Update on research related to (exo)planets under extreme conditions

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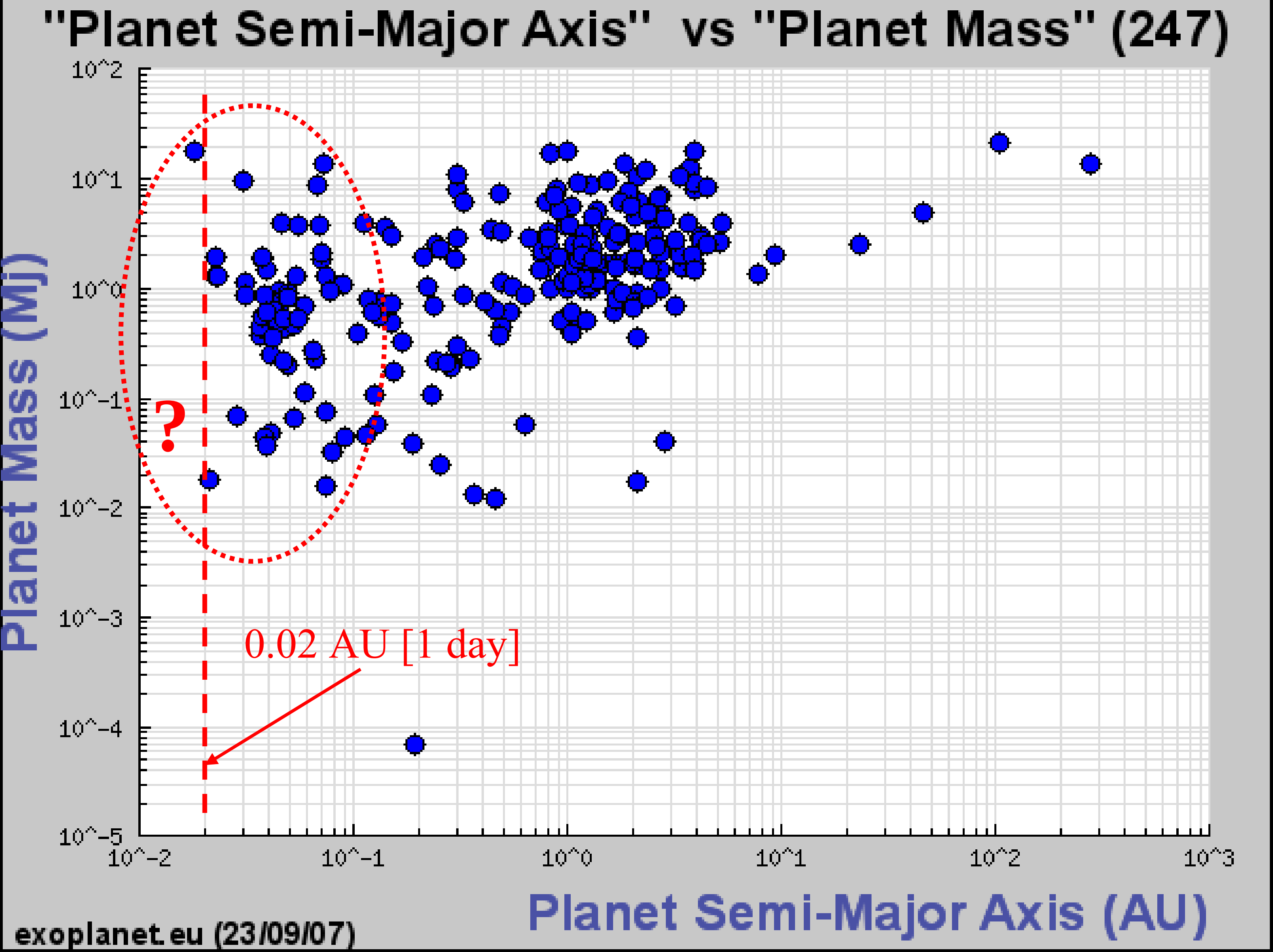
Mass vs. semi-major axis



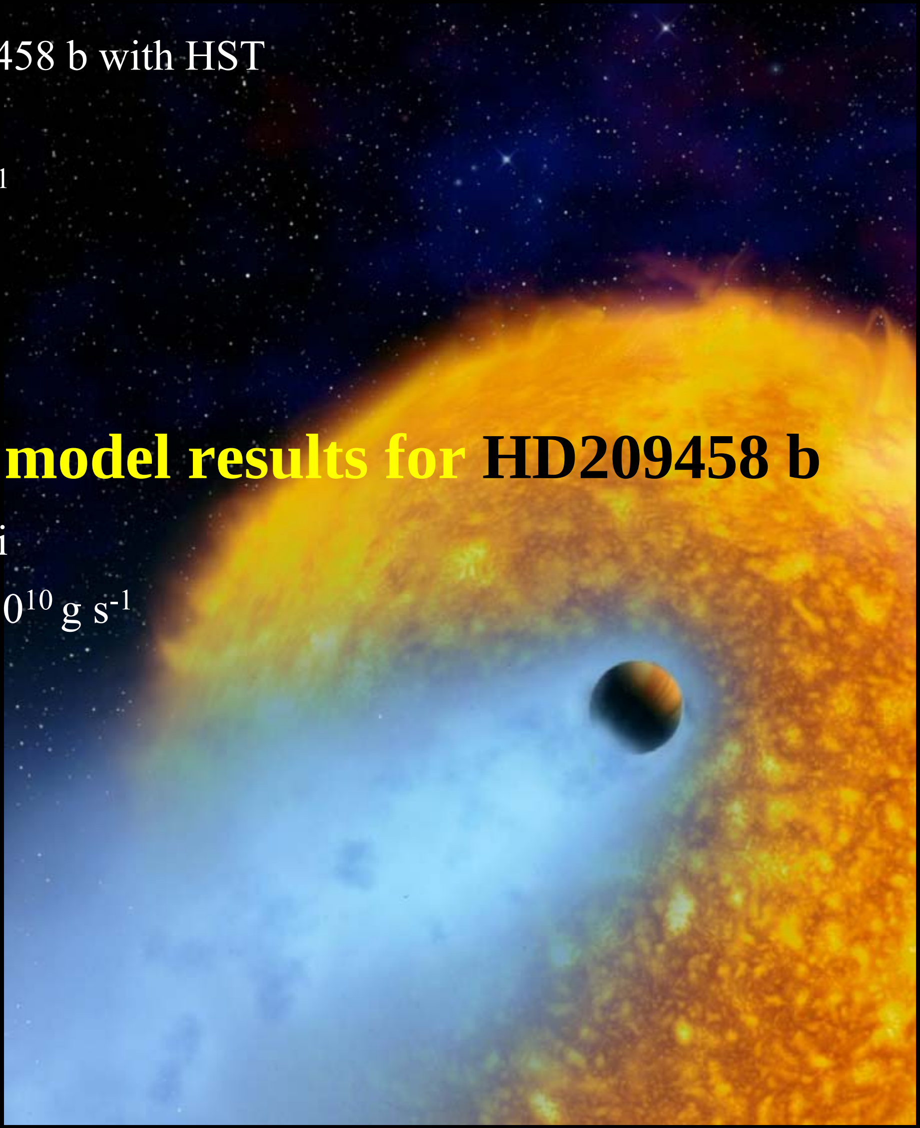
exoplanet.eu (23/09/07)

Evaporation of close & H-rich gas giants

Observation

- Hydrogen-cloud observed around HD209458 b with HST
- Expanded atmosphere
- Estimated lower mass loss rate $\geq 10^{10}$ g s^{-1}

[Vidal-Madjar *et al.* 2003]



Full hydrodynamic blow-off model results for HD209458 b

- Atmosphere expansion $\approx$ 3 planetary radii
- Estimated maximal mass loss rate $\approx 7 \times 10^{10}$ g s^{-1}

[e.g., Lammer *et al.*, 2003; Yelle 2004; Tian *et al.* 2005; Munoz 2007; Penz *et al.* 2007]

BUT !

Did they really observe the atmospheric hydrogen?

Hydrogen ENAs → form the observed cloud

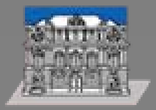
Stellar wind plasma interaction with an extended hydrogen atmosphere can explain the observations

→ information of the stellar wind around an other star at 0.045 AU!

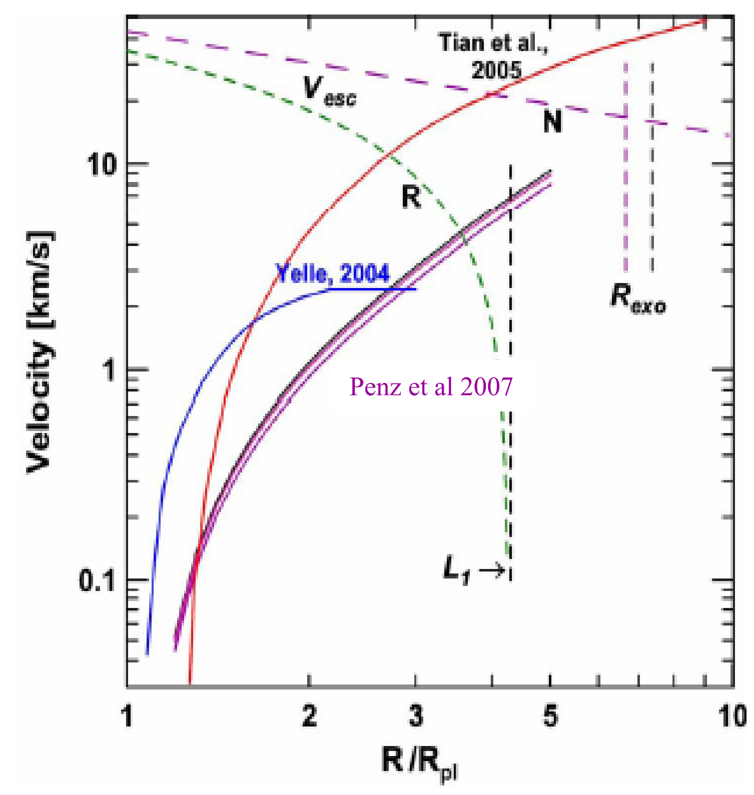
A parameter study can give information about the magnetosphere and planetary exosphere

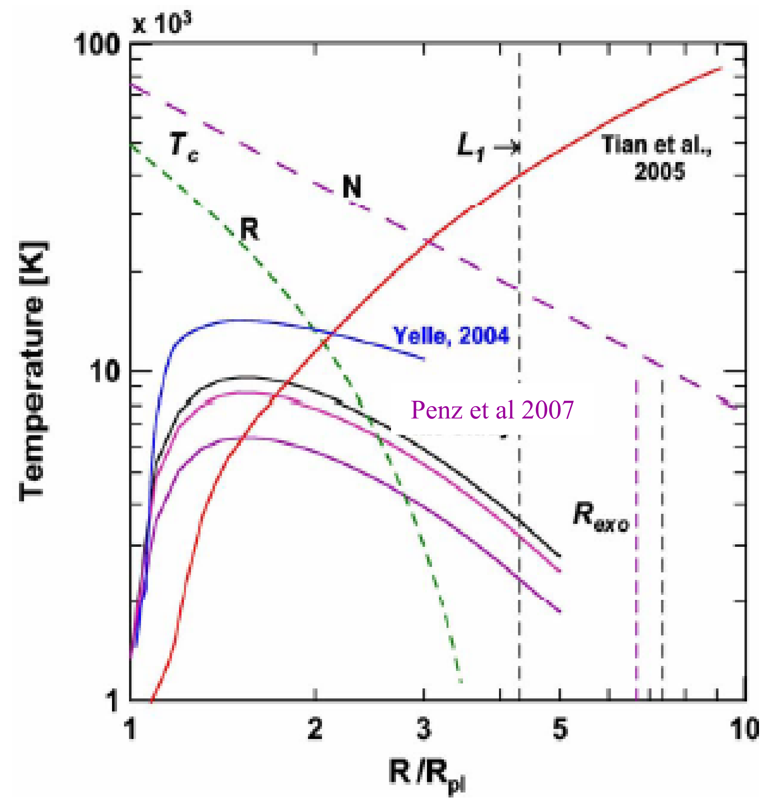
Very good example for solar system and exoplanet science synergies!

[Holmstroem *et al*., Nature under review, 2007]



Evaporation of close-in H-rich gas giants





$$\frac{\partial n}{\partial t} + \frac{1}{r^2}\frac{\partial n v r^2}{\partial r} = 0,$$

$$n\frac{\partial v}{\partial t} + nv\frac{\partial v}{\partial r} + \frac{1}{m}\frac{\partial p}{\partial r} = nF_{grav},$$

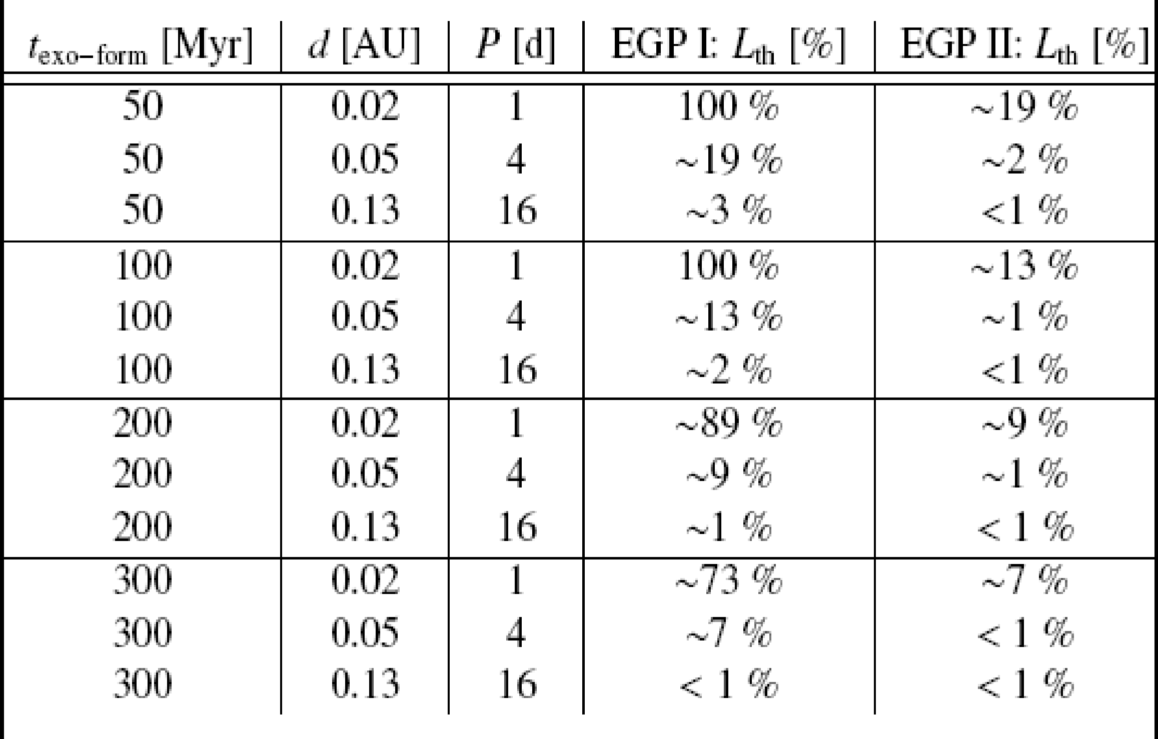
$$nm\left(\frac{\partial E}{\partial t} + v\frac{\partial E}{\partial r}\right) = q - p\frac{1}{r^2}\frac{\partial r^2 v}{\partial r} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\chi\frac{\partial T}{\partial r}\right)$$

$$F_{grav} = -\frac{GM_{pl}}{r^2} + \frac{GM_{st}}{(d-r)^2} - \frac{G(M_{st}-M_{pl})}{d^3}(s-r)$$

$$p = nkT, \quad E = \frac{1}{\gamma - 1}\frac{p}{nm}$$

[Penz *et al.* from revised version, submitted, PSS, 2007]

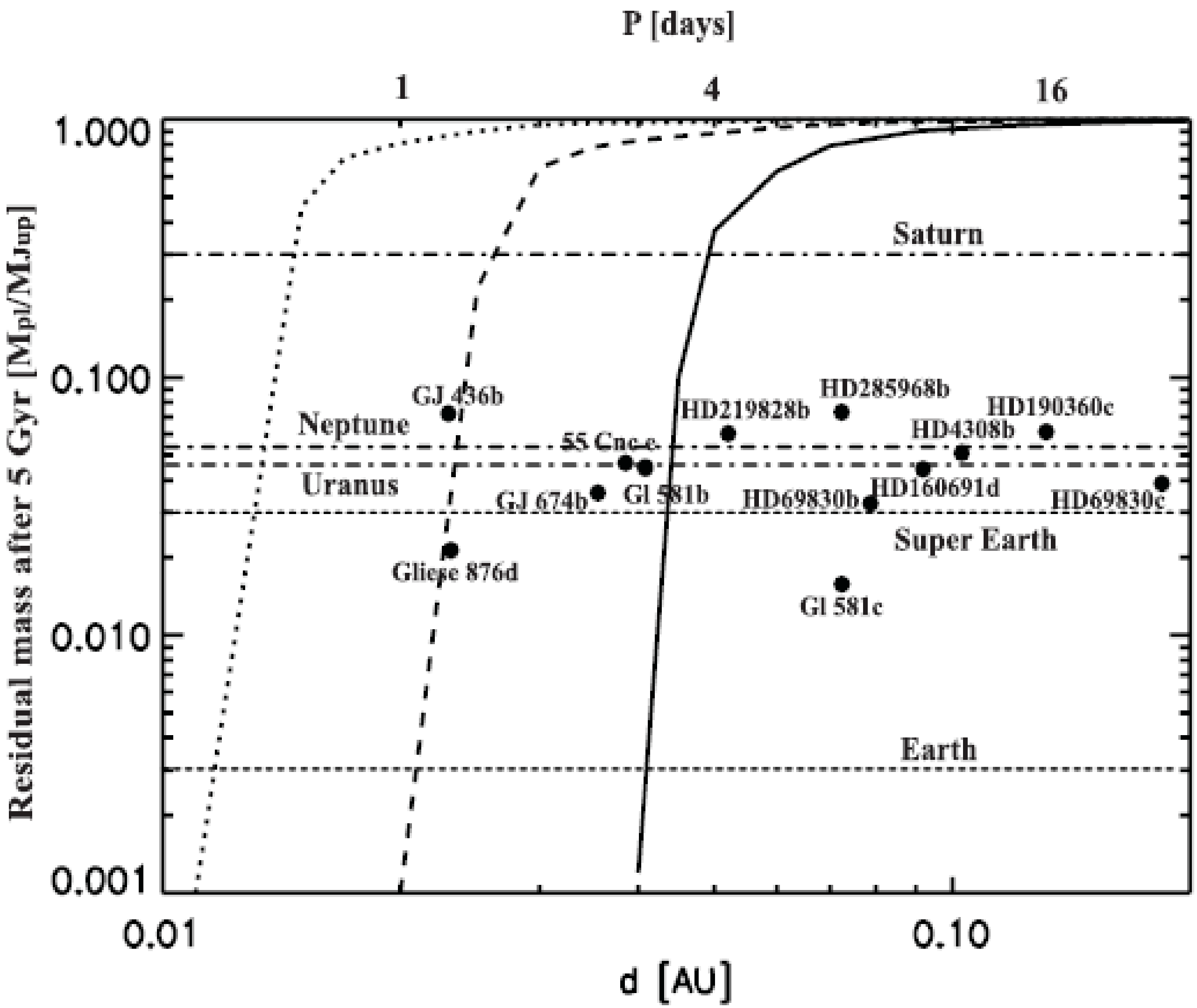
Evaporation of close-in H-rich gas giants in orbits around solar-like stars



$t_{\text{exo-form}}$ [Myr]	d [AU]	P [d]	EGP I: L_{th} [%]	EGP II: L_{th} [%]
50	0.02	1	100 %	$\sim$19 %
50	0.05	4	$\sim$19 %	$\sim$2 %
50	0.13	16	$\sim$3 %	$<$1 %
100	0.02	1	100 %	$\sim$13 %
100	0.05	4	$\sim$13 %	$\sim$1 %
100	0.13	16	$\sim$2 %	$<$1 %
200	0.02	1	$\sim$89 %	$\sim$9 %
200	0.05	4	$\sim$9 %	$\sim$1 %
200	0.13	16	$\sim$1 %	$<$ 1 %
300	0.02	1	$\sim$73 %	$\sim$7 %
300	0.05	4	$\sim$7 %	$<$ 1 %
300	0.13	16	$<$ 1 %	$<$ 1 %

Includes the X-ray/EUV evolution history from
Ribas *et al*., ApJ, 2005 EGP I: → 10^{26} kg;   EGP II: → 10^{27} kg

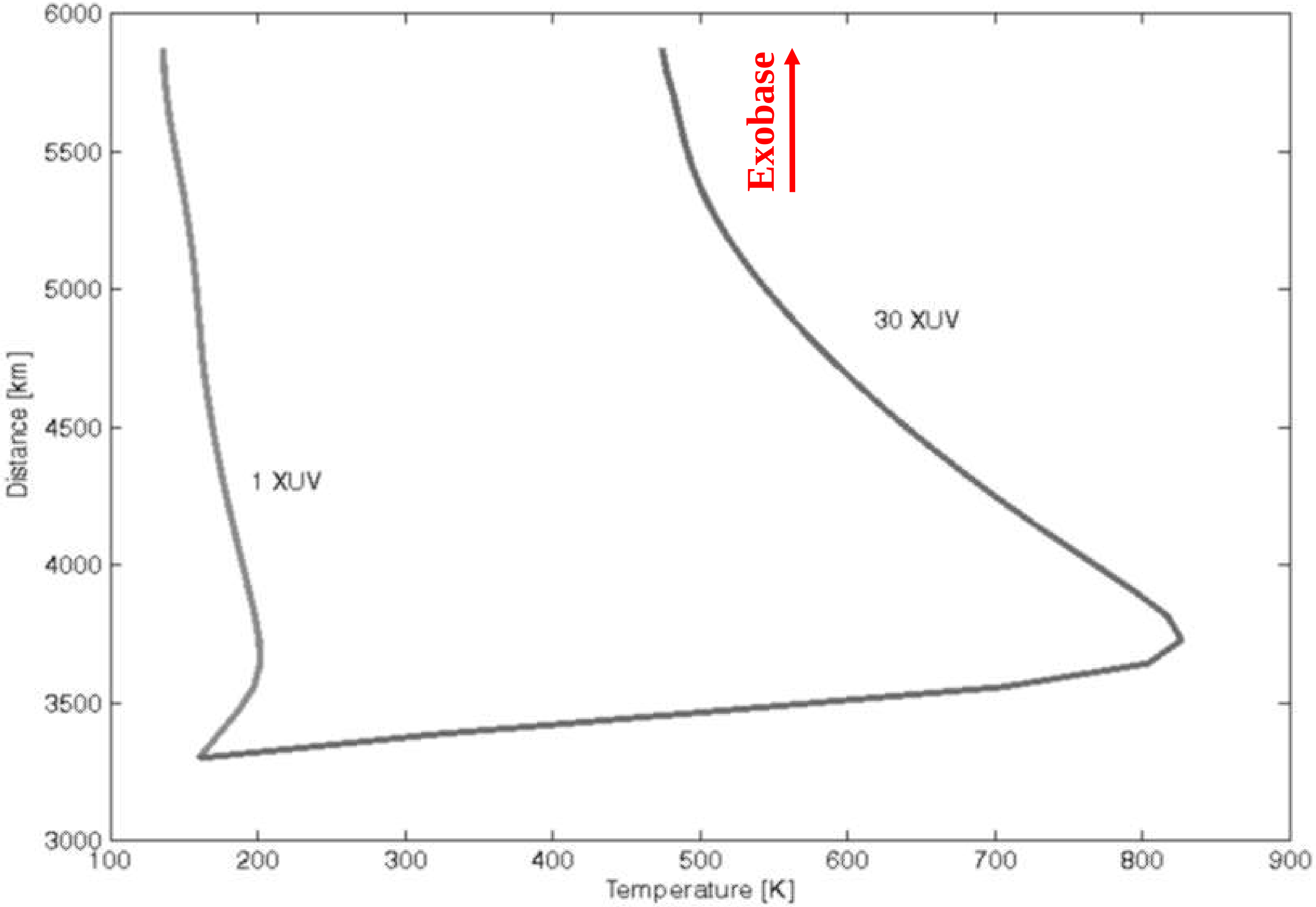
CME induced H^+ ion pick up loss at different orbital distances



[Lammer *et al.* 2007]

Early Titan: N$_2$ Hydrodynamic modelling → EUV 15, 20, 30 and 100 times higher

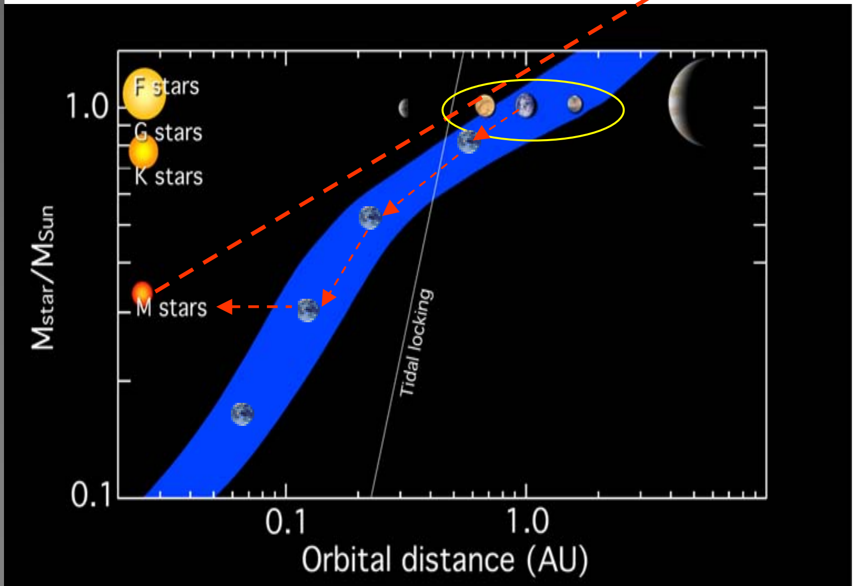
[preliminary model results by Penz]



No solar analogy for habitable zones of lower mass stars (K and M-types)

Atmospheric effects and habitability of Earth-like exoplanets within close-in habitable zones

- Enhanced EUV and X-rays
- Neutron fluxes
- Coronal mass ejections (CMEs)
- Intense solar proton/electron fluxes (e.g., SPEs)



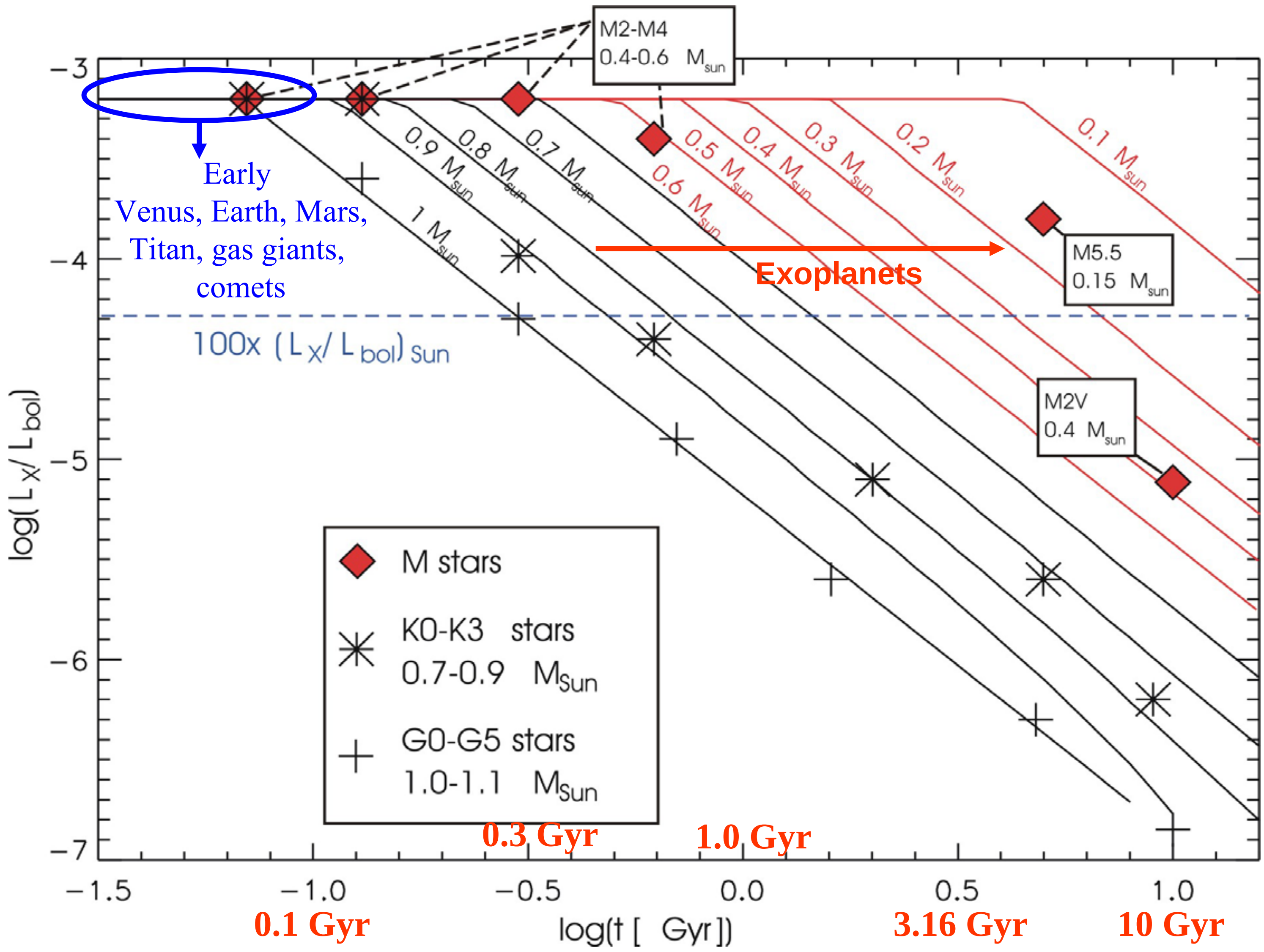
Solar – stellar analogy

- Data from Sun + Stars

Space and ground-based data

- Correlated analysis of events
- Establishing an extreme event data-base (Venus, Earth, Mars, exoplanets)
- Input for models

X-ray/EUV activity of low mass stars



Early
Venus, Earth, Mars,
Titan, gas giants,
comets

Exoplanets

0.3 Gyr

1.0 Gyr

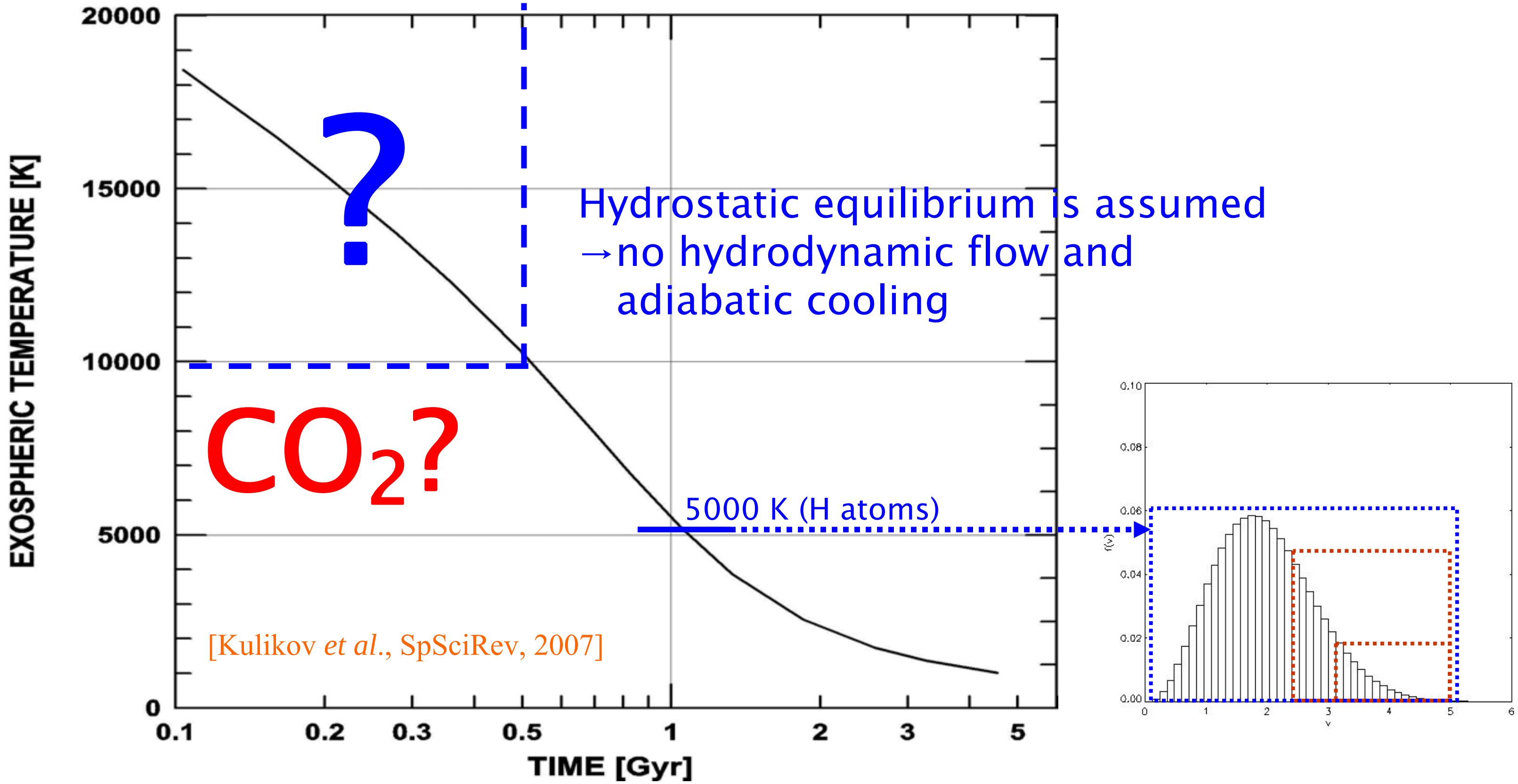
0.1 Gyr

3.16 Gyr

10 Gyr

[Scalo *et al*, Astrobiology, 2007]

Time evolution of the exobase temperature based on Earth's present atmospheric composition

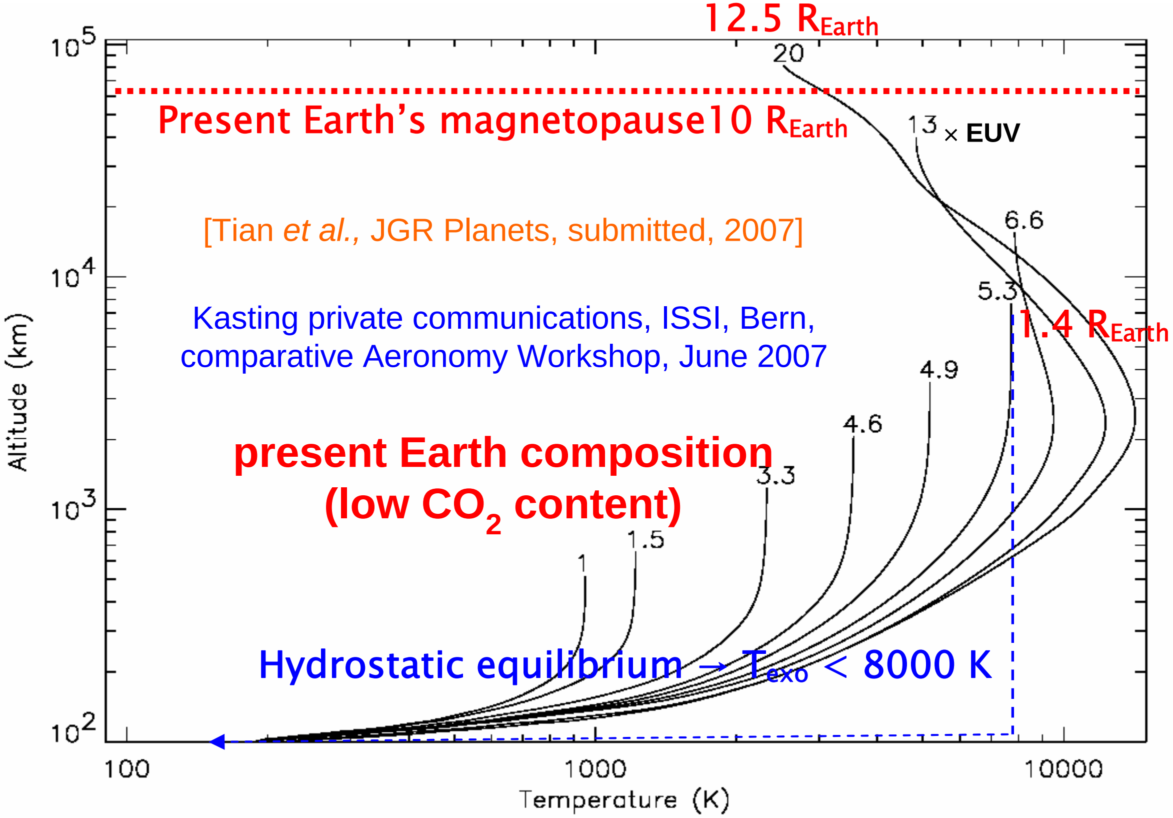


Hydrostatic equilibrium is assumed
→no hydrodynamic flow and
adiabatic cooling

[Kulikov *et al.*, SpSciRev, 2007]

- The blow-off temperature for atomic hydrogen of about 5000 K would be exceded during the first Gyr
- For XUV fluxes more than 10 times the present flux (> 3.8 Gyr ago) one would expect extremely high exospheric temperatures
- Therefore, the CO_2 abundance in the Earth's atmosphere during the first 500 Myr should be much higher than ~ 3.5 Gyr ago to survive

Coupled thermosphere – dynamic model yields interesting results



12.5 R_{Earth}

Present Earth’s magnetopause10 R_{Earth}

[Tian *et al.*, JGR Planets, submitted, 2007]

Kasting private communications, ISSI, Bern, comparative Aeronomy Workshop, June 2007

1.4 R_{Earth}

present Earth composition (low CO_2 content)

Hydrostatic equilibrium → T_{exo} < 8000 K

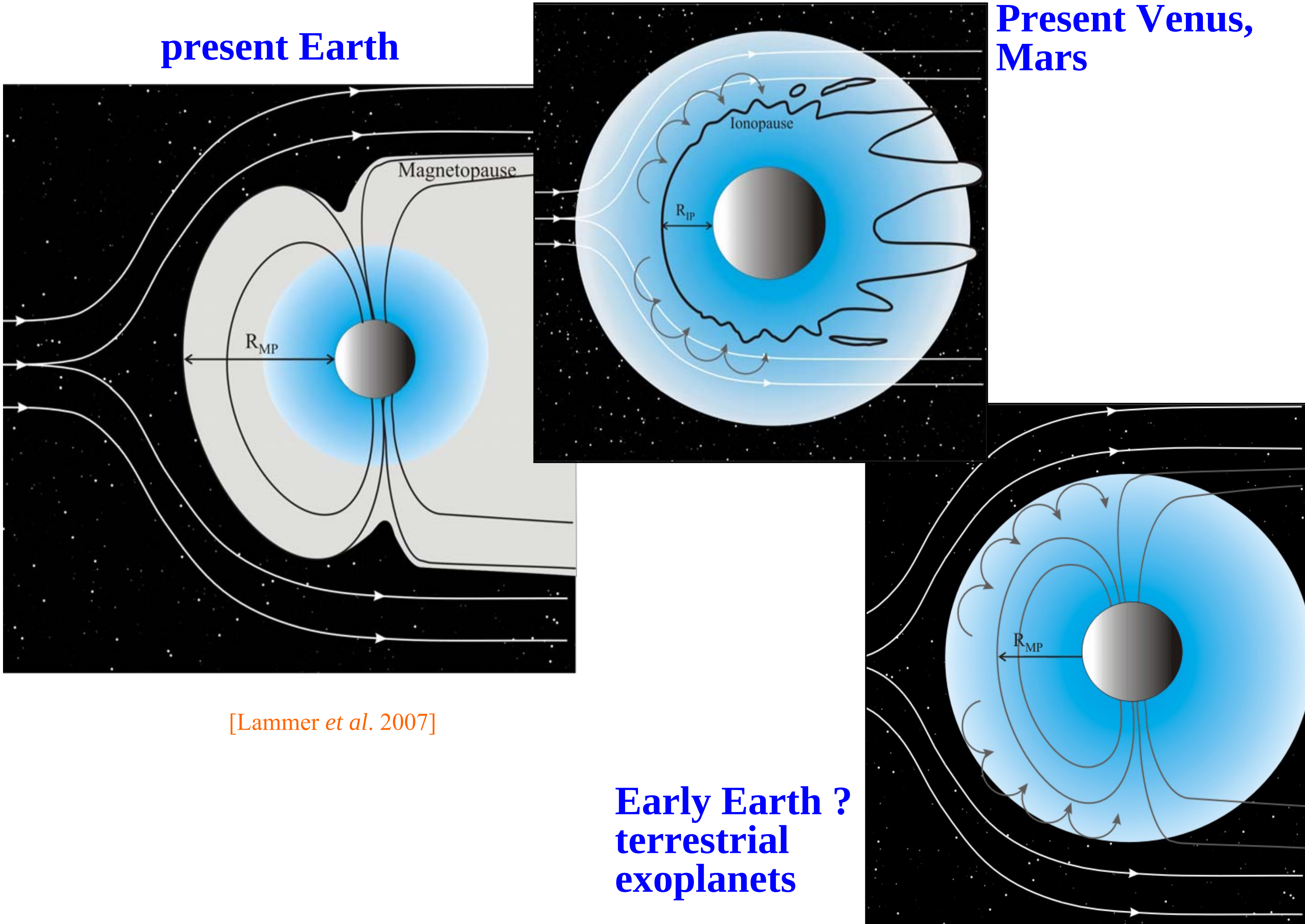
Hydrostatic equilibrium is only valid until 5.3 EUV (~ 3.5 Ga ago) for higher EUV fluxes the O and N start to flow hydrodynamically and adiabatic cooling occurs with related atmospheric expansion

→ extreme non-thermal loss rates can be expected

→ EUV >> 20 during the first 500 Ga

- Thermosphere model coupled with hydrodynamic flow model up to the exobase; above the exobase level kinetic Jeans approach
- For XUV fluxes more than 6 times the present flux (> 3.8 Gyr ago) one can expect extremely expanded upper atmospheres if not huge amounts of additional IR coolers lik CO_2 are present → extreme nonthermal loss rates can be expected (no magnetic protection)
- Therefore, the CO_2 abundance in the Earth's atmosphere during the first 500 Myr should be much higher than ~3.5 Gyr ago → in agreement with Kulikov *et al.* SpSciRev, 2007

Soft X-ray and EUV induced expansion of the upper atmospheres can lead to high non-thermal loss rates



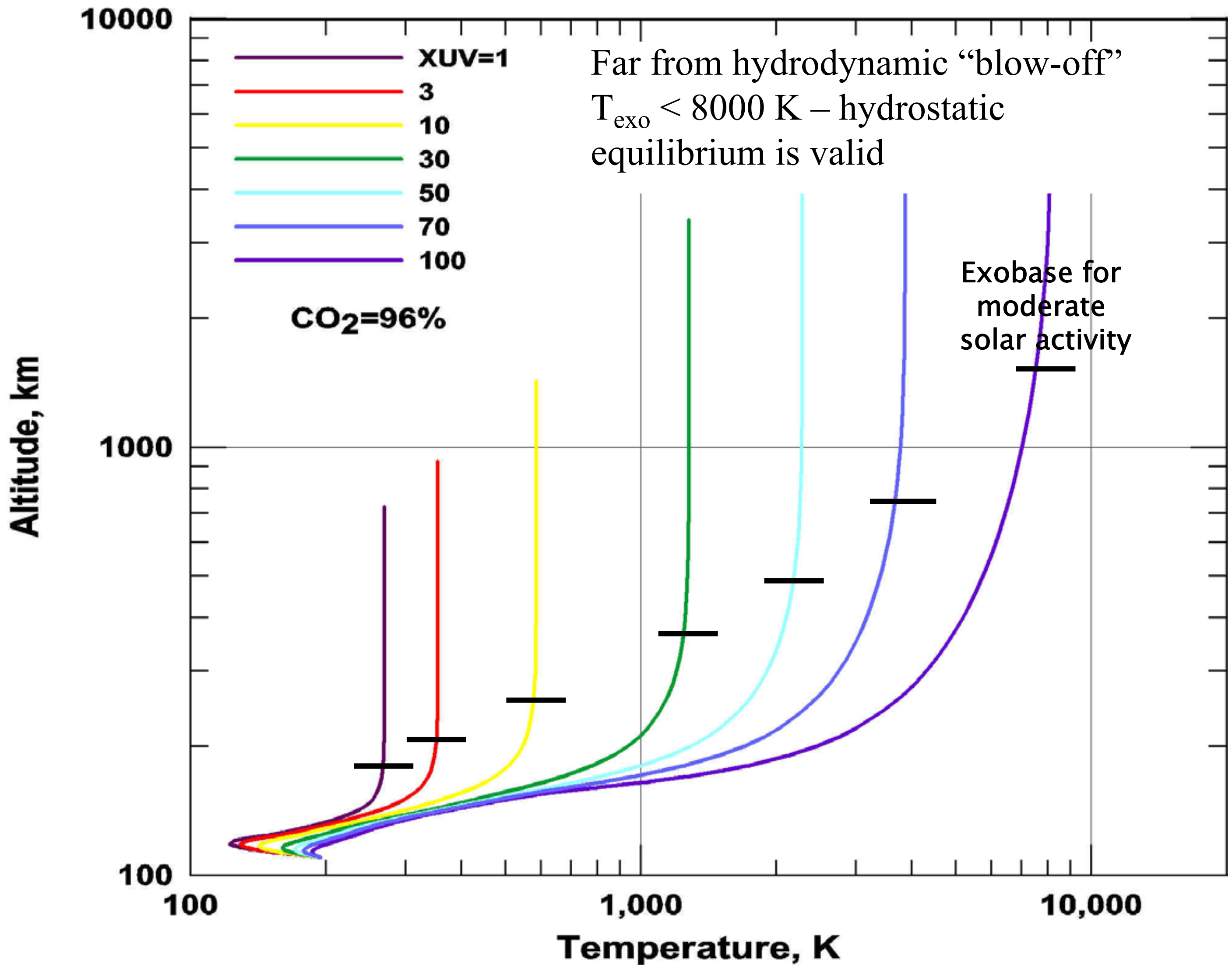
present Earth

Present Venus, Mars

Early Earth ?
terrestrial
exoplanets

[Lammer *et al*. 2007]

XUV response of the exobase temperature on a Venus-like thermosphere (dry case)

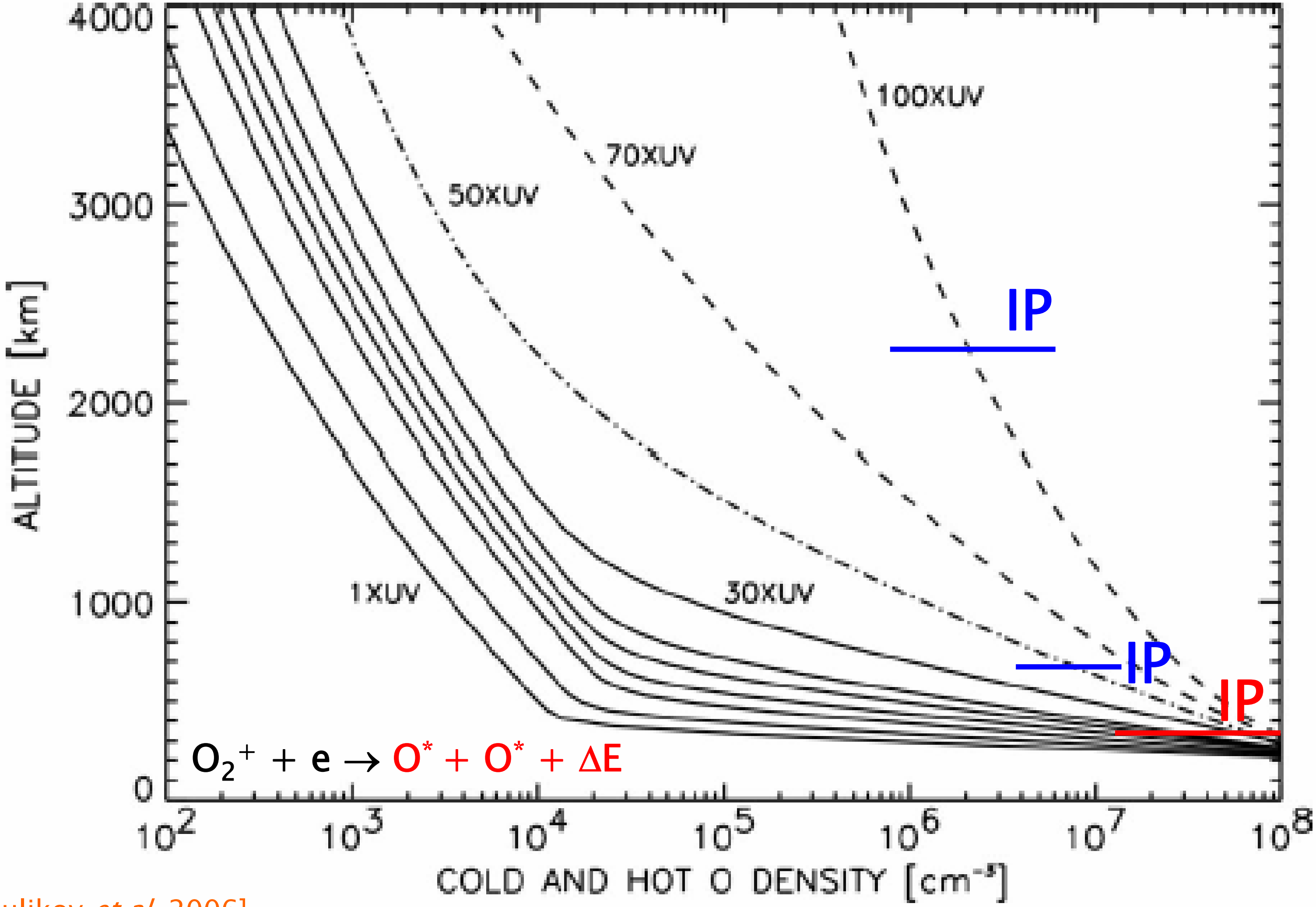


Far from hydrodynamic “blow-off”
T_{exo} < 8000 K – hydrostatic equilibrium is valid

Exobase for moderate solar activity

[Kulikov *et al.* 2006]

Hot and background O atoms as function of XUV flux for a "dry" Venus atmosphere

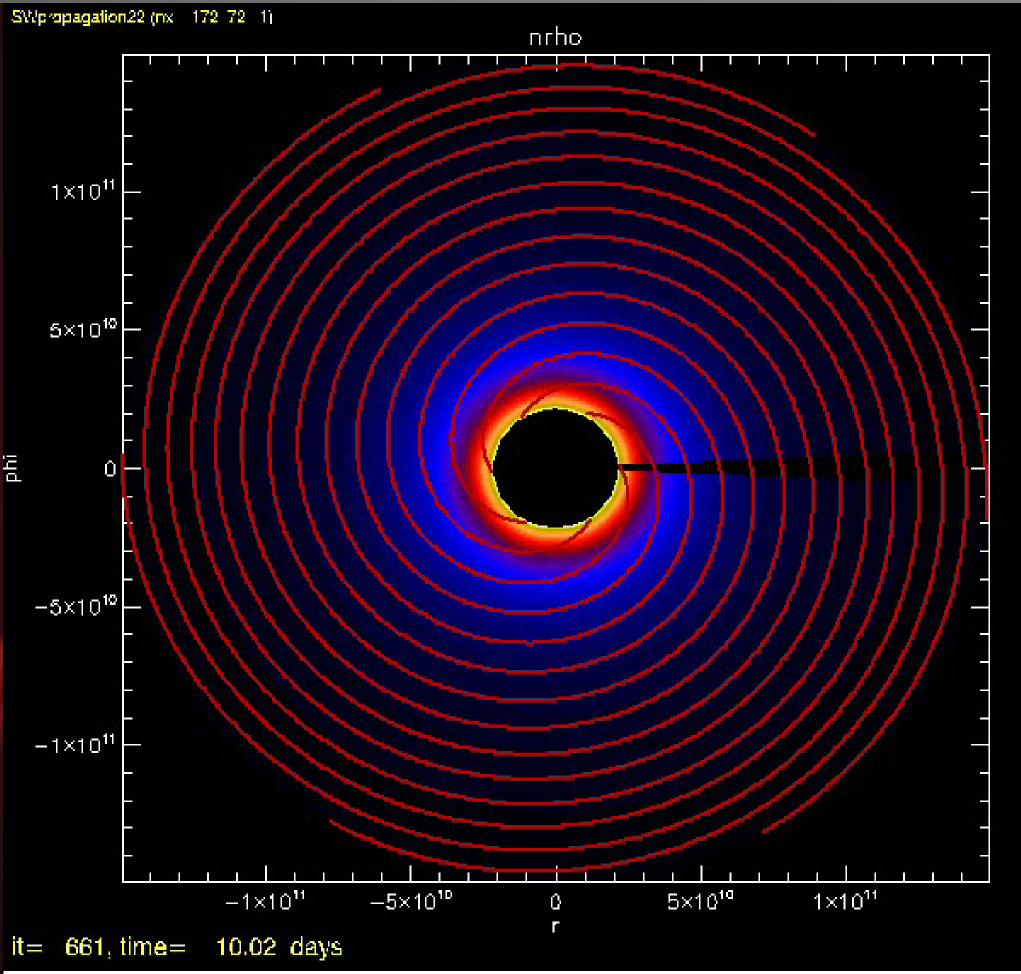


$O_2^+ + e \rightarrow O^* + O^* + \Delta E$

[Kulikov *et al*. 2006]

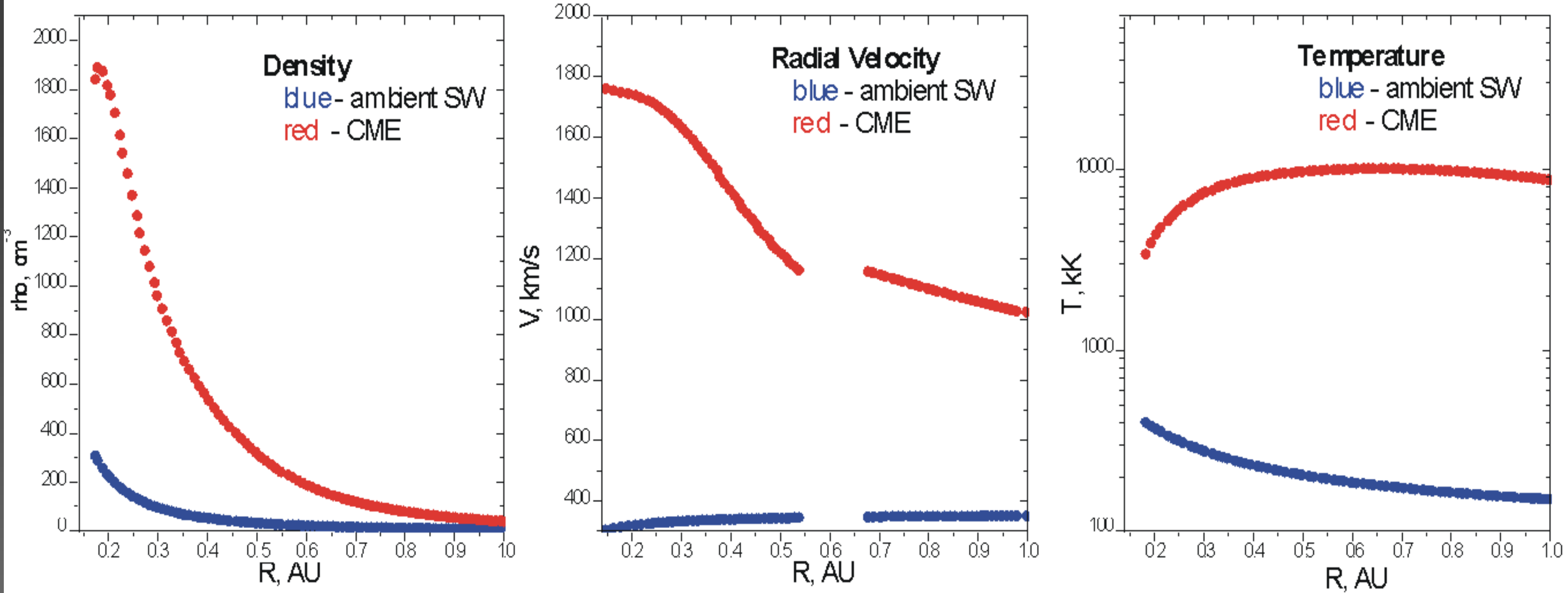
Extreme plasma interaction with extended atmosphere ?

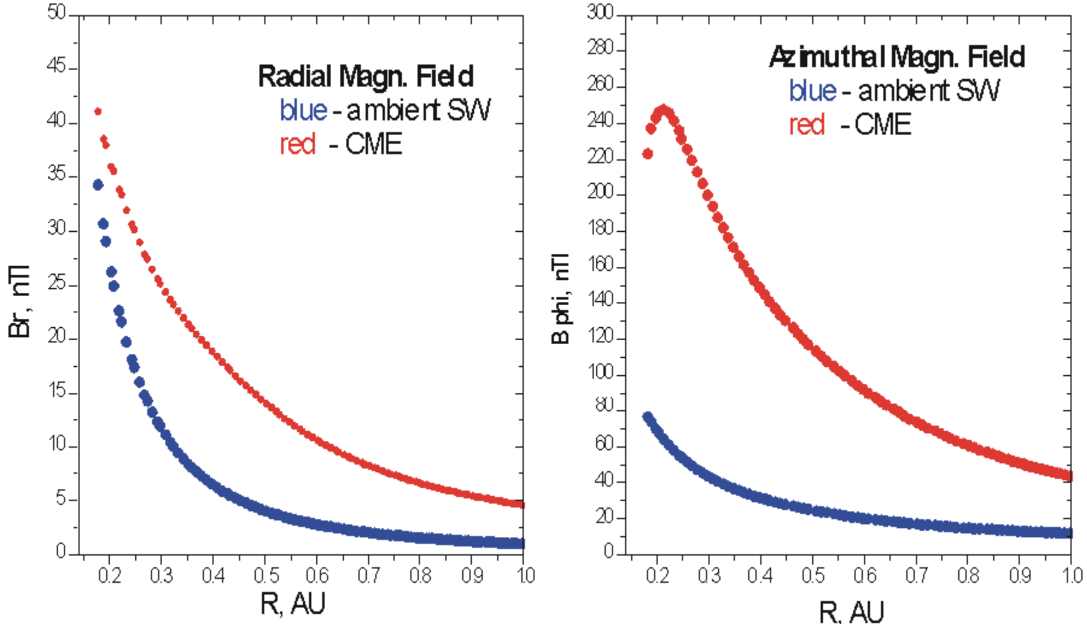
Plasma environment within close-in habitable zones



Versatile Advection Code (VAC): simulation of stellar CME propagation

Plasma environment within close-in habitable zones





M star

Grid:
R = 0.14 - 1 AU
dR = 0.005 AU
dφ = 5 deg.
dθ = 10 deg.

Initial parameters at R=0.14 AU:

rho_SW = 500 cm^{-3}	**rho_CME = 2000 cm^{-3}**
V_SW = 300 km/s	**V_CME = 1800 km/s**
T_SW = 500 kK	T_CME = 2000 kK
Br_SW = 57 nT	
Bφ_SW = - 108 nT	t_CME = 10 hour

Star parameters:
Mstar = 0.4 Msun
Ω_star = 10Ω_sun = 2.5 d

3D MHD simulation of Venus solar wind interaction with present & extreme conditions → N. Terada *et al.*

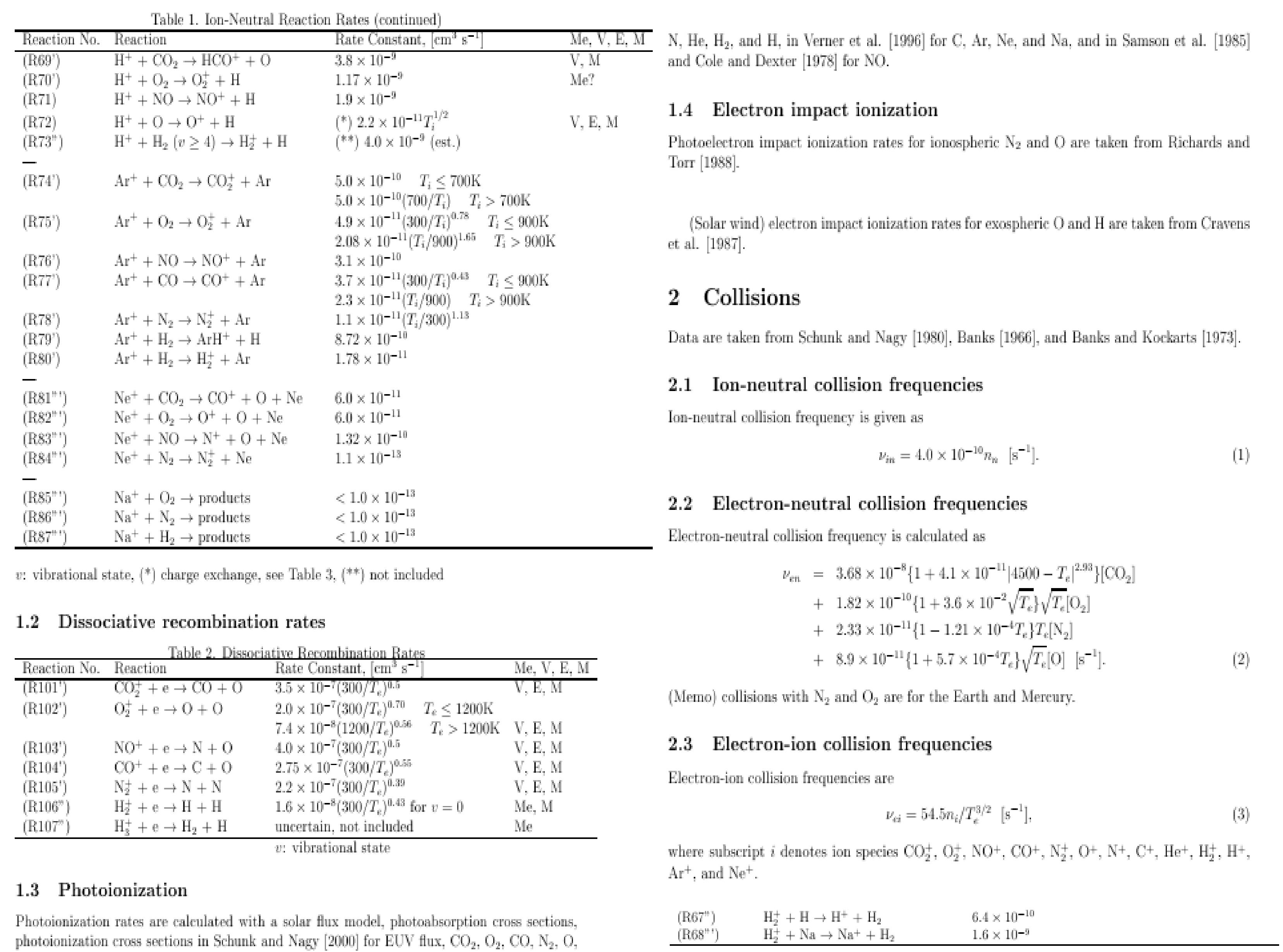


Table 1. Ion-Neutral Reaction Rates (continued)

Reaction No.	Reaction	Rate Constant, $[cm^3\ s^{-1}]$	Me, V, E, M
(R69')	$H^+ + CO_2 \rightarrow HCO^+ + O$	3.8×10^{-9}	V, M
(R70')	$H^+ + O_2 \rightarrow O_2^+ + H$	1.17×10^{-9}	Me?
(R71)	$H^+ + NO \rightarrow NO^+ + H$	1.9×10^{-9}	
(R72)	$H^+ + O \rightarrow O^+ + H$	(*) $2.2 \times 10^{-11} T_i^{1/2}$	V, E, M
(R73")	$H^+ + H_2\ (v \geq 4) \rightarrow H_2^+ + H$	(**) 4.0×10^{-9} (est.)	
—			
(R74')	$Ar^+ + CO_2 \rightarrow CO_2^+ + Ar$	5.0×10^{-10} $T_i \leq 700K$ $5.0 \times 10^{-10}(700/T_i)$ $T_i > 700K$	
(R75')	$Ar^+ + O_2 \rightarrow O_2^+ + Ar$	$4.9 \times 10^{-11}(300/T_i)^{0.78}$ $T_i \leq 900K$ $2.08 \times 10^{-11}(T_i/900)^{1.65}$ $T_i > 900K$	
(R76')	$Ar^+ + NO \rightarrow NO^+ + Ar$	3.1×10^{-10}	
(R77')	$Ar^+ + CO \rightarrow CO^+ + Ar$	$3.7 \times 10^{-11}(300/T_i)^{0.43}$ $T_i \leq 900K$ $2.3 \times 10^{-11}(T_i/900)$ $T_i > 900K$	
(R78')	$Ar^+ + N_2 \rightarrow N_2^+ + Ar$	$1.1 \times 10^{-11}(T_i/300)^{1.13}$	
(R79')	$Ar^+ + H_2 \rightarrow ArH^+ + H$	8.72×10^{-10}	
(R80')	$Ar^+ + H_2 \rightarrow H_2^+ + Ar$	1.78×10^{-11}	
—			
(R81"')	$Ne^+ + CO_2 \rightarrow CO^+ + O + Ne$	6.0×10^{-11}	
(R82"')	$Ne^+ + O_2 \rightarrow O^+ + O + Ne$	6.0×10^{-11}	
(R83"')	$Ne^+ + NO \rightarrow N^+ + O + Ne$	1.32×10^{-10}	
(R84"')	$Ne^+ + N_2 \rightarrow N_2^+ + Ne$	1.1×10^{-13}	
—			
(R85"')	$Na^+ + O_2 \rightarrow$ products	$< 1.0 \times 10^{-13}$	
(R86"')	$Na^+ + N_2 \rightarrow$ products	$< 1.0 \times 10^{-13}$	
(R87"')	$Na^+ + H_2 \rightarrow$ products	$< 1.0 \times 10^{-13}$	

v: vibrational state, (*) charge exchange, see Table 3, (**) not included

1.2 Dissociative recombination rates

Table 2. Dissociative Recombination Rates

Reaction No.	Reaction	Rate Constant, $[cm^3\ s^{-1}]$	Me, V, E, M
(R101')	$CO_2^+ + e \rightarrow CO + O$	$3.5 \times 10^{-7}(300/T_e)^{0.5}$	V, E, M
(R102')	$O_2^+ + e \rightarrow O + O$	$2.0 \times 10^{-7}(300/T_e)^{0.70}$ $T_e \leq 1200K$ $7.4 \times 10^{-8}(1200/T_e)^{0.56}$ $T_e > 1200K$	V, E, M
(R103')	$NO^+ + e \rightarrow N + O$	$4.0 \times 10^{-7}(300/T_e)^{0.5}$	V, E, M
(R104')	$CO^+ + e \rightarrow C + O$	$2.75 \times 10^{-7}(300/T_e)^{0.55}$	V, E, M
(R105')	$N_2^+ + e \rightarrow N + N$	$2.2 \times 10^{-7}(300/T_e)^{0.39}$	V, E, M
(R106")	$H_2^+ + e \rightarrow H + H$	$1.6 \times 10^{-8}(300/T_e)^{0.43}$ for $v = 0$	Me, M
(R107")	$H_3^+ + e \rightarrow H_2 + H$	uncertain, not included	Me

v: vibrational state

1.3 Photoionization

Photoionization rates are calculated with a solar flux model, photoabsorption cross sections, photoionization cross sections in Schunk and Nagy [2000] for EUV flux, CO_2, O_2, CO, N_2, O, N, He, H_2, and H, in Verner et al. [1996] for C, Ar, Ne, and Na, and in Samson et al. [1985] and Cole and Dexter [1978] for NO.

1.4 Electron impact ionization

Photoelectron impact ionization rates for ionospheric N_2 and O are taken from Richards and Torr [1988].

(Solar wind) electron impact ionization rates for exospheric O and H are taken from Cravens et al. [1987].

2 Collisions

Data are taken from Schunk and Nagy [1980], Banks [1966], and Banks and Kockarts [1973].

2.1 Ion-neutral collision frequencies

Ion-neutral collision frequency is given as

$$\nu_{in} = 4.0 \times 10^{-10} n_n \quad [s^{-1}]. \tag{1}$$

2.2 Electron-neutral collision frequencies

Electron-neutral collision frequency is calculated as

$$\begin{aligned} \nu_{en} &= 3.68 \times 10^{-8}\{1 + 4.1 \times 10^{-11}\lvert 4500 - T_e\rvert^{2.93}\}[CO_2] \\ &+ 1.82 \times 10^{-10}\{1 + 3.6 \times 10^{-2}\sqrt{T_e}\}\sqrt{T_e}[O_2] \\ &+ 2.33 \times 10^{-11}\{1 - 1.21 \times 10^{-4} T_e\} T_e [N_2] \\ &+ 8.9 \times 10^{-11}\{1 + 5.7 \times 10^{-4} T_e\}\sqrt{T_e}[O] \quad [s^{-1}]. \end{aligned} \tag{2}$$

(Memo) collisions with N_2 and O_2 are for the Earth and Mercury.

2.3 Electron-ion collision frequencies

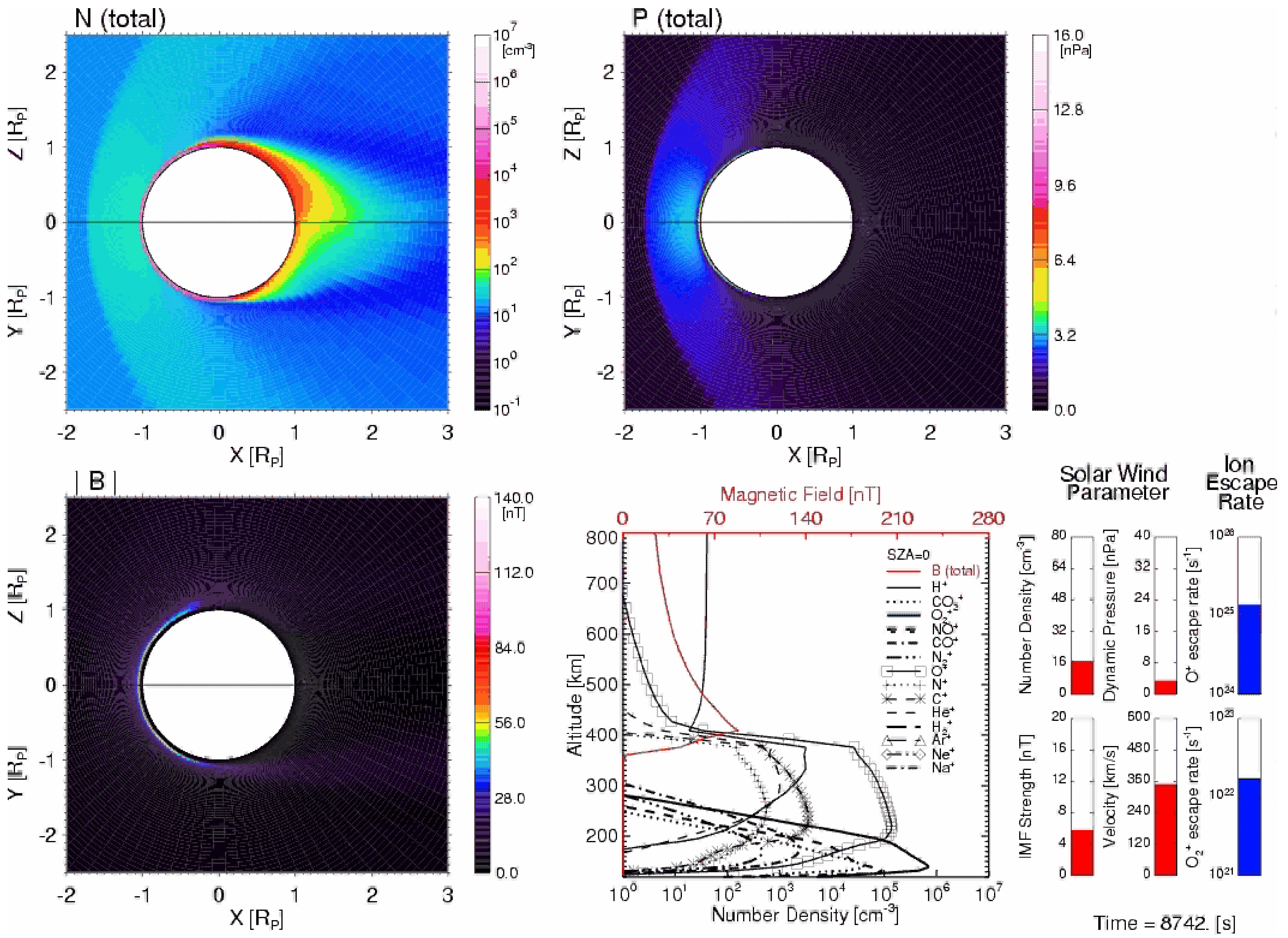
Electron-ion collision frequencies are

$$\nu_{ei} = 54.5 n_i / T_e^{3/2} \quad [s^{-1}], \tag{3}$$

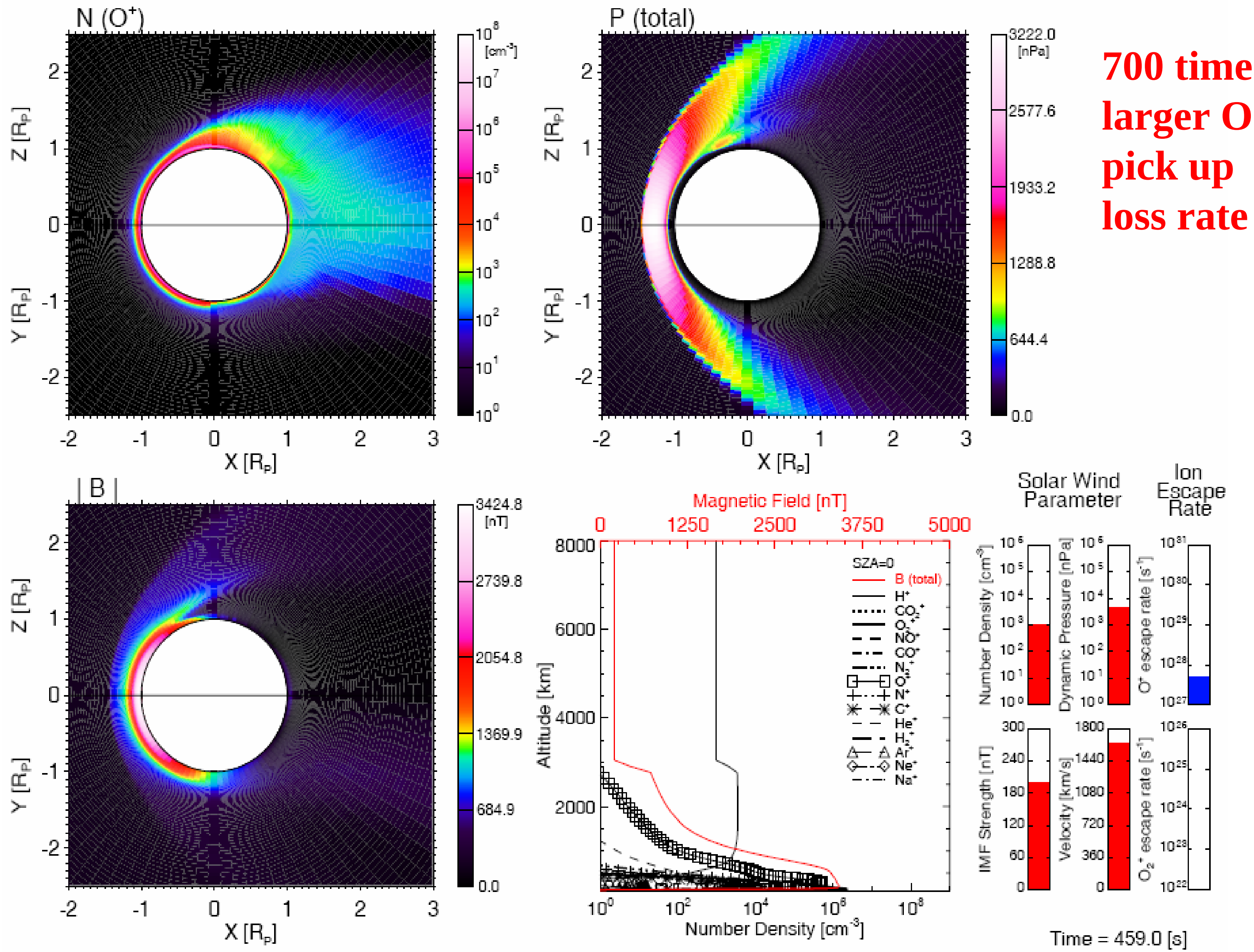
where subscript i denotes ion species CO_2^+, O_2^+, NO^+, CO^+, N_2^+, O^+, N^+, C^+, He^+, H_2^+, H^+, Ar^+, and Ne^+.

(R67")	$H_2^+ + H \rightarrow H^+ + H_2$	6.4×10^{-10}
(R68"')	$H_2^+ + Na \rightarrow Na^+ + H_2$	1.6×10^{-9}

O^+ pick up loss rates of present Venus at 0.7 AU

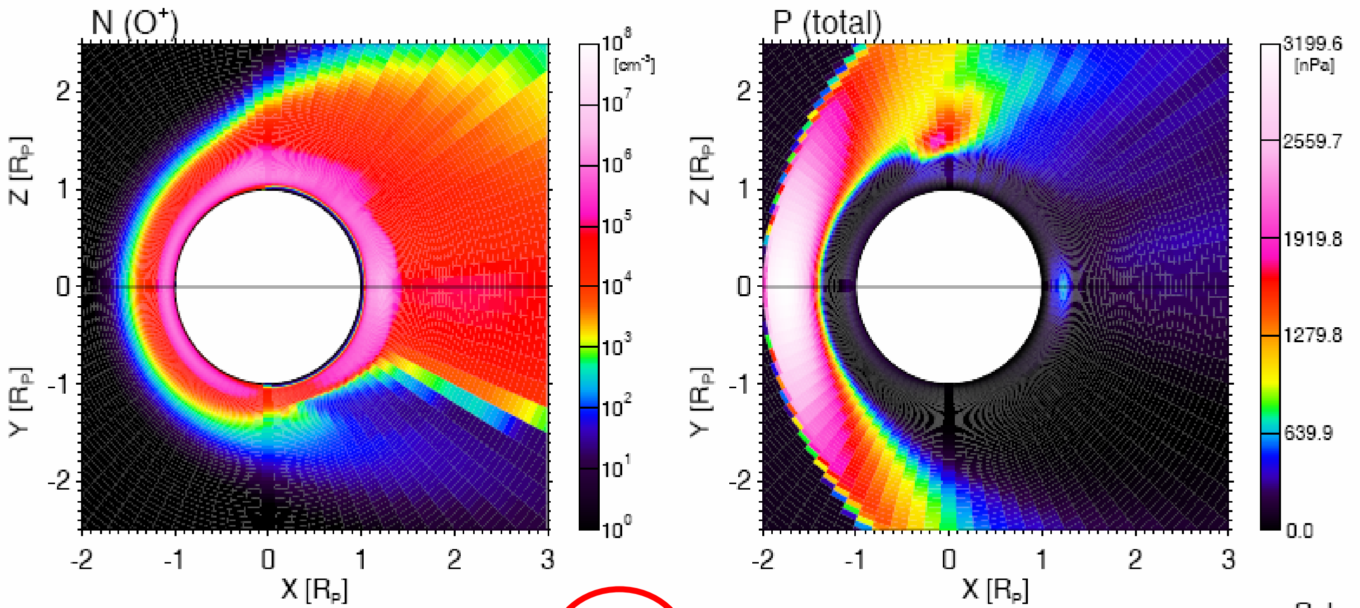


O^+ pick up loss rates of Venus 4.25 Gyr ago; 30 XUV; n_{sw}=1000 cm-3 or M-star Exo-Venus at 0.3 AU



700 times larger O^+ pick up loss rate

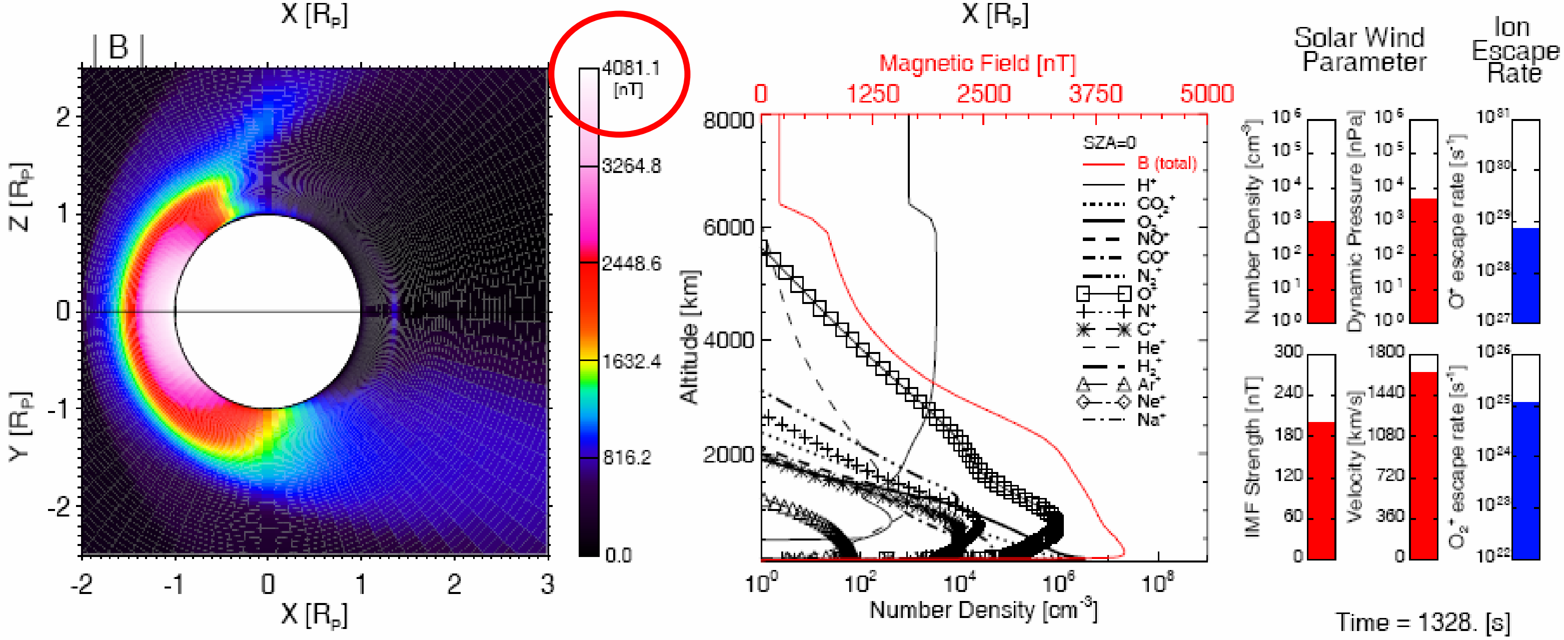
O^+ pick up loss rates of Venus 4.5 Gyr ago 100 XUV; n_{sw}=1000 cm^{-3} or (M-star) Exo-Venus at 0.3 AU



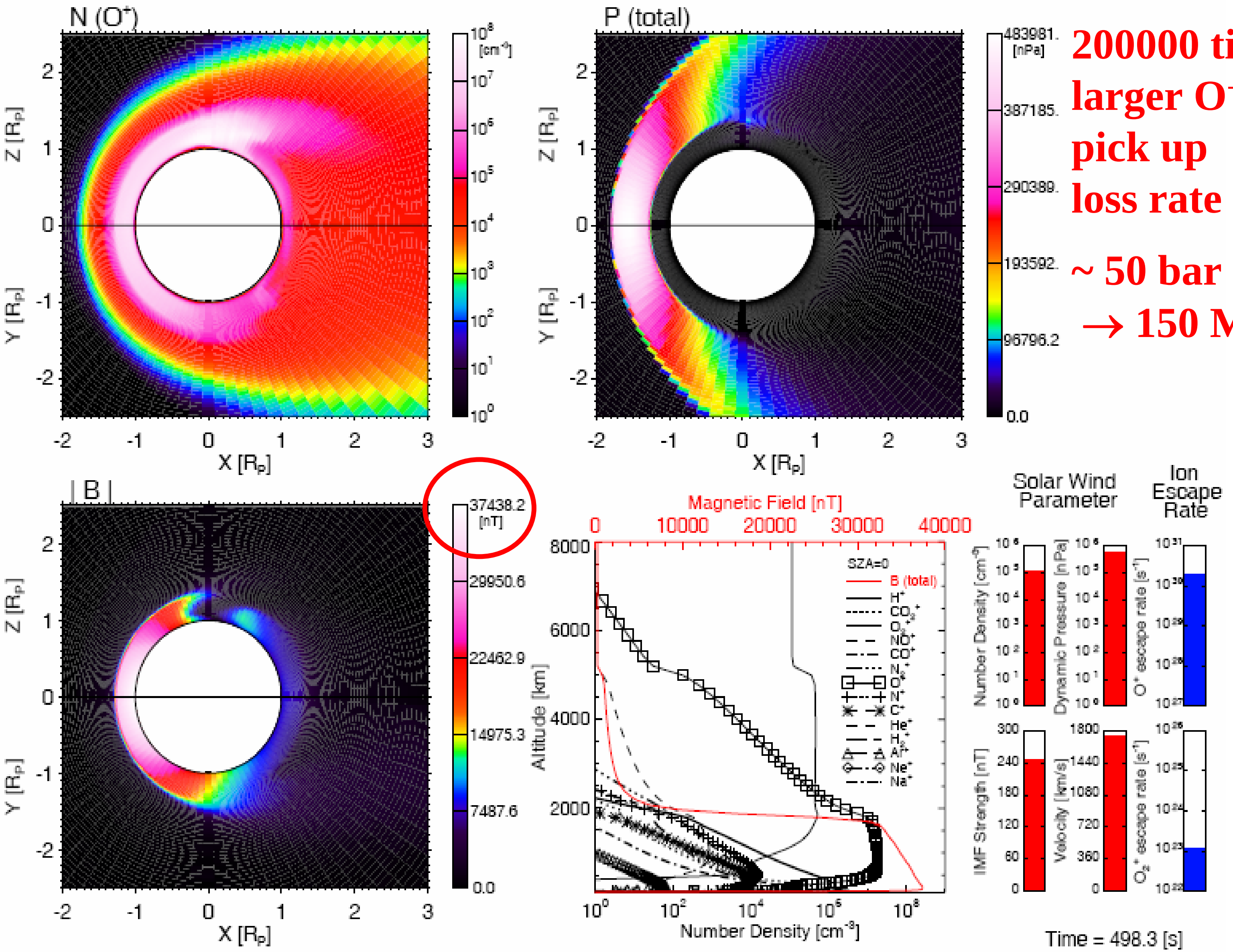
8000 times larger O^+ pick up loss rate

~ 2 bar → 150 Myr

Obstacle ~ 2000 km



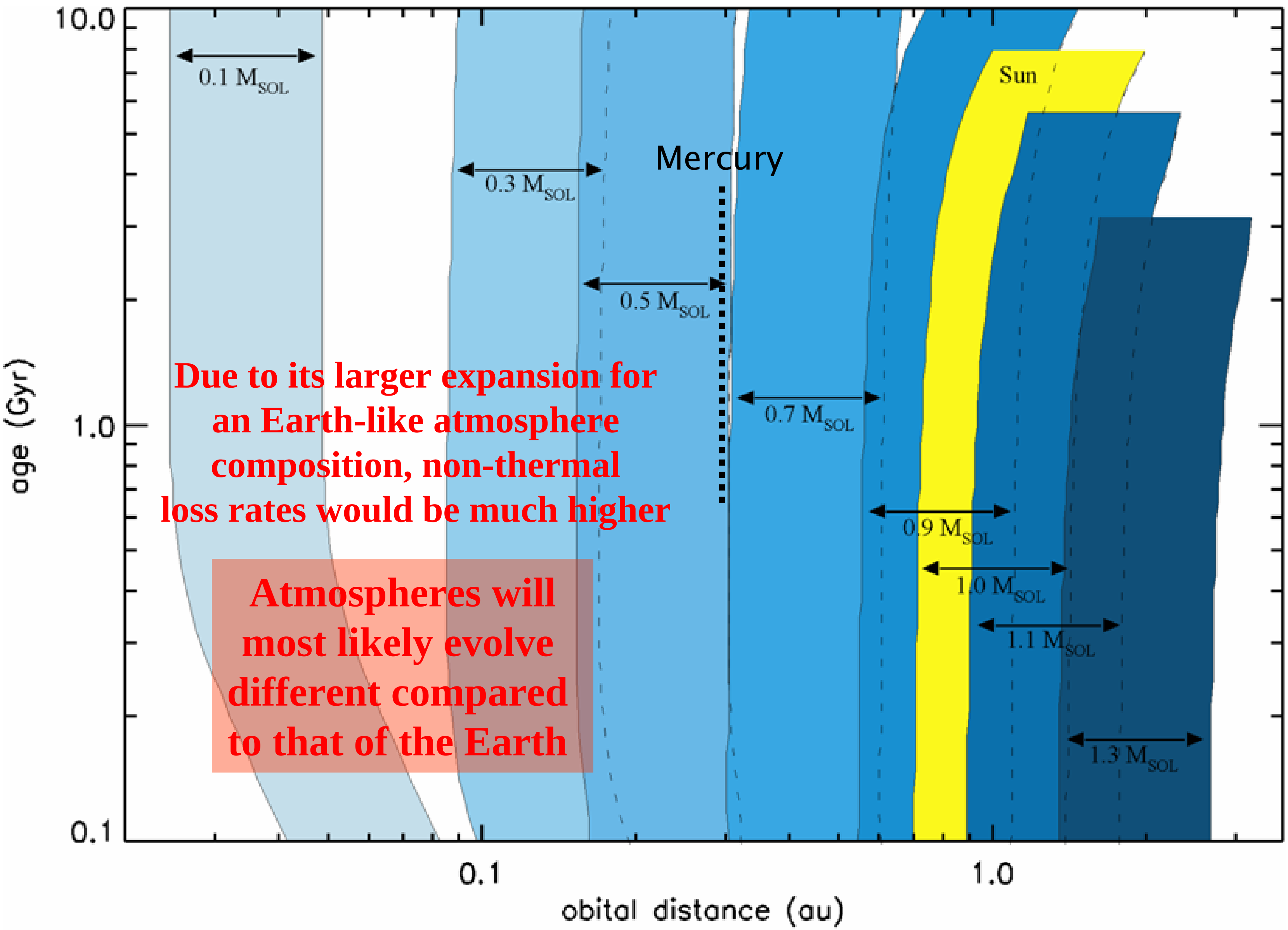
3D MHD simulation of a Venus-like planet under extreme solar/stellar wind conditions → 0.05 AU



200000 times larger O^+ pick up loss rate

~ 50 bar → 150 Myr

Water inventories and atmospheres are strongly effected due to non-thermal loss processes



Due to its larger expansion for an Earth-like atmosphere composition, non-thermal loss rates would be much higher

Atmospheres will most likely evolve different compared to that of the Earth

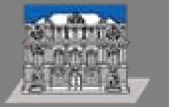
Conclusions

- Intrinsic or induced magnetic fields which are strong enough to balance the dense CME plasma pressure in the upper atmosphere are necessary!

- Ion pick up is only one of several non-thermal loss processes.
  → Inclusion of ionospheric-plasma bubbles, which may be triggered by instabilities, sputtering, cool-in outflow

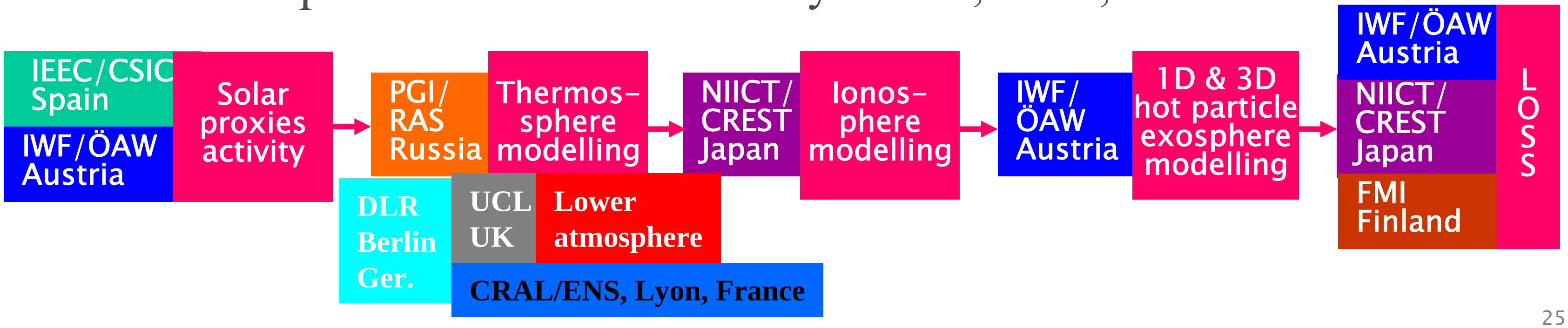
- Applications of 3D hybrid-codes (ion pick up & viscous processes including loss due to plasma instabilities) + 3D sputtering codes

- Weak magnetic planets may be eroded down to their core-mass/size
  → CoRoT should discover such cores and there exists an evaporation boundary beyond gas giants should keep their mass over evolutionary time scales



Ongoing activities and future outlook

- Solar/stellar drivers for thermal and non-thermal escape processes
- Thermosphere - ionosphere – exosphere → escape
- Recent and preliminary modelling efforts for extreme solar/stellar conditions
  - 1D diffusive-gravitational equilibrium and thermal balance modelling of Venus and Martian-type CO_2 atmospheres under extreme XUV conditions → early Venus, early Mars & CO_2-rich terrestrial exoplanets
  - ionosphere and 1D and 3D hot particle and exosphere modelling
  - application of test particle and 3D MHD and 3D hybrid models
  - for upper atmosphere – solar wind interaction under extreme
  - radiation/plasma conditions → early Venus, Mars, etc.



IEEC/CSIC Spain

IWF/ÖAW Austria

Solar proxies activity

PGI/RAS Russia

Thermosphere modelling

DLR Berlin Ger.

UCL UK

Lower atmosphere

CRAL/ENS, Lyon, France

NIICT/CREST Japan

Ionosphere modelling

IWF/ÖAW Austria

1D & 3D hot particle exosphere modelling

IWF/ÖAW Austria

NIICT/CREST Japan

FMI Finland

LOSS