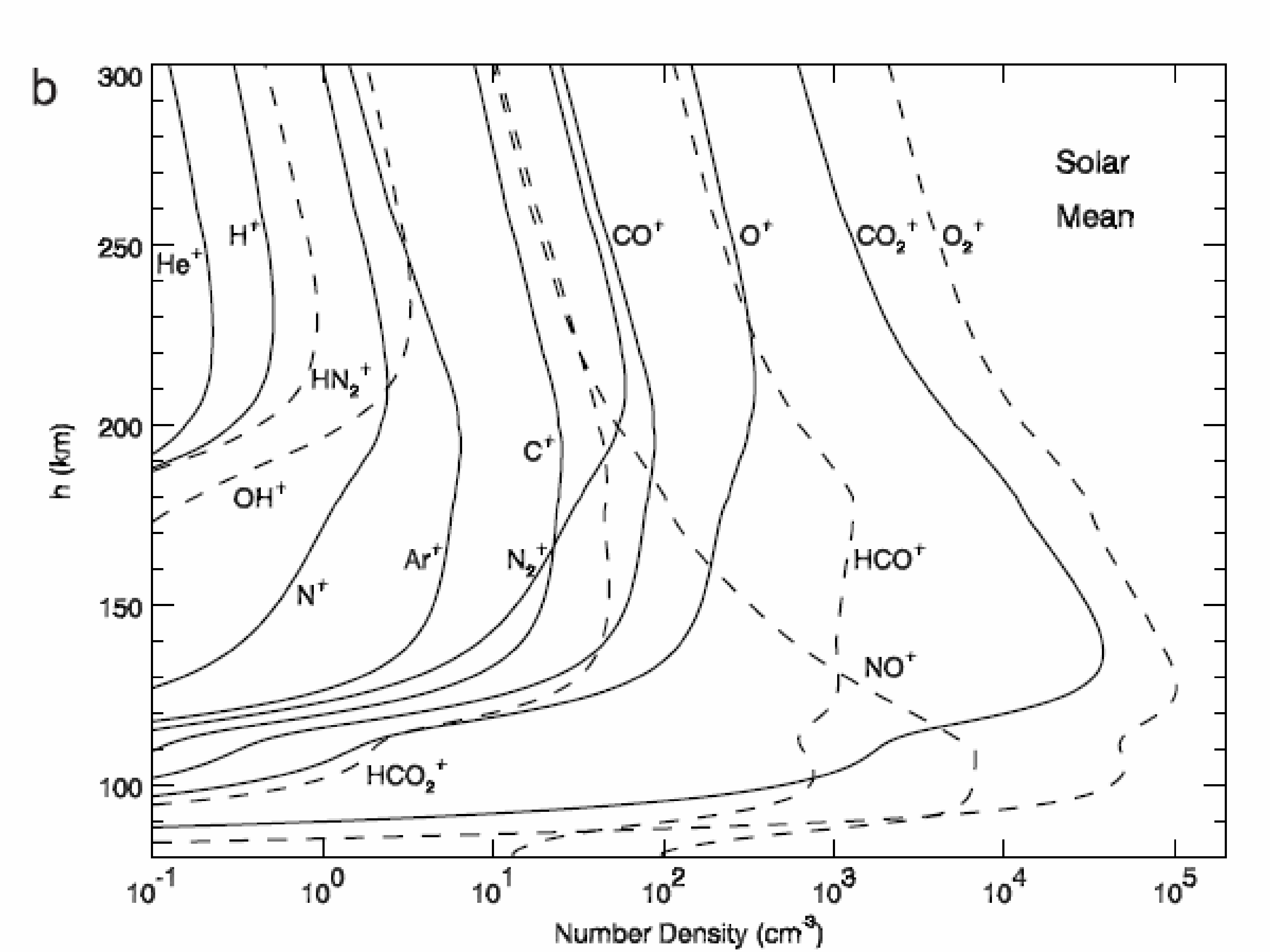
[a]Rate coefficients are in $cm^3\ s^{-1}$. Cross sections for reactions (1)–(14) are discussed in text, and limiting wavelengths are given. Reactions of deuterated species are similar to those of hydrogen species, and their rate coefficients for ion-neutral reactions are corrected for a factor of 0.82 (see text). 9.6 − 11 means 9.6×10^{-11}. Rate coefficients are from *Le Teuff et al.* [2000] unless cited below. Column rates are in $cm^{-2}\ s^{-1}$, corrected for radius, i.e., multiplied by $(1 + r/r_0)^2$, and refer to medium solar activity.

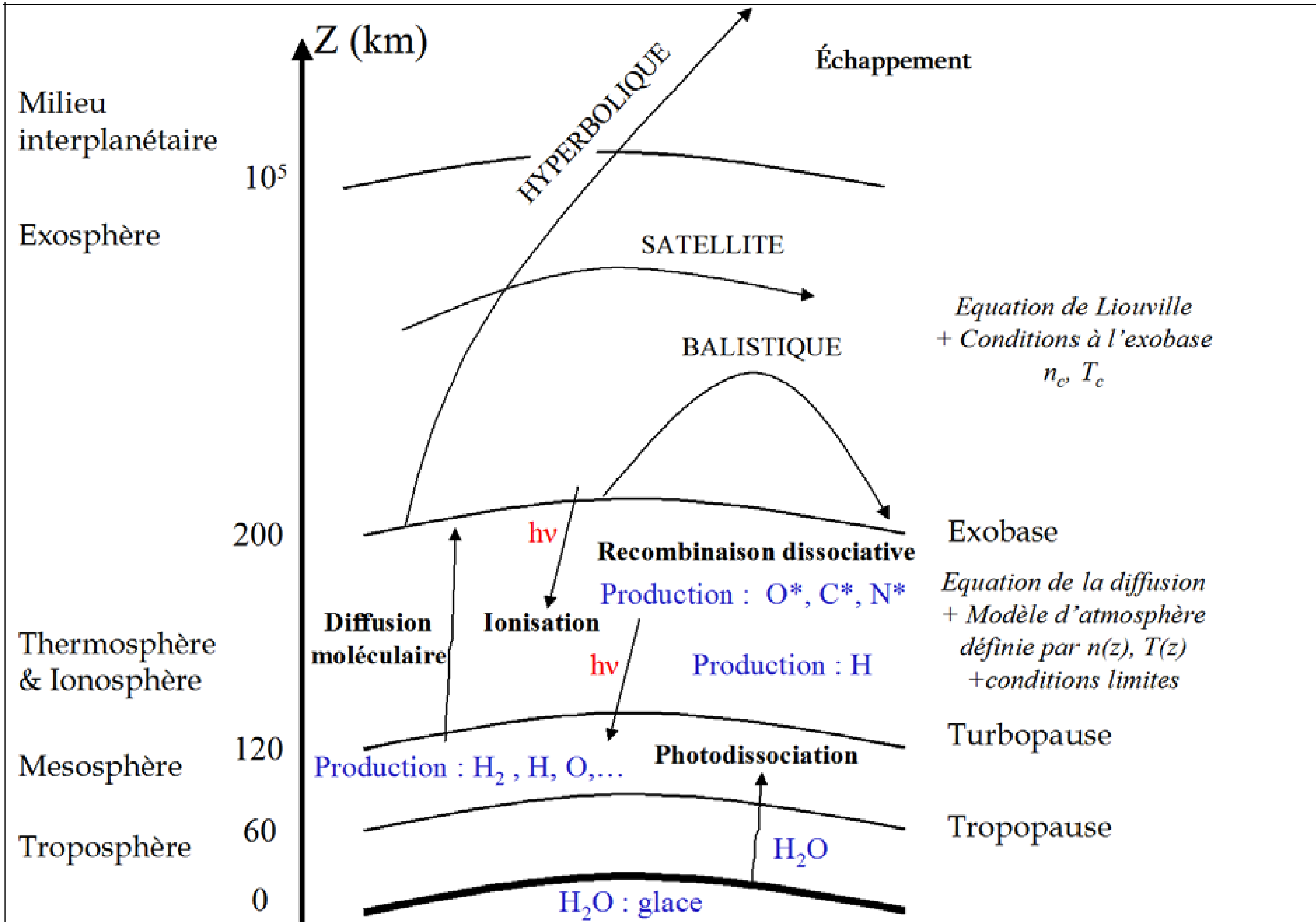
[b]*Scott et al.* [1997]

Photochemistry model Krasnopolsky 2002



Photochemistry model Krasnopolsky 2002: ionosphere



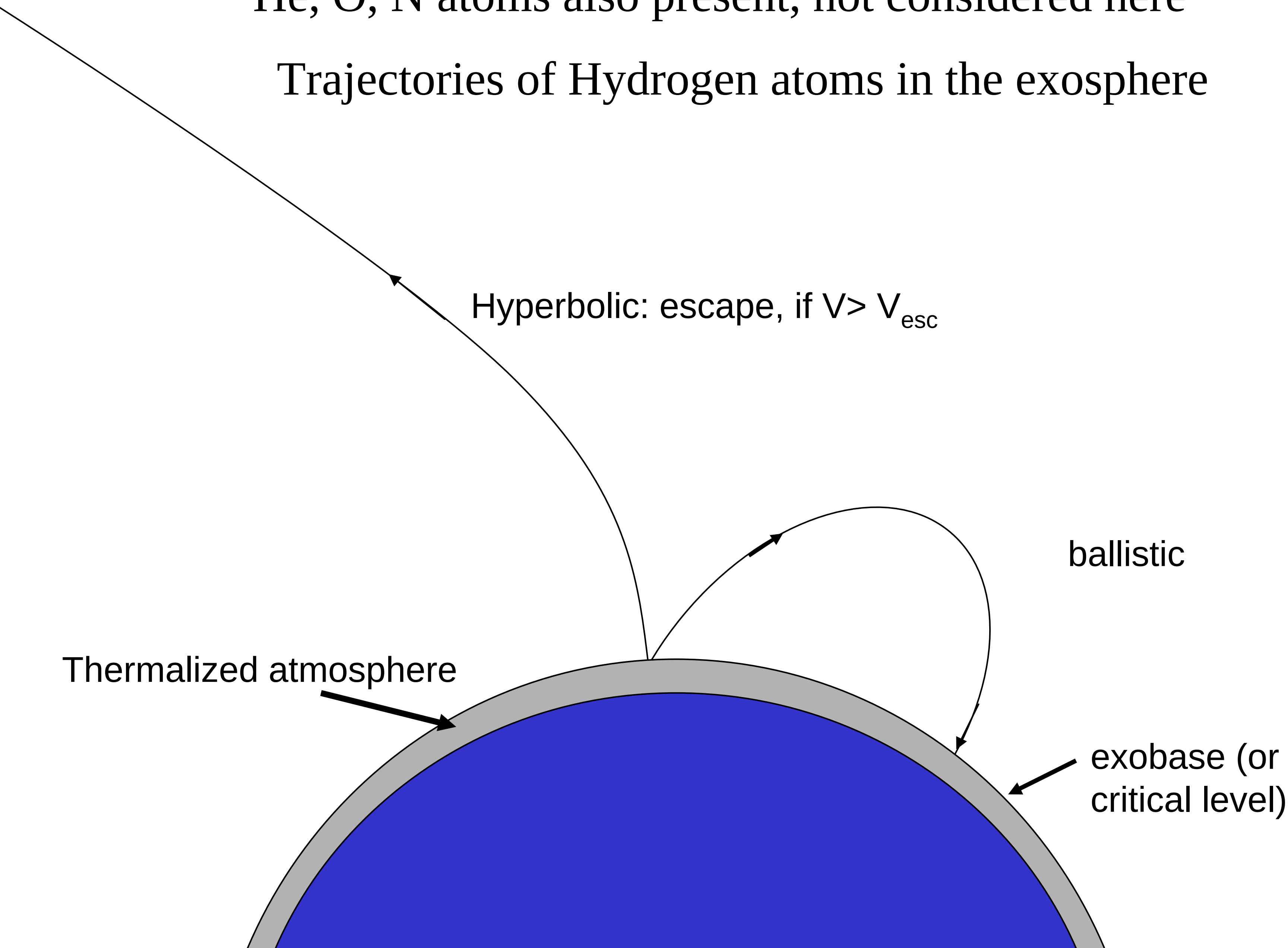


From Jean-Yves Chaufray

The exosphere (collisionless)

He, O, N atoms also present, not considered here

Trajectories of Hydrogen atoms in the exosphere



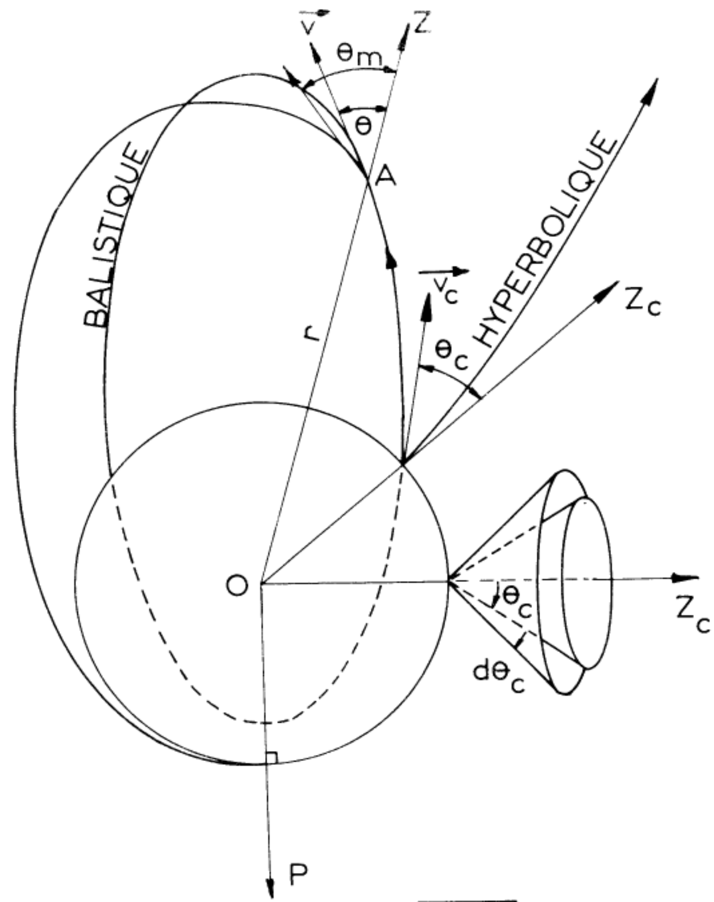
Liouville's therorem

- Along dynamical trajectories, the density in phase space is conserved.
- Phase space= 3D volume * velocity space

Recipe to compute numerically exospheric volume density at point A: integrate over velocity space, V, θ

-for each V, θ, compute trajectory, find Vc, θc at exobase level

Compute density in phase space at exobase for Vc, θc : Maxwell-Boltzmann distribution at temperature T



F. 17

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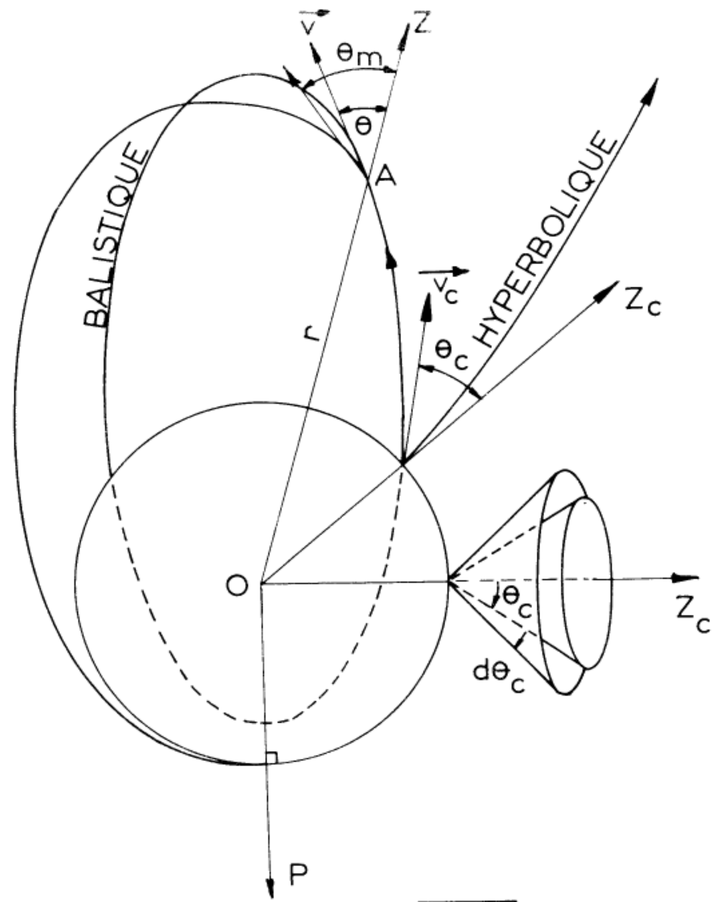
Chamberlain, 1963: spherical symmetry



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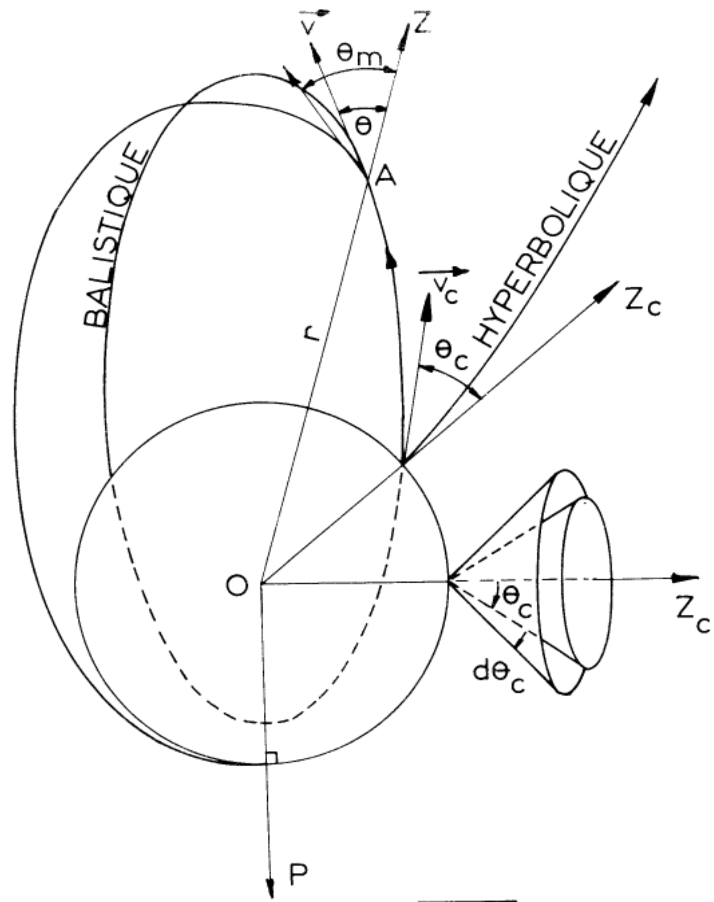
Chamberlain, 1963: spherical symmetry

Vidal-Madjar and Bertaux, 1973: general case, Nc and Tc variable at exobase



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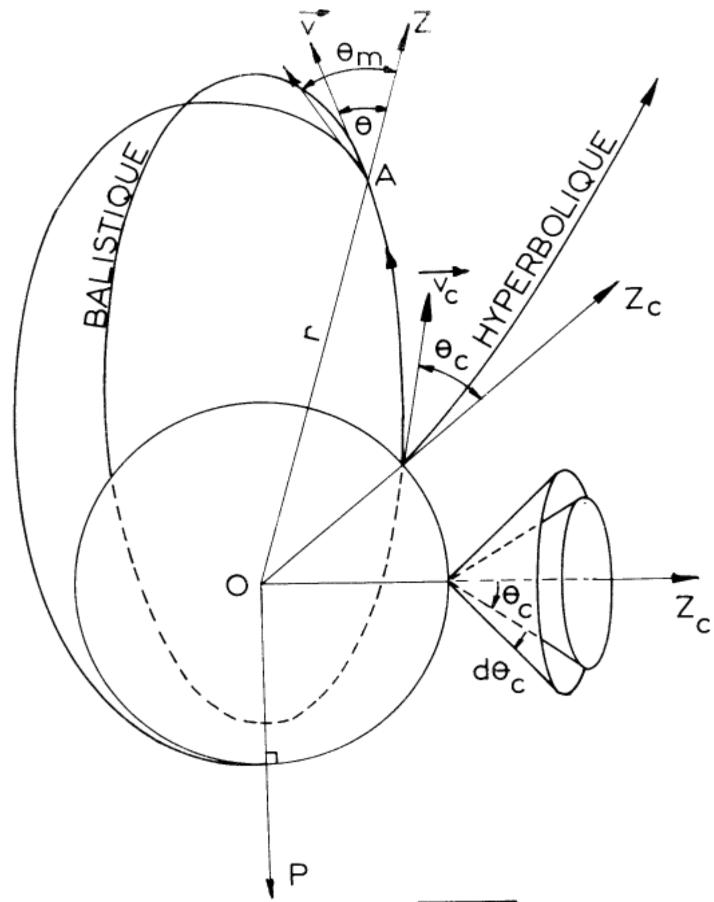
Chamberlain, 1963: spherical symmetry

Bertaux says today: full general case, non thermal case also. Possible for **any velocity distribution ! Liouville!**



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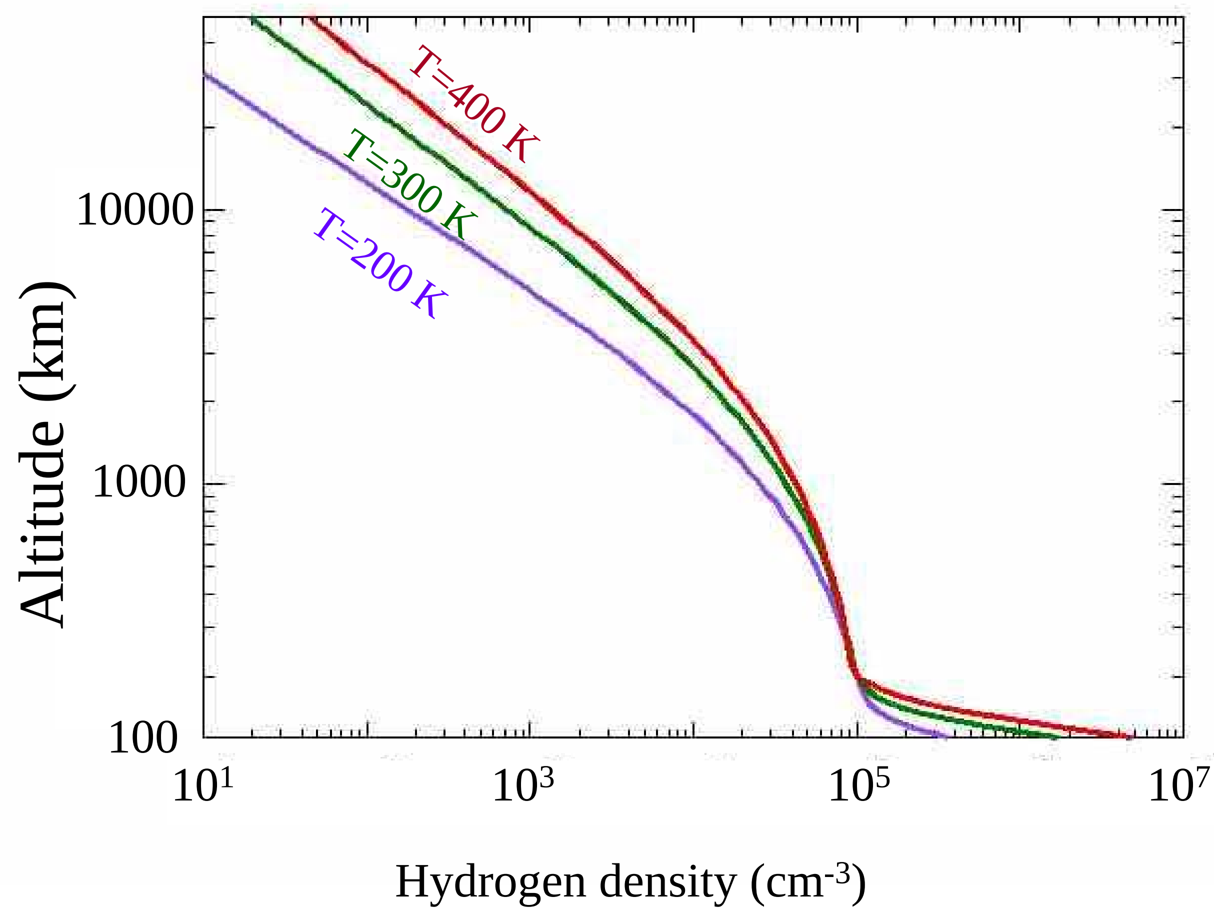
Model of Mars H exosphere



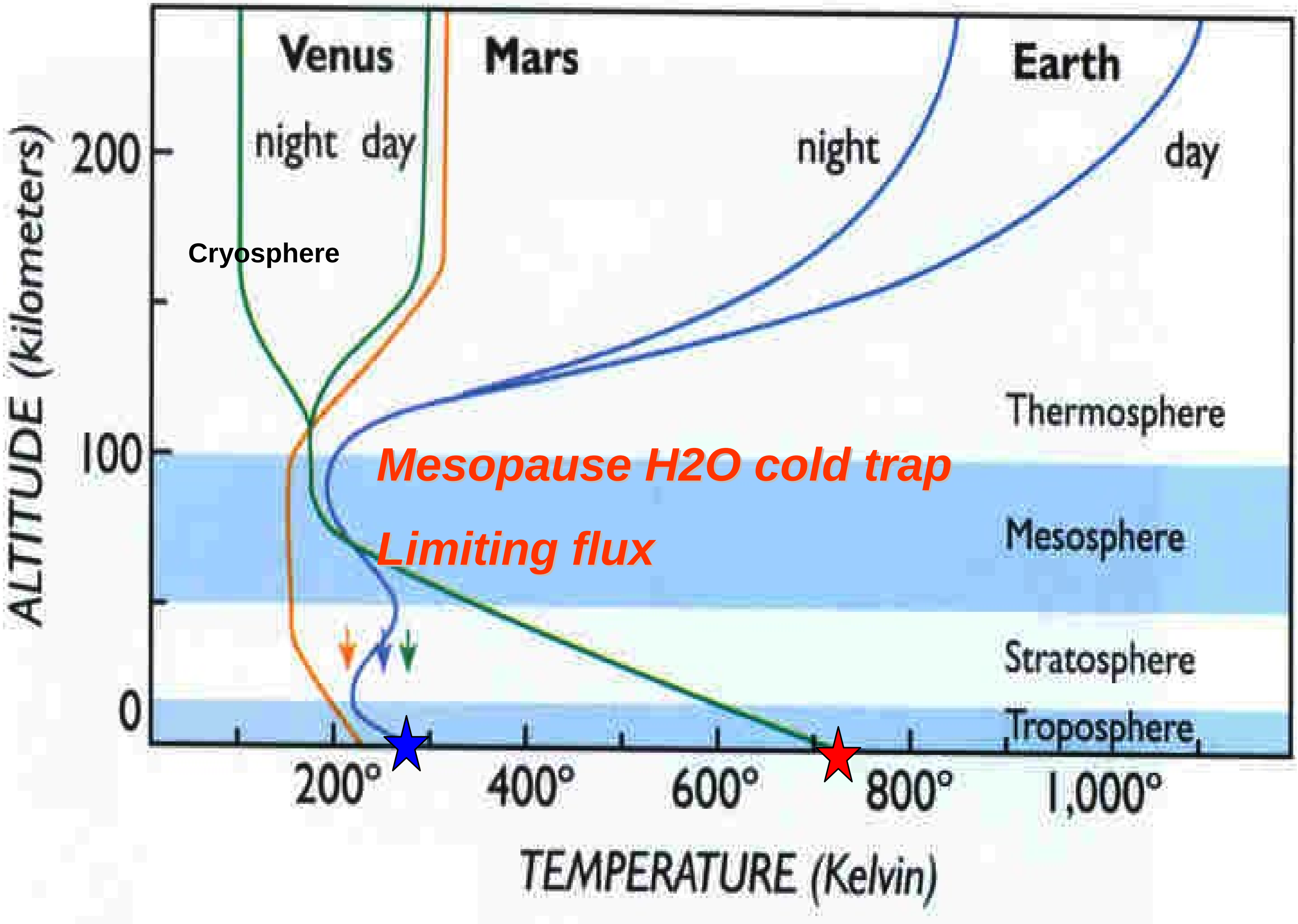
Exospheric Temperature Tex dictates the H distribution in the exosphere (Chamberlain, 1963) from Jean-Yves Chaufray, 2007

Temperature in the thermosphere

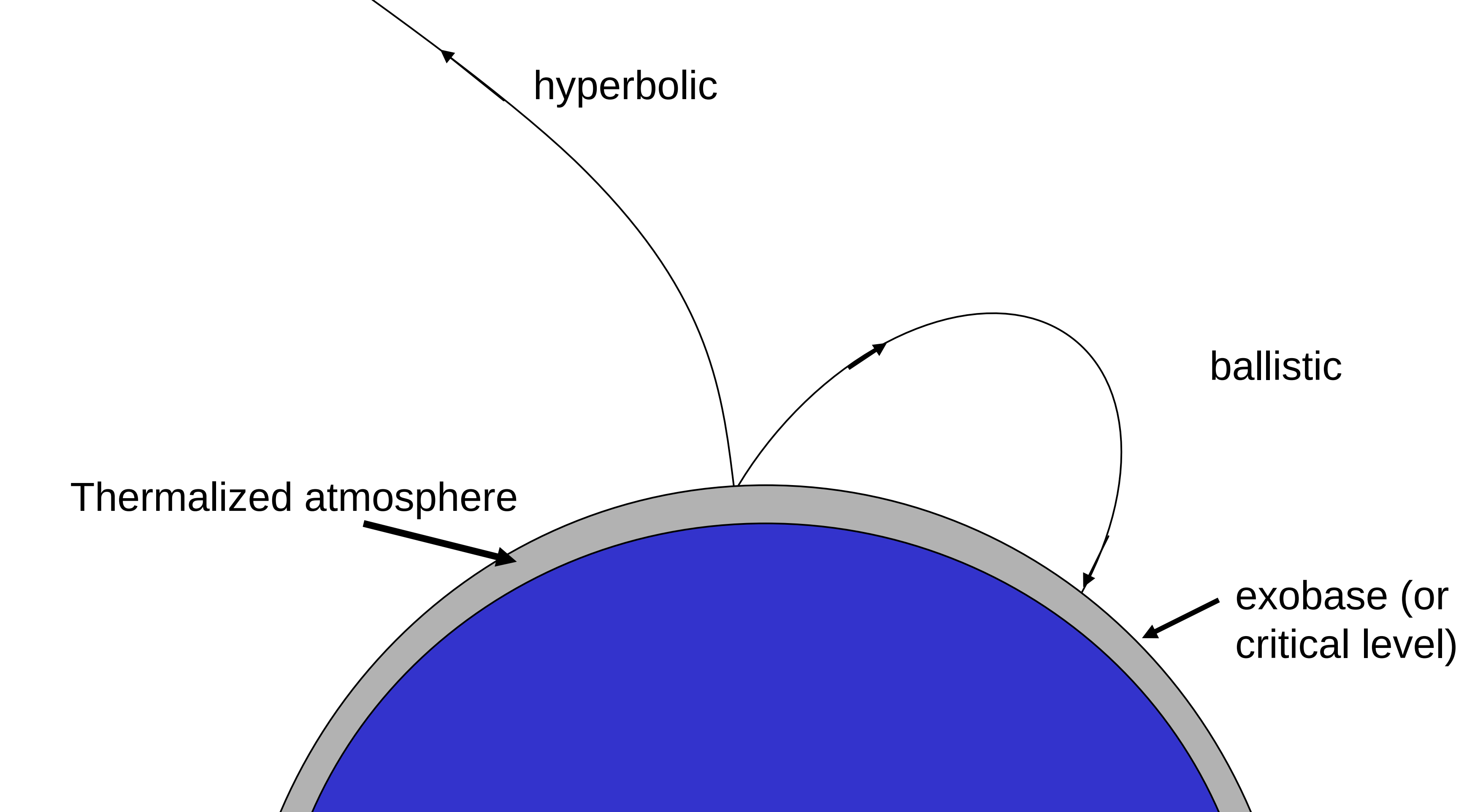
- Heating by solar EUV, XUV
- Conduction
- Radiative cooling (IR radiation)
  - O_2, N_2 homopolar molecules : no IR radiation
  - CO_2 : strong radiative cooling (night side of Venus: the cryosphere!)

Difference between Earth (1000 K) and Venus/Mars (220-280 K)

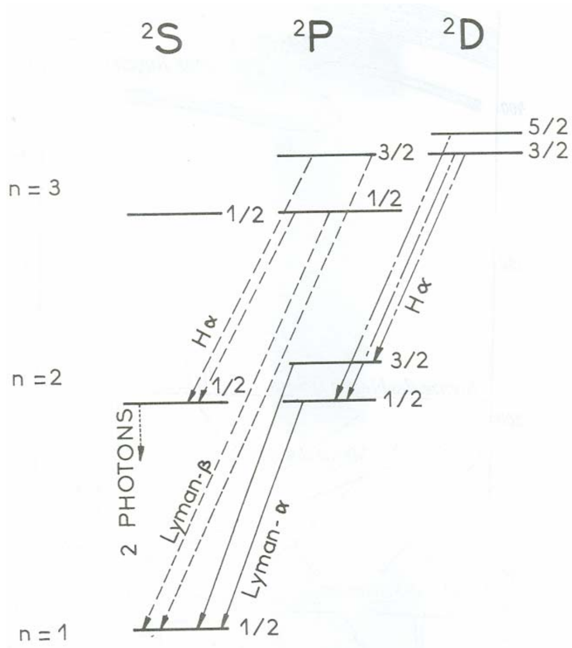
Compared temperature profiles



n_c, density of H atoms at the exobase
T_c, or T_{ex}, temperature of H at the exobase (exospheric temperature): from Maxwell velocity distribution, compute the fraction of atoms which have V> Vesc
compute the thermal escape flux (Jeans Escape, F_J~10^8 atoms/cm2 s =0.2 m H2O/Gyr)
-the density of Hydrogen atoms in the exosphere can be computed with Liouville's theorem (Chamberlain 1963): linear with n_c ,increases with T_c
- the converse is true: from H distribution in the exosphere, derive n_c, T_c, F_J

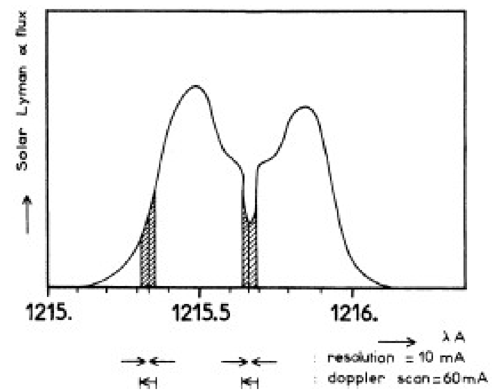


H atoms are illuminated by the sun at Lyman alpha :resonance scattering



Energy of H atom levels

Solar Lα line



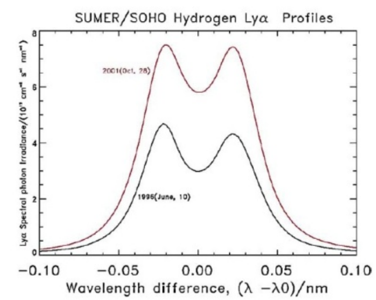
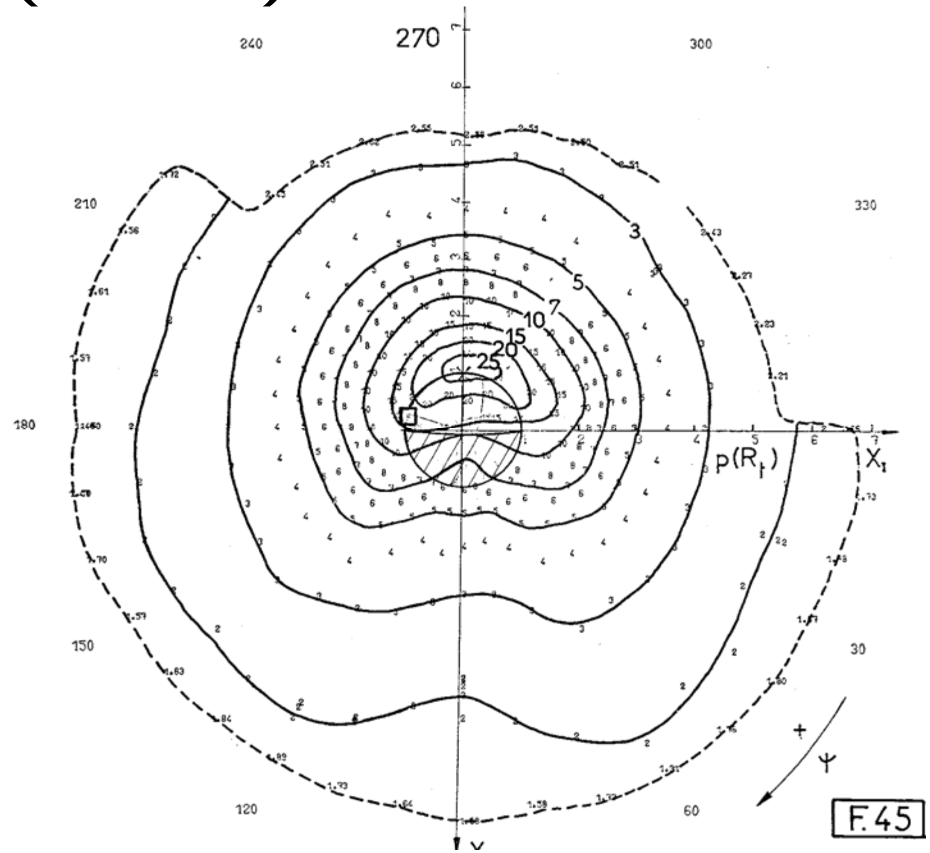
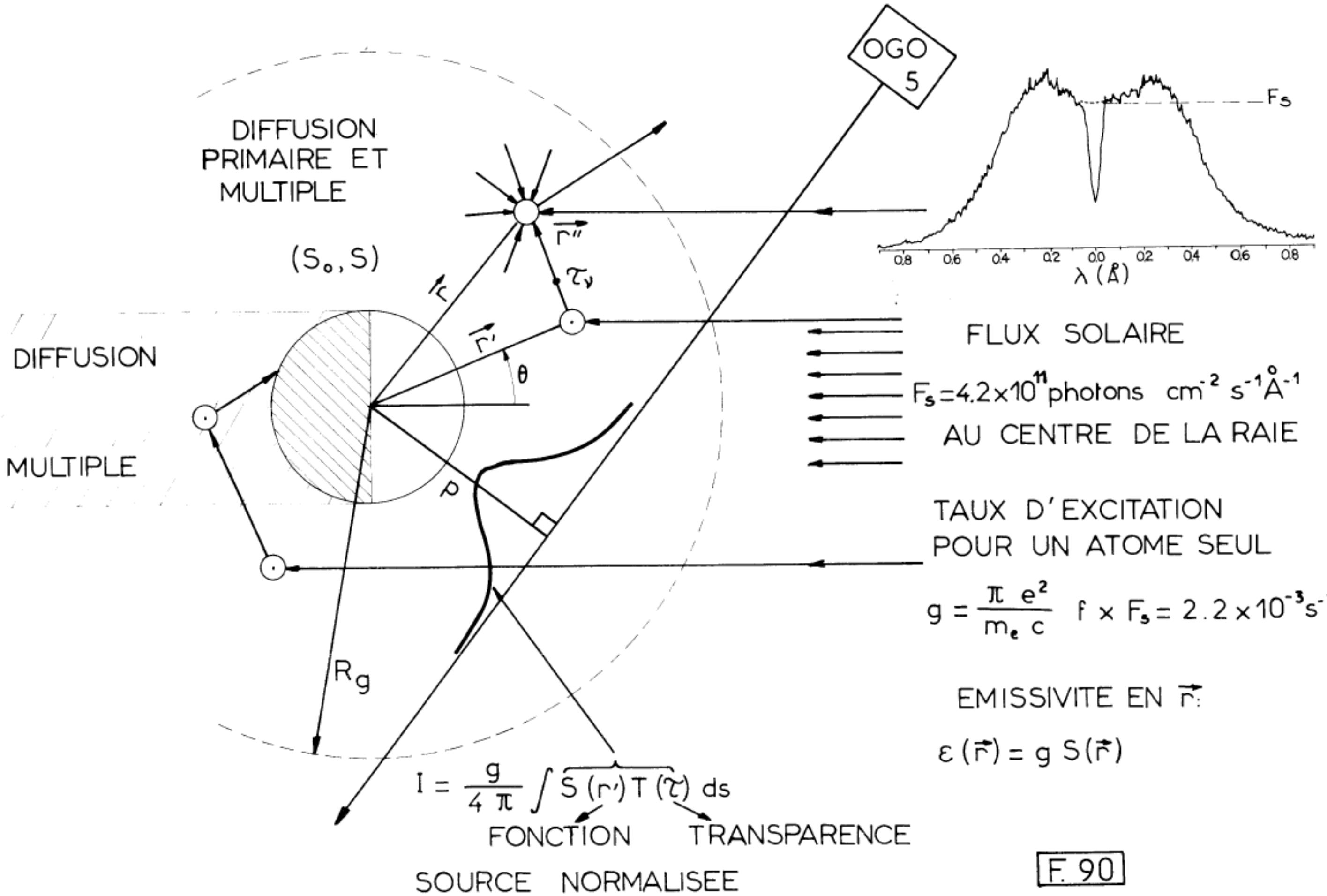


Fig. 2. Two SUMER/SOHO Lyα profiles—corresponding to different solar activities—are shown. The central self-reversed shapes are not affected by geocoronal absorption, directly providing the true central solar irradiance measurements. The total irradiances having been integrated on the same profiles, the relation obtained between the central and the total irradiances is free of experimental or modeling bias.

Earth’s geocorona seen in Lα light from OGO-5 (1968):~4x10^4 km




OGO 5
DIFFUSION PRIMAIRE ET MULTIPLE
(S_o, S)
$\vec{r}''$
τ_ν
$\vec{r}$
$\vec{r}'$
θ
DIFFUSION
MULTIPLE
p
R_g
F_s
0,8 0,6 0,4 0,2 0,0 0,2 0,4 0,6 0,8
λ (Å)
FLUX SOLAIRE
$F_s = 4.2 \times 10^{11}$ photons $cm^{-2}\ s^{-1}$ Å^{-1}
AU CENTRE DE LA RAIE
TAUX D'EXCITATION POUR UN ATOME SEUL
$g = \frac{\pi e^2}{m_e c} f \times F_s = 2.2 \times 10^{-3} s^{-1}$
EMISSIVITE EN $\vec{r}$:
$\varepsilon(\vec{r}) = g\, S(\vec{r})$
$I = \frac{g}{4\pi} \int \overbrace{S(r')\,T(\tau)}\, ds$
FONCTION SOURCE NORMALISEE
TRANSPARENCE

F. 90

Observations of Lyman alpha intensities

- Retrieval problem: from a set of observed Lα intensities, determine the H density altitude profile.
- direct inversion not possible :not optically thin!
- Comparison of data to a grid of Lyman α forward models

Lyman α forward model

- n_c, density of H atoms at the exobase
  T_c, temperature of H at the exobase (exospheric temperature):
- Compute the distribution of H in the exosphere (and below)
- Solve the Lyman α radiative transfer for a spherical exosphere of H (source function)
- Compute the Lyman α emission intensity that would be seen by SPICAM or SPICAV for the proper geometry
- Compare a grid of models to the data, best fit search for n_c and $T_{c.}$

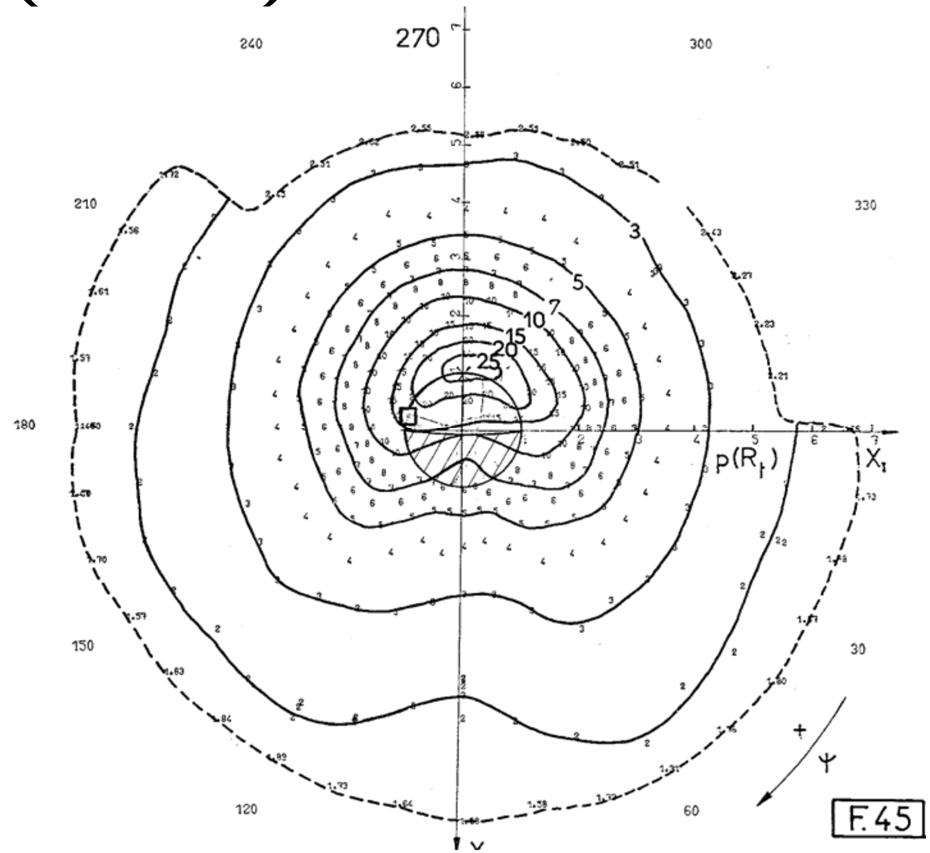
(single component search)

Extension to a combination of a cold and a hot component

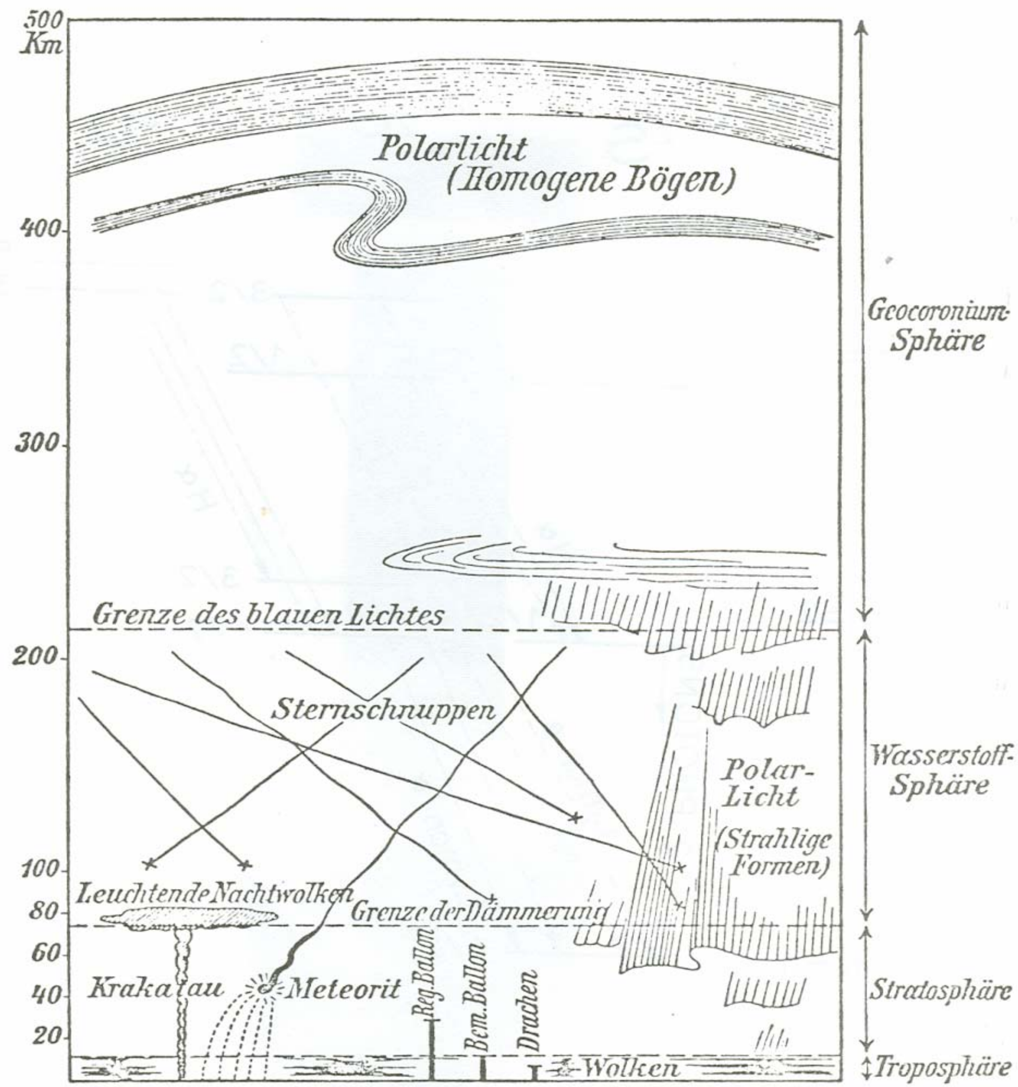
Earth’s geocorona seen in Lα light from OGO-5 (1968):~4x10^4 km

- n(H) at exobase (500 km):5x10^4- 1x 10^5 cm^{-3}
- T_{ex}=1100- 800 K
- Thermal escape
- ~2 x 10^8 H atom/cm2 s

- (Bertaux and Blamont, 1971)

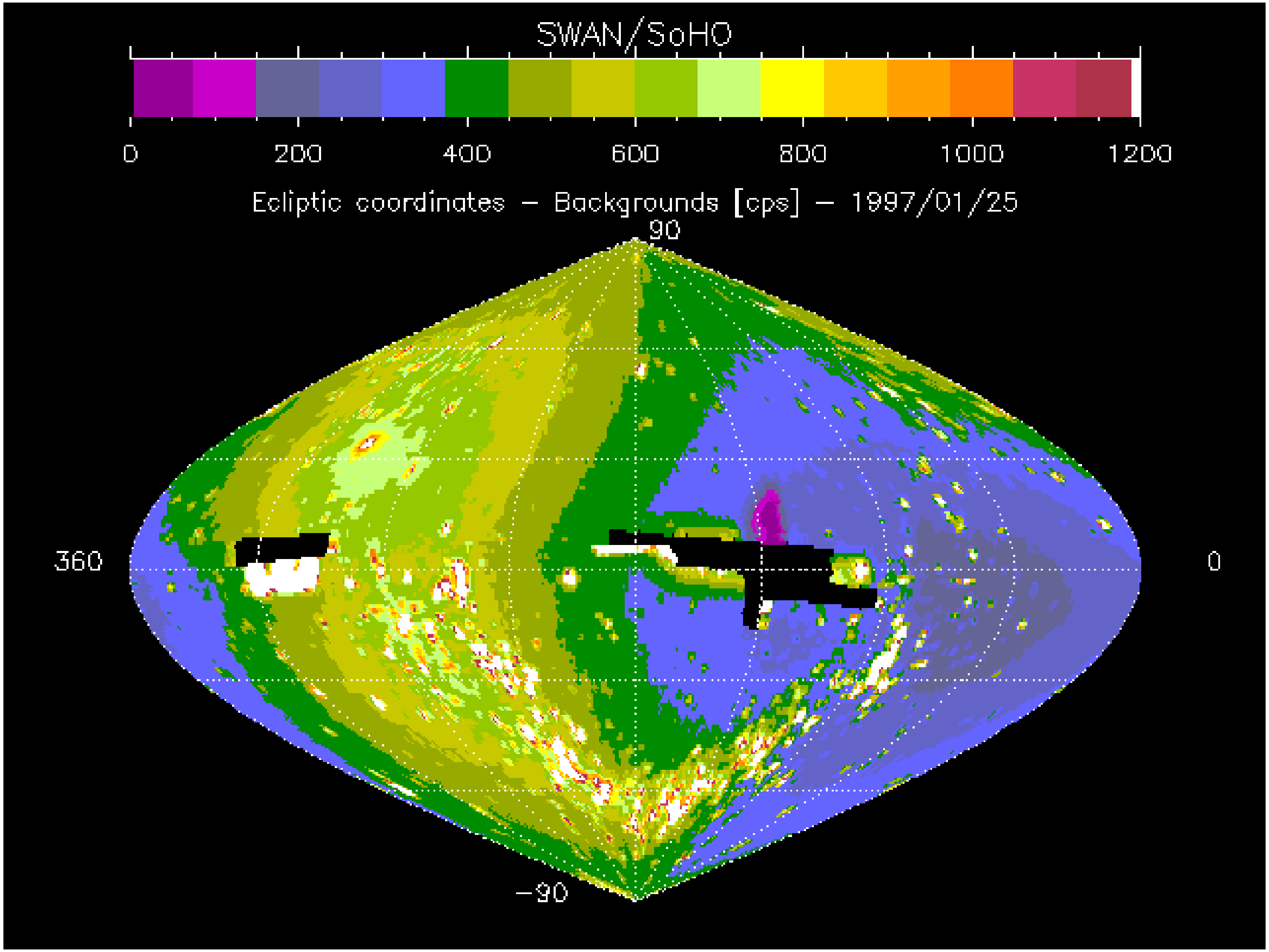


Geocoronium from Wegener (1911)

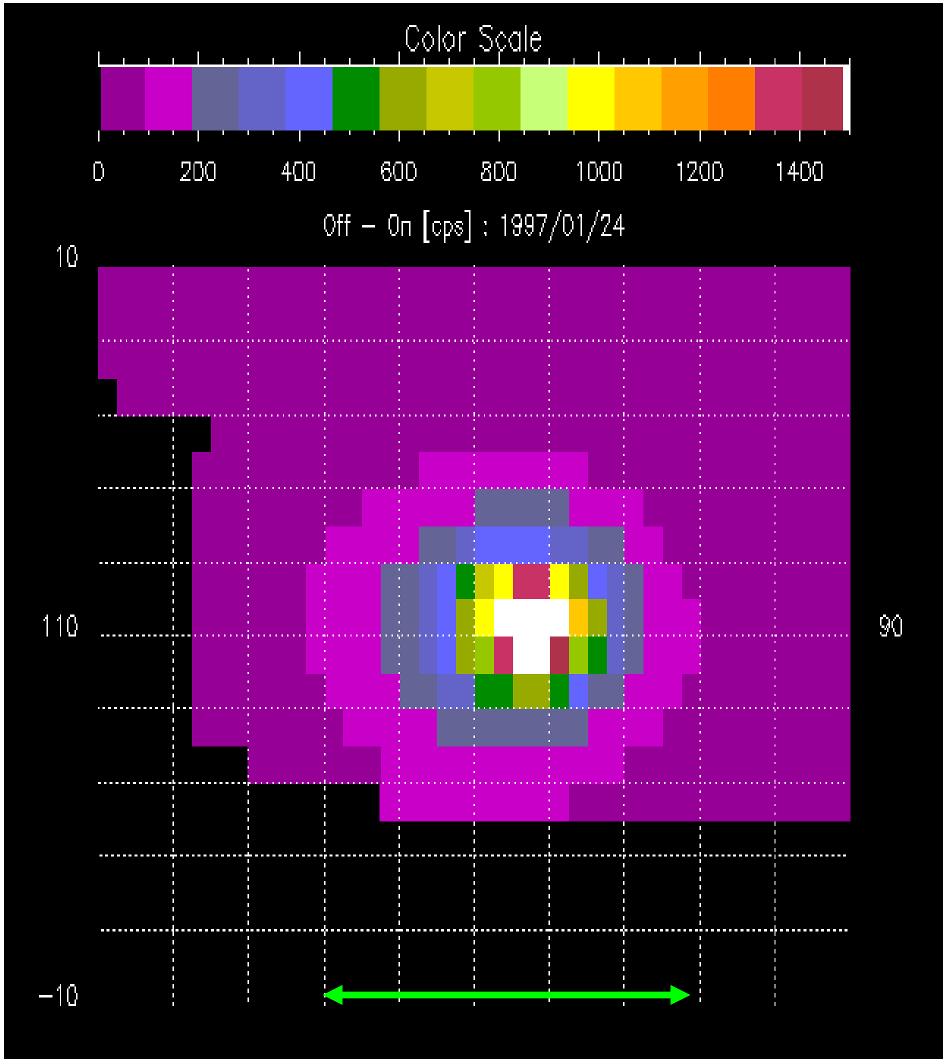


F. 2 Querschnitt der Atmosphäre (Wegener, 1911).

SWAN/SOHO Lα full sky map
at Lagrange L1 point, 1.5 x 10^6 km sun side



The geocorona seen by SWAN on SOHO

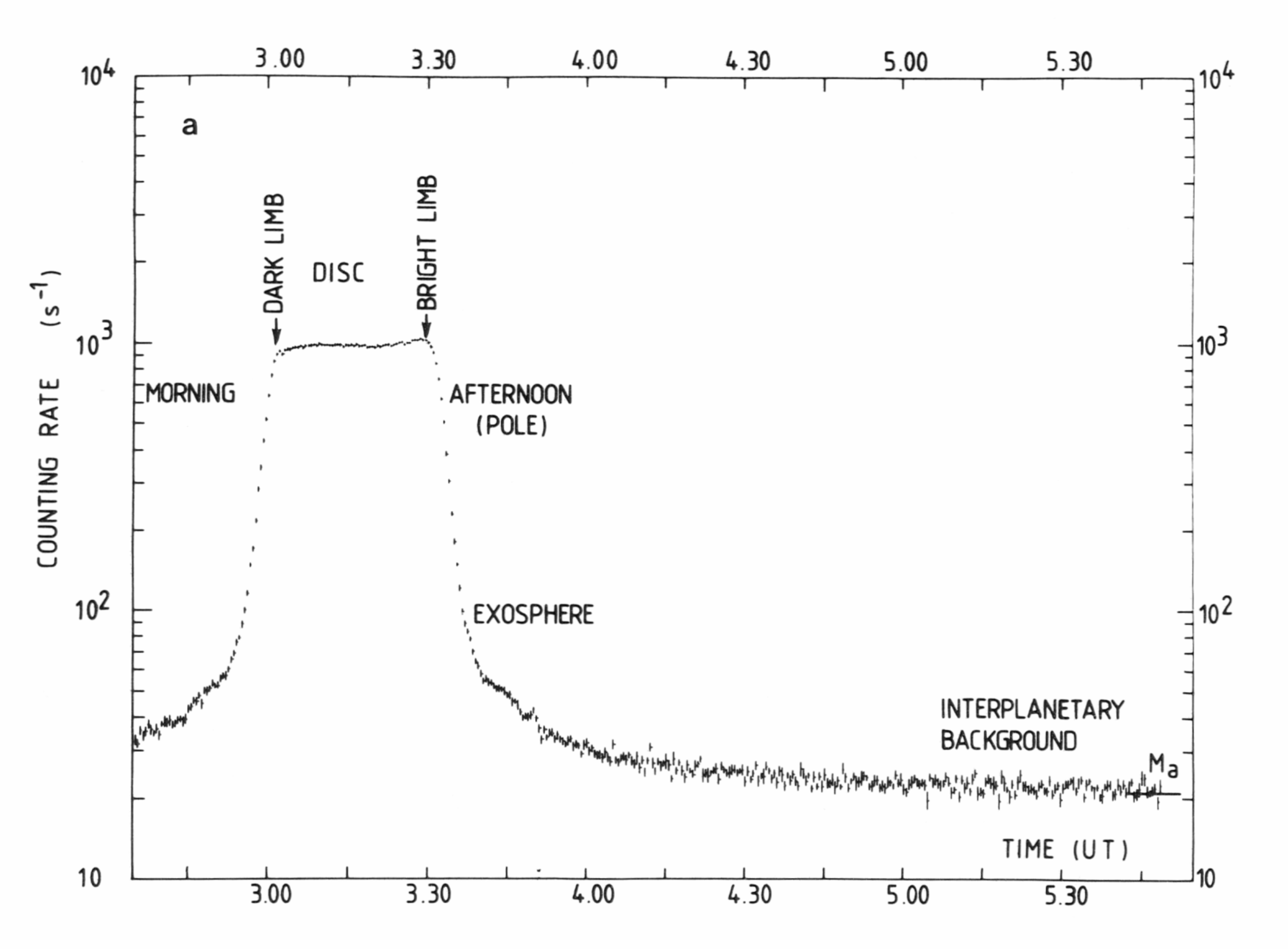


Extended geocorona: hot H atoms escaping ?

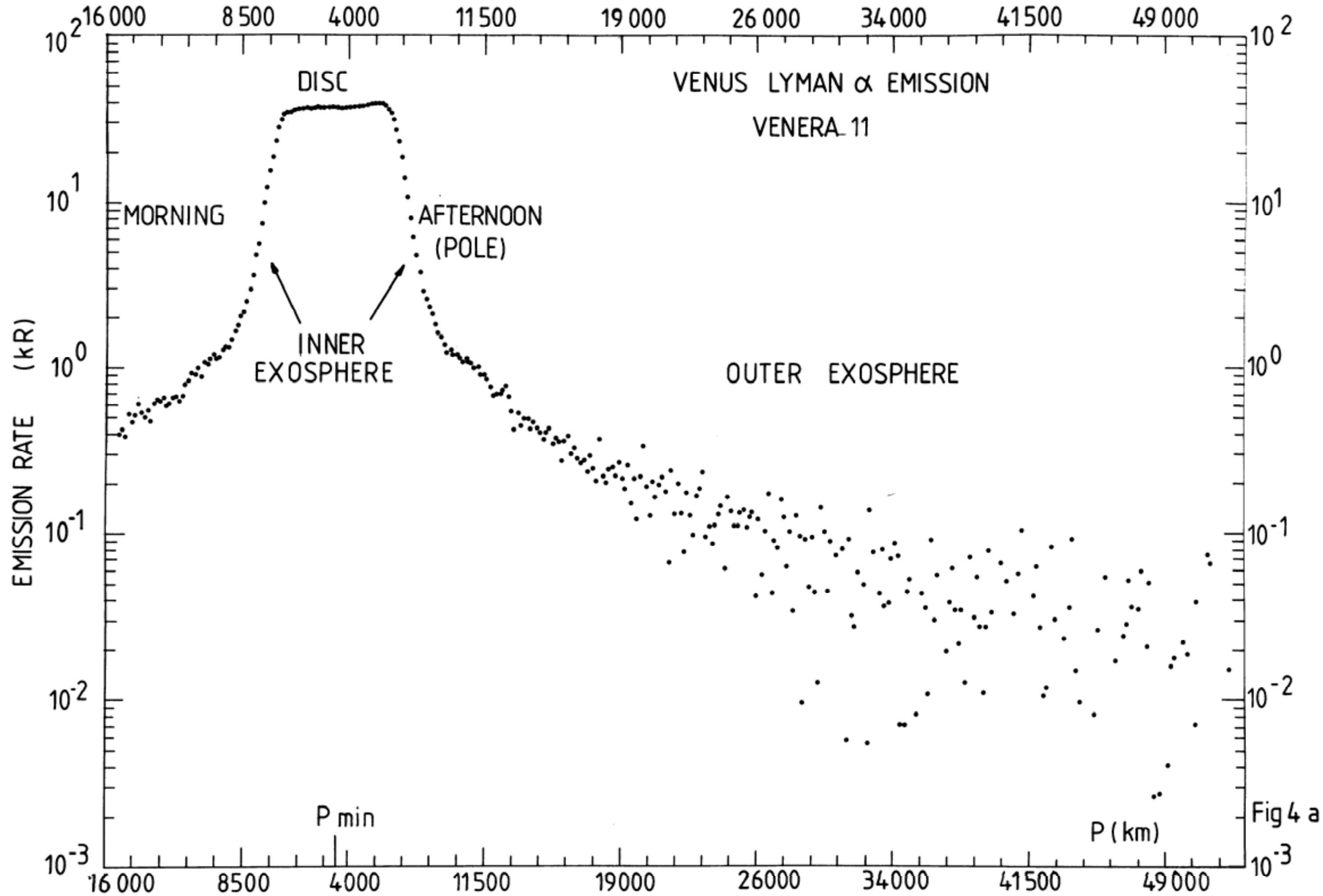
Difficulty : subtract the interplanetary Lyman α emission (interstellar H atoms flowing through the solar system).

>2.6 x 10^5 km ~ 40 Earth Radii

Venera 11 Lyman alpha (1978):atomic H illuminated by the sun (resonance scattering) in the exosphere of Venus



After subtraction of Interplanetary contribution: two scale heights, two different temperatures (like Mariner 10)



Mariner 6 and 7 fly bys of Mars (1969) Anderson and Hord, JGR 1971

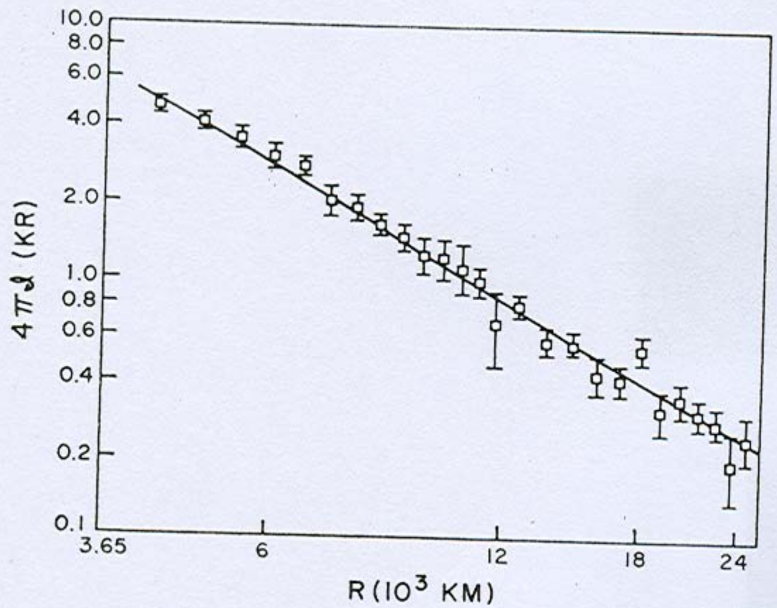
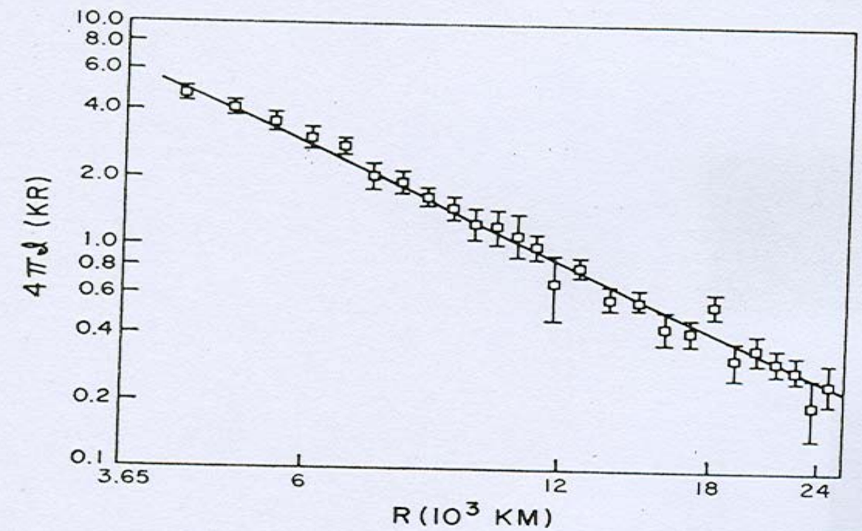


Fig. 2. Best fit to the Mariner 6 data including radiative transfer effects. Solid curve represents the intensity predicted by theoretical model with $T_o = 350°K$ and $n_o = 3.0 \times 10^4\ cm^{-3}$.



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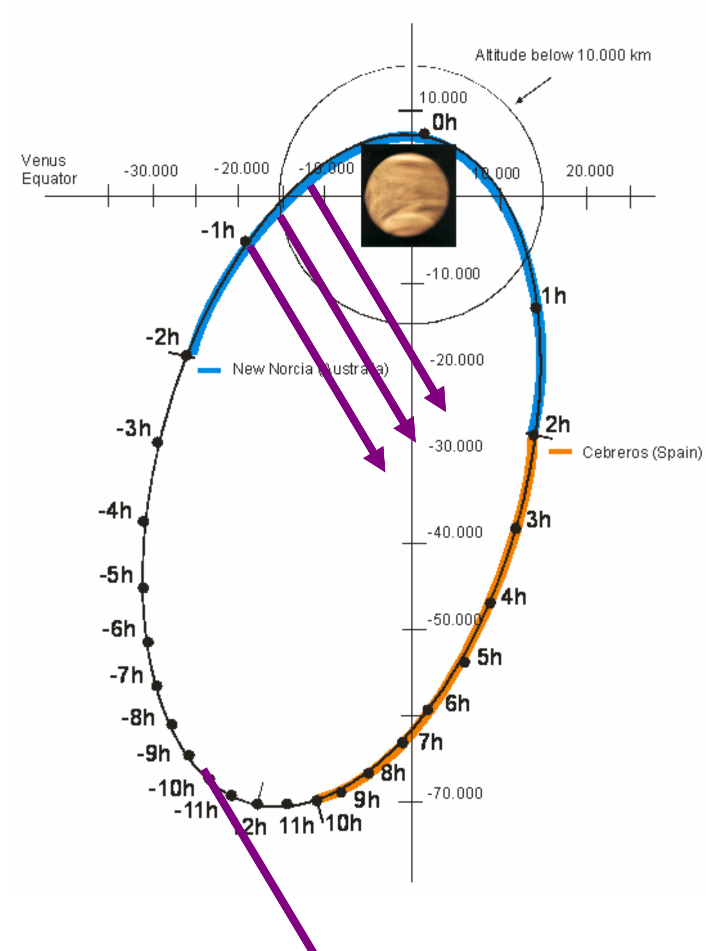
$N_{exo} = 2.5\text{-}3 \times 10^4\ cm^{-3}$, T = 350 K

of the Venusian hydrogen corona with SPICAV on Venus Express

Chaufray, J-Y., J-L. Bertaux, F. Leblanc, E. Quemerais, and E. Villard



The H exosphere of Mars

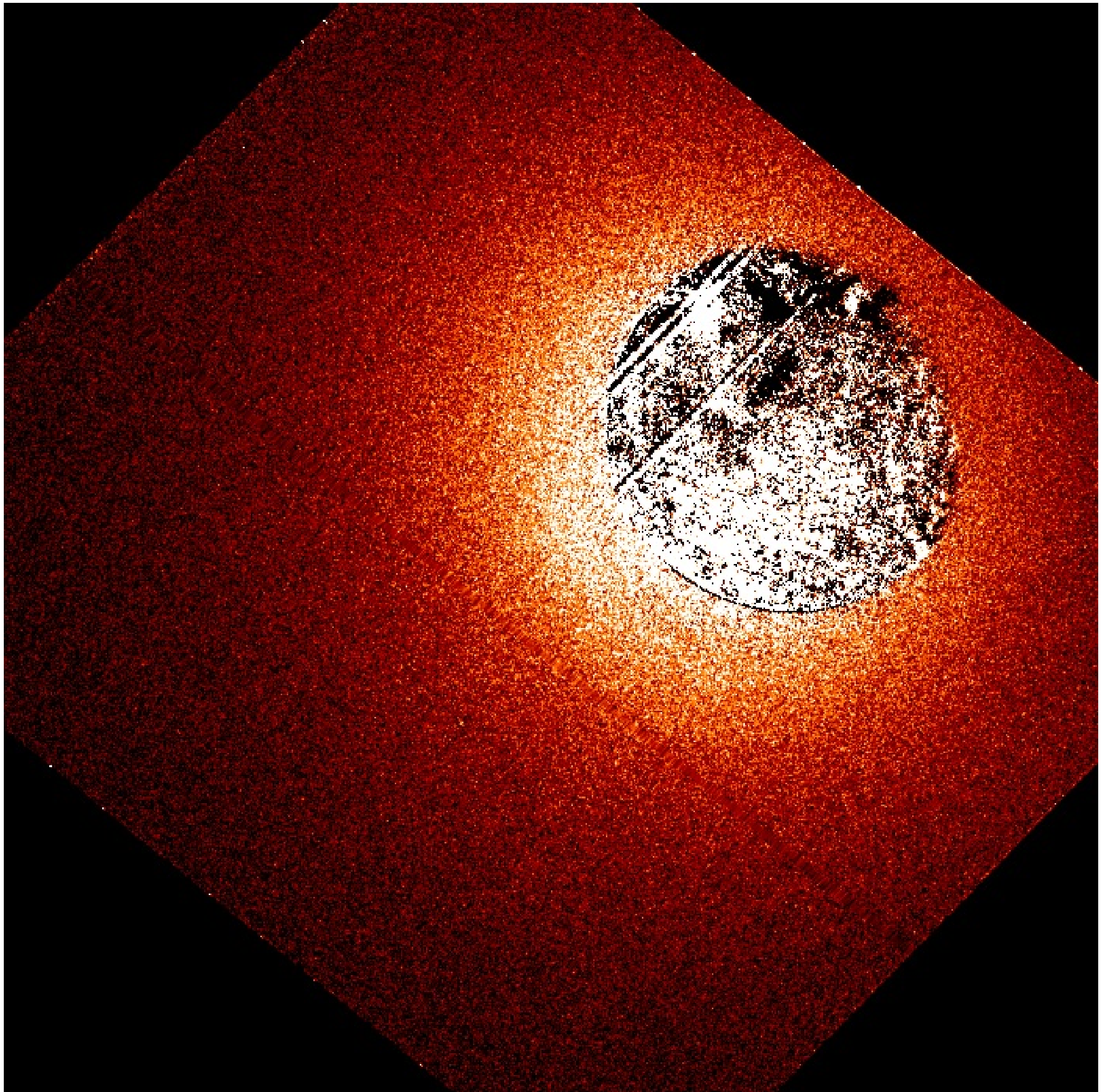
- Theory:The H distribution with altitude depends on exospheric temperature Tex (at ~200 km).
- Tex~200 K (from drag MGS, and SPICAM day glow data)
- More H seen by SPICAM in L α than model at 200 K (Chaufray et al., 2008) at 4,000 km.
- Discrepancy increases with altitude
- What happens at altitude z =10,000 km? (apocenter)

Coordinated observations with HST

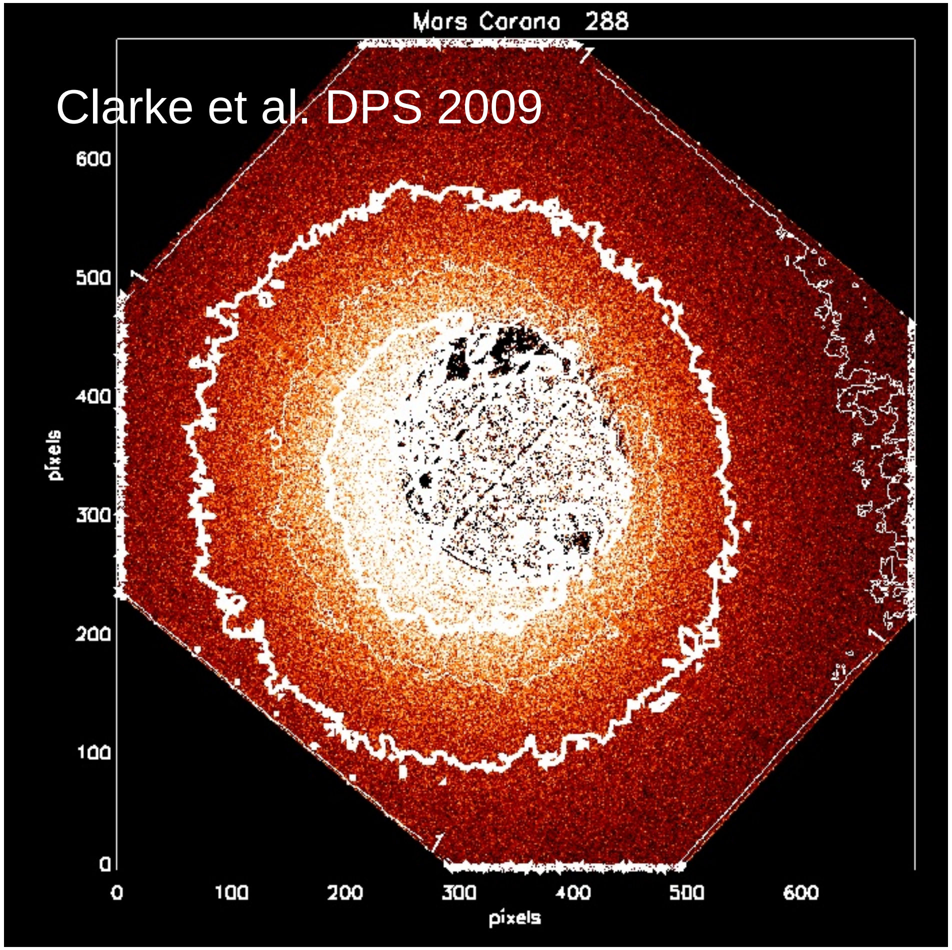
- UV camera of HST operated in Oct-Nov 2007 for getting Lα images of H corona FOV: ~3 Mars radii.
- (more or less) simultaneous observations of SPICAM Lα of H corona
- Purpose:
- 1.cross calibration of HST and SPICAM
- 2. investigate H corona as far as possible.
- 3.look for asymetries (latitude, SZA)

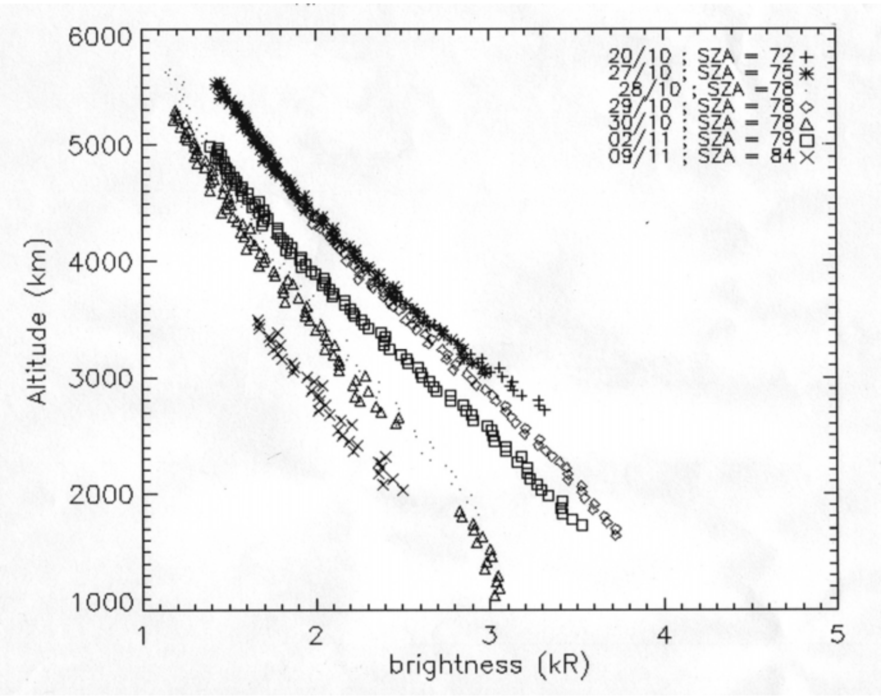
Lα images of Mars H corona: HST

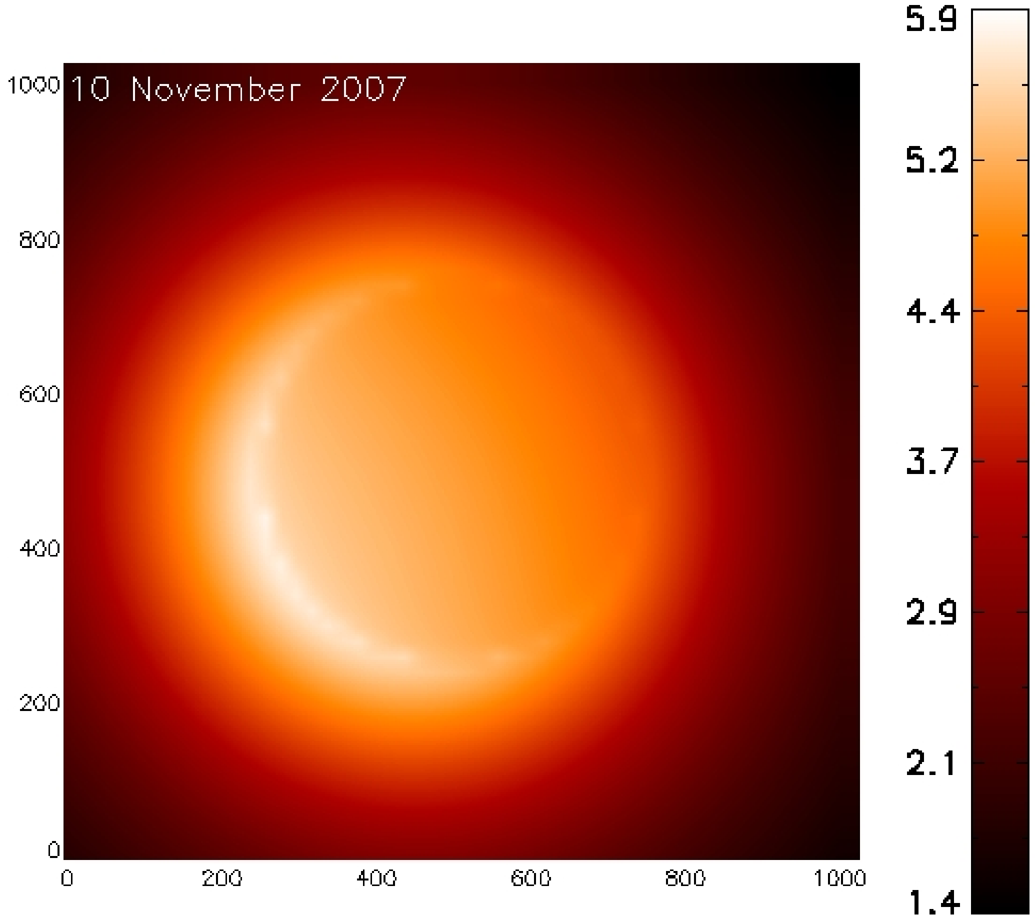
(John Clarke)



Hydrogen Corona : Observations (3/3)

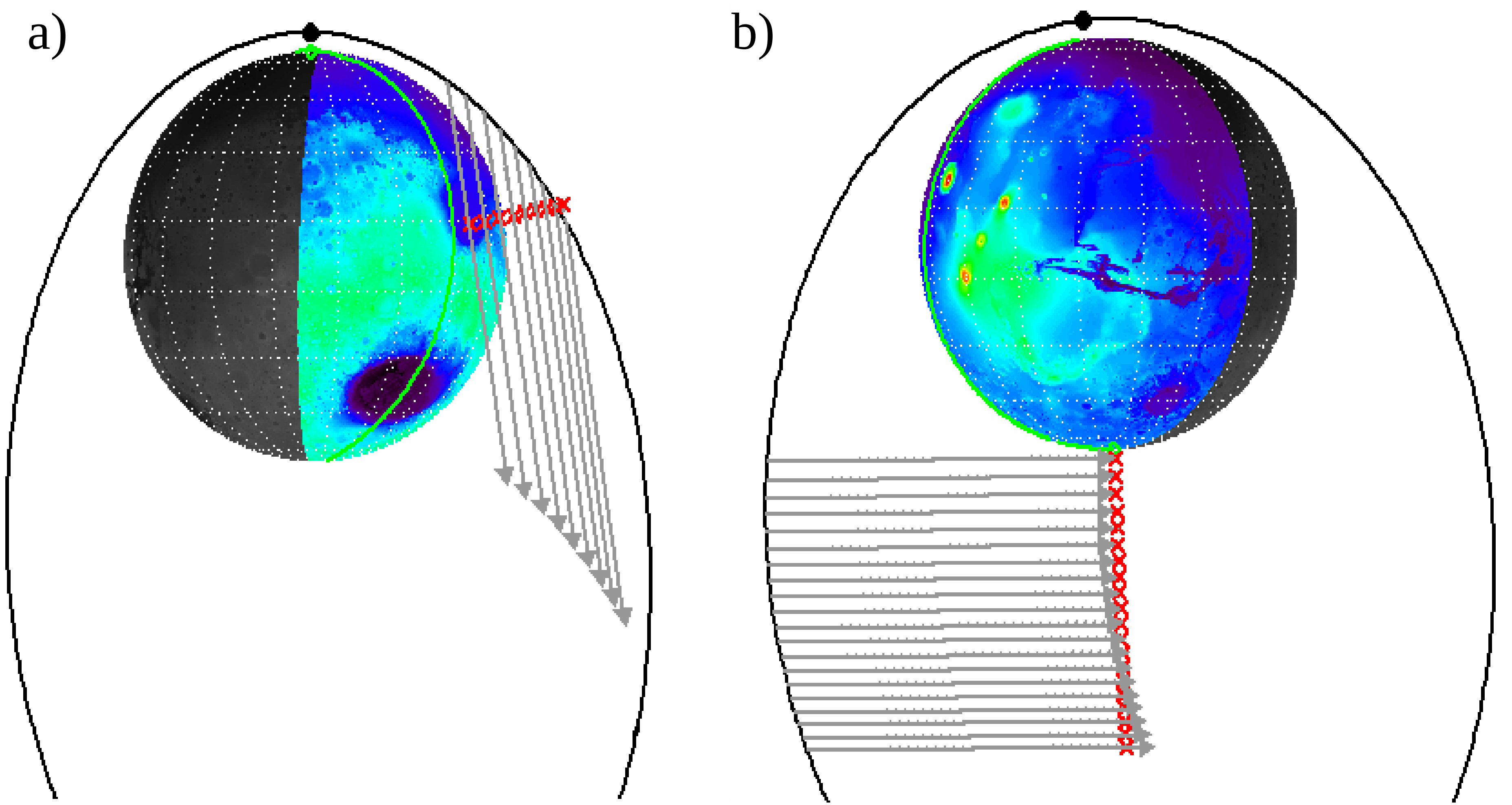






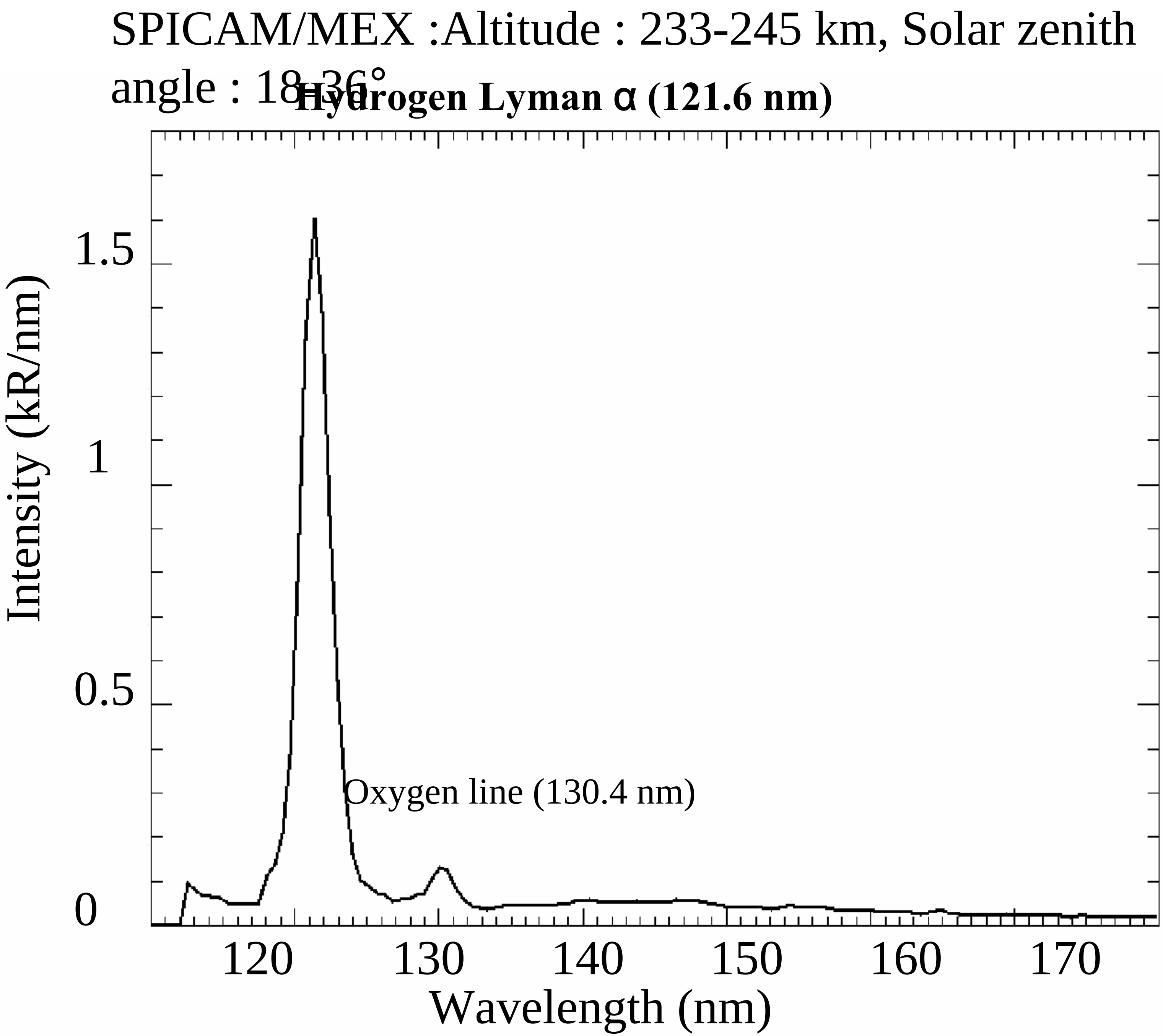
Lyman alpha simulation: JY Chaufray

SPICAM/MEX Observations of exosphere H Lyman alpha

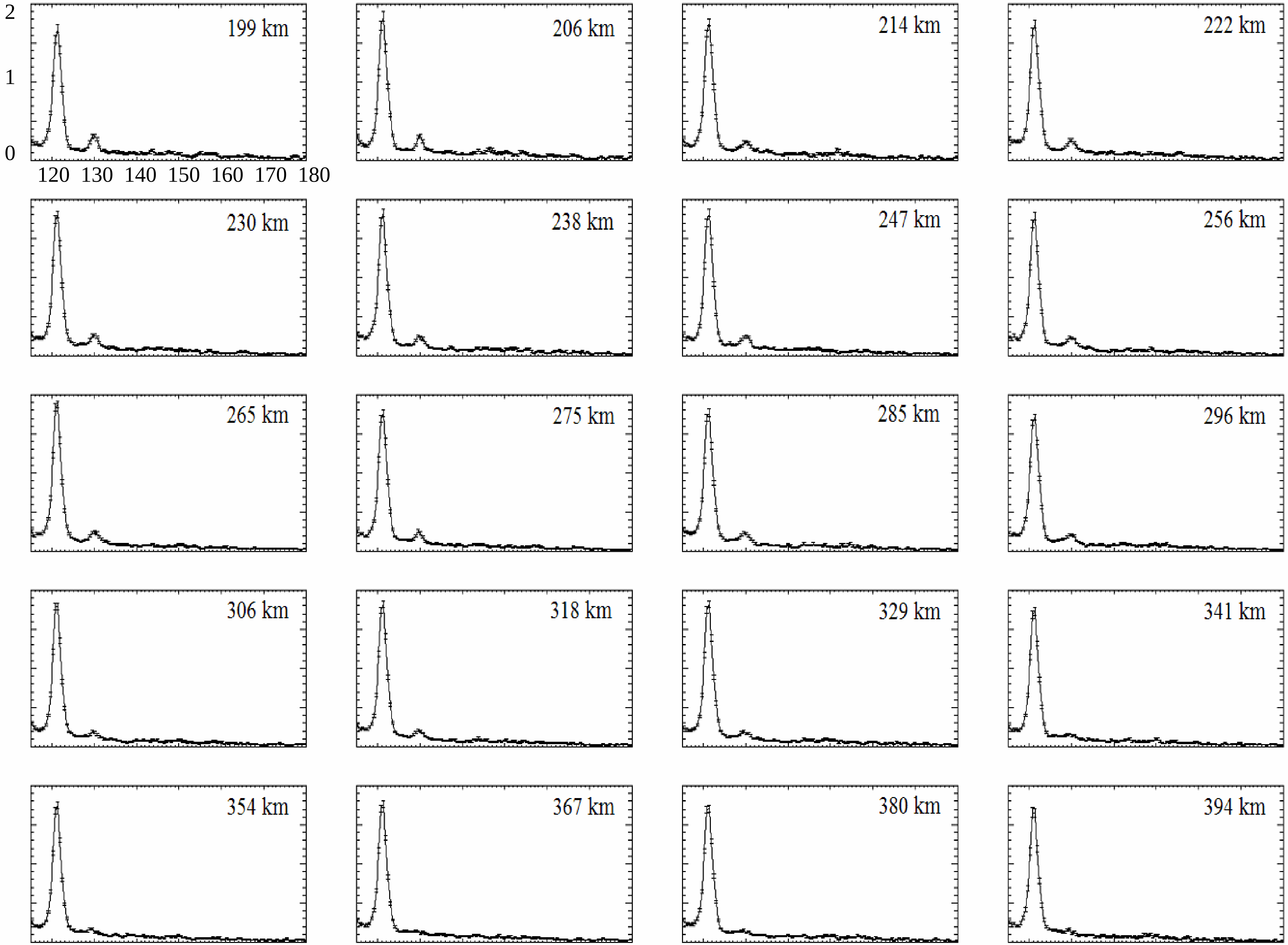


SZA=30° : high solar illumination

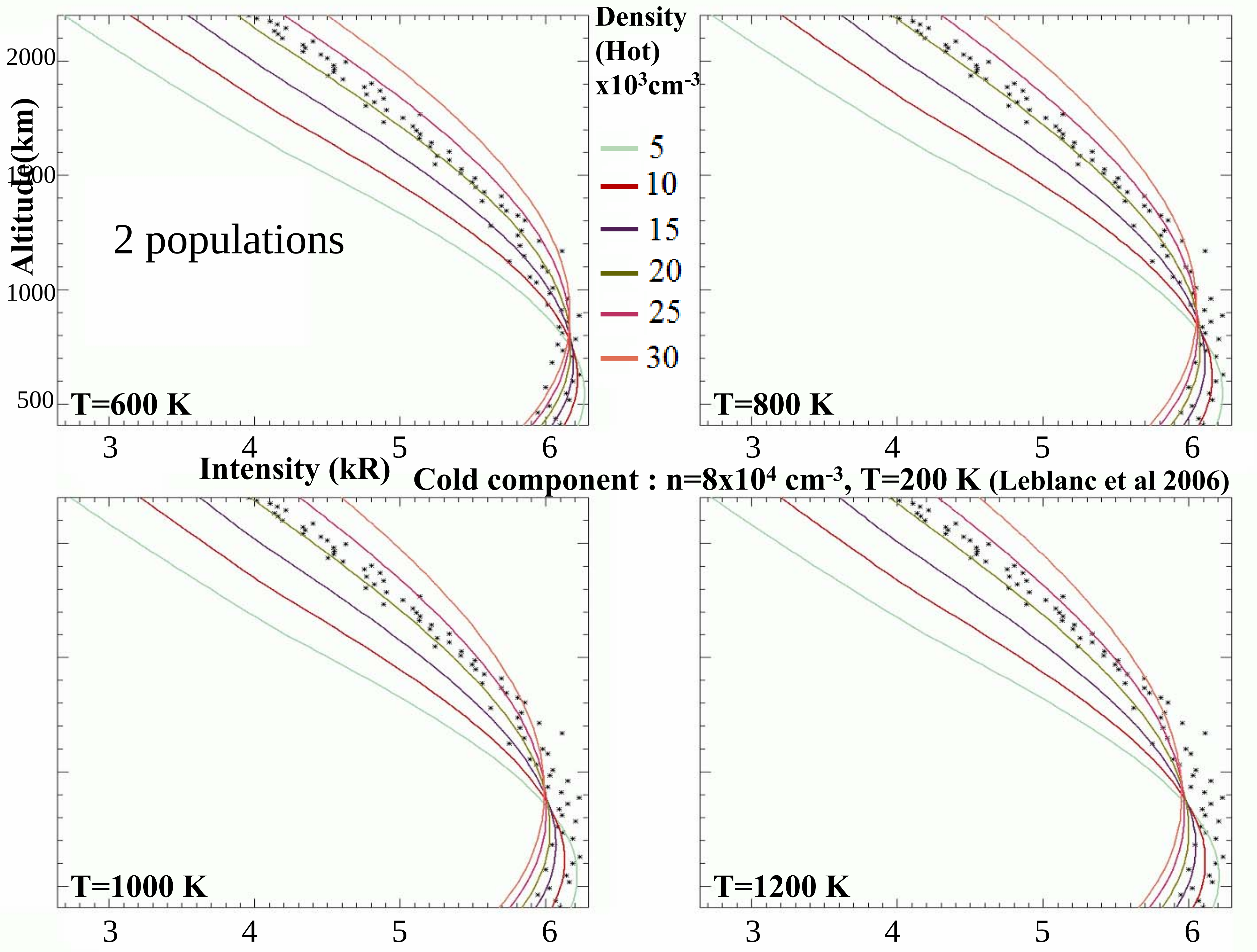
SZA=90° : low solar illumination



SPICAM/MEX :Altitude : 233-245 km, Solar zenith angle : 18-36°
Hydrogen Lyman α (121.6 nm)
Oxygen line (130.4 nm)
Intensity (kR/nm)
0
0.5
1
1.5
120
130
140
150
160
170
Wavelength (nm)

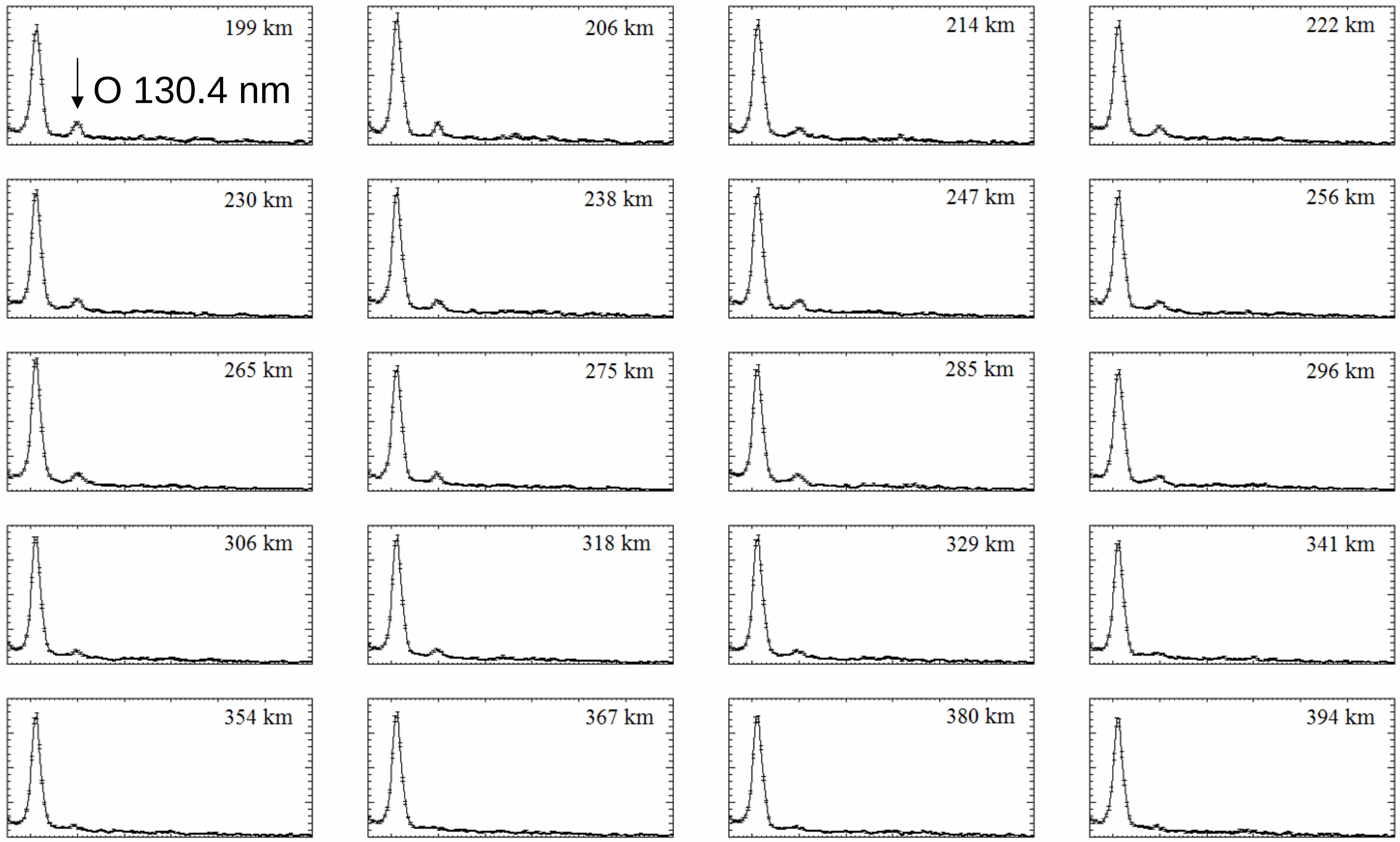


2
1
0
120
130
140
150
160
170
180
199 km
206 km
214 km
222 km
230 km
238 km
247 km
256 km
265 km
275 km
285 km
296 km
306 km
318 km
329 km
341 km
354 km
367 km
380 km
394 km

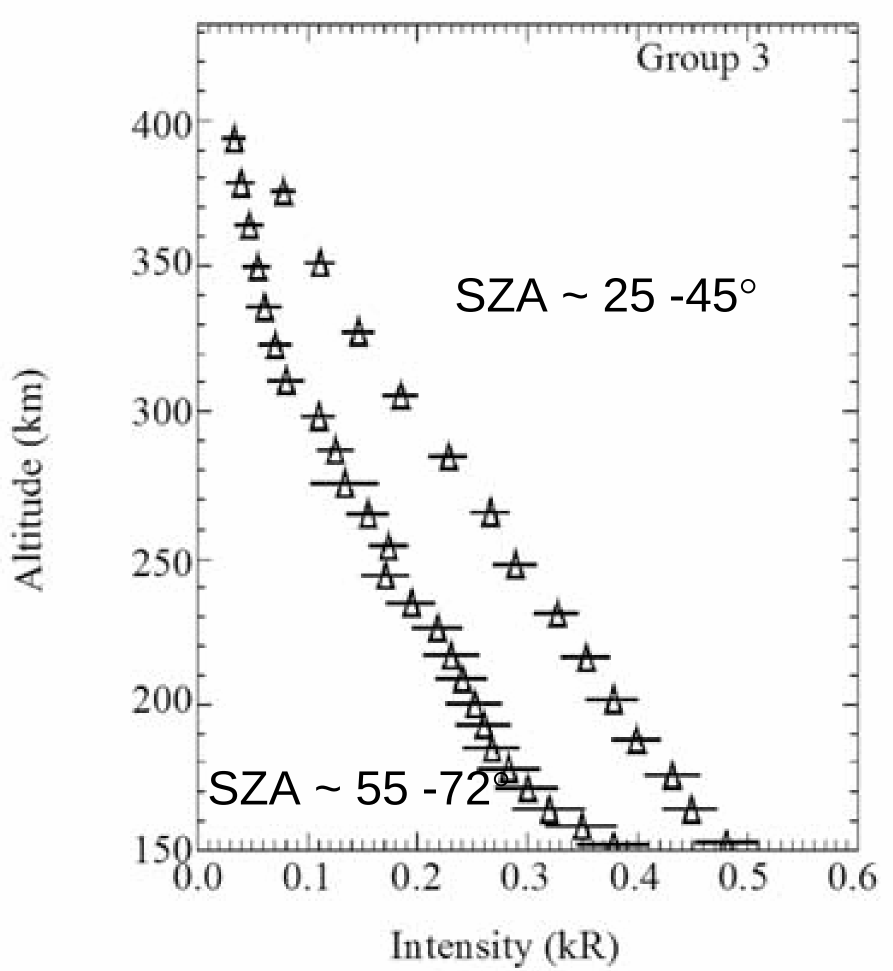


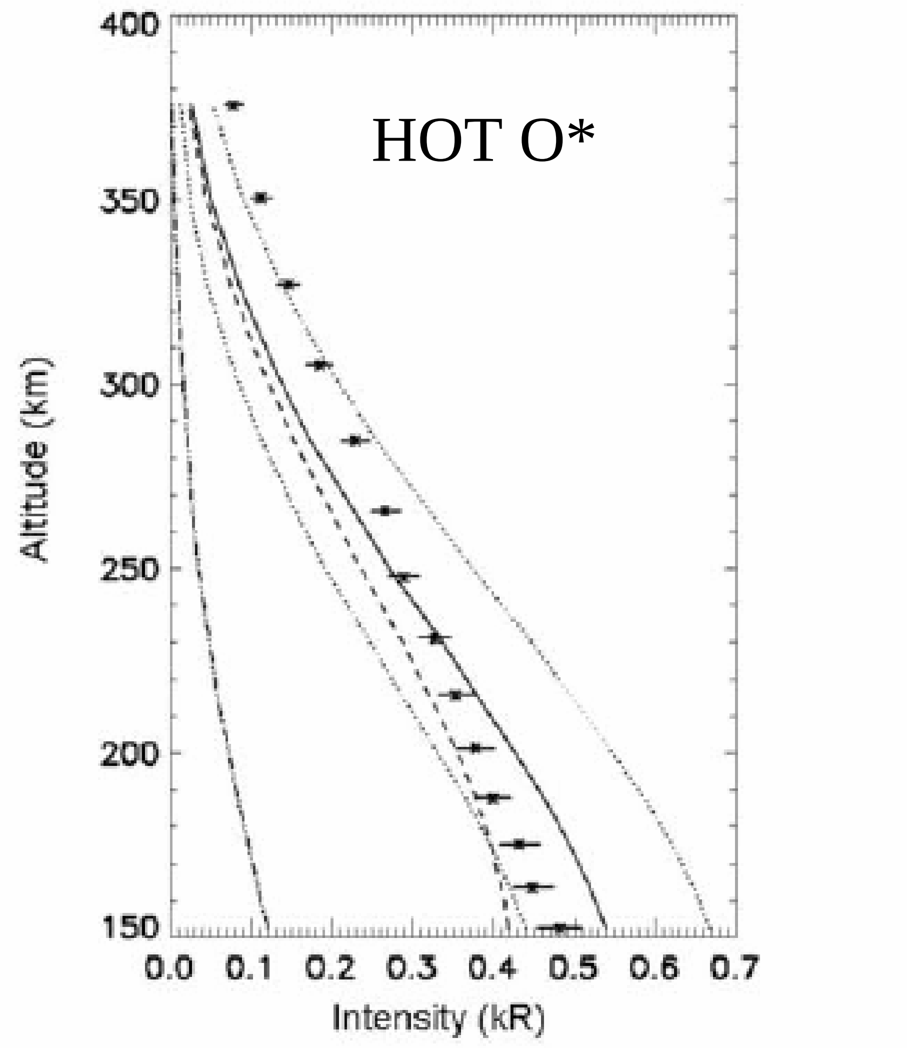
Density
(Hot)
x10³cm⁻³
5
10
15
20
25
30
2 populations
Altitude (km)
2000
1500
1000
500
T=600 K
T=800 K
T=1000 K
T=1200 K
3
4
5
6
Intensity (kR)
Cold component : n=8x10⁴ cm⁻³, T=200 K (Leblanc et al 2006)

Oxygen Corona : Observations



Oxygen Corona :SPICAM/MEX Observations
J.Y. Chaufray et al.,2009





GO TO JYC .ppt

Earth exospheric temperature T_{ex} :cooling

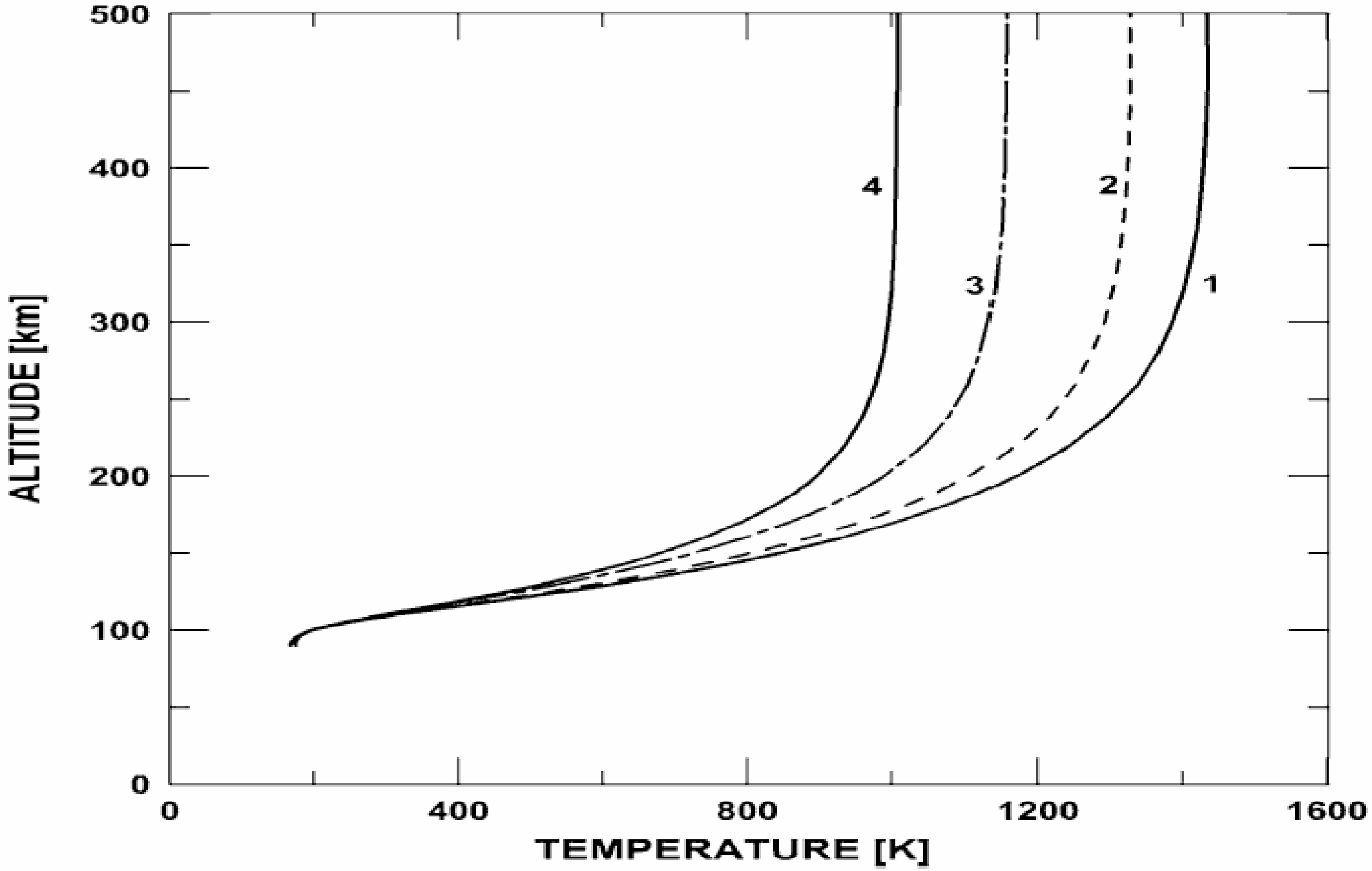


Fig. 1 Temperature of the present time Earth thermosphere showing the effect of various IR-radiating molecules on the temperature profiles. (*1*) Only 15 μm CO_2 fundamental band is cooling; (*2*) Cooling by O 63 μm IR-line plus CO_2 cooling; (*3*) NO cooling in the 5.3 μm fundamental band plus O and CO_2 cooling; (*4*) All the previously mentioned coolers including chemically excited IR bands of minor molecular constituents and cooling in the OH 2.8 μm, O_3 in 9.6 μm, and $O_2(^1\Delta_g)$ 1.27 μm bands are taken into account

Kulikov et al., Space Science Review, 2007

Mars exospheric temperature T_{ex} XUV(EUV+X) heating

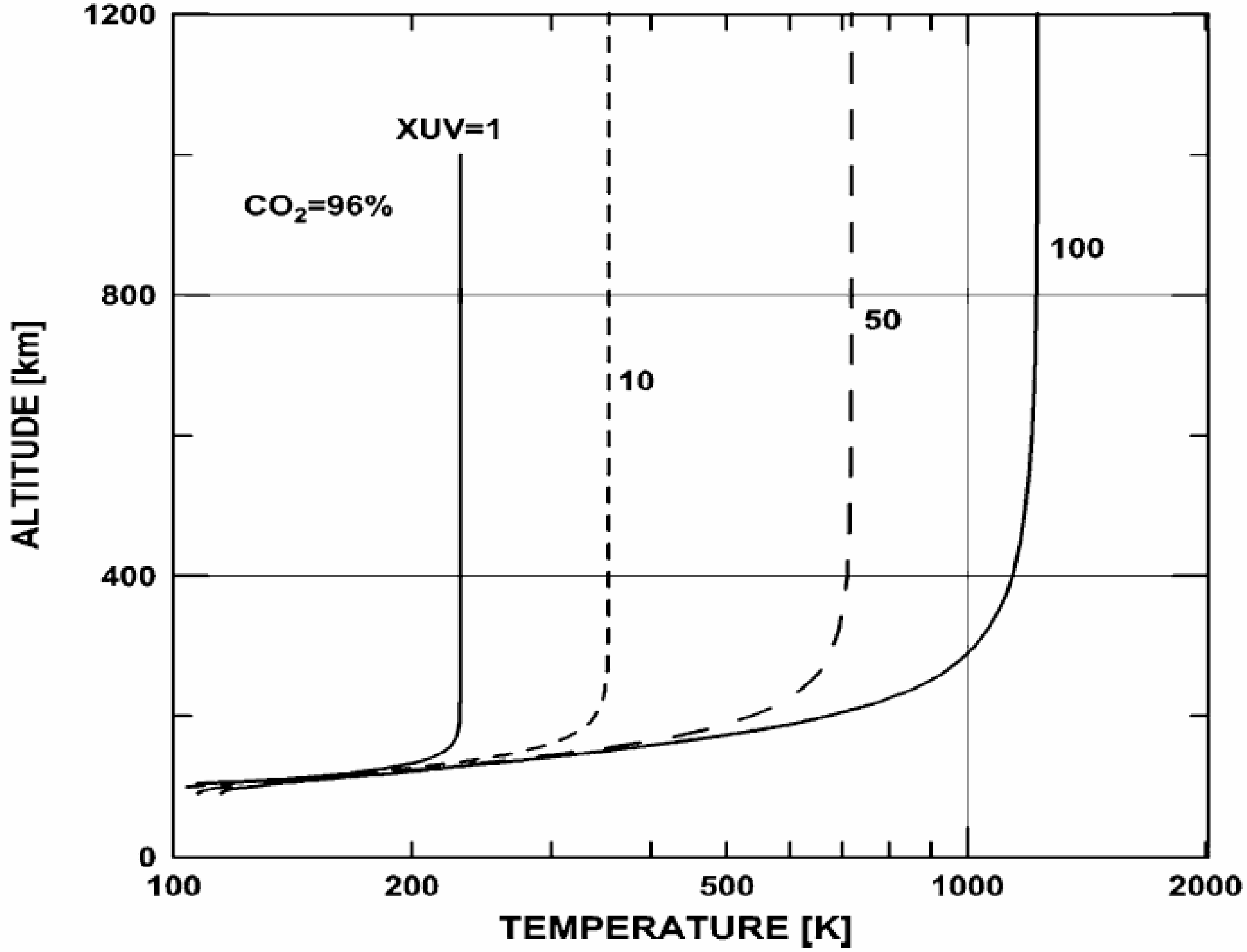


Fig. 7 Modelled martian temperature profiles in a 96% CO_2 thermosphere as a function of altitude for 1 XUV (present), 10 XUV (3.8 Gyr ago), 50 XUV (4.33 Gyr ago), and 100 XUV (4.5 Gyr ago) flux values for a low heating efficiency of ~8%

Kulikov et al., Space Science Review, 2007

Mars : T_{ex} versus solar XUV flux , CO2 Thermostat

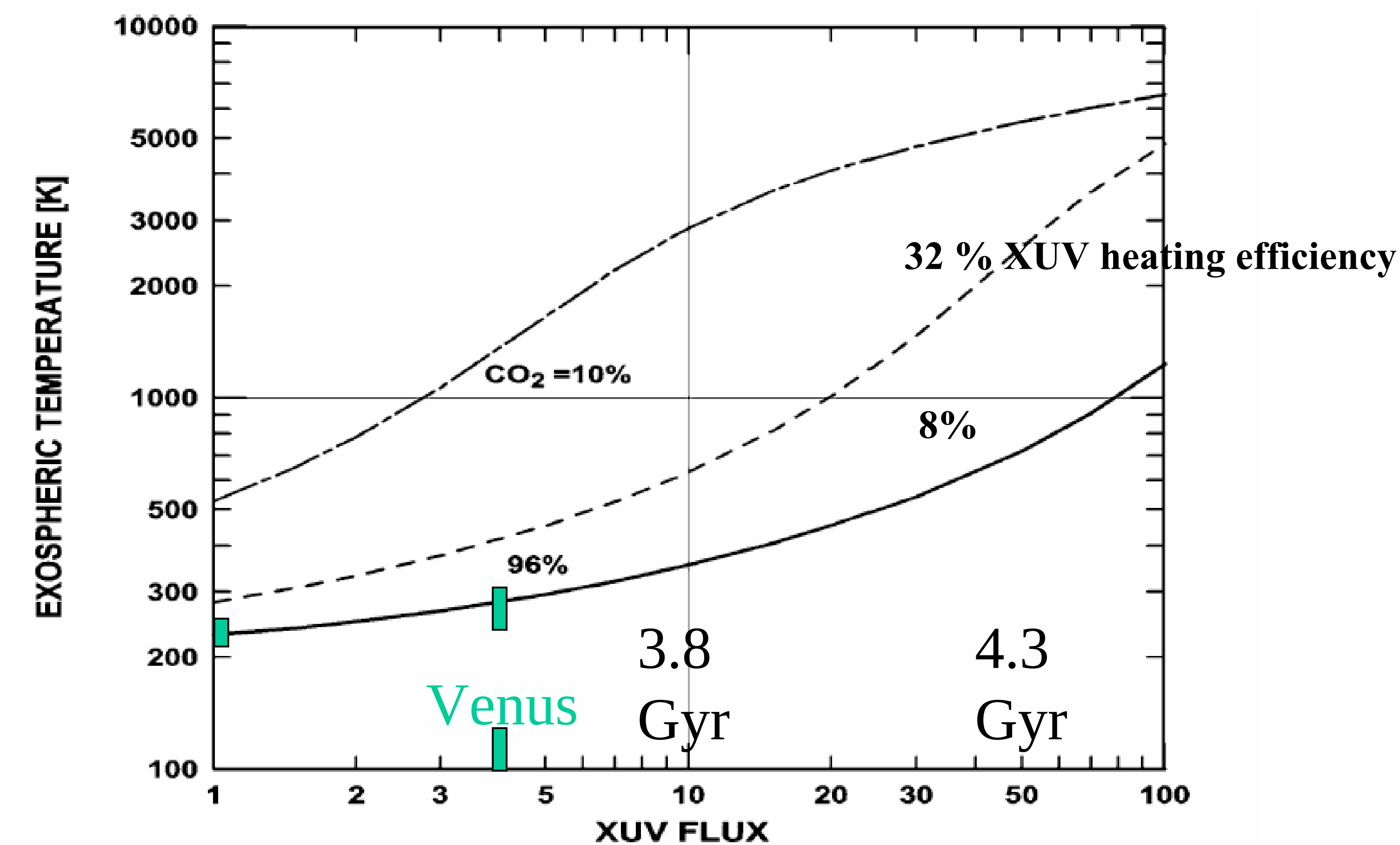


Fig. 8 Modelled martian exospheric temperatures as a function of solar XUV flux values for a 96% CO_2 atmosphere and for a heating efficiency of ~8% (*solid line*) and ~32% (*dashed line*). The *dashed-dotted line* corresponds to a martian atmosphere with a lower CO_2 mixing ratio of ~10%. The *horizontal thin solid line* corresponds to the H blow-off temperature of ~1000 K and the *vertical solid line* marks the conditions ~3.8 Gyr ago

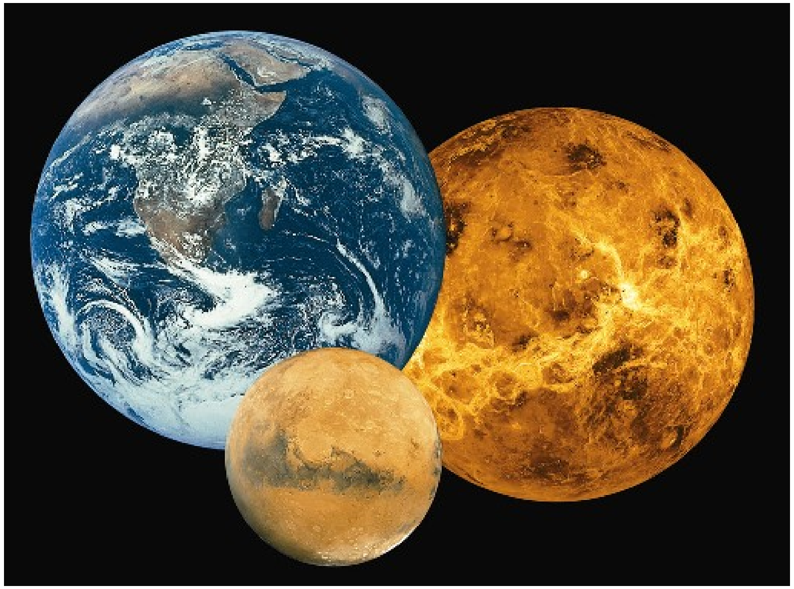
Kulikov et al., Space Science Review, 2007

Conclusions

- Hot component of H and O strongly suggested by SPICAM/MEX data (independent Tex is crucial).
- H Lα studies allow to determine present thermal escape rate, and estimate of non-thermal escape
- CO2 acts as a powerful thermostat (IR cooling) to keep cool the exospheres of Mars and Venus
- Extrapolation back in time are necessary to determine the importance for evolution. The history of Tex is crucial.

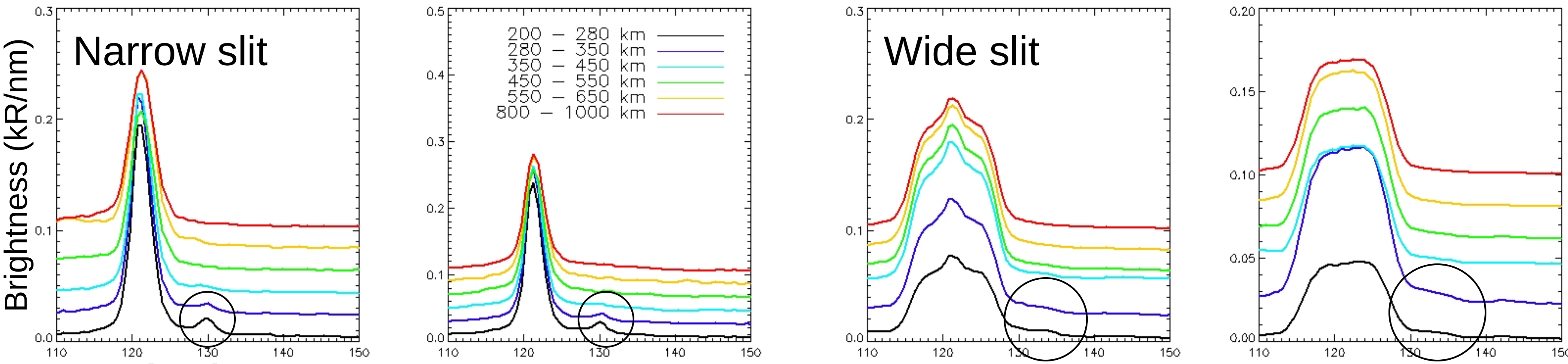
HDO/H2O ratio

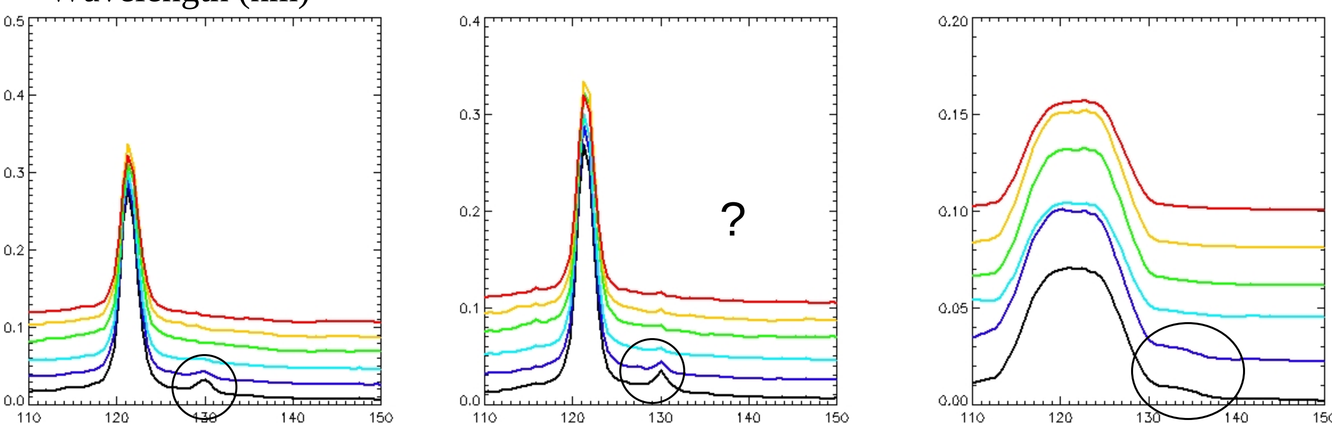
	Venus	Earth	Mars
Composition of atmosphere	**CO_2 96%**	**O_2, N_2**	**CO_2 96 %**
Water (equivalent liquid)	**30 mm**	**2.8 km**	**20 (polar caps)+20 m 10 µm (atm)**
Equivalent loss of water (m/Gyr)	?	1	0.7-1.5
Measured Enrichment HDO/H2O wrt Earth	150	1	5
Original water content	>4.5 m	2.8 km	?? see note



Note : at present escape rate on Mars, the whole atmospheric H_2O disappears in 13,000 years.
Comment: the measured HDO/H2O now may represent only the atmospheric ratio, and not the bulk ratio in the ice polar cap

Oxygen Corona : Hot Component ?





Sum of several thousands spectra

No detection above ~ 400 km

σ ~ 3 - 5 R/nm

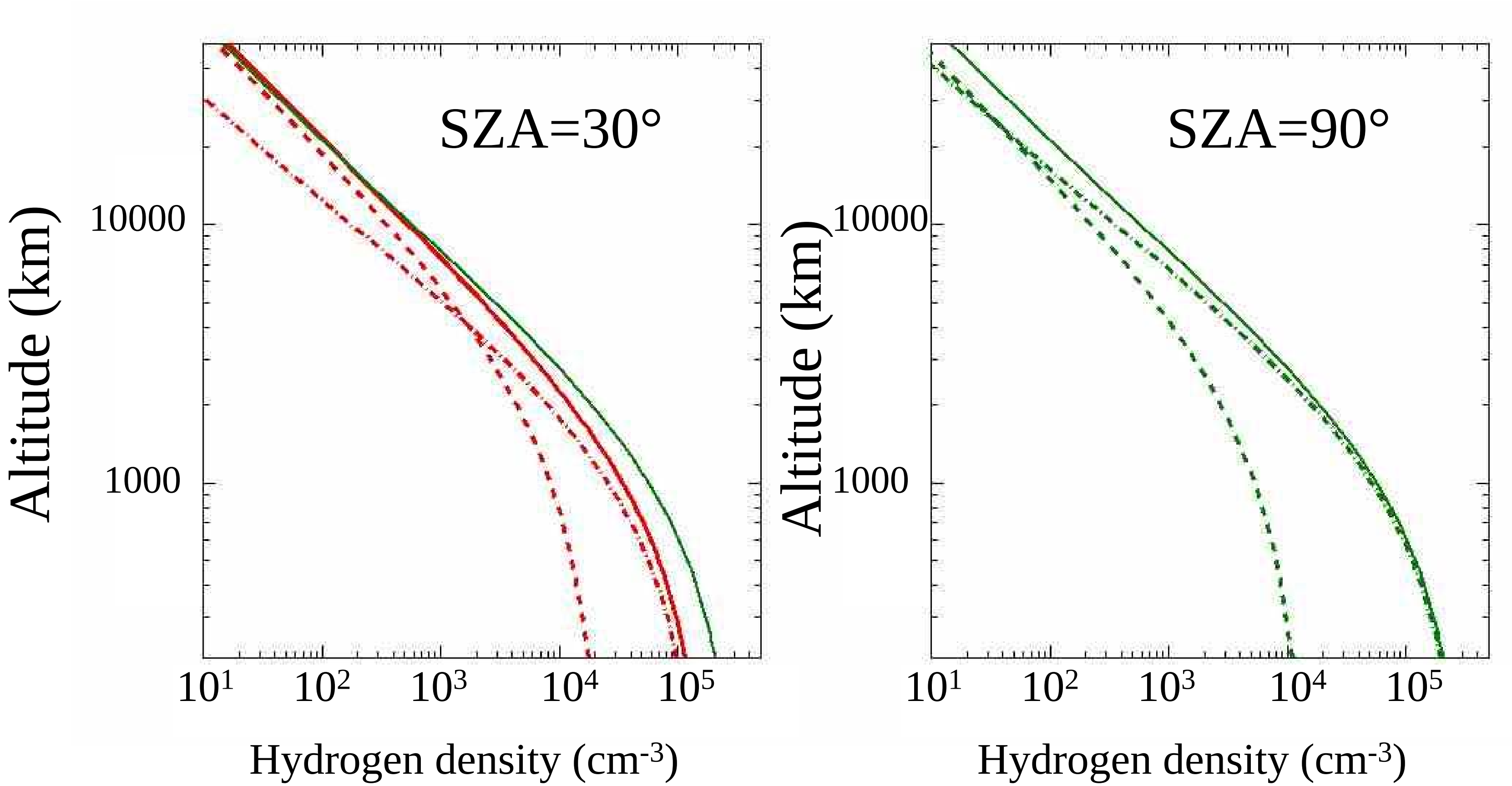
Mars summary of H corona Lα studies with SPICAM/MEX

<u>Lyman alpha</u>: 2 populations needed to fit the data

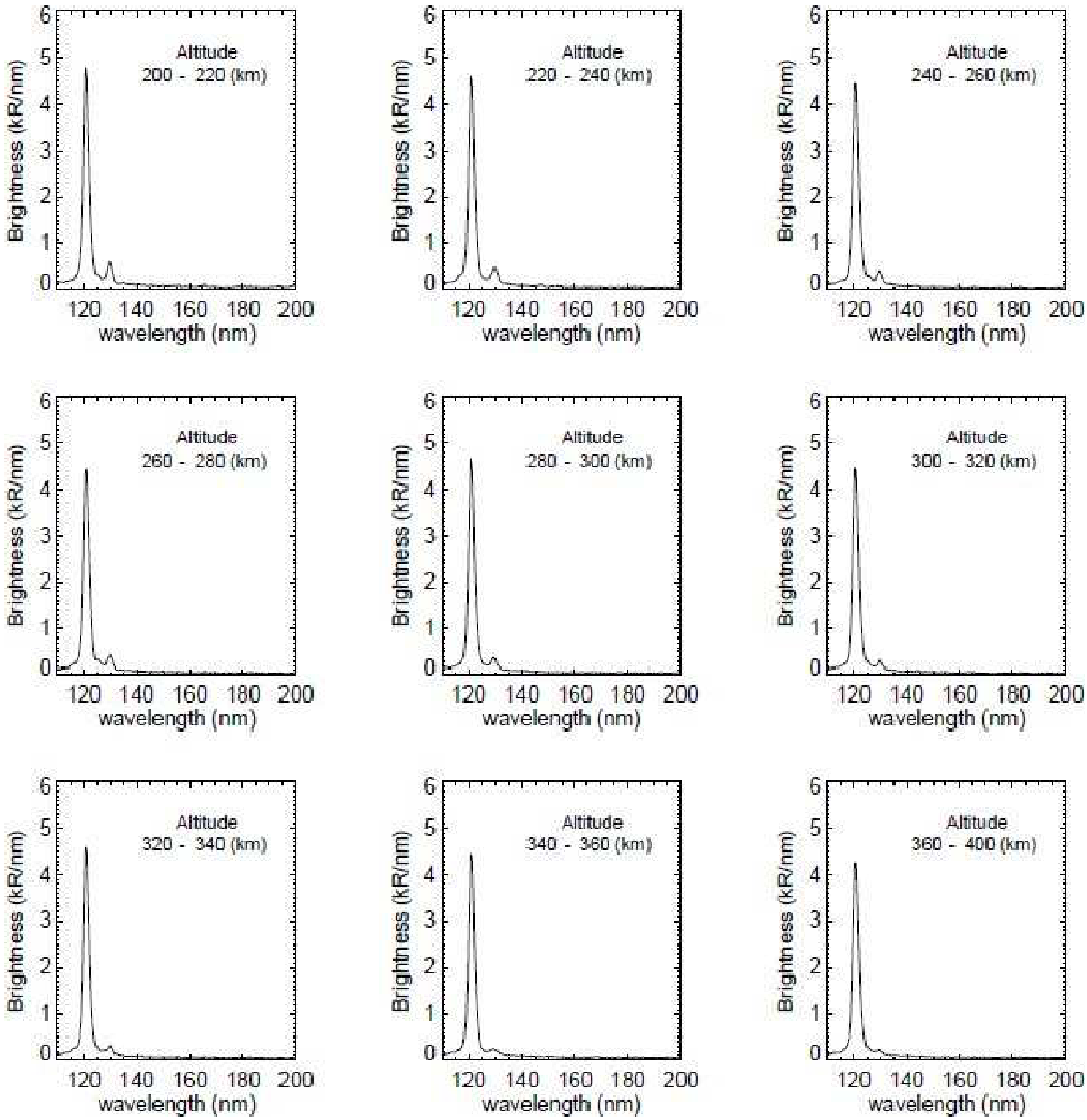
Cold: $\mathbf{n_{exo} = 1x10^5\ cm^{-3}, T_{exo} = 200\ K}$

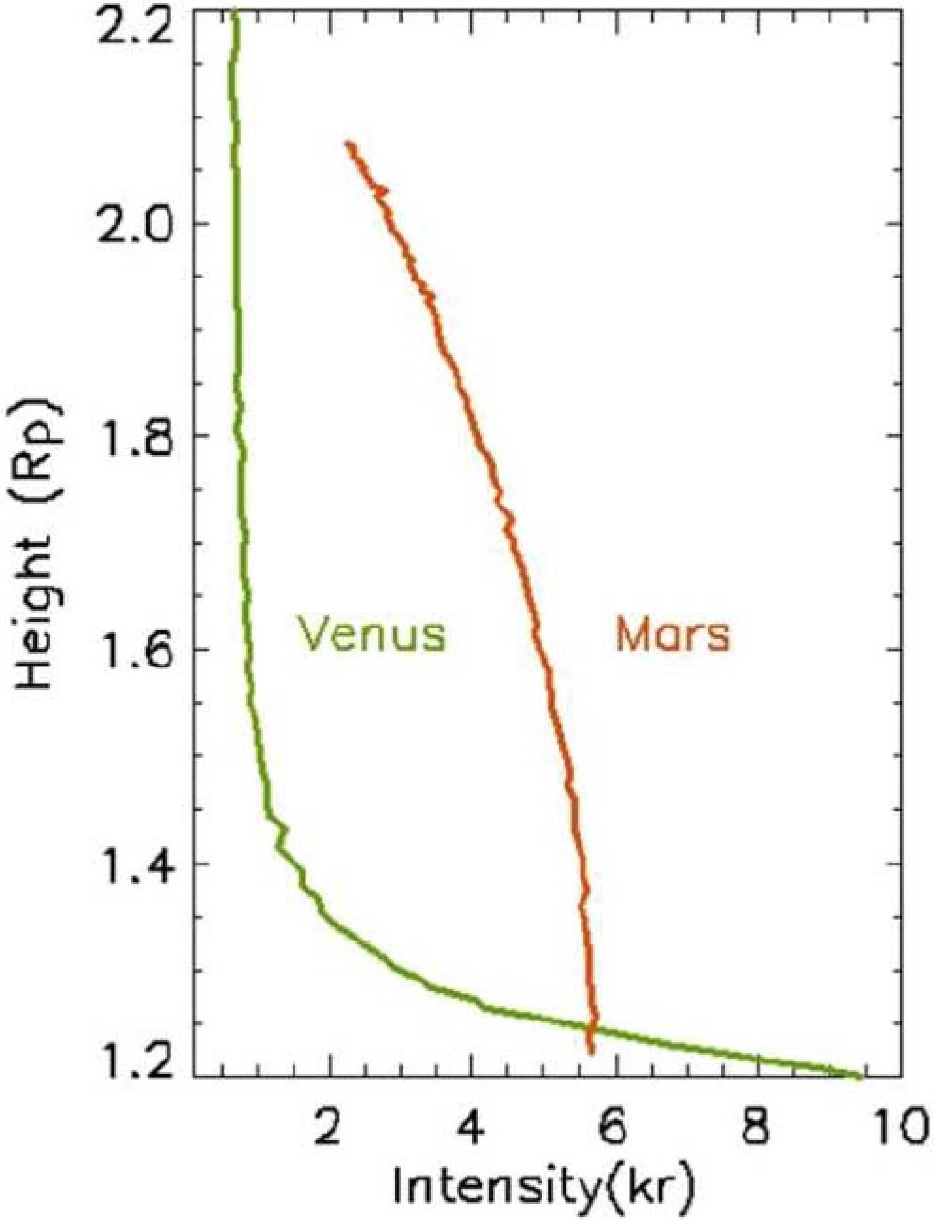
Hot: $\mathbf{n_{exo} = 2\ x10^4\ cm^{-3}, T_{exo} > 500\ K}$

Mars H corona: best fit results with two components: T=200 K and T=500 K



Dashed line: hot component; dashed-dotted:cold component.Solid:sum

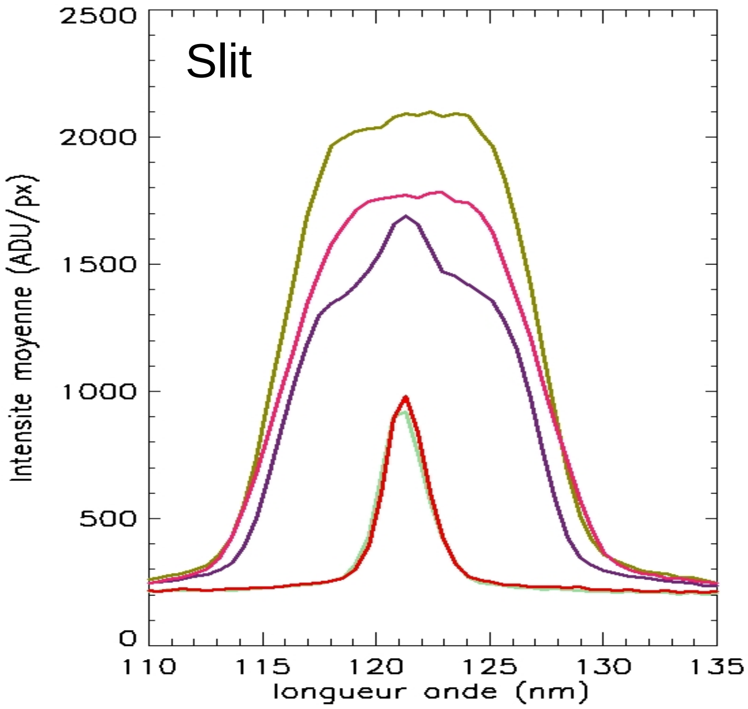

Altitude
200 - 220 (km)
Altitude
220 - 240 (km)
Altitude
240 - 260 (km)
Altitude
260 - 280 (km)
Altitude
280 - 300 (km)
Altitude
300 - 320 (km)
Altitude
320 - 340 (km)
Altitude
340 - 360 (km)
Altitude
360 - 400 (km)
Brightness (kR/nm)
wavelength (nm)

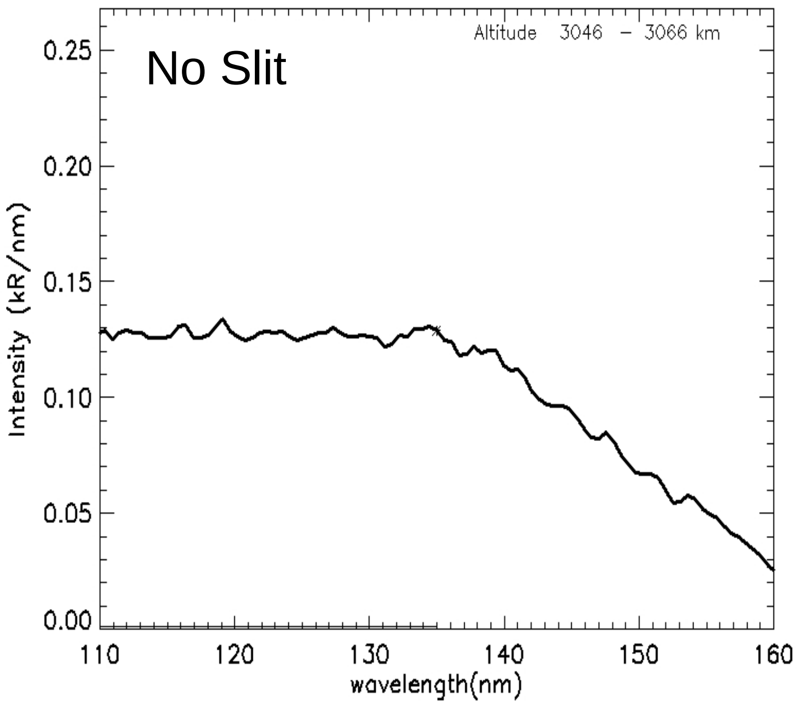


2.2
2.0
1.8
1.6
1.4
1.2
Height (Rp)
Venus
Mars
2
4
6
8
10
Intensity(kr)

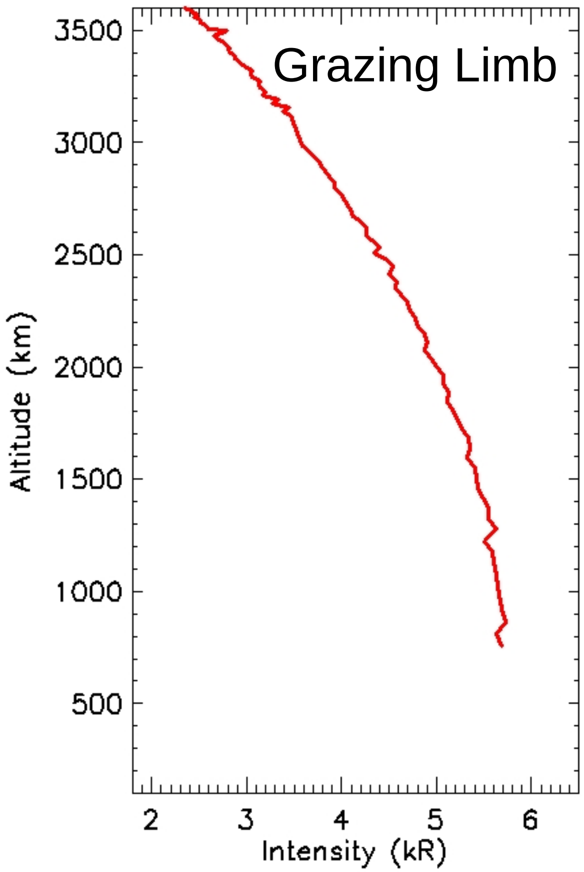
Observation of the Martian exosphere

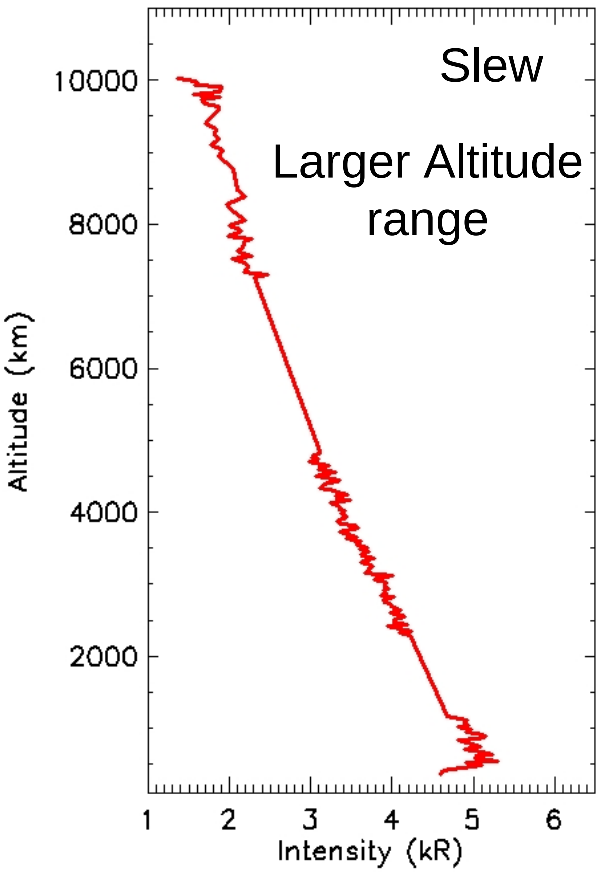
Hydrogen corona : Observations (1/3)



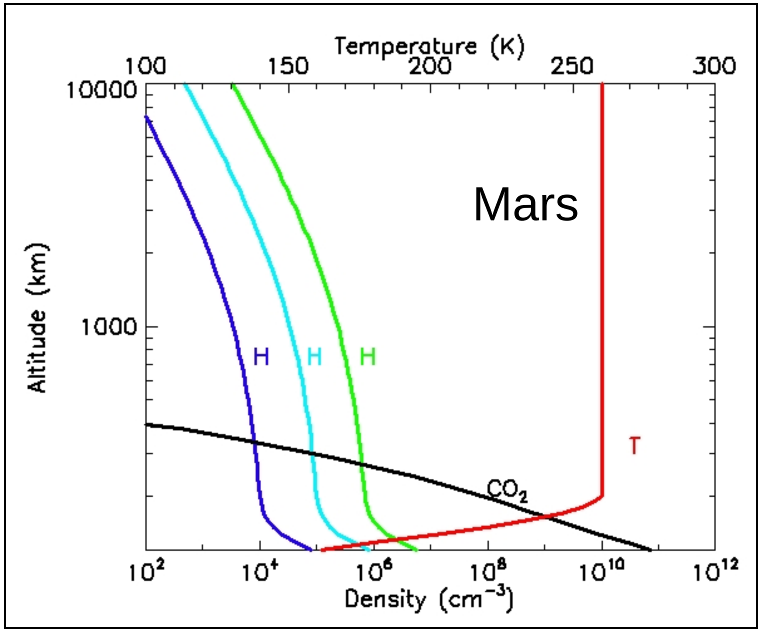


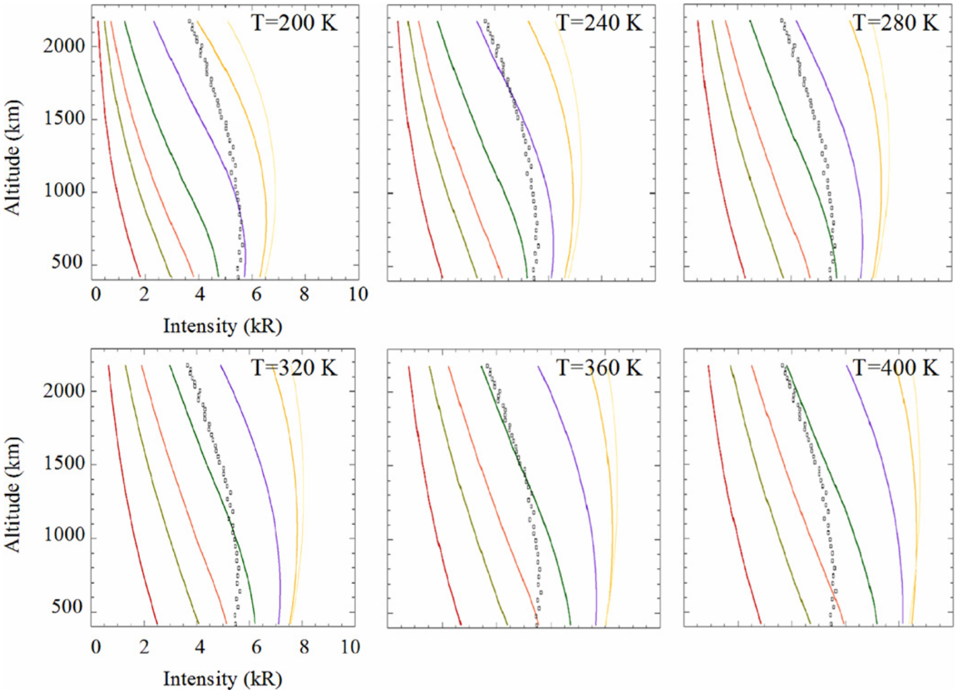
Hydrogen Corona : Observations (2/3)





Hydrogen Corona : Method





Mars Hydrogen Corona : Results

Best Results for 1 population model	Best Results for 2 populations model
Tc ~ 200 – 260 K	Tc = 200 K ; Th > 500 K
Nc ~ 1 – 4 $x10^5$ cm^{-3}	Nc ~ 1-2 $x10^5$ cm-3 ; Nh ~ 1-2 $x10^4$ cm^{-3}

<u>Internal Exosphere</u>

Hydrogen density profiles

Below the exobase

-Resolution of diffusive equation (H in CO_2 or H in O)

- Escape flux given (Paxton et al. 1986)

Above the exobase

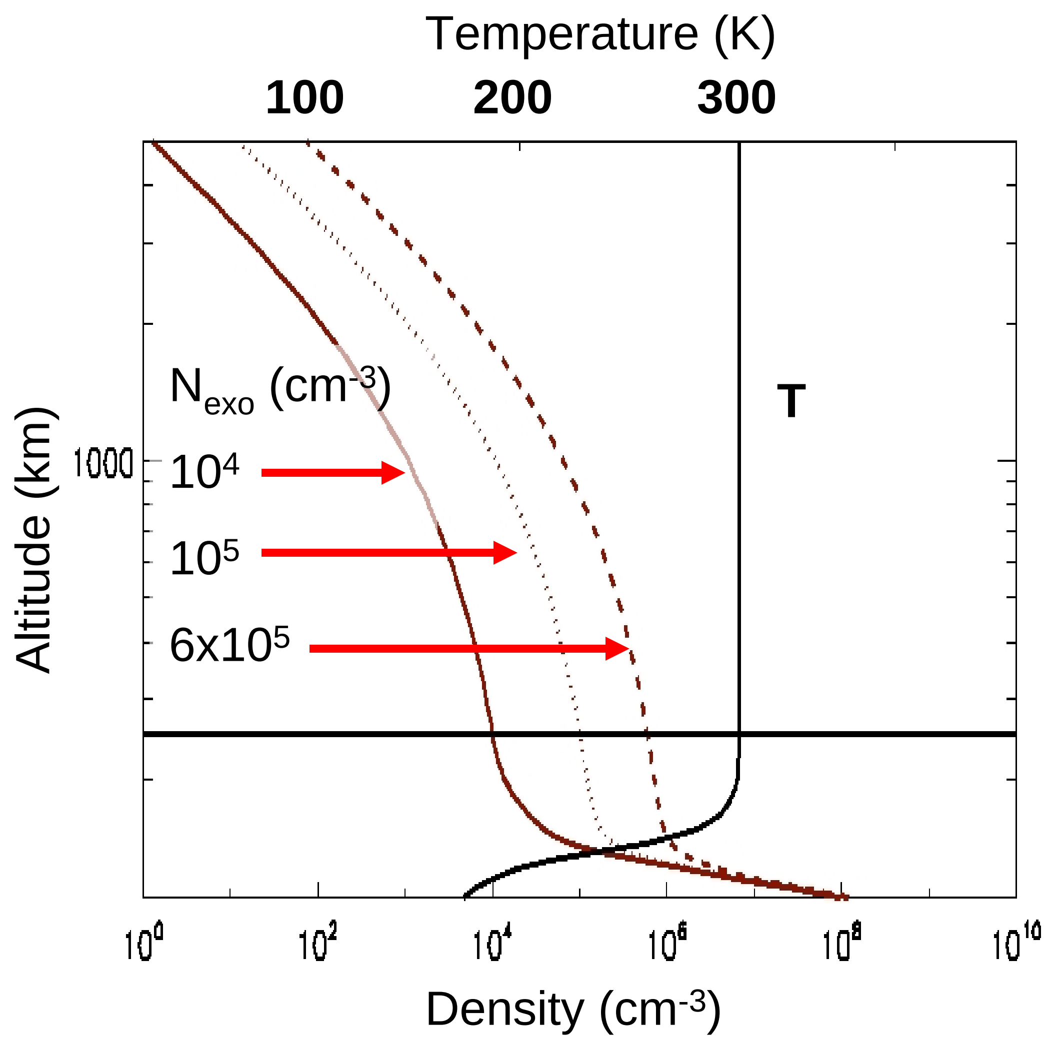
- Chamberlain density profiles

Radiative transfer model

-Spherical geometry

-Partial frequency redistribution

-Voigt profile



Conclusion

Lyman alpha: 2 populations needed to fit the data

Cold: $n_{exo} = 8x10^4\ cm^{-3}$, $T_{exo} = 200\ K$

Hot: $n_{exo} = 2\ x10^4\ cm^{-3}$, $T_{exo} > 600\ K$

Different from Mariner's mission

(one single population Nexo = 2.5-3 $x10^4$ cm-3, T = 350 K)

How to interpret the difference?

Conclusion

Lyman alpha: 2 populations needed to fit the data

Cold: $n_{exo} = 8x10^4\ cm^{-3}$, $T_{exo} = 200\ K$

Hot: $n_{exo} = 2\ x10^4\ cm^{-3}$, $T_{exo} > 600\ K$

Different from Mariner's mission (one single population T = 350 K)

How to interpret the difference?

•Solar activity? No.

•Mariner's single population (T=350K) consistent with SPICAM Lalpha intensities above 1000 km altitude).

•But at that time, T(exosphere) was unknown. Now, from CO_2 emission scale height: 200 K.

Conclusion

<u>Lyman alpha</u>: 2 populations needed to fit the data

Cold: $n_{exo} = 8x10^4\ cm^{-3}$, $T_{exo} = 200\ K$

Hot: $n_{exo} = 2\ x10^4\ cm^{-3}$, $T_{exo} > 600\ K$

The « hot population of H atoms » has always been there.

Number density is orders of magnitude larger than predicted by earlier models of excess energy in some reactions (Nagy and Cravens)

Therefore, origin is still TBD!

Candidates: charge exchange with solar wind protons….

Lyman α forward model

- n_c, density of H atoms at the exobase
  T_c, temperature of H at the exobase (exospheric temperature):
- Compute the distribution of H in the exosphere (and below)
- Solve the Lyman α radiative transfer for a spherical exosphere of H (source function)
- Compute the Lyman α emission intensity that would be seen by SPICAM for the proper geometry
- Compare a grid of models to the data, best fit search for n_c and $T_{c.}$

(single component search)

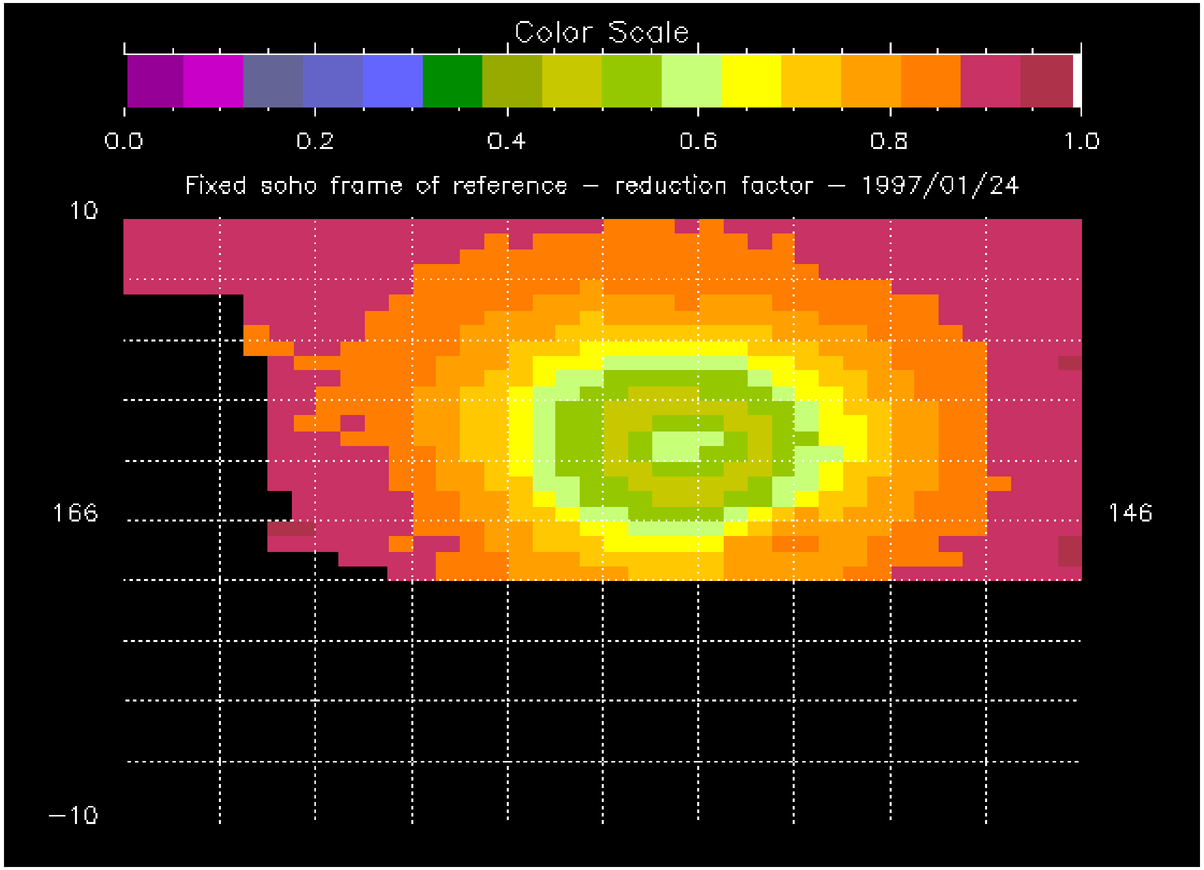
Or:

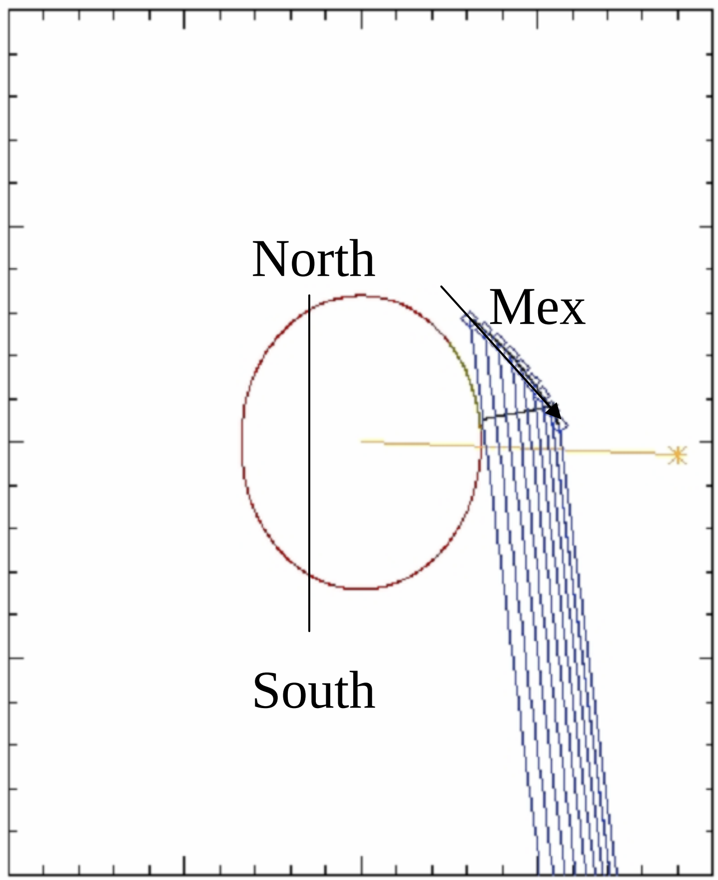
Fix the exospheric temperature by other means (Mars 200 K, from MGS drag, airglow…)

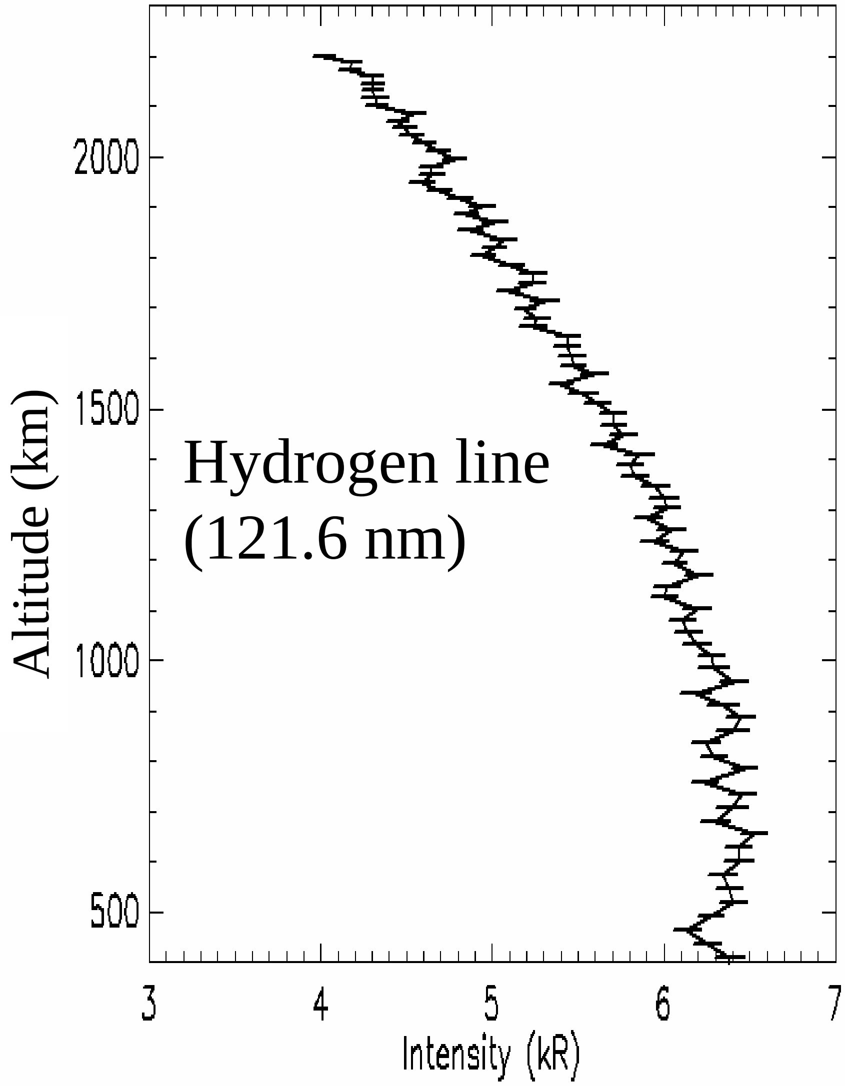
Add a second, hot component to fit the Lyman α intensity data.

Compute the additional escape rate for this component

Earth's geocorona seen in Lα light from SOHO/SWAN:~3x10^5 km




North
Mex
South


Altitude (km)
2000
1500
1000
500
Hydrogen line
(121.6 nm)
3
4
5
6
7
Intensity (kR)

H escape from Mars

- Cold population: F_J~0.5 10^8 atoms/cm2 s =0.1 m H_2O/Gyr)
- Non Thermal, Hot population:
- F_J~ 2.5 10^8 atoms/cm2 s =0.4 m H_2O/Gyr)

Mars: Non thermal escape of H

- Main productive reactions for H in the upper atmosphere (Krasnopolsky, 2002)
- $CO_2^+ + H_2$ ---- > $HCO_2^+ + H$ (1.05 10^8 / cm2 s) (1)
- $HCO^+ + e$ ---- > $CO + H$(1.17 10^8 / cm2 s) (1)

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- If the reaction occurs below the exobase ---- > thermalization of H

Mars: Non thermal escape of H

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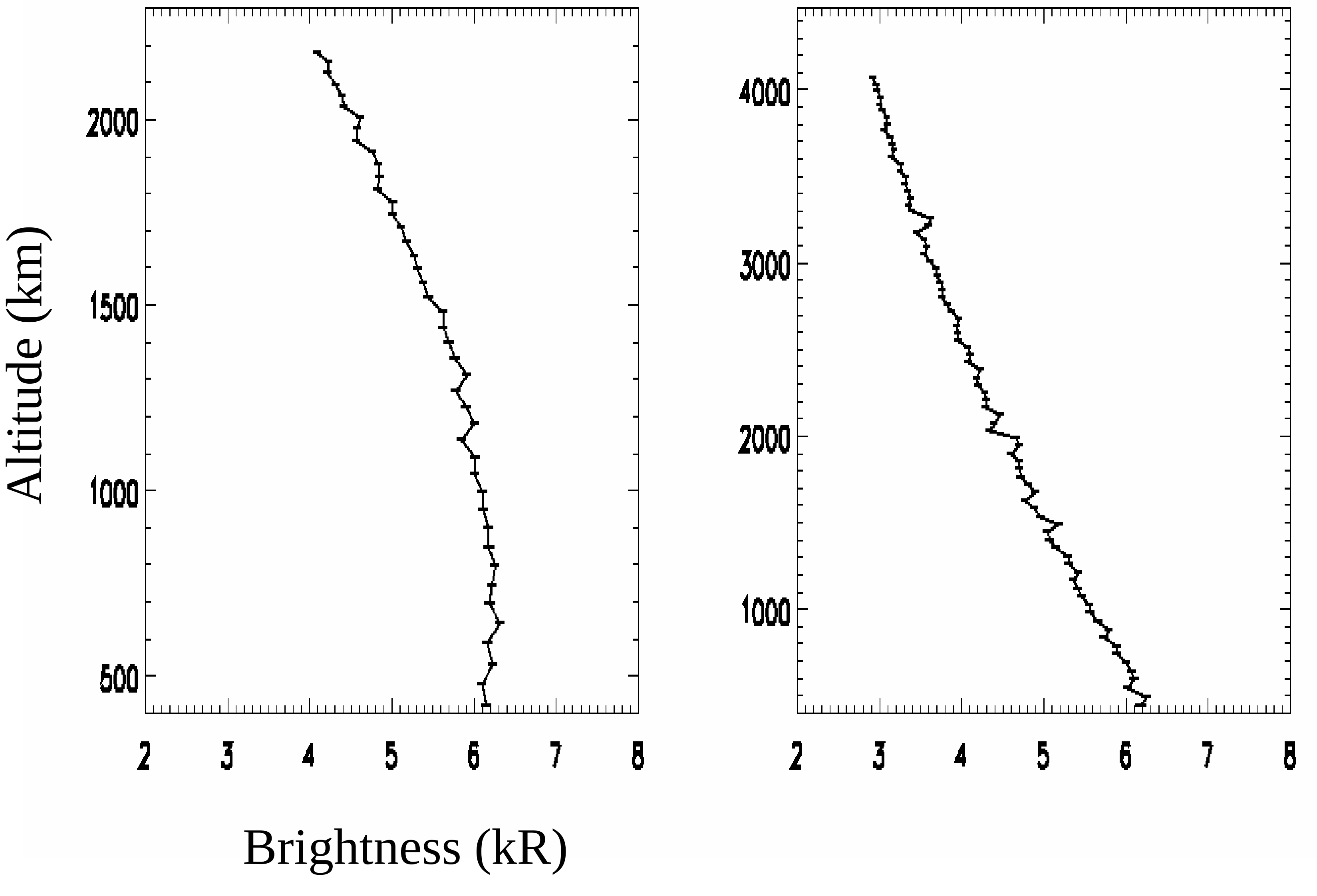
- $CO_2^+ + H_2$ ---- > $HCO_2^+ + H$ (1.05 10^8 / cm2 s) (1)

- $HCO^+ + e$ ---- > $CO + H$(1.17 10^8 / cm2 s) (1)

- If the reaction occurs below the exobase ---- > thermalization of H

- If the reaction occurs above the exobase ----> excess energy of H (0.1-1 ev)
- Escape of H atom on hyperbolic trajectory
- Other mechanisms: interaction with the solar wind (Review for Mars, Chassefiere and Leblanc, PSS,2004)



Interplanetary background : model based on SWAN (SOHO)

Model : H density profiles from 80 to 50 000 km :

Only 2 free parameters (exobase temperature, exobase H density)

Spherical symmetry

From 80 to 120 km (infinite scale height)

From 120 to 200 km diffusive model

Temperature and mixing coefficient profiles from Krasnopolsky et al 2002 : $f(T_{exo})$

From 200 to 50 000 km Chamberlain model (without satellites particles)

Radiative Transfer Model : (Resonant scattering) Spherical geometry.

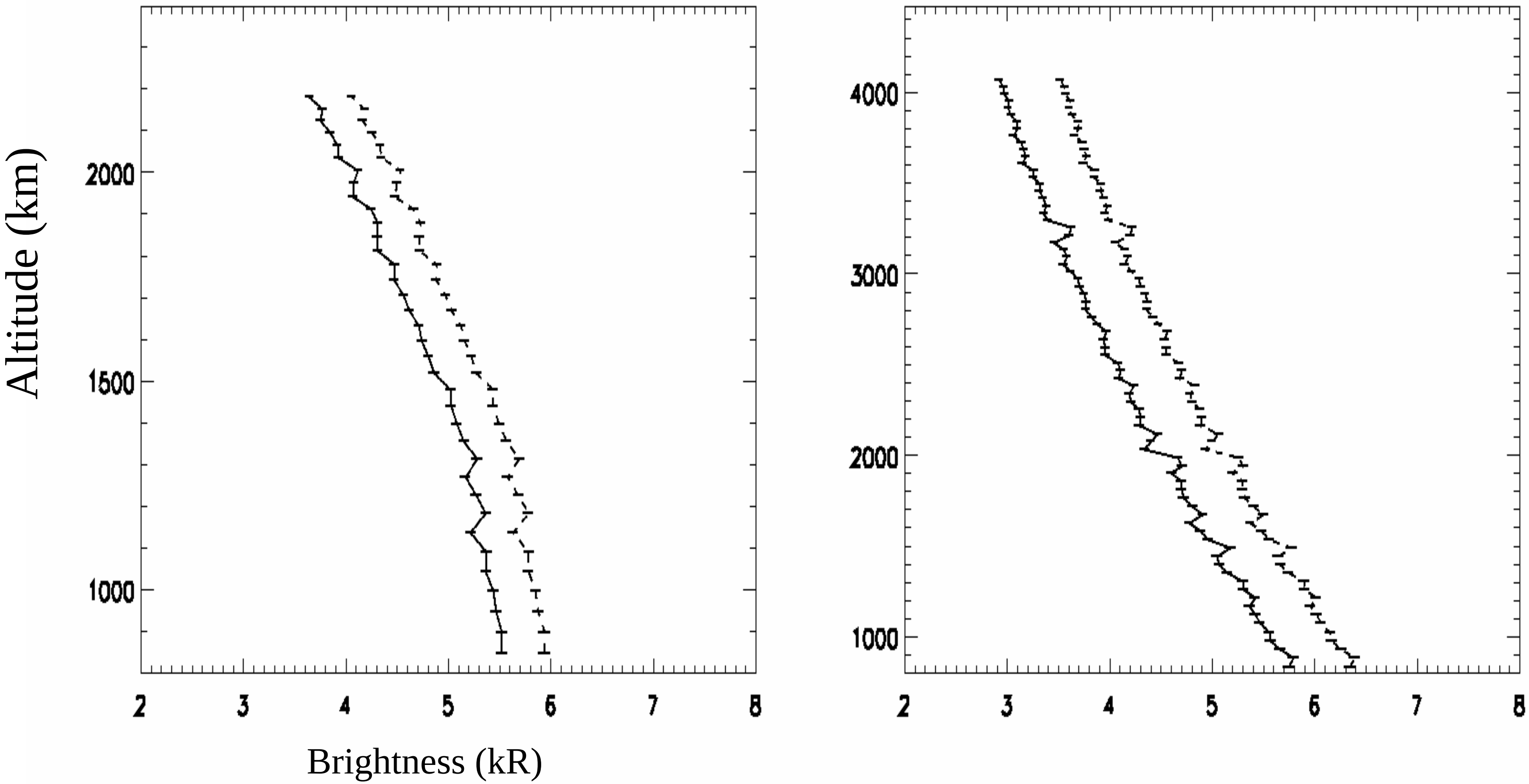
Lyman alpha radiative transfer

- H atoms above CO_2 absorption (~120 km) are illuminated by the strong solar Lα line
- Resonance scattering: all H atoms re-emit

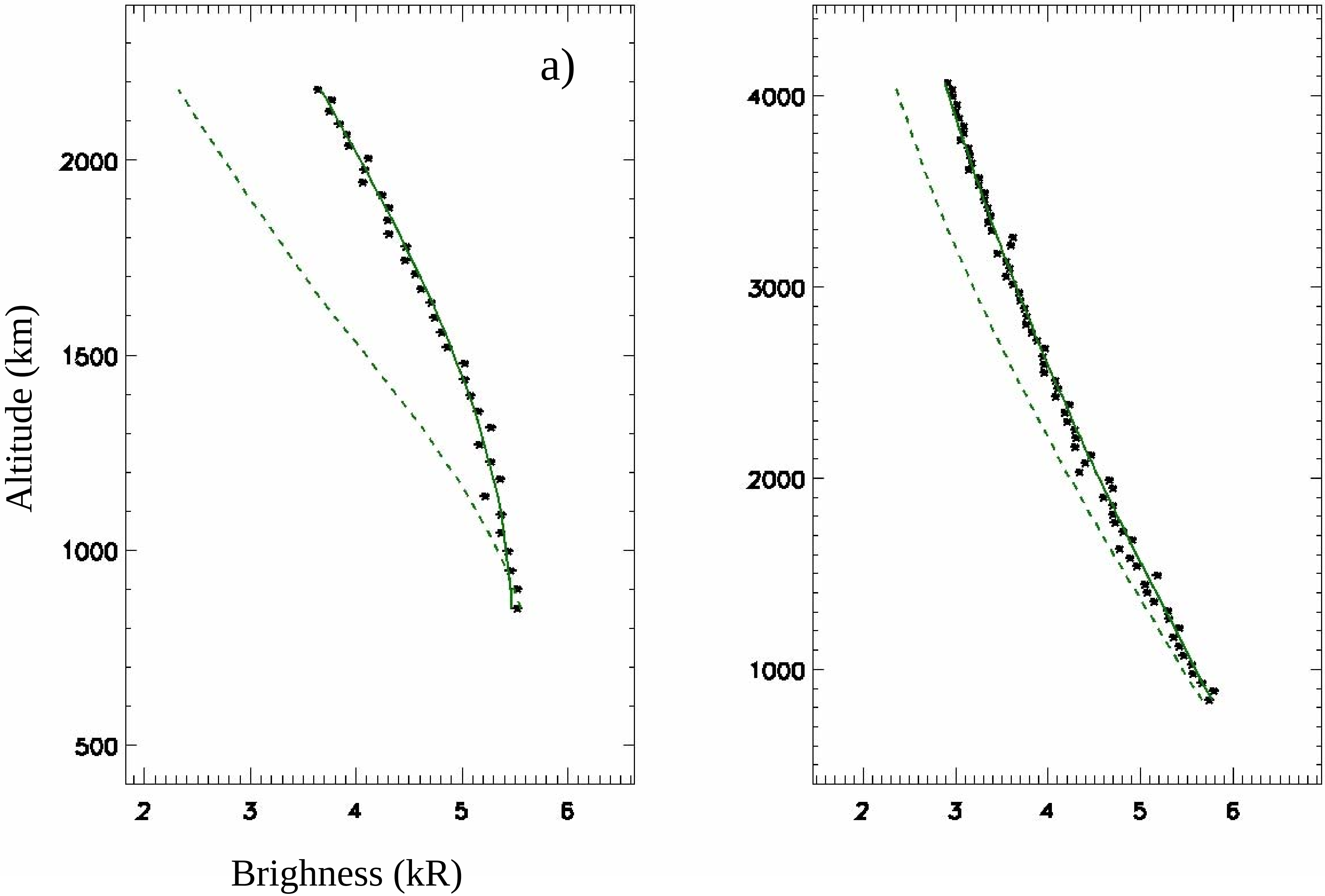
Lα, observable (121.6 nm)

Multiple scattering: Retrieval of H distribution from Lα not practical

Forward model:



Altitude (km)
2000
1500
1000
2
3
4
5
6
7
8
Brightness (kR)
4000
3000
2000
1000
2
3
4
5
6
7
8



a)
Altitude (km)
2000
1500
1000
500
4000
3000
2000
1000
2
3
4
5
6
2
3
4
5
6
Brighness (kR)

CONCLUSION

Brightness in good agreement with previous observations

Two hydrogen populations confirmed

<u>Cold population</u>

- Density : Good agreement with previous observations

- Temperature : Good agreement with previous observations

- Results : Sensitive to the absolute calibration (major uncertainty)

<u>Hot population</u>

- Presence confirmed

-**Temperature : Very difficult to constrain ; larger than previous observations**

-**Density : In the range of previous observations but hard to constrain**

-**Results : very sensitive to the interplanetary background value**

<u>Study to be continued</u>

~ 50 observations from November 2006 – November 2007 at different Solar Zenith angle, Local Time, …

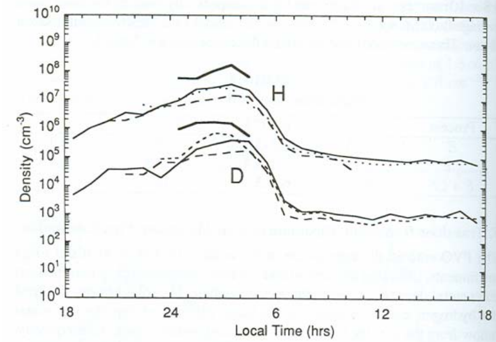
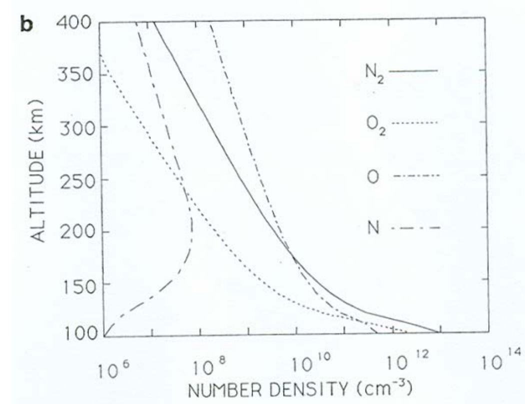
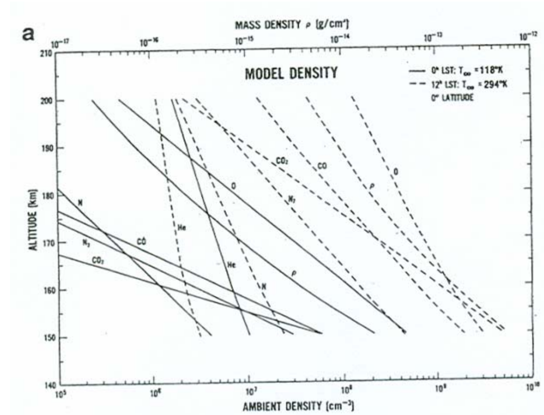


Figure 7. Hydrogen and deuterium PVO densities near 220 km, day time, and 160 km, night time. Heavy solid curve, 1992; light solid curve, Venus year 1; dotted curve, year 2; dark curve, year 3.


b
ALTITUDE (km)
400
350
300
250
200
150
100
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}
NUMBER DENSITY (cm^{-3})
N_2
O_2
O
N


a
MASS DENSITY ρ (g/cm³)
MODEL DENSITY
0° LATITUDE
ALTITUDE (km)
AMBIENT DENSITY (cm^{-3})
CO₂
CO
O
N₂
He
N
ρ

The H corona of Venus

- Error bars :

deduced from a Poissonian distribution of the events (Leblanc et al. 2006)

- Interplanetary background :

~ 515 R (from a model)

-Solar Flux at Venus

SPICAV/VEX (red) :

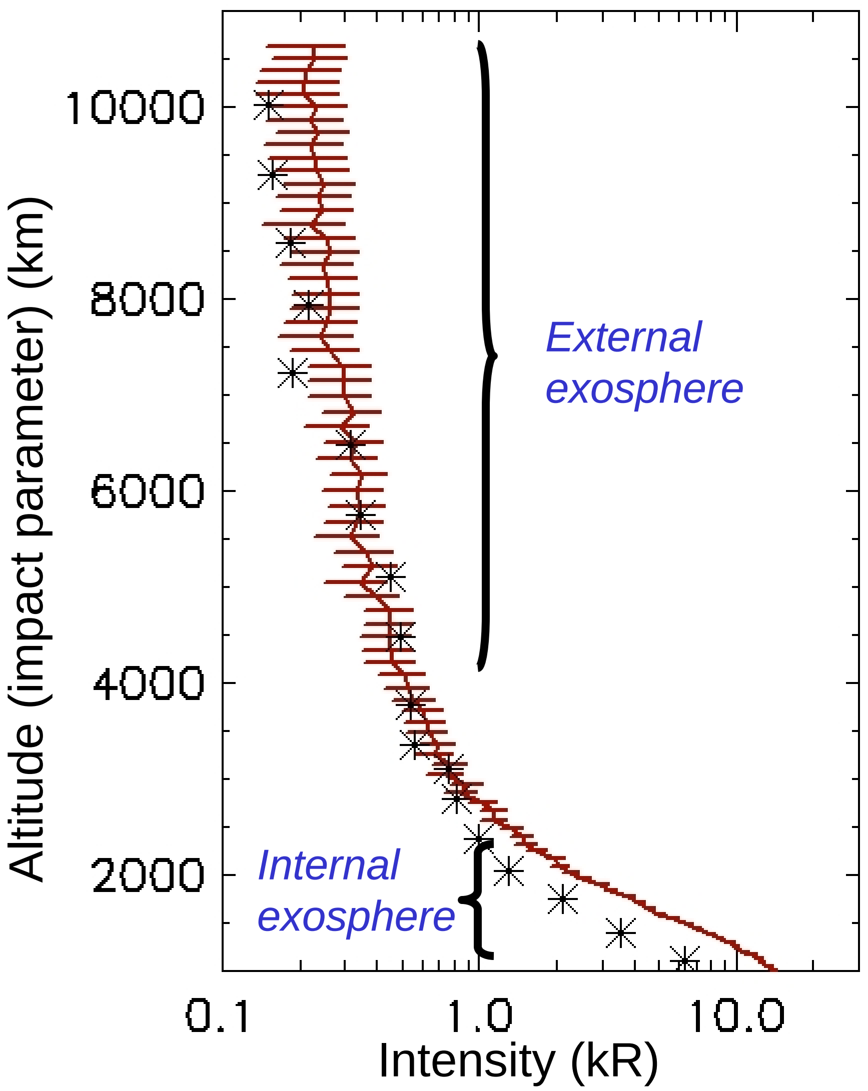
~ $6.6x10^{11}$ ph/cm²/s

VENERA 11 (*) (Bertaux et al. 1982)

~ $1.45x10^{12}$ ph/cm²/s

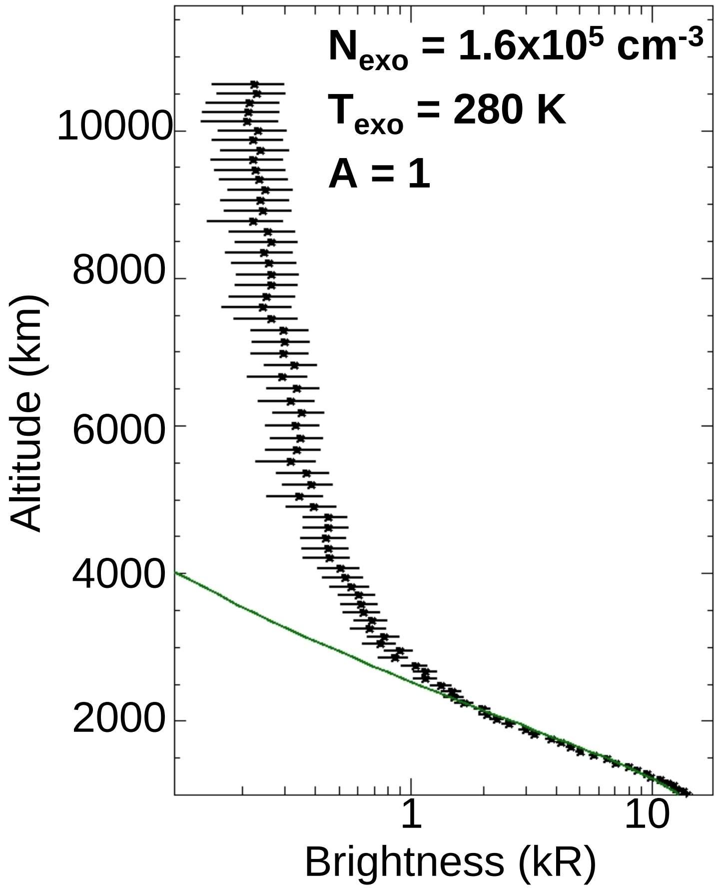
Here scaled to the SPICAV/VEX solar flux

Observation of a non-thermal hydrogen population dominant in the external exosphere by all previous missions



Internal exosphere

	VEX (This presentation)	Venera 11 (Bertaux et al. 1982)	Pioneer Venus (Stewart et al. 1979)	Mariner 5 (Anderson 1976)
N_{exo} (cm^{-3})	$>1.5 \times 10^5$	$4 \pm 3 \times 10^4$	$1\text{-}2 \times 10^5$	$2 \pm 1 \times 10^5$
T_{exo} (K)	< 300 K	300 ± 25	~ 300 K	275 ± 50 K



<u>External exosphere</u>

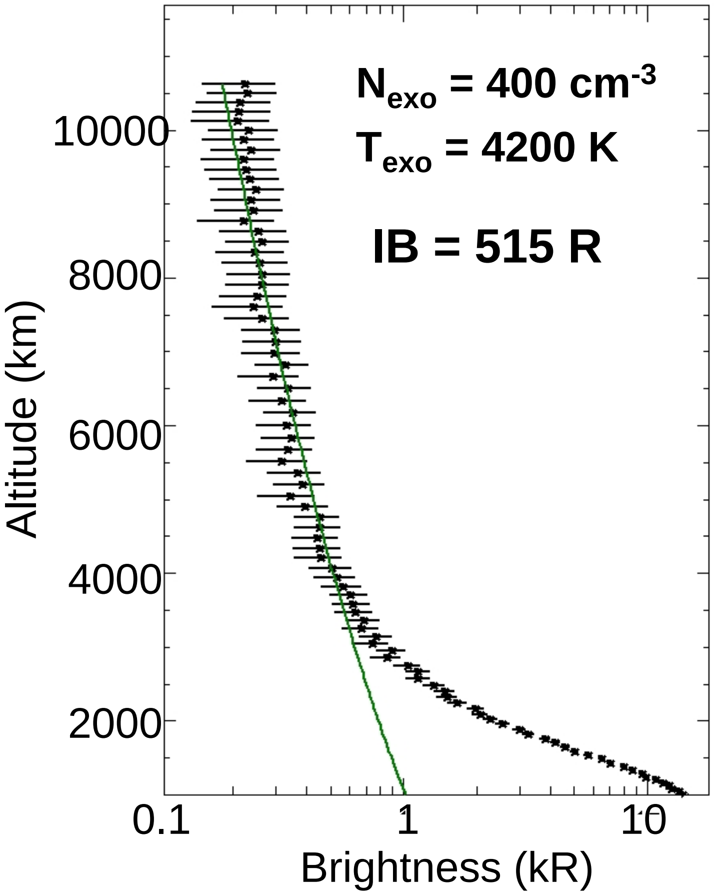
Chamberlain's profile without satellite particles

Difficult to constrain

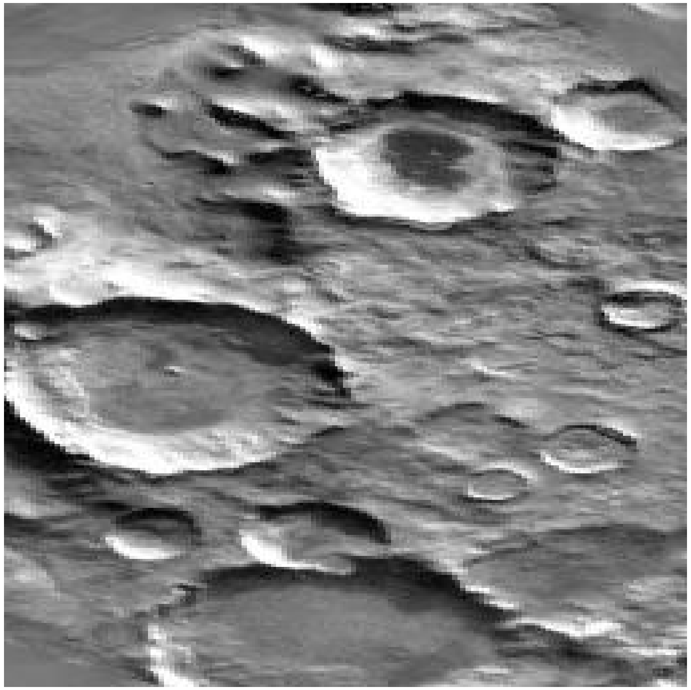
$N_{exo} \in [400 - 1800]\ cm^{-3}$

$T_{exo} > 1000$ K

Best profile $N_{exo} = 400\ cm^{-3}$; $T_{exo} = 4200$ K



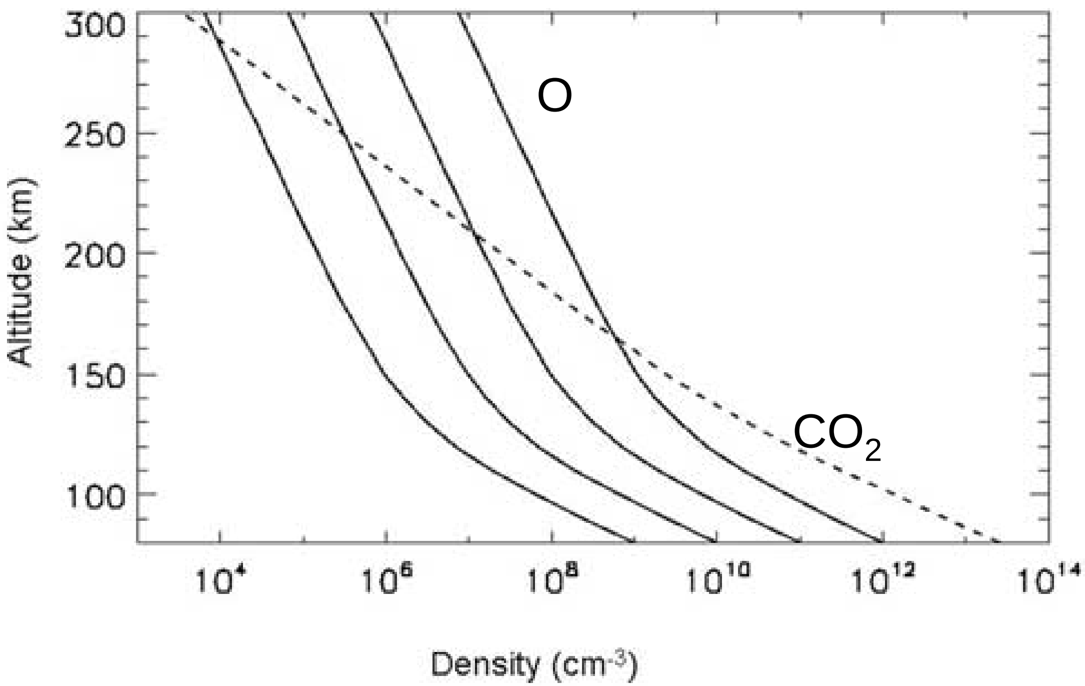
My favorite scenario for atmospheric loss on Mars



« It’s a hell-of-a-lot difficult to get rid of an atmosphere! »

Don Hunten, 2005, private communication

Oxygen Corona : Methods



	Venus	Earth	Mars
Composition of atmosphere	CO_2 96%	O_2, N_2	CO_2 96 %
Water (equivalent liquid)	30 mm	2.8 km	20 (polar caps)+20 m
Exobase altitude (km)	250	500	250
Exospheric temperature T_{ex} (K)	240-290	800-1200	200-240
H density at exobase (cm^{-3})	$1.5\text{x}10^5$	$5\text{x}10^4$-$1\text{x}10^5$	$1.0 \pm 0.2 \times 10^5$
H hot component	$4\text{x}\ 10^2$ T~4200 K		$1.9 \pm 0.5 \times 10^4$ cm−3 T>500 K
H Thermal escape ($cm^{-2}\ s^{-1}$)		$2\text{x}\ 10^8$	$0.5\text{-}1.4 \pm 0.6 \times 10^8$
H Non thermal escape			$2.5\text{x}\ 10^8$
Area of exobase (cm2)	$1.25\ \text{x}10^{18}$	$1.48\text{x}10^{18}$	$0.34\text{x}10^{18}$
Equivalent loss of water (m/Gyr)	?	1	0.7-1.5

-H Density at exobase remarkably similar in the 3 planets ! Mesospheric cold trap, and limit of diffusion

-Present escape rate weak for significant evolution of water

-T_{ex} very different for the non CO_2 atmosphere (Earth)